ENHANCED MULTICHANNEL ROUTING PROTOCOLS IN MANET

by

Nawaf Saleh Mirza

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Abstract

Utilising multiple non-overlapping channels in MANET networking can improve performance and capacity. Most multichannel MAC and routing protocols rely on an extra radio interface, a common control channel or time synchronisation to support channel selection and routing, but only at the expense of hardware and power consumption costs. This thesis considers an alternative type of multichannel wireless network where each node has a single half-duplex radio interface and does not rely on a common control channel or time synchronisation.

Multichannel MAC and routing protocols that adopt the Receiver Directed Transmission (RDT) communication scheme are investigated to assess their ability to implement a multichannel MANET.

A novel multipath multichannel routing protocol called RMMMC is proposed to enhance reliability and fault-tolerance in the MANET. RMMMC introduces new route discovery and recovery processes. The former establishes multiple node and channel disjointed paths in different channels and accumulates them to acquire a full multi-hop path to each destination. The latter detects broken links and repairs them using pre-discovered backup routes.

To enhance communication reliability, a novel cross-layer multichannel MAC mechanism called RIVC is proposed. It mitigates transmitting/rerouting data packets to a node that does not have an updated route information towards a destination and only allows data packets with valid routes to occupy the medium. The optional access mode in the MAC protocol is modified to early detect invalid routes at intermediate nodes and switchover to an alternative path.

A new cross-layer multichannel MAC mechanism called MB is proposed to reduce contention in a busy channel and enhance load balancing. MB modifies the MAC back-off algorithm to let a transmitter node invoke an alternative path in the alternative channel when the retry count threshold is reached. The proposed multichannel protocols are implemented and evaluated by extensive NS2 simulation studies.

Dedication

To my parents Jawaher and Saleh

To my Wife Ansar

To my daughter Layan, and my sons Rayan and Saleh

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All praise is to the Almighty Allah, the most Gracious and the most Merciful for his favour, grace, guidance and giving me the strength to undertake this research.

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My final and deepest gratitude to my parents, my wife, my daughter and sons and my siblings you have been extremely understanding and supportive. Thank you for your patience, support and encouragement you have a major role in my success.

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Citation details	Nawaf S Mirza and Peter JB King, Would a multichannel increase ad hoc wireless network capacity?. In PGNET Proceedings of the 15th Annual Postgraduate Symposium on the Convergence of Telecommunications, Networking and Broadcasting, pages 13-17, Liverpool, UK, 2014.
Nawaf S Mirza	Review related literature and write the paper.
Peter JB King	Supervision, guidance in all stages and proofreading.
Signature:	
Date:	25/09/2019

Citation details	Nawaf S Mirza, Mohamed A Abdelshafy, and Peter JB King. Performance evaluation of Receiver Directed Transmission protocol with a single transceiver in MANETs. In Wireless Days (WD), pages 241-244. Porto, Portugal, 2017
Nawaf S Mirza	Design, implement, evaluate the proposed protocol and write the paper.
Mohamed A Abdelshafy	Supervision, critical review and guidance.
Peter JB King	Supervision, guidance in all stages and proofreading.
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Nawaf S Mirza	Design, implement, evaluate the proposed protocol and write the paper.
Peter JB King	Supervision and guidance in all stages.
Imed Romdhani	Critical review, help in the design stage and proofreading.
Mohamed A. Abdelshafy	Supervision, critical review and guidance.
Atif A Alghamdi	Critical review, guidance and helping in the design stage.
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Citation details	Nawaf S Mirza, Hamish Taylor, Mohamed A. Abdelshafy, Peter JB King, Imed Romdhaniy. and Atif A Alghamdi. Cross-Layer Multipath Multichannel MAC Protocol for MANETs. In International Symposium on Networks, Computers and Communications (ISNCC), pages 1-8, Rome, Italy, 2018.
Nawaf S Mirza	Design, implement, evaluate the proposed mechanisms and write the paper.
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Peter JB King	Guidance in all stages.
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Glossary

ACK	Acknowledgement
AODV	Ad hoc On Demand Distance Vector
AOMDV	Ad hoc On-demand Multipath Distance Vector
AP	Access Point
BBS	Basic Service Set
CBR	Constant Bit Rate
CRL	Channel Retry Limit
CSMA/CA	Carrier Sense Multiple Access/Collision Avoidance
CS	Carrier Sense
CTS	Clear To Send
CW	Contention Window
DCF	Distributed Coordination Function
DIFS	DCF Inter-Frame Space
DSDV	Destination Sequenced Distance-Vector
DSR	Dynamic Source Routing
DTN	Delay Tolerant Network
ESS	Extended Service Set
FANET	Flying Ad hoc Network
FSR	Fisheye State Routing
HCF	Hybrid Coordination Function
iAware	interference Aware routing metric
IBSS	Independent Basic Service Set
IEEE	Institute of Electrical and Electronics Engineers

IETF	Internet Engineering Task Force
IP	Internet Protocol
LHF	Least Hop First Algorithm
LLC	Logical Link Control
MAC	Medium Access Control
MANET	Mobile Ad hoc Network
MB	Modified Backoff
MIMO	Multiple-Input Multiple-Output
MPR	MultiPoint Relay
NAV	Network Allocation Vector
NIC	Network Interface Card
NS-2	Network Simulator version 2
OFDM	Orthogonal frequency-division multiplexing
OLSR	Optimized Link State Routing
OMN	Opportunistic Mobile Network
ORCA	On-demand Routing with Coordinate Awareness
OSI	Open Systems Interconnection
OTcl	Object oriented Tool command language
PAN	Personal Area Network
PCF	Point Coordination Function
PDA	Personal Digital Assistants
PER	Packet Error Rate
PLCP	Physical Layer Convergence Procedure
PMD	Physical Medium Dependent
RDT	Receiver Directed Transmission

RERR	Route Error
RF	Radio Frequency
RIVC	Route Information Validity Check
RMMMC	Route Migration over Multiple link failure in Multichannel routing
RREP	Route Reply
RREQ	Route Request
RSSI	Received Signal Strength Indicator
RTS	Request To Send
SIFS	Short Inter-Frame Space
SMR	Split multipath routing
SNR	Signal-to-Noise Ratio
TCL	Tool Command Language
TCP	Transmission Control Protocol
TPC	Transmission Power Control
TTL	Time To Live
UDP	User Datagram Protocol
VANET	Vehicular Ad hoc Network
VCO	Voltage Control Oscillator
WCETT	Weighed Cumulative Expected Transmission Time
WEED	Weighted End-to-End Delay
Wi-Fi	Wireless-Fidelity
WiMAX	Worldwide Interoperability for Microwave Access
WLAN	Wireless Local Area Networks
ZRP	Zone Routing Protocol

Publications

1. Nawaf S Mirza and Peter JB King, Would a multichannel increase ad hoc wireless network capacity?. In PGNET Proceedings of the 15th Annual Postgraduate Symposium on the Convergence of Telecommunications, Networking and Broadcasting, pages 13-17, Liverpool, UK, 2014.

2. Nawaf S Mirza, Mohamed A Abdelshafy, and Peter JB King. Performance evaluation of Receiver Directed Transmission protocol with a single transceiver in MANETs. In Wireless Days (WD), pages 241-244. Porto, Portugal, 2017.

3. Atif A Alghamdi, Peter JB King, and Nawaf S Mirza, Colour-Based Forwarding Scheme with Variable-Range Transmission Power in AODV. In Wireless Days (WD), pages 248-251, Porto, Portugal, 2017.

4. Nawaf S Mirza, Peter JB King, Imed Romdhani, Mohamed A. Abdelshafy. and Atif A Alghamdi, Reliable Multipath Multi-Channel Route Migration over Multi Link-Failure in Wireless Ad Hoc Networks. In Wireless and Mobile Computing, Networking and Communications (WiMob), pages 123-130, Rome, Italy, 2017.

5. Nawaf S Mirza, Hamish Taylor, Mohamed A. Abdelshafy, Peter JB King, Imed Romdhaniy. and Atif A Alghamdi. Cross-Layer Multipath Multichannel MAC Protocol for MANETs. In International Symposium on Networks, Computers and Communications (ISNCC), pages 1-8, Rome, Italy, 2018.

Chapter 1

Introduction

Mobile Ad hoc Networks (MANETs) are self-configured, decentralised infrastructure-less wireless networks. Mobile nodes can communicate wirelessly in a single or multi-hop fashion without relying on a pre-existing network infrastructure. In a MANET nodes move freely and configure themselves on-the-fly without relying on centralised control. Due to dynamic and normally unpredictable node movements, its topology may change frequently and without warning [1]. Lack of pre-existing network infrastructure and self-configuring capabilities make MANET communication possible anytime anywhere. Conventionally, MANETs were used as a means to set up a temporary network and facilitate communication where it is difficult or expensive to establish a complete communication network, such as rural areas without a communication infrastructure, disaster recovery, combat zones, rescue missions, and more [2]. The low cost and flexibility associated with MANET deployment make it a popular area of research in the wireless network community.

In spite of these impressive benefits, MANETs inherit the traditional problems of wireless and mobile communications and have critical limited capacities. The main reason for this limitation is the broadcast nature of wireless communication. A shared wireless medium (or channel) is used by neighbouring nodes tuned to that channel in the same vicinity. Only one node can transmit and consume bandwidth on the channel at any given time to avoid interference and collisions, which reduces the network's capacity. One way to increase network capacity in a wireless network is to enable concurrent communication in multiple non-overlapping (orthogonal) channels to take place in the same vicinity [3, 4].

Wireless communication standards such as IEEE 802.11 specify multiple frequency channels for communication in the physical layer. For instance, IEEE 802.11b [5] divides the frequency spectrum into 14 channels, 3 of which are non-overlapping channels. Concurrent communication among adjacent nodes is possible when orthogonal channels are assigned to different nodes or flows. Although the wireless communication standard IEEE 802.11 defines multiple spectrum frequencies in the same wireless medium, the IEEE 802.11 MAC protocol is designed to operate in a single frequency band (or channel), which reduces network capacity and under-utilises available resources. Hence, extensive research has been conducted to enable the MAC and routing layer protocols to utilise and benefit from the already defined multiple channels, in order to improve network capacity.

1.1 Thesis Scope

The aim of this thesis work is to design, develop and evaluate new protocols for multi-hop MANETs that utilise multiple non-overlapping channels to enhance network performance, under the following constraints: 1) each node in the network is equipped with a single half-duplex transceiver; 2) no common control channel or time synchronisation is required. Utilising multiple non-overlapping (orthogonal) channels under a single transceiver for each node is not trivial, because different nodes operating in different channels cannot hear each other. Equipping nodes with multiple radio interfaces may simplify protocol design and improve channel utilisation further. However, it is more expensive in terms of hardware cost and energy consumption, and may therefore not be suitable in low-cost battery powered devices such as PDAs, phones and laptops.

Utilising a common control channel and/or time synchronisation can facilitate channel assignment and coordination in a multichannel network. However, the common control channel may suffer from control channel saturation problems [6].

Clock synchronisation is a difficult task to accomplish in a large-scale decentralised infrastructure-less dynamic network such as a MANET. Hence, the scope of this thesis is limited to designing multichannel protocols with a single radio interface and without relying on a common control channel or time synchronisation.

This thesis focuses on MAC and routing protocols. Multichannel MAC and multichannel routing protocols aim to utilise multiple channels to improve network performance, but they deal with multiple channels in different ways. For instance, a multichannel MAC protocol is concerned with channel assignment, coordination and medium control in a local vicinity (one-hop). On the other hand, a multichannel routing protocol is concerned with finding a route to a destination and has a wider view of the network (multi-hop).

1.2 Motivation

Current MANET protocols are largely designed to communicate using a single shared channel, despite the availability of multiple channels in wireless communication standards. Although this simplifies the design and implementation of the MAC and routing protocols, it limits network capacity. As the number of nodes and/or amount of traffic in the network increases, interference, contention and collisions in the single shared medium increase and degrade network performance [7, 8]. However, multichannel communication can reduce these issues in the wireless medium by dividing the collision domain into smaller separate domains, thereby improving network performance.

To exploit multichannel communication in wireless networks, three issues need to be addressed: a) the number of available radio interfaces (single or multiple radio) per node, which concerns the capability of the wireless device to transmit and/or receive at the same time; b) the adopted channel assignment approach, which is concerned with assigning a channel to a radio interface, facilitating channel negotiation (agreement); and c) the adopted routing mechanism, which is concerned with discovering and maintaining a single or multiple routes to a destination and transmitting data packets. The decision to use single or multiple half-duplex radio interfaces, and the choice of channel assignment and routing approaches, greatly depend on the implementation requirements, which are determined by various factors such as related hardware and energy consumption costs, the compatibility of wireless devices, and ease of deployment among others.

Due to the unreliability of a wireless medium, its broadcast nature and unpredictable topology changes, single path routing is prone to frequent link failure in MANETs which make routing protocols unreliable [9]. In order to improve communication reliability, multipath routing protocols can be used [10]. In this approach multiple routes are discovered between source and destination nodes that are used to recover from a single or multiple broken links and provide load balancing to the routing protocol [11, 9].

This thesis has the following objectives:

- Study and investigate the impact of using a semi-dynamic channel assignment approach on a MANET. More specifically, study the impact of using a Receiver Directed Transmission (RDT) [12] communication scheme to implement a multichannel network.

- Design and implement a new multipath multichannel routing protocol that can enhance routing reliability and provide error resilience and fault-tolerance in a MANET. The design of multipath multichannel routing protocol should be based on a single radio interface per node. In addition, it should not rely on use of a common control channel or time synchronisation.

- Design and implement cross-layer mechanisms to share multipath multichannel routing information with the multichannel MAC protocol in order to exploit already available routing information.

- Investigate the impact of synergising the multichannel MAC and the multipath multichannel routing protocol in order to enhance multipath multichannel communication in MANET where nodes have a single transceiver.

- Evaluate the performance of the proposed multichannel solutions by considering various MANETs scenarios and configurations, namely network density, node mobility and number of connections. In addition, compare the performance of the proposed solutions to some existing MANET routing protocols.

1.3 Contributions

This thesis makes the following contributions to research in this field:

1. It designs and implements a multichannel MAC (RDT-MAC) and routing (RDT-AODV) protocols that use the Receiver Directed Transmission (RDT) [12] communication scheme. Unlike other studies this research assumes that each node is equipped with only a single half-duplex radio interface, and does not rely on a common control channel or time synchronisation. Additionally, the study evaluates the performance of the multichannel RDT routing protocol under various network configurations.

2. It designs and implements a novel fault-tolerant multipath multichannel routing protocol called Route Migration over Multiple link failure in Multichannel routing protocol (RMMMC). RMMMC aims to improve reliability and resilience to link failure in multichannel routing protocols in MANETs. RMMMC proposes new route discovery and recovery mechanisms. The route discovery mechanism supports route accumulation in a reactive routing protocol and aims to identify multiple node and channel dis-jointed paths between source and destination nodes. The proposed route recovery mechanism enables a node detect a broken link to reroute the data packets seamlessly to an alternative node in different channels without incurring an extra routing overhead or a delay in recovering from the broken link. Additionally, RMMMC improves local connectivity in the multichannel routing protocol by enabling nodes to maintain their local connectivity with neighbour nodes operating in different channels.

3. It designs and implements a novel cross-layer multichannel MAC mechanism to enhance the reliability of communication in the multipath multichannel routing protocols. The proposed multichannel MAC mechanism is called Route Information Validity Check (RIVC). RIVC modifies the working process of the optional access mode (RTS/CTS) in IEEE 802.11 DCF to support the route validity check. RIVC improves the reliability of communication by enabling a transmitter node to check the validity of a route at the receiver node before any transmission/rerouting process takes place. Additionally, RIVC enables a transmitter node, which is informed about the invalidity of routing information at a receiver node, to reroute data packets opportunistically using a pre-discovered alternative path in a different channel.

4. It designs and implements a new cross-layer multichannel MAC mechanism to reduce congestion in a busy channel and enhance load balancing in multipath multichannel routing protocols. The proposed multichannel MAC mechanism is called Modified Back-off (MB). MB modifies the back-off algorithm in IEEE 802.11 DCF. MB reduces traffic in the busy channel and provides a way to balance load by enabling a transmitter node to reroute data packets via a pre-discovered alternative route when the retry count threshold is reaches.

5. The new multichannel protocols in this thesis were implemented and extensively assessed using the well-known Network Simulator (NS-2). Extensive simulations were conducted to evaluate the proposed multichannel protocols under different network configurations, while considering different network densities, mobility and number of connections (offered load) in the network. The performances of the proposed multichannel solutions were also compared against different multichannel and single channel routing protocols.

   This thesis's contributions are spread over two layers: layer 2 (data link) and layer 3 (network). An overview of this thesis's contributions in accordance with the OSI-model for MANETs is given in Figure 1.1.

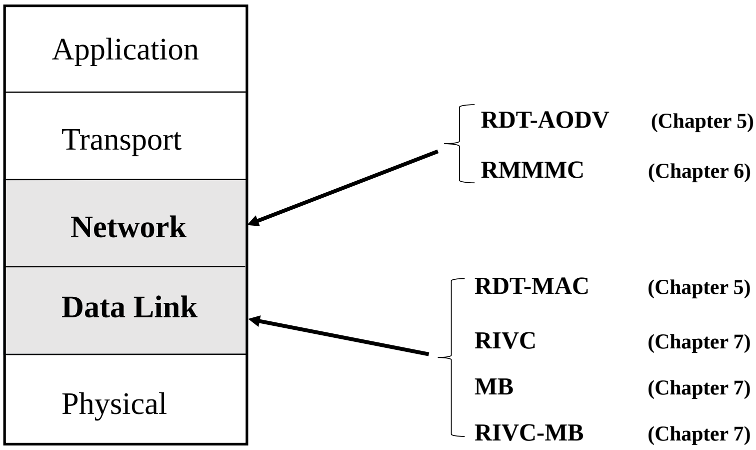

Figure 1.1: Overview of thesis contributions

1.4 Thesis Organisation

This thesis consists of eight chapters and is structured as follows:

Chapter 1: specifies the scope of this thesis along with the motivation behind carrying out the research. Then the main intellectual contributions of this thesis and its organisation are given.

Chapter 2: provides background information related to MANETs. This is required to understand the proposed solutions in subsequent chapters. This chapter starts with an overview of wireless networks, followed by a detailed explanation of some mechanisms in the de facto wireless standard, the IEEE 802.11 MAC, which are modified in proposed solutions in subsequent chapters. Then, an overview of MANETs along with their characteristics and different possible applications is provided, followed by a detailed explanation of different strategies and classifications employed in single channel routing protocols in MANETs.

Chapter 3: presents an overview of multichannel communication in wireless ad hoc networks, along with its benefits, challenges and the impact of having multiple interfaces per node. Then detailed descriptions of different approaches in the literature to implement channel assignment in MAC layer protocols are provided. This is followed by a review of different routing approaches to support multichannel communication in MANETs. There is then a detailed discussion related to the impact of having a number of radio interfaces, channel assignment and multichannel routing approaches in MANETs. This is followed by a justification of the approaches adopted in this thesis.

Chapter 4: describes and justifies the research methodology used to conduct simulation studies. Brief descriptions of the chosen routing protocol and the chosen cross-layer design approach are given. Different system modelling techniques used in the wireless network research community are briefly discussed and then selection of a suitable simulation tool is justified. This is followed by an explanation of the extension used to support multichannel communication in the network simulator (NS-2). Finally, the simulation environment, assumptions and performance metrics to evaluate the proposed protocols are presented.

Chapter 5: evaluates the performance of the multichannel RDT communication scheme where each node is equipped with only a single half-duplex radio interface, without relying on a common control channel or time synchronisation. Additionally, it reviews existing multichannel protocols using the RDT communication scheme as their main approach to implementing a multichannel network. Finally, it investigates and analyses the effect of varying the node density, mobility and number of connections in a MANET network on RDT-AODV protocol performance. It compares its performance against the single channel single radio protocol (AODV) and the multichannel multi-radio protocol (xRDT).

Chapter 6: presents a multipath extension to the multichannel routing protocol presented in Chapter 5, called RMMMC. Chapter 6 outlines the required modifications to the routing table and control packets to support multipath functionality in RMMMC. Then a detailed description is provided of the working process of the proposed route discovery and recovery mechanisms in RMMMC. Finally, the chapter investigates and analyses the effect of varying node density, mobility and number of connections in a MANET network on multipath multichannel routing protocol's (RMMMC) performance. It compares its performance against a multipath single channel routing protocol (AOMDV) and a single path multichannel routing protocol (RDT-AODV).

Chapter 7: presents two cross-layer multichannel MAC mechanisms that aim to improve the reliability of communication and load balancing in the multipath multichannel routing protocols presented in Chapter 6. The first mechanism is called Route Information Validity Check (RIVC), while the second mechanism is called Modified Back-off (MB). This chapter describes in detail the working process of each mechanism along with their benefits for the multipath multichannel routing protocol. Then, a combination of both mechanisms is presented, called RIVC-MB. Finally, the chapter investigates and analyses the effect of varying node density, mobility and number of connections in the network on the proposed MAC mechanisms' (RIVC, MB and RIVC-MB) performance. It compares their performance against a multipath multichannel routing protocol (RMMMC).

Chapter 8: provides conclusions to the work presented in this thesis and proposes future work.

Chapter 2

Background

2.1 Introduction

This chapter aims to provide background information which is required to understand subsequent chapters. This chapter starts with an overview of the wireless network, followed by a detailed description of some mechanisms in the de facto wireless standard, the IEEE 802.11 MAC. Reviewing the IEEE 802.11 MAC protocol is important, and the protocol is expanded on in subsequent chapters. This is followed by an overview of the MANET architecture, characteristics and different possible applications. Then, a classification of different strategies employed in MANET routing, along with their advantages and disadvantages, is presented.

Despite the availability of multiple channels in the communication standard, the IEEE 802.11 MAC DCF protocol, which is employed by MANETs, is designed to use a single channel in communication, which leads to significant performance degradation as the network density and offered load increases. Utilising a single channel leads to higher contention and collision, which leads to frequent route failure and thus degrades network performance. Conventional routing protocols consider a single channel in their communication, and this is based on the design of the underlying layer (MAC protocol). Utilising a common channel leads to a higher degree of contention and collision, which in turn leads to frequent route failure, thus degrading network performance. Depending on a single channel limits routing functionality and performance, despite the different routing strategies proposed, i.e.

single path and multipath.

The remainder of the chapter is organised as follows. Section 2.2 presents an overview of wireless networks. In section 2.3, detailed descriptions of some mechanisms in the IEEE 802.11 MAC protocol are provided. Section 2.4 presents an overview of MANETs, and their architecture, characteristics and applications. The different classifications of routing with MANETs are outlined in section 2.5. Section 2.6 presents a discussion regarding limitations in the current MAC and routing protocols in MANETs, and reveals possible solutions to overcome these issues. Finally, section 2.7 summaries the chapter.

2.2 Wireless Networks

Wireless communication has seen a sharp increase in popularity and growth worldwide in recent years. This is mainly due to recent advances in wireless technology and mobile computing, along with their flexibility and decreased costs. Mobile wireless devices such as mobile phones, laptops, wireless sensors, Personal Digital Assistants (PDAs) and satellite receivers have become smaller, lighter and sufficiently portable to be carried by mobile users [13]. In wireless networking, the information is exchanged among nodes by the transmission of electromagnetic waves through the air (radio frequency signals).

Wireless communication networks have advantages over traditional wired networks as they enable anywhere/anytime connectivity. Furthermore, wireless communication can be deployed in remote area without a pre-existing wire infrastructure, or in areas where it is difficult and expensive to install cables. Moreover, the cost associated with the installation and maintenance of a wireless network is much lower than that of its counterpart wired network, which makes it an attractive option. In addition, the flexibility and rapid setup of a wireless network makes it an appealing option for mobile users. For instance, a mobile user can connect their laptop and PDA to the Internet at public places such as hospitals, university campuses, airports and coffee shops, and move around freely within the area of the network. On the other hand, there are disadvantages of wireless networks, such as having a high error rate and being more prone to interference among nodes. The general speed of a wireless connection is usually much slower than that of a wired network. Additionally, the connection deteriorates as users move farther from the router. Furthermore, wireless connections may suffer from obstructions in a household, such as walls and furniture. Moreover, wireless networks and information transmitted in such networks are less secure compared to wired networks. All the above factors make wireless networks an appealing and challenging form of connectivity at the same time.

There are many kinds of wireless communication, such as cellular telephony, Worldwide interoperability for Microwave Access (WiMAX), satellite-based communication and Wireless Local Area Networks (WLANs).

The WLAN is a network that allows devices to connect wirelessly, and data is transmitted over the air using a communication standard, such as the Institute of Electrical and Electronic Engineers (IEEE) 802.11 standard [14]. IEEE 802.11 standard defines the specifications of the first two layers, namely the Physical and Data Link Layers of the Open System Interconnection (OSI) model [15].

Depending on the underlying configuration, the IEEE 802.11 standard defines two major types of wireless networks for WLANs, namely infrastructure-based and infrastructure-less (ad hoc) networks.

Infrastructure-based WLANs require a special node or terminal, called an Access Point (AP), to connect users to the network via existing wired LANs. The APs are used to coordinate and regulate communication among mobile nodes, such as PDAs and laptops, and the wired network. This configuration is known as Wireless-Fidelity (Wi-Fi) hotspots [16]. For example, APs are used at airports, university campuses and public places to provide wireless Internet access. The set of mobile nodes associated with an AP is called the Basic Service Set (BSS) [17]. A number of BSSs can be connected together to form an Extended Service Set (ESS) to extend the coverage area of the Wi-Fi. Figure 2.1 illustrates an infrastructure-based WLAN.

Infrastructure-less or ad hoc WLANs provide an efficient alternative where the cost and difficulty associated with deploying an infrastructure-based WLAN is not

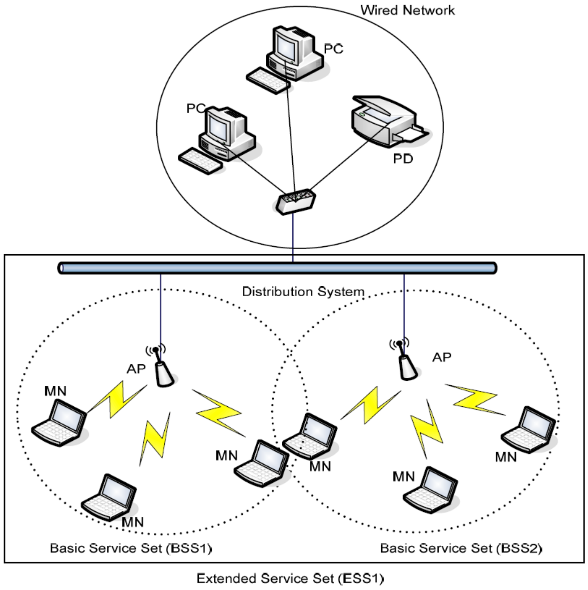

Figure 2.1: Infrastructure-based WLAN

practical or acceptable, as in battlefields, temporary conference meetings and disaster sites. The ad hoc WLAN does not require any fixed infrastructure to be established. However, it requires the mobile nodes to cooperate in a peer-to-peer manner to form an Independent Basic Service Set (IBSS) for data exchange [18]. To increase the communication range of the IBSS, mobile nodes may be used as forwarding agents. However, as the configuration of the IEEE 802.11 standard is limited to single-hop communication, the node must rely on the upper layers of the protocol stack (network layer) to forward a packet along a multi-hop path. This necessitates the implementation of a routing protocol mechanism at each mobile node to make it capable of forwarding a packet towards its intended destination [19, 20, 21]. In such a scenario, mobile nodes act as routers and form the backbone of a spontaneous network. This extends the communication range of an ad hoc WLAN (multi-hop) beyond the transmission range of a single-hop one. This configuration of ad hoc WLANs is known as a Mobile Ad Hoc Network (MANET) [22, 23]. Figure 2.2 illustrates a MANET.

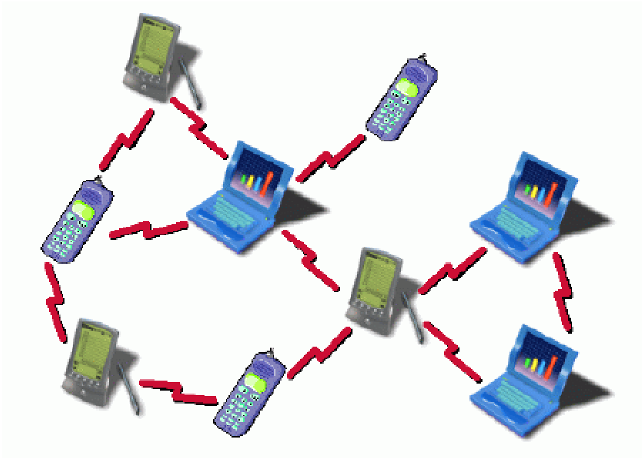

Figure 2.2: Mobile Ad Hoc Network (MANET)

2.3 IEEE 802.11 MAC Protocol

The IEEE 802.11 standard [14] defines a communication protocol for wireless local area networks (WLANs), and it is widely used for wireless contention-based networks such as MANETs. The MAC layer is a sublayer of the Data Link layer defined in the IEEE 802.11 standard. It is responsible for regulating access to the shared wireless medium and preventing collisions and contention among nodes. IEEE 802.11 MAC defines two mechanisms of the MAC layer, namely a Distributed Coordination Function (DCF) and a Point Coordination Function (PCF). The DCF is the fundamental media access method of 802.11 and MANETs. The DCF protocol uses a Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) protocol for sharing access to the medium. The CSMA/CA protocol is primarily designed to reduce the probability of collision among multiple stations accessing the wireless medium at the point where collisions are most likely to occur. The PCF provides a contention-free medium access method. The wireless medium is centrally controlled and a token-based access scheme is provided. The PCF is designed for infrastructure networks where an access point is presented and nodes communicate via the AP. Therefore, PCF cannot be used in ad-hoc networks. The focus in this research will be on DCF, which allows automatic medium sharing.

DCF is the basic medium access mechanism for legacy IEEE 802.11 WLANs. It lets automatic medium sharing between compatible devices by using CSMA/CA and a random backoff procedure. Additionally, it uses an immediate positive acknowledgement (ACK) frame for data traffic. If no ACK frame is received, retransmission of the frame can be scheduled by an error recovery procedure. In the DCF protocol, the transmitter node should sense the channel before transmitting (carrier sense) any frame to determine whether the medium is free or not. When the medium is busy, the transmitter node will defer its transmission until the medium becomes free again. If the medium is free for a constant period, called a DCF Inter-Frame Space *(DIFS)* interval, then the transmitter will generate a random backoff interval from the current Contention Window (CW) value before transmitting (this is the Collision Avoidance feature), to reduce the probability of collision between multiple waiting transmitters. If the medium becomes busy during $DIFS$ or backoff waiting time, the backoff timer is frozen until the medium become free again and then the timer will be resumed at the point at which it stopped. The transmitter transmits the whole frame when the backoff timer reaches zero.

The IEEE 802.11 standard evolved to incorporate several new amendments such as 802.11g, n, ac and ax to improve its capabilities [24]: increase data rate, provide higher security, new operation band, etc. For instance, the 802.11g defines an OFDM-based PHY in 2.4GHz to improve the link rate from 6 Megabits per second (Mbps) up to 54 Mbps. The 802.11n amendment uses the Multiple-Input Multiple-Output (MIMO) to obtain data rates up to 600 Mbps and increase the channel width. The 802.11ac enhance the 802.11n to obtain a link-rate of the order of Gigabits Per Second (Gbps). The 802.11ax improves the 802.11ac to support link rates of the order of tens of Gbps. With recent specification amendments to the 802.11 standard, a tailored amendment is needed to fulfil requirements for MANETs.

The following subsections highlight some of the IEEE 802.11b, which is widely used in MANETs, MAC mechanisms that are used/modified in subsequent chapters.

2.3.1 Carrier Sense Mechanisms

Both physical and virtual carrier sense may be used to determine whether the medium is in a busy or idle state. If either mechanism indicates a busy medium, then the medium is considered to be busy; otherwise, it is considered to be idle.

A physical carrier sense mechanism is provided by the physical layer. It detects activities on the radio interface and conveys this information to the MAC. More information about the physical carrier sense can be found in Clause 12 in [14].

A virtual carrier sense mechanism is provided by the MAC. This mechanism is referred to as the Network Allocation Vector (NAV). The NAV is a timer which used to reserve the medium for a fixed period of time. When a non-destination node receives Request-To-Send (RTS), Clear-To-Send (CTS) frames or data packets, it should set/update its NAV timer according to the provided duration in the RTS/CTS or data packet and stay silent during this time.

The carrier sense mechanism combines the physical carrier sense with the virtual carrier sense (NAV) and the station's state to determine the state of the medium (free or busy). A NAV counter counts down to zero. When the NAV counter is non-zero, it indicates that the medium is still busy, while the counter being zero indicates it is idle.

Two channel-access modes are defined by 802.11 DCF: basic and optional (Request-To-Send/Clear-To-Send (RTS/CTS)) base access.

2.3.2 Basic Access Mode

In basic access mode the transmitter will transmit the data frame after it observes that the medium is free for a *DIFS* interval, plus a random backoff time. On the other hand, if the medium is busy, the node should defer its transmission until the medium becomes idle again, and then wait for a *DIFS* and generate a random backoff delay, which is uniformly chosen in the range *[0, CW-1]*, where *CW* is the Contention Window. The backoff counter is decreased as long as the medium is sensed idle, and suspended when a transmission is detected in the medium. When the backoff counter reaches 0, the transmitter may transmit the packet. When a packet is received correctly by the receiver node, it is required to wait for a Short Inter-Frame Space *(SIFS)* interval before transmitting an ACK back to the transmitter node confirming correct reception of the frame. If the source node does not receive an ACK frame, then it assume that the data frame is collided and lost and hence the source will double the *CW* for the backoff timer and schedule the data frame's retransmission.

2.3.3 Optional Access Mode

In optional access mode the transmitter and receiver exchange short control frames, called RTS and CTS, to gain control of the medium before transmitting an actual data frame. The RTS and CTS frames contain duration/id fields which define the period of time during which the medium will be used to transmit the actual data frame and the returning ACK frame. After observing the medium access rules, the transmitter node will transmit an RTS frame. When the destination node receives the RTS, it will defer for an *SIFS* interval, and then reply with a CTS frame. Upon receiving the CTS frame, the transmitter can transmit the data frame and wait for an ACK frame. All neighbour nodes within reception range of either the RTS transmitter or the CTS transmitter (destination node) learning of the medium reservation will update their NAV, and should defer from contending within the medium during the period specified in the RTS or CTS frames. This mechanism is also known as virtual carrier sense, which is achieved by distributing reservation information for the impending use of the medium.

Exchanging RTS/CTS frames has some advantages over basic access mode, such as reserving the medium, alleviating the hidden node problem, and improving reliability of communication in the wireless medium. Additionally, it provides faster collision inference and validation of the transmission path existence [14]. Furthermore, collisions between two or more RTS frames will cause less bandwidth wastage in comparison with collision of larger data frames in basic access mode.

The RTS/CTS cannot be used for broadcast or multicast packets because there are multiple destinations for the RTS, and thus potentially multiple concurrent CTS frames sent in response. The use of the RTS/CTS protocol is under the control of an RTS Threshold attribute and can be configured to enable using RTS/CTS exchange always, never, or only for data frames longer than a specified length.

2.3.4 Binary Exponential Backoff Algorithm

In the CSMA/CA protocol a node with a packet to transmit should wait until the medium becomes idle for the *DIFS* period. Then the node may set up its backoff timer using the following expression: (*random* * *aSlotTime*) where *aSlotTime* is the time required at the node to detect a packet transmission from another transmitter, and *random* is a pseudo-random integer between *[0, CW]*. The Contention Window *(CW)* is an integer within the range of values of the physical layer characteristics between *(CWmin* and*CWmax)*, *(CWmin* $\leq$ *CW* $\leq$ *CWmax)*.

In 802.11 the default value of *aSlotTime* is *9* μ for 802.11a/g and *20* μ for 802.11b. The backoff slot is decreased by *aSlotTime* if there is no activity sensed in the medium during a particular backoff slot. If the medium is sensed busy during a backoff slot, the backoff time is frozen until the medium becomes idle for the duration of a *DIFS* period, then the backoff timer should resume counting down. A transmission may start when the backoff timer reaches zero. Successful transmission in the medium is indicated by reception of an ACK. If the transmission is successful, then the transmitter should reset its backoff timer to the default *(CWmin)*. On the other hand, the *CW* should increment exponentially to the next value in the series every time there is an unsuccessful attempt to transmit. This allows a longer backoff time for transmitter nodes, which should normally reduce contention/congestion in the medium. When the *CW* value reaches the maximum window size *CWmax*, the *CW* should remain at the value of *CWmax* until the *CW* is reset. The *CW* value should be reset to *CWmin* after a successful attempt at transmitting data, or after a station's *short_retry_count* is reached, which is set to be after seven retries. The backoff procedure should be invoked when a transmitter node is ready to transmit and finds that the medium is busy, as indicated by either the physical or virtual carrier sense mechanisms. The backoff procedure should also be invoked when a transmitting node fails to receive acknowledgement for a transmitted data packet. In these cases the transmitter should increment its *CW* and select a random backoff period following a *DIFS* period, during which the medium is determined to be idle. Any activity in the medium during the backoff period, detected using the CS mechanisms, will halt the backoff timer. If no activity is indicated by the backoff procedure for a *DIFS* period, then the backoff procedure is allowed to resume decremented by *aSlotTime*.

2.3.5 Recovery Procedure and Retransmit Limits

In IEEE 802.11 DCF, error recovery is always the responsibility of the transmitter node, which initiates a frame exchange sequence, for example, when a transmitter transmits an RTS frame but does not receive a CTS frame. This may occur due to a collision with another transmission, or because the receiver node is in active virtual carrier sense state (indicating a busy medium period), or because the receiver node has moved out of the communication range of the transmitter node. A transmitter initiates the error recovery process by retransmitting the failed frame. The transmitter should retry transmitting the frame until the transmission is successful, or until the relevant retry limit is reached, whichever occurs first.

Every node should maintain a *short_retry_count* and a *long_retry_count* for each data packet waiting for transmission. The former used for frames shorter than the RTS Threshold while the latter is used for frames longer than the RTS Threshold. These counts are incremented and reset independently of each other. For example, if the RTS transmission fails, the *short_retry_limit_count* for data and the node's *short_retry_count* are incremented. A transmitter node may continue attempts to transmit a frame until the frame is successfully received or the retry count reaches its limit. In the latter case, the retry attempt should cease, and the data packet should be discarded. Furthermore, the DCF protocol should notify its upper layer about the link failure to act accordingly.

2.4 Mobile Ad hoc Network (MANETs)

The Mobile Ad hoc wireless Network (MANET) has become a popular research area in the wireless network community. This is mainly due to the flexibility and low cost associated with such networks. MANETs can be defined as decentralised self-configured networks of mobile nodes, which communicate wirelessly without any need for pre-existing infrastructure [25]. The word "Ad hoc" is derived from Latin and literally means "for this purpose only" [26]. MANETs can be deployed when there is a need (impromptu) to perform a specific task within a certain communication range, using the available resources [27]. In such networks, mobile nodes are considered to be an end system and a router at the same time, relaying messages for other participating nodes. The Internet Engineering Task Force (IETF) has created a new working group to study MANET [28].

MANETs are self-configured networks and nodes having a dynamic topology. Hence, mobile nodes (routers) can freely move and arrange themselves on the fly, meaning that the topology of MANET may be subject to frequent unpredictable changes [29]. MANETs can adapt to take a different structure depending on the circumstances and applications. They can operate in mobile, standalone and networked structures without any help from the base station (infrastructure) or central administration [30]. Nodes in an ad hoc network are mobile and move spontaneously at different directions and speeds, and may leave/join the network as they wish. Therefore, MANETs need self-organisation and self-healing mechanisms to ensure that the network can still function, even if some nodes move out of the transmission range of others. As mobile nodes have limited transmission range, nodes may need intermediate nodes to relay a packet through several hops (multi-hop communication) until it reaches its destination.

Motivated by MANETs networking paradigms, several new ad hoc networking paradigms (also known as MANET-born networks) have been evolved in recent years such as Mesh, Sensor, Vehicular Ad hoc NETworks (VANETs), Flying Ad hoc NETworks (FANETs), Delay Tolerant Networks (DTNs) and Opportunistic Mobile Networks (OMNs) [31]. These networks developed and used a more pragmatic approach to resolve the issues associated with MANETs such as: 1) implementation, integration and experimentation; 2) simulation credibility; and 3) socio-economic motivation [31]. Although several commonalities exist between these networks, there are major differences in the deployment environment [2]. The next subsection highlights MANETs protocol stack, followed by its characteristics and applications.

2.4.1 MANETs and OSI Reference Model

Typical designs of communication systems in wired and wireless networks, such as Open System Interconnection (OSI) [15], the Transmission Control Protocol (TCP) and the Internet Protocol (IP) (or TCP/IP) [32] protocols stack are based on a layering principle. In such designs each layer is assigned certain functionality. Neighbouring layers can only interact with each other.

Standards for layered protocol stacks are mainly designed for wired networks to provide modularity in protocol design. This helps to reduce network design complexity, enables fast development of interoperable systems, and improves the design of communication protocols [33].

OSI [15] is a well-known reference model for network communication protocol standards. It consists of seven layers, each of which has a particular functionality. In contrast to OSI, most communication mechanisms in ad hoc networks are linked to protocols operating in layers 1, 2 and 3 of the OSI model. Hence, the operational layer system for ad hoc network reference model consists of five layers - the application, transport, network, data link and physical layers. The communication mechanisms of the higher layers are only active at the end points of communications (source and destination). Figure2.3 shows a communication architecture model for MANETs compared with the OSI reference model. A brief description of these layers is provided as follows:

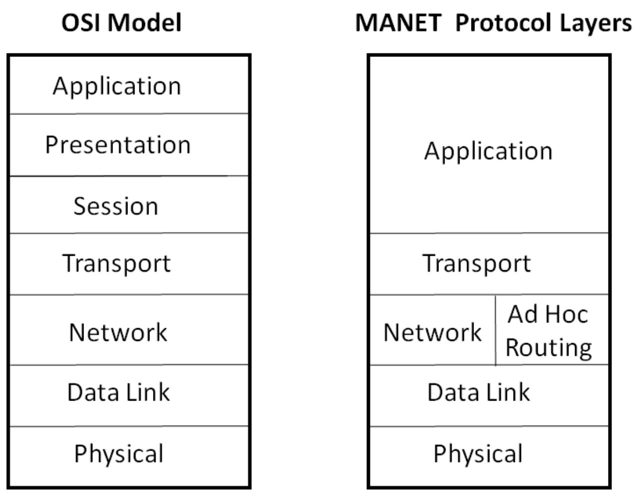

Figure 2.3: OSI reference model and MANET protocol layers

- **Application Layer:** This layer generates data packets and passed to the next lower layer for delivery.
- **Transport Layer:** This layer ensures the reliability of delivering data between source and destination nodes and provides an end-to-end connection. It performs some important tasks, such as supporting data integrity and congestion control [34]. Transmission Control Protocol (TCP) and User Datagram Protocol (UDP) [35] are two well-known protocols implemented in this layer.
- **Network Layer:** This layer provides end-to-end transmission operations, which include exchanging routing information to discover a feasible path to a destination, forwarding data packets, and repairing and maintaining links.
- **Data Link Layer:** This layer performs several important functions, such as framing, error and flow control, addressing, and regulating access to the medium. It consists of two sub-layers [34], Logical Link Control (LLC) sublayer and Medium Access Control (MAC) sublayer.
- **Physical Layer:** This layer is responsible for transmitting and receiving data bits over a wireless medium. In addition, it provides mechanisms to sense the wireless medium and inform the MAC sublayer when the signal is detected or the medium is idle. The physical layer consists of two sub-layers: the Physical Layer Convergence Procedure (PLCP) sublayer and the Physical Medium Dependent (PMD) sublayer.

2.4.2 Characteristics and Challenges

MANETs are self-configuring decentralised dynamic networks, where topology changes on the fly without the involvement of the administrator [36, 23, 37]. Although MANETs share many of the properties of a wired network, there are certain unique characteristics derived from the nature of the wireless medium channel, the distributed medium access mechanisms and the unpredictable dynamic topology. MANET characteristics and their related issues can be categorised as follows:

- **Wireless medium** - the physical nature of a wireless medium (or channel) makes communication highly prone to transmission impediments. Signal attenuation, interference and multipath fading [38].

  Signal attenuation - a degrading in the quality of a single is a natural consequence of transmitting the signal over a long distance. This is due to the fact that the intensity of the electromagnetic energy decreases as the distance to the receiver increases. The receiver node can successfully receive and decode the signal if the Received Signal Strength (RSS) is above a certain threshold, called the Signal-to-Noise Ratio (SNR).

  Multipath fading - reception via multiple routes is another transmission impediment related to wireless signals. It occurs due to different versions of the same signal having received via different paths at different times. It is mainly caused by the type of propagation mechanisms used, and more precisely, by the reflection, refraction or diffraction of the transmitted signal by obstacles [39, 40].

  Interference - where a shared wireless medium is used by all nodes in the same area, wireless communication is prone to signal interference [41], which can reduce the network's bandwidth. Co-channel interference and adjacent channel interference are the two main types of signal interference [42]. Co-channel interference is caused by nearby communications which share the same transmission frequency (channel). To reduce the impact of co-channel interference, the IEEE 802.11 MAC protocol introduces a distributed coordination mechanism, that enables contending mobile nodes to access the shared medium dynamically, while reducing mutual interference. Another solution is the use of directional antennas which help to radiate radio signals in a particular direction to reduce physical interference [43, 44]. Adjacent channel interference occurs when a signal of a nearby frequency interferes with the ongoing communication in the adjacent channel (overlapping channel). In such a case the benefits of utilising multiple channels vanish. However, by carefully introducing a guard band between allocated frequencies, or by utilising non-overlapping (orthogonal) channels, the impact of adjacent interference can be minimised or avoided [45, 46].

Spatial contention and reuse - in wireless networks with an omni-directional antenna, the transmission of a packet will reserve the whole area around it for the transmission time required to transmit it. During this time, no other communication is expected to take place (or contend) in the same area, as this will result in a collision and waste bandwidth. Spatial reuse refers to the possibility of simultaneous transmission that may occur in the same area without causing interference or collision. The MAC protocol is responsible for coordinating access to the medium and maximising spatial reuse. One way to increase spatial reuse is to enable concurrent communication in multiple non-overlapping channels to take place in the same vicinity [3, 4].

- **Mobility** - the network topology of MANETs is highly dynamic due to the ability of nodes to move randomly in any direction. This may cause frequent path breaks for ongoing communication. Frequent path breakage in MANETs can be related to individual random mobility, group mobility, movement of a node along pre-planned routes [47] , and unpredictable nodes joining/leaving the network at any time. In order to maintain network connectivity in such a dynamic environment, a periodic exchange of network information is essential. However, this may increase the communication overhead and degrade the network's performance. Therefore, an efficient and effective routing protocol for MANETs is required to address mobility management [48].

- **Bandwidth** - the available Radio Frequency (RF) communication bandwidth in the wireless channel is significantly lower compared with the wired network [38]. Since the wireless channel is shared by all nodes located within the same transmission range, the bandwidth available per wireless channel depends on the the volume of traffic and the number of mobile nodes they each generate in the network. This means only a fraction of the already-scarce bandwidth is available for each node. Limited available bandwidth also imposes a constraint on routing protocols when maintaining topology information. Thus, an efficient routing protocol should provide a balance between maintaining consistent topological information, the communication overhead, and bandwidth utilisation caused by that.

- **Limited resources** - as opposed to their wired counterparts, nodes in MANETs such as laptops, PDAs and sensors often have limited resources, such as limited energy, computational power and memory [49, 50].
  - **Limited energy** - nodes in MANETs tend to depend on batteries for their energy resources. However, since battery life is limited and the battery may need to be recharged or replaced from time to time, considering the power source when designing a routing protocol is important. Battery power is consumed in wireless signal transmission, reception, retransmission and beaconing. Surveys of several approaches to conserving energy by using energy aware mechanisms are given in [51, 52].
  - **Computational power** - as mobile nodes tend to be small, they have limited computing components, such as processor, memory and processing power. Therefore, algorithms for communication protocols that minimise computational and storage requirements must be considered [53].
- **Network security** - MANETs are less secure than wired networks. They are susceptible to information attacks and physical threats, as they use an unprotected shared wireless channel and broadcast packets. Moreover, security solutions are reliant on individual nodes due to the absence of a central administration and difficulty in implementing distributed solutions [54, 55, 56].
- **Low connectivity and reliability** - connectivity in MANETs is achieved through routing and cooperative forwarding among mobile nodes. Disruption may occur in the system when nodes fail to forward packets. This usually occurs due to unpredictable circumstances such as battery failure, nodes acting selfishly, broken links or congested channels. As nodes use and contend for a shared medium, signal collision and interference can provide low network connectivity and an unreliable communication medium. The high transmis-

sion error rate in the wireless medium makes communication in MANETs less reliable [22].

- **Autonomous and infrastructure-less** - a MANET is considered to be an autonomous system consisting of nodes interconnected wirelessly, without any pre-existing infrastructure or a centralised administrator. Every node in the system serves as an independent router. It can generate and forward messages to other nodes outside its transmission range in a multi-hop manner [31, 57].

Based on the aforementioned unique characteristics and issues of MANETs, MANETs are prone to several types of faults and failures [9] such as:

Transmission errors - the unreliability of the shared wireless medium and the dynamic topology of MANETs may lead to transmitted packets being garbled and thus received in error.

Node failures - nodes in MANETs may fail and drop out of the network at any time due to different reasons: hazardous conditions in the environment, voluntarily, or when their energy supply is depleted.

Link failures - unpredictable node movements, changing environmental conditions (e.g. increased level of interference), and node failures may cause links between nodes to break.

Route breakages - dynamic movement in the network topology, along with node/link failures, can cause routes to become stale and thus incorrect. Depending on a stale route to forward packets may either cause an additional delay, or packets will get dropped and degrade the mobile network's performance.

Congested nodes or links - due to the nature of the routing protocols and the dynamic topology of the network, the over-utilisation of nodes or links could cause channel congestion, which leads to additional contentions, collisions and packets dropped, as well as increasing the delay.

2.4.3 Applications

Due to the flexibility of implementing MANETs anywhere and anytime with no pre-existing infrastructure, there has been quite a growth in the use of MANETs. Below are some significant examples of MANET applications [27, 58]:

- **Battlefield operation** [59]: MANETs can be used to establish and facilitate communication and operation in the battlefield, where no fixed infrastructure is available.
- **Emergency services** [60, 61]: MANETs can be quickly deployed to establish search and rescue operations and disaster recovery where existing infrastructure has been destroyed by natural disasters such as earthquake and hurricanes.
- **Commercial environment** [62]: MANETs can also be used in e-commerce applications to advertise products, news, films, weather and road conditions.
- **Educational application** [63]: MANETs can be set up to establish ad hoc communication between mobile users while they are away from standard offices. Additionally, they can be used to establish a virtual classroom.
- **Personal area network (PAN)** [64]: A PAN is a short-range localised network where nodes are usually associated with a specific person. It allows the proximal electronic devices like laptops, mobile phones, cameras and televisions to dynamically share information using an autonomous home network.

2.5 Routing in MANETs

Routing protocols are responsible for discovering a feasible route from a source to a destination based on routing metrics, exchanging route information and mending a broken route. Hop length, minimum power required, or greater capacity are examples of commonly used routing metrics. In MANETs a route consists of a set of ordered intermediate nodes, which can be used to transport a packet across the network from a source to a destination.

The unique characteristics of MANETs, such those discussed in section 2.4.2, make the design of a robust routing protocol a more challenging task than would be the case for a wired network. Firstly, unpredictable node mobility results in rapid topological changes, causing frequent route failure. Secondly, the underlying wireless channel, which is shared by all nodes, provides an unreliable communication medium with a high error rate and low variable bandwidth.

To increase understanding, the routing functions life cycle in MANETs can be explained in three main phases: route discovery, data forwarding and route maintenance, as shown in Figure 2.4. It starts with a route discovery phase, where the source node attempts to find a feasible route to the destination node. Once the route is discovered, a data forwarding phase begins, in which data communication commences. During the course of communication, if a link is broken - for example, due to reasons such as node mobility (i.e. the destination or an intermediate node moving out of communication range), battery failure or congestion in the wireless medium - an alternative route needs to be discovered/exploited in order for communication to continue. This is where a route maintenance phase starts. In this phase, a node which detects a broken link attempts to find an alternative route from its local cache to repair the route, if available. If there is no other route available, then the node initiates another route discovery phase to identify another route to the same destination node.

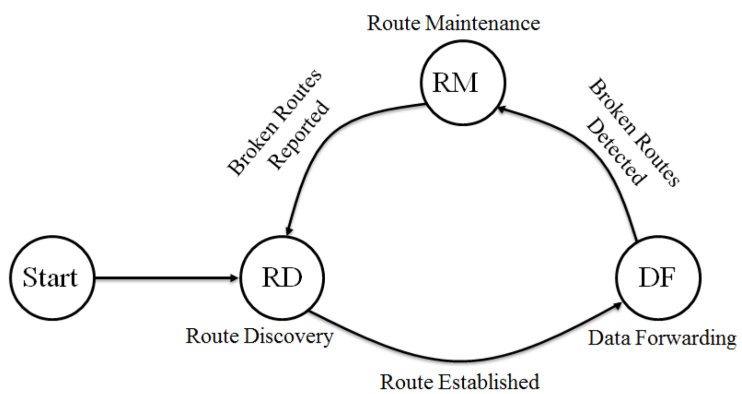

Figure 2.4: Routing Operation Cycle Model in MANETs

Significant research has been devoted to developing MANET routing protocols [19, 20, 21]. These protocols can be classified, based on the number of discovered paths, into two main categories: single path and multipath routing protocols. Extensive, detailed classifications of routing protocols for MANET are presented in [65, 66, 67, 68].

2.5.1 Single Path Routing in MANETs

Routing protocols belonging to this category establish a single route between a source and a destination node. Data packets are forwarded using a discovered route. In the case of link breakage between intermediate nodes involved in the route, a new route discovery process is required with a high overhead and delay. The majority of routing protocols in MANETs belong to this category. Single path routing protocols can be further classified, based on their route discovery and information update mechanisms, into three main sub-categories, namely proactive, reactive and hybrid routing protocols. A detailed description of the AODV routing protocol is given as it is extended in subsequent chapters.

2.5.1.1 Proactive Routing Protocols

Proactive MANET protocols are table-driven protocols which attempt to maintain consistent, up-to-date routing information on paths to other nodes in the network. A node frequently updates its routing information by propagating periodic topology updates to minimise route selection time. Furthermore, a route can be immediately selected from a routing table when needed. However, these protocols incur a large amount of control traffic overhead to maintain an up-to-date view of the network topology. Thus, proactive MANET routing protocols best suit a small-sized network with low node mobility. The Destination Sequence Distance Vector routing (DSDV) [21], Fisheye State Routing (FSR) [69] and Optimised Link State Routing (OLSR) [70] are well-known examples of proactive routing protocols.

2.5.1.2 Reactive Routing Protocols

Reactive routing protocols are on-demand protocols, where routes are created by the source node whenever they are required. When a source node requires a route to a destination, it initiates a route discovery procedure by flooding the entire network with Route REQuest (RREQ) packets. The source node, then, waits until it receives a Route REPly (RREP) packet from the destination node itself, or from an intermediate node which has a fresh route to that destination. The established route is maintained through a route maintenance procedure for as long as it is required. These protocols use less bandwidth to maintain the routing table to each node by avoiding unnecessary periodic updates of routing information, compared with the proactive routing protocols. However, the route discovery latency in reactive routing protocols, which leads to a longer packet delay before communication can start, is greater than that of proactive routing protocols. Thus, reactive MANET routing protocols suit networks which have high node mobility and density. Dynamic Source Routing (DSR) [20] and Ad hoc On Demand Distance Vector (AODV) [19] are well-known examples of this category of routing protocols.

Ad hoc On-demand Distance Vector (AODV)

AODV [19] is a reactive routing protocol that borrows the use of a destination sequence number from DSDV [21] and the on-demand route discovery mechanism from DSR [20] to formulate an on-demand, single-path, loop-free, distance vector routing protocol. DSR uses a source routing mechanism where a source node includes in the data packet the full route to be followed, to deliver a packet to the destination node. Furthermore, DSR supports caching of multiple routes to a single destination, which can be used by intermediate nodes for data forwarding. In contrast to DSR, AODV uses a hop-by-hop routing mechanism where each node on the active route maintains the information of the next hop towards each destination. Furthermore, AODV caches only a single route entry for each destination in the routing table. Using a hop-by-hop routing mechanism in unpredictable environments such as MANETs helps to reduce communication overheads and power consumption related to frequent topology updates and yet maintain complete knowledge of all routes in the network. The routing mechanism in AODV consists of two phases: a route discovery phase and a route maintenance phase. A review of some key features of AODV is provided below to provide sufficient background for the proposed multichannel routing protocols in the subsequent chapters.

Route Discovery Phase: When a source node has data to send to a destination, it first checks its routing table to identify whether there is a valid route available towards this destination. If there is a valid route, then the source node will send data using this route. Otherwise, the source node will start a route discovery process. Typically, the route discovery process involves flooding the network with a RREQ for the required destination and waiting for a RREP.

The source node broadcasts a RREQ, which includes the source id and the broadcast id, which are used to detect duplicates, to its one-hop neighbour using a new sequence number. An intermediate node receives a non-duplicate RREQ and first establishes a reverse route back to the source node and records the first node from which it receives the RREQ as a next hop towards the source (see Figure 2.5 (a)). Furthermore, it updates its routing table if the RREQ packet contains more recent information about the source (i.e. higher sequence number or lower number of hops). If the intermediate node does not have a valid route towards the destination, then it will increment the hop count and rebroadcast the RREQ. If the destination node or an intermediate node with a fresher routing information towards the destination receives the RREQ, it unicasts a RREP back to the source node. To check the freshness of the route at the intermediate node, the sequence number in the RREQ is compared against the recorded sequence number in its routing table towards the destination. The RREP is routed via the reverse route back to the source node. An intermediate node receives the RREP and this will create/update a forward path towards the destination. This enables all intermediate nodes in the discovered path to acquire a route towards the source and destination nodes (see Figure 2.5 (b)). Furthermore, intermediate nodes along the discovered path are required to only maintain information about the next hop node leading to the source or destination nodes. Routing information only needs to be stored in the source, the destination and intermediate nodes involved in the active path, which minimises the use of network resources and memory.

Route Maintenance Phase AODV uses a timer-based mechanism to purge stale routes promptly. Each route entry in the routing table is associated with a soft state timer called *ACTIVE_ROUTE_TIMEOUT*. This timer is refreshed whenever this route is used. The expired routes are periodically invalidated and thus cannot be used for data forwarding or sending RREP.

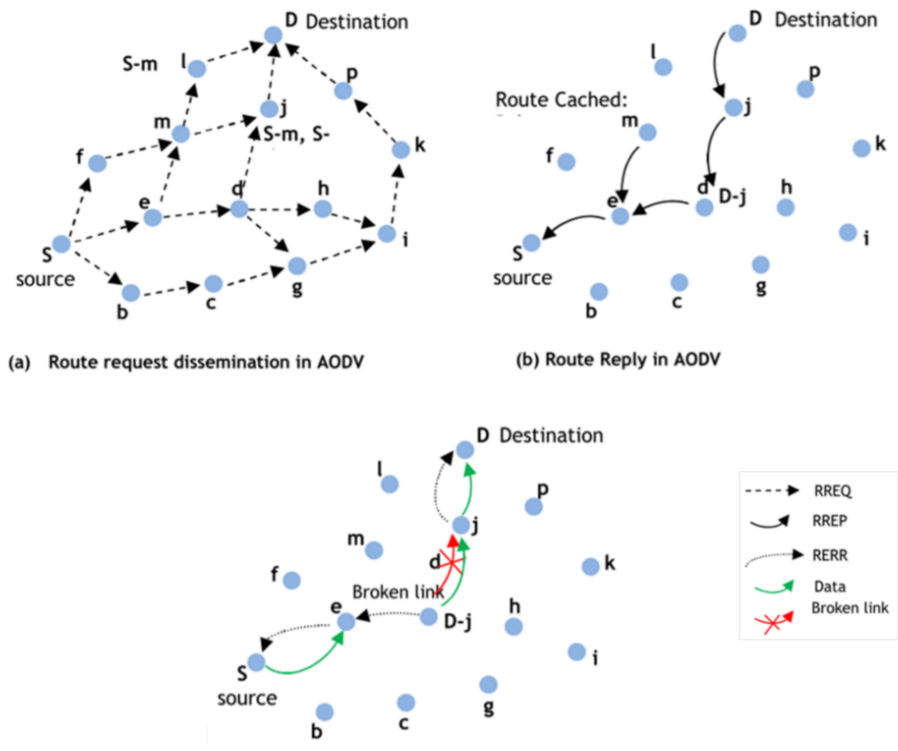

Figure 2.5: Route discovery and maintenance in AODV

Route maintenance is done using Route Error (RERR) packets. When a node detects a link failure (through the absence of several Hello packets or link layer feedback), routes to destinations that use the broken link become unreachable and invalidated (see Figure 2.5 (c)). Then, a RERR packet, which includes a list of unreachable destinations that are using the failed link with their sequence numbers, is broadcast to the upstream neighbour. The RERR propagating mechanism ensures that all affected source nodes using the failed link receive the RERR. RERR is also generated when a node receives a data packet to forward but it does not have a valid route towards this destination. Upon receiving a RERR from a downstream neighbour, the node first checks whether the node that sent the RERR is its next hop to any destination listed in the RERR. If this the case, then the node will invalidate the corresponding routes in its routing table, update the sequence number from the RERR and rebroadcast the RERR towards the source. The same process repeats until the RERR is received by the source node. This procedure enables intermediate nodes that are using the affected link to invalidate corresponding routes. It also enables the source node to identify the failure and to re-initiate a new route discovery process if a route is still required.

2.5.1.3 Hybrid Routing Protocols

Hybrid routing protocols are designed to combine the best features of both reactive and proactive routing protocols and overcome their various weaknesses. The hybrid protocols are proposed to reduce control traffic overhead in a proactive routing approach, and decrease route discovery latency in a reactive routing approach [71]. In hybrid route protocols, proactive routing techniques are usually used to fetch routes to neighbouring nodes, while reactive routing techniques are used to discover a route to nodes located further away. The performance of this type of routing protocol depends on the selection approaches of proactive and reactive approaches. Zone Routing Protocol (ZRP) [72], Core Extraction Distributed Ad hoc Routing Protocol (CEDAR) [73] and Hybrid Ad Hoc Routing Protocol (HARP) [74] are examples of hybrid routing protocols.

2.5.2 Multipath Routing in MANETs

Multipath routing is a routing technique which consists of discovering and maintaining multiple routes between a source and a destination. It is one of the ways to improve the reliability of transmitting information in wireless networks [75]. Unlike single path protocols, multipath routing initiates a new route discovery process when all available paths fail. Multipath routing can improve aggregate bandwidth and provide load balancing and fault tolerance in the network. The multiple routes can be used to compensate for the dynamic and unpredictable nature of MANETs. Several multipath routing protocols have been proposed recently, and many of them are based on the reactive routing protocols, DSR and AODV. Utilising multiple paths in a reactive routing protocol can improve the reliability of the protocol by different means. For instance, transmitting several copies of the data packets through different paths can improve the reliability of delivering at least one copy of the packet to the destination. Moreover, reliability can also be achieved by selecting an alternative route, when link failure is detected, to replace the broken link without re-initiating a new route discovery process.

2.5.2.1 Benefits

Discovering and maintaining multiple paths incurs certain overheads, but can provide several benefits to the network and improve the reliability of the communication of the routing protocols in MANETs. Reducing the end-to-end delay, fault tolerance, load balancing and aggregate bandwidth are examples of such benefits [75, 76]:

- **Reduce end to end delay** - route failures in a single-path routing protocols trigger a new route discovery process to discover a fresh path to the destination. That causes a delay and incurs an extra control packet overhead. Delay and additional overheads are reduced in multipath routing by utilising a pre-discovered (alternative/backup) route. Furthermore, discovering multiple paths and observing their QoS enables the node to switch between them to satisfy end-to-end delay requirements of the application.

- **Improving the fault-tolerance** - one way to provide route resilience and improve reliability in communication is by having redundant packets routed to the destination via multiple paths. In the presence of route failure the destination node will receive the packet as long as at least one of the paths to it does not fail. However, to reduce the traffic and energy overhead caused by redundancy, a more sophisticated approach can be employed, such as using a source code [77]. Route resiliency largely depends on the selected routing metrics of the available paths, such as spatial diversity and disjointedness. Dulman *et al.* [78] have investigated the trade-off between the additional overhead caused by such redundancy and an increase in the degree of reliability.

- **Load balancing** - multipath routing can improve the network's performance and reduce the risk of traffic congestion and bottlenecks. When certain nodes or links become over-utilised and cause congestion, multipath routing can spread/divert the traffic through alternative paths to alleviate the burden of congested nodes/links. This might lead to less delay, collision and packet loss. However, it can lead to an additional delay if the alternative route has been badly chosen. Hurni *et al.* [79] have investigated the efficiency of using multipath routing with load balance and cross-layer information to improve the lifetime of Wireless Sensor Networks (WSNs).

- **bandwidth aggregation** - multipath routing may increase the aggregate bandwidth by splitting the data to the same destination into multiple streams, with each stream being routed via a different path. This technique is particularly useful when the required bandwidth for the application is greater than an individual link's capacity on such route. On the other hand, utilising multiple paths to increase the aggregate bandwidth may interfere with transmission from other nodes along other paths sharing the same medium (known as a route coupling issue), consequently limiting achievable throughput.

2.5.2.2 Components

Multipath routing protocols consist of three main components to construct multiple paths and distribute network traffic over the discovered paths. These components are route discovery, traffic allocation and route maintenance.

1. **Route discovery**: it takes place where multiple routes between the source and destination nodes are discovered based on certain parameters. Different parameters are used to construct multiple paths during the route discovery process. Among these parameters, path disjointedness is the main distinguishing criterion. This parameter describes the independency of the discovered paths in terms of shared resources [76], and can be further classified based on the degree of path disjointedness into non-disjointed paths and disjointed paths.

   (a) **Non-Disjoint Paths**: this can also be referred to as joint multi-paths, where it is possible to discover paths with links and nodes in common. It is easy to discover a non-disjoint path in the network. However, the failure of a node or link along the path may cause several route failures.

   (b) **Disjoint Paths**: it takes place where route discovery attempts to discover disjointed paths based on a different degree of independency. In principle disjointed multipath routing provides a higher degree of fault tolerance than non-disjointed paths. However, it is more difficult to discover. For example, a single link/node failure in a non-disjoint path can cause routes to fail, whereas in a disjoint path only a single route containing the failed link/node is affected. A disjointed path approach is generally considered more robust than the non-disjointed approach [9]. Figure 2.6 shows different types of disjointed multipath techniques, which are described as follows:

- **Node-disjoint multipath**: this occurs in sets of paths where there are no common nodes in the discovered paths except the source and destination nodes, as shown in Figure 2.6 (a).The failure of a node included in the set of node-disjoint paths will result in the failure of only a single path. Node disjointness implies link-disjointness, and provides a higher degree of fault tolerance, utilising most of the available network resources. However, the number of discovered node disjointed paths is limited and more difficult to accomplish.
- **Link-disjoint multipath**: this occurs where a set of paths are constructed with no common links among them, as shown in Figure 2.6 (b). However, there might be common intermediate nodes connecting different links. Therefore, the failure of a node included in the set of link-disjoint paths may result in faults in several links which share the failed node. It is easier to construct a link-disjoint path, but it is less reliable than the node-disjoint approach, as the failure of a link could lead to the invalidation of several routes.
- **Partially-disjoint multipath**: this can include multiple paths sharing several links and nodes, as shown in Figure 2.6 (c). Failure in links or nodes in a set of partially disjointed paths may result in the failure of several paths. However, it is easier to construct a partially disjoint path.
- **Radio-disjoint multipath**: this happens where a set of paths with minimum/no radio interference are constructed. This form of dis-

covery aims to reduce as much as possible the effect of interference among nodes belonging to different paths and sharing the same channel (known as route coupling). Based on the allowed level of interference, a radio-disjoint multipath can be fully or partially disjoint. In full radio-disjoint paths there is zero mutual interference between all intermediate nodes in any active path. In partially disjoint paths some of the intermediate nodes in the selected paths are in physical interference range of each other. Full disjoint paths must be node-disjoint, and this is difficult to accomplish using a single channel network. However, it is possible to achieve it by discovering multiple paths in multiple non-overlapping channels, as we will see in Chapter 6. On the other hand, partially disjoint paths can be either link or node-disjoint paths and can be accomplished in a single and multi channel network.

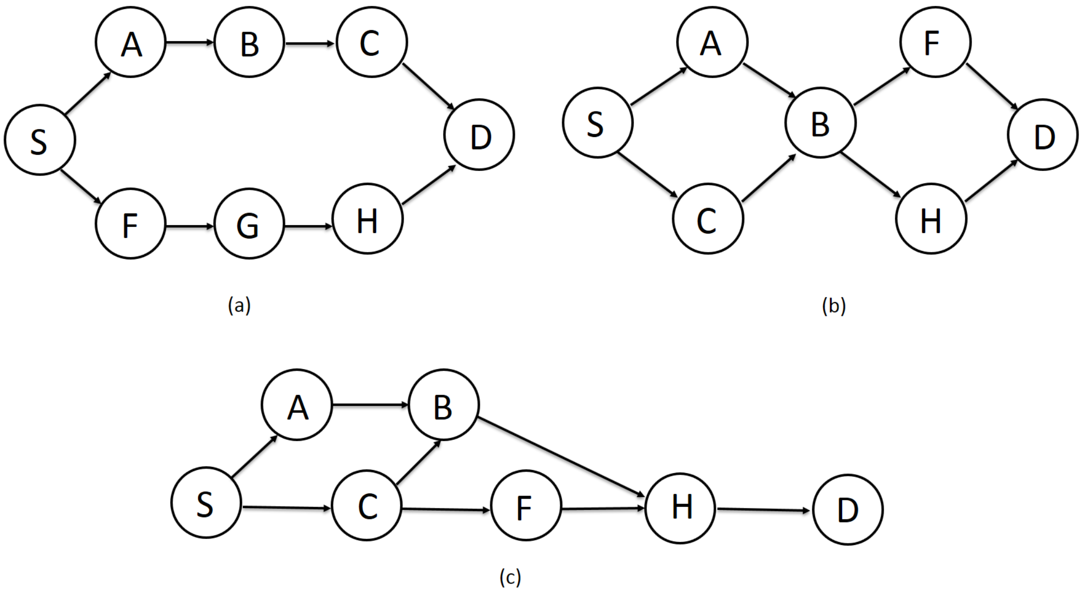

Figure 2.6: Various types of path disjointness - (a) Node-disjoint paths; (b) Link-disjoint paths; (c) Partially disjoint paths

2. **Traffic allocation**: based on main purpose of the multipath protocols and performance requirements of the intended application, various strategies may be proposed for allocating traffic over available paths. One strategy is to utilise only one path, which has the best metrics (e.g. hop count, path disjointness,

available bandwidth, etc.), for data transmission, while keeping other discovered paths as backup paths for fault tolerance purposes. Other strategies may select several discovered paths concurrently for reliable data transmission, or even traffic distribution. In the latter approach, the issues of how traffic is split over the paths and how to handle out-of-order packets at the destination need to be addressed, possibly at the transport layer. Furthermore, utilising multiple paths for concurrent transmission or even traffic balancing may cause the well-known issue of route coupling, which will be discussed in section 2.5.2.3.

3. **Route maintenance**: due to possible failure types in MANETs, which were discussed at the end of section 2.4.2, paths may fail. As in unipath routing, path maintenance should be performed when route failure is detected. Path rediscovery can be either initiated after each path failure, when a certain number of active paths have failed, or when all discovered paths have failed.

AOMDV [80] and SMR [81] are well-known multipath routing protocols.

Ad hoc On-demand Multipath Distance Vector Routing (AOMDV)

AOMDV [80] is an extension to the single path AODV routing protocol to provide multiple loop-free and link/node-disjoint paths per route discovery. AOMDV is designed to provide efficient route recovery from a link failure, and to improve the fault tolerance in the routing protocol. During the route discovery, AOMDV discovers and maintains multiple link and/or node disjointed paths. When link failure is detected, the protocol switches to a different path, which avoids re-initiating a new route discovery process. Route discovery is initiated when all cached paths to a specific destination fail. During a route discovery process in AOMDV, duplicate RREQ packets are used to create loop-free reverse paths to a source at the destination and intermediate nodes. Unlike AODV, the destination in AOMDV generates multiple RREP packets, which travel along the multiple loop-free reverse paths which have already been created during the RREQ dissemination, to create multiple loop-free forwarding paths towards the destination node. The *advertised_hop_count* is used to guarantee loop freedom and select the best route towards the destination by advertising the maximum acceptable hop count towards any destination. Routes with a higher hop counts than the *advertised_hop_count* are discarded.

Route maintenance in AOMDV is similar to that of AODV, except that the RERR in AOMDV is generated when all cached paths towards a destination have failed. Furthermore, when link failure is detected in AOMDV and a node has an alternative route, the node will salvage the packet using the broken link in the interface queue (link layer queue) with the new route (alternative route).

2.5.2.3 Route Coupling

Due to the wireless channel characteristics, which were discussed in section 2.4.2, interference among different transmissions may occur in different paths sharing the same medium, even if the paths satisfy the link or node disjointness property. This will limit the benefits of having multiple paths and reduce achievable throughput, leading to two paths which impact each other with regard to forwarding packets. This situation is known as route coupling [82]. Route coupling may occur when two routes are located physically in interference range of each other during transmission. In such a case nodes belonging to each route are competing for the same medium, and this will limit the benefits of having two routes (alternate path routing).

Waharte *et al.* [83] studied the impact of route coupling in wireless networks using multipath routing protocols. They distinguished three types of route: (a) routes sharing common nodes, (b) routes with common links, and (c) routes with no common collision domains. They concluded that the path of type (c) produced the best achievable throughput. This is because the common collision domains of the multiple paths are confined to the source and destination nodes, and in their transmission along paths, they are independent of each other. With respect to the degree of disjointness which is explained in section 2.5.2.2, a multipath routing protocol with the radio-disjointness property may produce the best achievable throughput and load balancing as its routes operate independently.

2.6 Issues in MANETs

In the following subsections a discussion of some issues related to techniques used to establish communication in MANETs are provided. In particular, we concentrate on two areas: the Medium Access Control (MAC) and Routing-layer protocols.

2.6.1 MAC-layer protocol for MANETs

The unique nature of communication in MANETs and the wireless radio communication medium pose several challenges to the applicability of existing MAC-layer protocols, for example, the hidden terminal problem, exposed terminal problem, and high interference, contention and collisions in a single common medium.

The hidden terminal problem occurs as a result of the limited transmission range of radio. When two transmitting nodes are not in communication range of each other, and thus cannot hear each other, transmitting to a third node may cause a collision. In Figure 2.7 (a), nodes A and C are not in communication range of each other, but they are in the transmission range of node B. Ongoing communication may already be set up between node A and B. Node C may have data to send to node B as well. Node C follows the CSMA/CA mechanism, and concludes that the medium is free, since node A is too far from it. Consequently, node C starts communication with node B. This could well cause a collision at node B with node $A's$ transmission to node B.

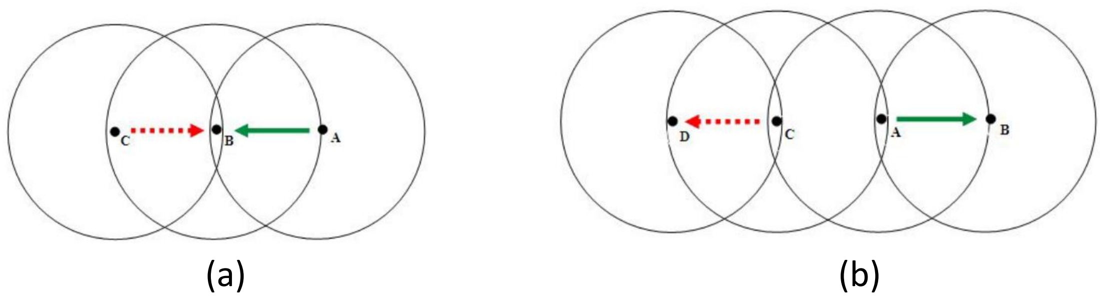

Figure 2.7: (a) Hidden terminal, (b) Exposed terminal problems

The exposed terminal problem occurs when neighbour nodes cannot communicate with other nodes as there is ongoing communication in their transmission range, which limits spatial reuse. For instance, in Figure 2.7 (b), node A may be transmitting data to node B, and node C may also be in the transmission range of node A. Node C may have data to send to node D as well. Following the CSMA/CA mechanism, node C cannot transmit the data to node D, as the medium is busy with node A transmission. Despite the fact that the transmission between node C and D would not interfere with the reception of node B or cause collision, due to the distance between node C and node B, node C cannot transmit concurrently with the transmission of node A.

The hidden terminal and the exposed terminal problems reduce the utilisation of the wireless medium and affect the network's capacity. The former increases the number of collisions in the network and the latter causes unnecessary delays in transmission. IEEE 802.11 alleviates the hidden terminal problem by introducing a four-way handshake (RTS/CTS/DATA/ACK), as discussed earlier in section 2.3.3.

Although the wireless communication standard such as IEEE 802.11 PHY has defined multiple spectrum frequencies in the physical layer, the IEEE 802.11 MAC considers only one frequency band which reduce network capacity. Using a single shared medium to exchange control and data packets in the wireless medium may cause several issues, such as an exposed terminal, congestion and collision in a dense heavy load network, besides underutilising the available wireless medium.

To overcome these issues, using multiple non-overlapping channels, which is provided for in the wireless communication standard, can improve the network's performance by enabling multiple concurrent communications in different channels. This should alleviate the possibility of an exposed terminal problem, interference and collisions, and improve usability of the spatial area.

2.6.2 Routing-layer protocol for MANETs

Different routing techniques have been proposed to improve routing functionality in MANETs. However, the unique characteristics of MANETs make the design of a robust routing protocol a more challenging task than in a wired network. Firstly, unpredictable node movement may result in rapid network topology changes, which cause frequent route failure. Secondly, the underlying wireless channel shared by all nodes provides an unreliable communication medium with a high error rate and low variable bandwidth. Therefore, increasing node density, traffic and mobility in the network may increase interference, contention and collisions in a single shared medium, which may cause channel congestion and frequent link breakage, consequently reducing the mobile network's performance.

Depending on the number of discovered paths in the routing protocol, link breakage may necessitate a new route discovery process. For single path routing protocols, a link failure should trigger a new process of route discovery, which will increase the routing overhead and delay in delivering data packets. On the other hand, multipath routing approaches could instantly recover from a broken link by utilising a pre-discovered route (alternative/backup).

The multipath routing approach has improved the reliability and fault tolerance in routing protocols in MANETs. However, establishing robust multiple paths in a single shared medium is difficult. The benefit of having multiple paths mainly depends on the degree of disjointness, as discussed in section 2.5.2.2. Node and link disjointed approaches provide a better performance in sequence. However, they may still suffer from interference and route coupling issues, as discussed in section 2.5.2.3. On the other hand, a full radio-disjoint approach may overcome the issue of interference and routing coupling, but it is difficult to accomplish using a single shared medium. However, discovering multiple paths in multiple non-overlapping channels may ease discovery of the full radio-disjoint paths.

Another issue in routing in MANETs is dependence on a stale route which is caused by node movement. Thus, a discovered route may no longer represent the current network topology. This issue occurs more in multipath routing protocols. Due to dynamic topology changes, a cached route may not represent the actual network topology. Depending on the routing approach used to maintain an overview of the network topology, proactive or reactive, invalid (stale) routes can be quickly discovered. A proactive routing approach maintains an up-to-date network topology view, and thus it can rapidly detect topology changes and invalidate stale routes.

However, this comes at a cost of higher routing overhead and greater consumption of bandwidth. On the other hand, reactive routing protocols produce less routing overhead in maintaining an overview of the network topology, but may take longer to discover topology changes, thus increasing delay in recovering from a broken link. Attempting to send data packets to a node via a stale route may cause the dropping of the data packet, and increase the time required to recover from that broken link.

This thesis is an attempt to improve routing functionality in MANETs by utilising multiple non-overlapping channels. Furthermore, it studies the impact on network performance of employing single path multichannel routing protocols in Chapter 5 and multipath multichannel routing protocols in Chapter 6. Chapter 7 explores how cross-layer interaction between layer two and layer three can be exploited and benefit the network in certain aspects such as via early invalid route detection and rerouting and also by reducing the traffic on a congested path by rerouting the data via an alternative path.

2.7 Conclusions

MANETs have become increasingly popular as a research area in the wireless network community. This is due to the flexibility and applicability of such networks in challenging environments. Due to the unique characteristics of MANETs, such as the absence of centralisation, limited channel bandwidth, dynamic topology changes and constrained node resources, routing in MANETs is a challenging task.

Several routing approaches have been proposed to provide a robust solution for routing in MANETs. The proposed routing solutions can be classified, based on the number of discovered paths, into single path (including proactive, reactive and hybrid) and multipath routing protocols. In a single path routing protocol, a single route between source and destination nodes is discovered. Link failure in this approach necessitates a new route discovery process, which can increase the routing overhead and delay. To increase reliability and provide fault tolerance in routing, multiple routes between a source and a destination are discovered. When link failure is detected, an alternative route can be rapidly used to reroute data packets.

The efficiency of multipath routing approaches greatly depends on the degree of disjointness. Although a multipath routing protocol can improve the reliability of routing protocols in MANETs, it suffers from interference and the route coupling issue, which limit the benefits of discovered routes.

Utilising multiple non-overlapping channels may reduce the interference, contention and collisions in a single shared medium, thus improving the performance of routing protocols in MANETs. Furthermore, it can also alleviate exposed node and routing coupling issues in a single channel network. The next chapter provides a literature review of multichannel communication in MANETs.

Chapter 3

Multichannel Ad hoc Network

3.1 Introduction

Despite the availability of more than one radio frequency (channel) in wireless communication standards (i.e. IEEE 802.11), the majority of proposed routing protocols in MANETs are designed with the assumption that all nodes in the network are listening to/utilising a single common channel. This assumption has facilitated the design and implementation of the routing protocol. However, as the number of nodes and the amount of traffic in the network increase, more collisions, interference and contention occur in a single shared medium. Consequently, link failures are more frequent, which degrades network performance and increases the challenges for routing protocols.

Multichannel protocols are designed to enhance network performance by utilising already defined channels. To exploit multiple channels in wireless networks, three issues need to be addressed: 1) the availability of radio interface per node, which is concerned with the capability of the wireless device to transmit and/or receive at the same time. 2) the channel assignment mechanism, which is concerned with assigning a channel to radio interface, facilitating channel negotiation (agreement); and 3) the routing mechanism, which is concerned with discovering and maintaining routes to a destination and routing packets through a discovered route.

This chapter provides an overview of different multichannel techniques used in wireless ad hoc networks along with their benefits and challenges. This is followed by different MAC channel assignment approaches identified in the literature to realise multichannel networks, and a literature review of different approaches to implementing multichannel routing protocols.

The remainder of the chapter is organised as follows. Section 3.2 presents an overview of multichannel communication in wireless ad hoc networks, along with its benefits, challenges and the impact of the number of available interfaces per node. In section 3.3 detailed descriptions of different approaches to channel assignment in MAC protocols are provided. Section 3.4 presents different approaches to routing with multichannel MANETs. Section 3.5 presents a discussion regarding limitations and challenges encountered in multichannel MAC and routing protocols in MANETs, and introduces the approaches proposed in this thesis. Finally, section 3.6 provides a summary of the chapter.

3.2 Multichannel Communication in MANETs

In traditional wireless ad hoc networks, all nodes are assumed to use a single shared channel for communication. In such networks all nodes are contending to use the same shared medium for communication and only one node at a time can transmit or receive in any communication range. A MAC protocol is used to control and regulate access to the medium and reduce the probability of contention and collisions among transmitting nodes while accessing the medium.

The IEEE 802.11 standard specifies multiple channels for communication in the physical layer. For example, Figure 3.1 illustrates the frequency spectrum of the IEEE 802.1 lb/g [5, 84] which operates in the 2.4GHz band. As can be seen in Figure 3.1, the frequency spectrum of the 2.4GHz band is divided into 14 channels, 3 of which are non-overlapping (orthogonal) channels, namely channels 1, 6 and 11. The width of each channel is 22 MHz and each one is separated by 5 MHz. Concurrent communication between adjacent nodes can be achieved without interference if the non-overlapping channels are used.

The majority of MAC protocols based on the IEEE 802.11 standard use a single shared channel and are known as single channel MAC protocols [7, 85, 86]. However,

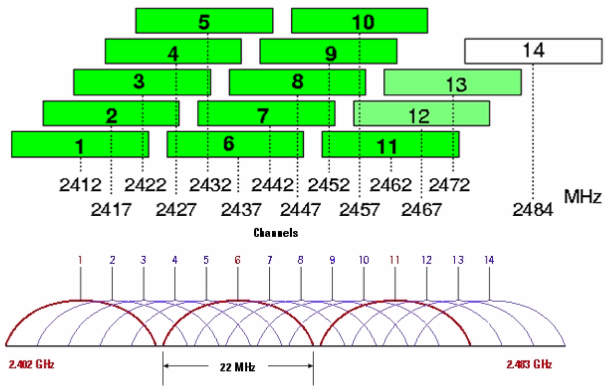

Figure 3.1: Frequency spectrum of IEEE 802.11b/g in 2.4GHz

due to the broadcast nature of the wireless signal, wireless links interfere with each other, which causes collisions and wastes the bandwidth, as discussed in section 2.4.2. Furthermore, as the number of transmitter devices sharing the same medium increases, the performance of the network drastically decreases [7, 8]. This is mainly due to the higher degree of contention/collisions in the single shared medium. The interference issue is worse in multi-hop networks such as MANETs as interference from adjacent hops along the same path induces inter-path interference.

Li *et al.* [87] found that only 1/7 of the available bandwidth can be used in a chain set-up when using a single shared wireless medium for communication. Kyasanur *et al.* [88] have extended the analysis of wireless capacity done by Gupta and Kumar [7] to investigate the capacity of multichannel wireless networks. In their analysis they found that utilising multiple channels in communication can significantly improve the network capacity of wireless channels, even if the number of used transceivers per node is less than the number of used channels.

To capitalise on the benefits of non-overlapping channels, a wireless Network Interface Card (NIC) needs to support channel switching. Current off-the-shelf 802.11 cards support switching between different channels at the cost of a certain amount of switching delay. The channel switching delay time varies depending on the specifications of the hardware specifications from tens to hundreds of micro seconds [88, 89, 90, 91, 92].

3.2.1 Benefits of Multichannel Communication

Multichannel communication can provide several benefits to a wireless network and they can be summarised as follows [93, 94, 95]:

- Increase the parallel transmission in the network by assigning different channels to different adjacent nodes. This will increase the packet delivery rate, network throughput and thus the network capacity.
- Reduce or minimise the interference range in the medium by enabling neighbour nodes to communicate in different non-overlapping channels. This improves spatial reuse.
- Alleviate the exposed terminal problem by enabling adjacent nodes to communicate in different channels.
- Reduce contention in the medium by providing multiple contention mediums and increase the possibility of avoiding congested channels.
- Divide the wireless collision domain into multiple collision domains, which helps to reduce the occurrence of collisions and thus improves the utilisation of the medium.
- Reduce data gathering delay, which is desirable in some network such as WSNs.

3.2.2 Challenges in Multichannel Wireless Communication

In a traditional wireless network all nodes are listening to a single common channel for local connectivity and communication. On the other hand in a multichannel wireless network with a single transceiver nodes are only aware of other nodes operating (tuned to) in the same frequency channel. Therefore, nodes will not be aware of neighbouring nodes located in their communication range that operate in a different channel. To capitalise on the benefits of multichannel communication, nodes may switch their channel dynamically in order to discover and communicate with other neighbour nodes. This requires detailed coordination (negotiation) between senders and receivers to agree on the communication channel to be used, before they switch to the respective channel.

Supporting multichannel communication in MANETs is a challenging task. This is due to limited resources in mobile nodes (processing, memory, energy etc.), which are usually equipped with a single transceiver, and the decentralised nature of MANETs. Although utilising multiple channels in wireless networks has the potential to improve network performance, it introduces new challenges or makes existing ones more complex [96, 97]:

- **Multichannel hidden terminal problem.** In a single channel wireless network a hidden terminal problem occurs when at least two nodes are not in transmission range of each other and try to send to a third node. In contrast in a multichannel wireless network a multichannel hidden terminal problem occurs due to a node missing an RTS/CTS exchange on one channel while listening (tuned) to another channel. In Figure 3.2 let us assume that there is ongoing communication between nodes A and B on channel 2, and node C, a neighbour of node B, is busy with other communication when node A and B negotiate the channel. Therefore, node C is not aware of the channel reservation and sends an RTS to node B on channel 2. Consequently, a collision will occur at node B and data will be dropped. In this case node C is considered as a hidden terminal because it is not listening to the RTS/CTS exchange and channel negotiation [98].

- **Multichannel deafness node.** This problem occurs when a transmitter node wrongly concludes that a receiver node is no longer reachable. This occurs when the receiver node is tuned to another channel to handle another communication while the transmitter is trying to communicate with it. Consequently, the transmission will fail and a link failure notification will be (wrongly) issued.

- **Broadcast Support Problem:** In wireless network broadcast communications are used to advertise a service or to disseminate information that has a regional scope value (between immediate neighbours to maintain local connectivity or across the whole network to discover a route). In a single channel

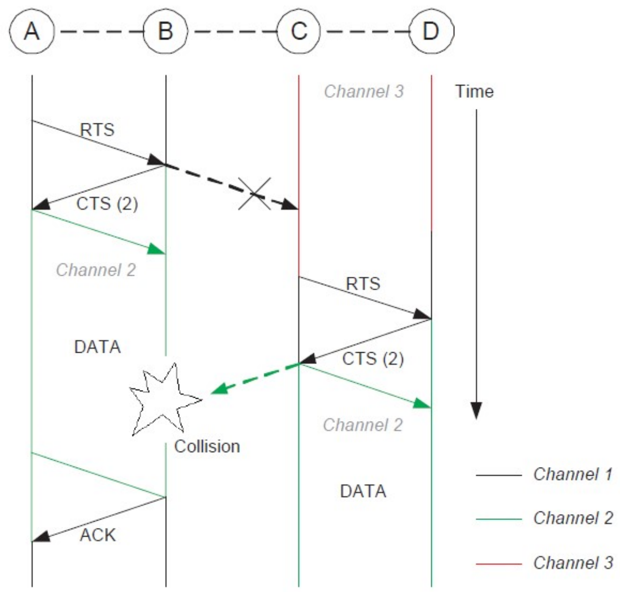

Figure 3.2: Multichannel hidden terminal problem

network broadcast packets are potentially received by all the nodes in the region or the network. However, supporting the broadcast in a multichannel network depends on the channel assignment approach used. For instance if all nodes are using a common control channel, then one copy of the broadcast message is sent in this channel and potentially received by all neighbours. On the other hand if no common channel is available, then a copy of the broadcast message may be broadcast in most/all available channels. The former approach produces an overhead cost comparable with that of a single channel network, whereas the transmission delay of broadcast packets will be increased [99]. Additionally, it may cause a bottleneck in a common control channel and it may require tight time synchronisation, which is hard to achieve in a large-scale MANET. The latter approach allows more flexibility for channel assignment, but it produces a considerable overhead in the network and the node may become deaf when broadcasting in all channels.

Selecting an appropriate technique to support broadcasting in a multichannel network is a tricky task and may need a trade-off between the incurred overhead and the freshness of local connectivity. Also it depends on how many broadcasts or how frequently broadcasts are required by the application. If broadcast traffic is more regular, then using a common channel may be better as the overhead is acceptable.

- **Network Partitions:** A network may be partitioned if two transceivers nearby are fixed on different channels, and then cannot communicate with each other, even if they are in the communication range of each other.

- **Channel switching.** Depending on the channel assignment approach used, channel switching may be performed by (1) the sender if the channel is assigned to the receiver, (2) by the receiver if the channel is assigned to the sender, or (3) by both if the channel is assigned to a link. The radio interface cannot switch between channels instantaneously as it takes some time. This delay is needed to reset the Voltage Control Oscillator (VCO) and provide a stable frequency output. The channel switching delay depends largely on the hardware specification. For example, the channel switching delay for the commercial off-the-shelf 802.11 transceiver is about 150 to 200 μsec [100, 101].

3.2.3 Single Interface or Multi Interfaces

Mobile nodes in MANETs are usually battery powered and constrained in size and resources (as explained in section 2.4.2). Half-duplex transceivers are usually adopted for mobile nodes and therefore they can only either transmit or receive at any given time. According to the number of available radio transceivers and utilised channels in each node, proposed protocols for MANETs can be divided into three types: single radio interface using single channel, single radio interface using multiple channels and multiple radio interfaces using multiple channels. For each type multiple MAC and routing protocols have been proposed to improve the performance of MANETs.

- **Single Radio interface Single Channel (SRSC)**:

  In a SRSC wireless network all the nodes are constantly listening and contending to use the same shared channel. The majority of MAC protocols proposed for MANETs usually have a single half-duplex radio interface and a single channel (referred to as a single-channel MAC protocol) in mind. This assumption simplifies the design and implementation of such protocols. Due to the wireless signal broadcast nature, however, as the number of nodes contending to use the medium increases, the amount of interference and collisions increases, which significantly affects the network capacity. This could also cause interruption to routing operations and consequently makes routing a more challenging task.

Despite the availability of multiple channels in the physical medium in IEEE 802.11 PHY standard, the IEEE 802.11 MAC DCF protocol is designed to coordinate access to a single shared medium while reducing collision probability and ensuring fairness among contending nodes. Consequently, routing protocols in MANETs usually assume a single channel in their design and operation.

Routing protocols in SRSC usually discover and maintain either a single path [20, 19] or multiple paths [80, 102] in a single channel. In section 2.6, a detailed explanation of some issues related to MAC and routing protocols of this type was given.

- **Single Radio interface Multiple Channels (SRMC)**:

  In an SRMC wireless network all nodes are equipped with a single half-duplex transceiver and are capable of switching channels dynamically, but they can only transmit/receive or listen to one channel at a time. Designing a MAC protocol that exploits multiple channels, while the device is equipped with a single half-duplex transceiver, is challenging.

  Several MAC and routing protocols utilising multiple non-overlapping channels with a single transceiver have been proposed [103, 104, 98] to enhance network capacity, while minimising the hardware and energy consumption costs. Unlike the MAC protocols in SRSC the MAC protocols in SRMC need to address two issues: channel assignment and medium access control. Channel assignment determines which channel is to be used by which hosts; and medium access control address the problem of contention/collision when using the medium. However, the multichannel hidden terminal problem, deafness and supporting broadcasts are some of the issues experienced with utilising multichannels with a single radio interface, as discussed earlier in section 3.2.2.

Several MAC protocols have been proposed to overcome the aforementioned issues [98]; that require either time synchronisation, a common control channel or redundant retransmissions in all channels, as we will see in section 3.3.1.

Routing protocols in SRMC usually discover and maintain either a single path [105] or multiple paths [106] in multiple channels. Further discussion of protocols belonging to this category will be given in section 3.4.1.

- **Multiple Radio interfaces Multiple Channels (MRMC)**:

  Utilising multiple channels over multiple radio interfaces can further improve network capacity and minimise expected issues related to the multichannel communication, even if the number of radio interfaces is less than the number of available channels [107]. In this case, switching between channels is still necessary to utilise them fully. It is usual practice in multi-interface multichannel protocols to predetermine a receiving channel associated with a radio interface for each node in order to facilitate data communication set-up [108, 109]. Also, a dedicated common control channel may be used to support network connectivity, broadcasting and minimising the control packet overhead [110, 111]. Two types of multi-radio interface protocols can be identified: a full data packet radio interface and a busy-tone radio interface. The former uses all the provided radio interfaces for data transmission while the latter uses a single frequency tone for signalling to prevent any collision of data packets [112, 113].

  Routing protocols in MRMC usually discover and maintain either a single path [114] or multiple paths [115] in multiple channels. Further discussion of protocols belonging to this category will be given in section 3.4.2.

3.3 Multichannel MAC Protocols for MANETs

In single channel MANETs all nodes are continually listening and contending to use the same shared channel. This causes a high degree of interference and collisions, which leads to a higher packet loss and degrades network performance. Introducing multichannel communication in wireless networks help to keep interference and collisions down and thus improves the available network bandwidth. Nodes in multichannel wireless networks are required to switch between different channels in order to handle communication for other nodes, or to transmit in a parallel manner with the aim of increasing the network's capacity.

In a single channel network, the MAC protocol only needs to decide when it is suitable for nodes to communicate in order to reduce the probability of collisions. In contrast, in a multichannel network, the MAC protocol needs to address two issues: channel assignment, where a node decides which channel is to be used by which hosts; and medium access, where the problem of contention/collision when using a particular channel is resolved. The next subsection describes different channel assignment approaches used to realise multichannel communication in the MAC layer protocol.

3.3.1 Channel assignment approaches

Channel assignment approaches are used to assign channels to nodes and to coordinate which channel should be used for communication. Several multichannel MAC protocols for MANETs have been proposed using different channel assignment approaches. Different channel assignment approaches have different trade-offs in terms of complexity of design, the overhead required to realise them and hence the expected gain for network performance. Optimal channel assignment methods in a spontaneous network such MANET have been proven to be NP-complete [114] or NP-hard problems [116] (similar to the graph colouring problem).

A survey of existing channel assignment approaches for wireless ad hoc networks can be found in [117, 96, 97, 118]. Channel assignment approaches in a multichannel wireless network can be classified into: static, semi-dynamic and dynamic approaches [97]. A brief description and discussion of these types follows:

3.3.1.1 Static Channel Assignment

In this approach nodes are often grouped into different clusters such that all nodes in a cluster are assigned to a common channel which is different from that of a neighbouring cluster. This is to avoid/reduce interference between different frequencies in neighbouring clusters. However, nodes in the same cluster communicate using the common channel and they follow the CSMA/CA protocol to access the medium. Clustering and channel assignments are performed in the network initialisation phase. Channel assignment in this approach can be renewed, for instance due to a changing interference condition. However, radio cannot switch its operating channel during communication.

The main advantages of a static channel assignment approach are simplicity of implementation and lowering the frequency of channel switching. On the other hand this scheme is not adaptive to topology changes and thus is not suitable for networks with a dynamic topology. Additionally, it may cause network partitioning. Cluster-based multichannel management protocol (CMMP) [35] and component-based [103] are examples of static channel assignment approach.

3.3.1.2 Semi-dynamic Channel Assignment

The main idea of this approach is to assign a fixed channel to every node and permit them to switch their radio interface between available channels for communication. Channel assignment is performed in the network initialisation phase but it can updated whenever needed. Since each node is assigned a fixed channel, either the sender or the receiver has to switch its interface to the other node's channel, follow the CSMA/CA protocol to access the medium and then start communication.

A semi-dynamic approach has an advantage over a static approach as nodes have the ability to switch to different frequencies to communicate with their neighbours, and it can also tackle the network partition issue. Furthermore, it facilitates channel negotiation and coordination as only one node is required to switch its interface to another node's channel. Additionally, it is easy to implement as a software extension over 802.11 compliant cards [117]. However, it may require efficient coordination between the sender and receiver to explore which channel to use for data communication. Channel switching may cause a number of problems such as a multichannel hidden terminal problem, a deafness problem and a broadcast support problem.

Receiver Directed Transmission (RDT) [12] and xRDT [112] are well-known examples of the semi-dynamic channel assignment approach. In RDT every node is assumed to have selected (or been assigned) a well-known quiescent channel that it will listen to when idle. When transmitting/forwarding a packet, the transmitter will switch its quiescent channel to the intended receiver's quiescent channel and transmit the packet. After all packets have been delivered successfully, the sender returns to listening to its quiescent channel. A full description of RDT and xRDT will be provided in chapter 5.

3.3.1.3 Dynamic Channel Assignment

In a dynamic channel assignment approach nodes can dynamically switch their channels between all the available channels in order to communicate with their neighbours and deliver data. Therefore, channel negotiation, selection and switching may be required before every data transmission.

The dynamic channel assignment approach has greater flexibility and reaction to topology changes than both the static and semi-dynamic approaches and can further enhance network performance. Furthermore, it can significantly reduce interference levels by assigning different channels to different data flows, but it needs frequent updates of global topology information and much channel negotiation and coordination. Moreover, as all nodes in the network are equipped with a single transceiver, a dynamic channel approach suffers from problems such as deafness, the multichannel hidden terminals, broadcast support and control channel saturation.

Dynamic channel assignment can be further classified based on the coordination method used to agree on the communication channel into three sub-categories: a) dedicated control channel, b) split phase and c) frequency hopping [97]:

- **Dedicated control channel**: The rationale behind using a dedicated common control channel in a multichannel protocol is to exchange broadcast and the control packets (RTS, CTS) to simplify the negotiation process and select a communication channel. The remaining channels are intended only for data packets. The separation in channels between control and data packet channels is to avoid/reduce the interference/collision between control and data packets and to simplify the channel negotiation process. However, dedicating part of the available bandwidth (one channel, for example) exclusively for control packets and negotiation reduces the available number of channels for data communication by about one third in the case of utilising three non-overlapping channels in IEEE 802.11b in 2.4GHz.

Although a dedicated control channel facilitates channel assignment without the need for time synchronisation, it is prone to a control channel saturation problem [6] as well as multichannel hidden terminals, deafness and channel switching delay. Jain *et al.* [119] have proposed a multiple channel carrier sense multiple access (M-CSMA) protocol using power sensing as a mechanism for selecting a channel from a channel list.

- **Split phase**: In this approach nodes access the medium in two phases: a control phase and a data exchange phase. In this approach, nodes are assumed to be synchronised. During the control phase all nodes switch to the control channel to negotiate a channel to use in a data exchange phase. Usually access to the medium during a control phase is a contention-based similar to CSMA/CA. When the control phase ends, a data exchange phase starts when the sender and receiver are tuned to the agreed channel during the control phase, and then start transferring data. During the data exchange phase protocols differ according to the channel access mechanisms they support [120]. Some protocols are contention-based protocols like Multichannel MAC (MMAC) [98]; whilst others are based on a schedule access like Multichannel Access Protocol (MAP) [121] and TMMAC [122].

  The advantages of a split phase approach are mitigating multichannel hidden terminal and deafness problems and supporting broadcast by synchronising all the nodes to listen to the same channel in the control phase. In contrast with a dedicated control channel approach, a split phase approach utilises all the channels during a data exchange phase. Furthermore, it is challenging to determine the best duration of the control and data exchange phases. The control phase needs to be no longer or shorter than the require time to agree on a channel. A split phase approach requires tight time synchronisation among all nodes, and high channel switching delay. Furthermore, no data channels are used during a control phase which underutilises the available bandwidth.

- **Frequency hopping**: In a frequency hopping approach nodes hop (switch) over a set of available frequencies (channels). Hopping patterns can be common or independent for all nodes.

  In a common hopping approach all nodes listen to the same frequency at same the time, meaning that all nodes hop to the same pattern. When two nodes want to exchange data then they carry out a handshake to remain in the current channel, while other nodes continue hopping in the common hopping sequence. After a data exchange is completed, both nodes re-join the common hopping sequence. Channel-hopping Multiple Access (CHMA) [123] is an example of the common frequency hopping approach.

  A independent frequency hopping approach also divides time into slots or discrete intervals, and nodes do not share a common hopping sequence. Instead, every node follows its individual hopping sequence. Usually nodes hop to a common channel after following their sequence, which permits them to exchange and learn each other's hopping sequence pattern. When a sender wants to send data to a destination, it hops to the next channel of the receiver's hopping sequence and starts communication. Slotted Seeded Channel Hopping (SSCH) [104] is an example of an independent frequency hopping approach.

  The main advantage of channel hopping approaches is eliminating the channel negotiation process, and the channel bottleneck problems. Nodes simply follow their hopping pattern to exchange packets. Conversely, common hopping protocols require tight time synchronisation mechanisms. Higher channel switching delay may affect the data process, and thus degrade network performance. According to [117] common hopping protocols are not compatible with IEEE 802.11 MAC cards. In addition there are issues observed with independent hopping protocols. For instance, if a sender does not have information about the hopping sequence of the receiver node or if the information is outdated, high latency penalties may be incurred. Furthermore, in a highly dense network it is not easy to track the sequence of all neighbours and doing so limits the amount of available memory. In addition, broadcast support is not guaranteed in this scheme due to the same problem as that found in dedicated control channel protocols.

A dynamic channel assignment approach can reduce interference and increase parallel communication in the network, but it needs frequent information sharing, channel negotiation and coordination before any data transmission. Furthermore, it may need a dedicated common control channel and tight time synchronisation, which are difficult to support in large-scale MANETs.

The main idea of using multichannel MAC protocols in MANETs is to improve network performance and capacity. This is achieved by enabling parallel communication among adjacent nodes in different channels and also by reducing interference, contention and collisions in the medium. However, different multichannel MAC protocols lead to different challenges, which are discussed in section 3.2.2.

Utilising multiple channels in a MAC protocol helps to reduce interference, contention and collisions in a wireless medium and improves network capacity. Following channel negotiation and switching to the communication channel, a node will use the CSMA/CA mechanism to access the medium and then forward the data packets to its next-hop neighbour, as specified by the routing protocol. In multi-hop MANETs mobile nodes are considered as senders, receivers and routers at the same time. Thus, routing in a MANET plays a crucial role in enabling each node to forward data packets to its next-hop neighbour towards the final destination. In multichannel MANETs several routing protocols have been proposed to improve routing by utilising already defined multiple channels. The next subsection provides the main routing techniques for multichannel MANETs.

3.4 Multichannel Routing Protocols for MANETs

Traditional routing protocols in MANETs are designed to operate using a single common channel among all nodes in the network, despite the availability of multiple channels in the wireless communication standards. Due to high degree of interference, contention and collisions in a single shared channel, network performance degrades as node density and traffic load increase [124, 125]. Routing protocols that utilise more than one channel for data communication have the potential to improve network performance. This is achieved by enabling multiple concurrent communication among neighbouring nodes in different channels, reducing their interference, contention and collisions compared with single-channel routing protocols.

Different routing strategies have been proposed to design and implement multichannel routing protocols in MANETs. These strategies vary based on a number of factors, including the number of available radio interfaces per node (single or multiple), the adopted channel assignment approach (static, semi-dynamic or dynamic) and the number of discovered paths per destination (single path or multipath).

This thesis classifies multichannel routing protocols based on the number of available radio interfaces per node, into a multichannel routing protocol with a single radio interface or multi-radio interfaces per node. Each main category is further divided into two sub-categories based on the number of discovered paths per destination, i.e. single-path or multipath multichannel routing protocols. Hence, the multichannel routing protocols can be classified as: single-path [105, 126, 127, 128] and multipath [106, 129, 130, 131] single-transceiver multichannel routing protocols, and single path [108, 132, 133, 114, 134, 135] and multipath [10, 115] multi-transceiver multichannel routing protocols. Figure 3.3 illustrates the different categories of multichannel routing protocols in MANETs that have been discussed in detail in this thesis. The following section reviews some of the proposed multichannel routing protocols in each category.

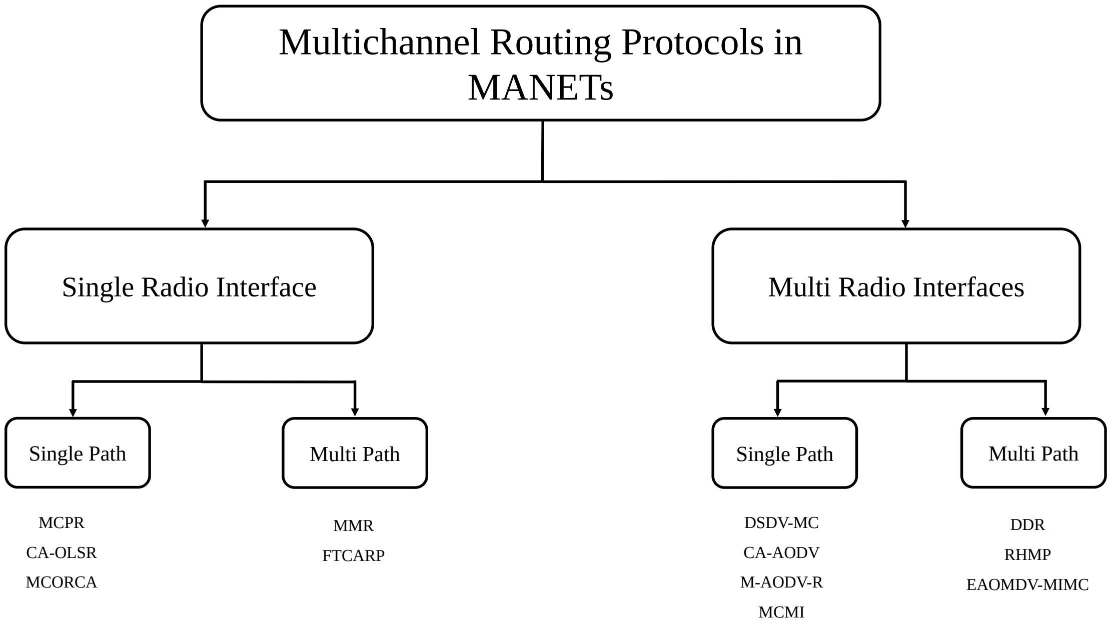

Figure 3.3: Classification of multichannel routing protocols

3.4.1 Single Radio Interface

This section reviews multichannel routing protocols where each node is equipped with a single half-duplex transceiver and hence each node can only transmit or receive at any given time. Multichannel routing protocols in this category can be further classified into, single-path and multipath multichannel routing protocols.

3.4.1.1 Single-Path Multichannel Routing

Single-path multichannel routing protocols discover only one path between source and destination nodes. Unlike single-path single-channel routing protocols, single-path multichannel routing protocols can exploit parallel communication among adjacent nodes operating in different channels. Due to this parallel communication in multiple channels, network capacity and performance are improved.

So *et al.* [105] propose a routing protocol for MANET called Multi-Channel Routing Protocol (MCPR). Each node in MCPR is assumed to be equipped with a single half-duplex transceiver, which can switch between channels with a delay of less than 80 μsec. In MCPR all nodes involved in the flow are assigned a common channel, which means that the intermediate nodes are not required to switch channels during data transmission. MCPR employs a similar routing scheme to AODV

[19]. However, as the nodes are equipped with a single transceiver and in order to discover a route to the destination, MCPR must switch between available channels quickly to broadcast the RREQ on each channel in a round robin manner. The intermediate nodes create a reverse path to the source node and record the channel number used in the reverse route in their routing table entry; they then rebroadcast the RREQ in a round robin manner. The RREQ contains two tables, the channel and flow tables, which are propagated along with each RREQ packet. The channel table lists channels used on a single flow route. The flow table lists current flows on a single channel. These tables enable the destination node to select a best route among the received RREQs. The destination node unicasts a RREP to the source node via the selected route. Intermediate nodes receiving the RREP change their operating channel to the channel selected by the destination node. Upon receiving the RREP, the source node transmits the data packets using the established route. Increased channel switching and rebroadcasting of RREQ in all channels in MCPR increases routing overhead and the node switching delay.

Gong *et al.* [126] propose an extension to the well-known proactive routing protocol OLSR [70] to support multichannel communication. The proposed multichannel routing protocol is called Channel Assignment OLSR (CA-OLSR). CA-OLSR assumes that each node is equipped with a single transceiver and adopts dynamic channel assignment. In the proactive OLSR routing protocol, neighbour nodes exchange their neighbours' tables periodically via a Hello packet in order to have a complete and up-to-data overview of the network topology. CA-OLSR benefits from this attribute in OLSR to assign a distinct channel to active nodes only within k number of hops from the source node, with the aim of reducing inter-flow interference. In CA-OLSR each node periodically sends a Hello packet that includes its own channel along with a list of its one-hop neighbours' channels. This enables the node to calculate the Multi-Point relays (MPRs) nodes and also to assign a distinct channel to active nodes in the 2-hop neighbourhood in order to minimise interference and collisions. Although CA-OLSR benefits from the robust routing of OLSR, it is greatly affected by the high volume of routing overheads and the computational time required to maintain an up-to-date view of the network topology.

Wang *et al.* [128] propose Multi-Channel On-demand Routing with Coordinate Awareness (MCORCA) to improve MANET's performance. MCORCA is a combination of channel assignment in the MAC layer and the ORCA routing protocol (On-demand Routing with Coordinate Awareness [136]). Each node in MCORCA is equipped with a single transceiver and utilises the time-slotting approach SSCH for channel assignment [104]. Also, there is a dedicated common control channel, which is used to perform channel assignment, and support multiple data channels. Before initiating route discovery (RREQ and RREP), a sender has to schedule a data channel with the intended receiver by broadcasting a scheduling packet in the common control channel to a set of neighbours. Each receiver has to acknowledge reception of a packet by sending a binary digit (either 1 or 0, which represent accepting or rejecting channel assignment respectively) to the sender upon receiving the schedule packet. Upon receiving any feedback token, the sender and receiver switch to the data channel and broadcast the RREQ packet. All committed receivers have to switch their channel to the agreed data channel. The same process repeats until the RREQ reaches its destination or an intermediate node with a valid route towards the destination. Then, an RREP packet is unicast in the reverse path towards the source and accumulates the path from the source to the destination. The node unicasting the RREP must broadcast the schedule packet in the control channel first, to do the channel assignment. The same process is repeated until the RREP is received by the source. Upon receiving the RREP, a route between the source and destination is established and the source starts transmitting data packets along it. To transmit a data packet, a sender has to assign a data channel to the next hop by broadcasting the schedule packet in the control channel. Once the token "1" for acceptance is received, they switch to the data channel for data transmission. Although MCORCA proposes a distributed cross-layer routing and multichannel assignment, it require much channel switching before transmitting any packet (RREQ, RREP and Data) and the control channel may become a bottleneck.

3.4.1.2 Multipath Multichannel Routing

Yan *et al.* [106] propose a Multipath Multichannel Routing (MMR) protocol. MMR is an extension to the well-known reactive routing protocol DSR. MMR assumes that each node is equipped with a single transceiver and that channel assignment takes place in the MAC layer. MMR aims to eliminate co-channel interference in multipath routing by assigning a different frequency band to each route. Route discovery is performed in a single channel and follows the DSR mechanism. The RREP process is modified to allow multiple route formation. Then the source node selects the best two routes for data transmission. Several routing metrics are used to select the best two routes, including least hop count, the consumed power budget and the path with the lowest number of joint nodes. Then two selected paths are assigned to two distinct channels, which helps to eliminate co-channel interference. While route discovery and maintenance in MMR are established in a single channel, data packet transmission occurs using two different channels, which improves protocol performance. However, in scenarios where only a single route is established between the source and destination nodes, it would not be possible to transmit data in two channels and therefore no improvement could be achieved.

Che-aron *et al.* [131] propose a Fault-Tolerant Cognitive Ad hoc Routing Protocol (FTCARP). FTCARP is a reactive distance-vector routing protocol that introduces a fast and efficient route recovery mechanism when path failure is detected. FTCARP jointly exploits different paths and channels in data routing. This enables a secondary user to switch between different pre-discovered paths in different channels in the presence of activity from a primary user. When link failure is detected, a node can rapidly exploit the backup route to transmit newly arriving data without causing service disruption. Different route recovery mechanisms are proposed to handle different reasons for failure (i.e. presence of primary user, node mobility or link failure). FTCARP sends a Primary Route REQuest (P-RREQ) in all available channels except the channel with primary user activity. Intermediate nodes create several primary reverse routes towards the source and then rebroadcast the P-RREQ in all available channels except the channel with primary user activity. The destination node or an intermediate node with an updated route towards the destination sends the Primary RREP (P-RREP) to the source along all its available primary reverse paths in different channels. When the source node receives the P-RREP, data packets are transmitted using the primary route. Then, an intermediate node involved in the forwarding route broadcasts a Backup Route REQuest (B-RREQ) with limited TTL to its neighbours via its idle channels to discover a backup route. Neighbour nodes that have a valid route towards the destination send a Backup Route REPly (B-RREP) to establish a backup route. If a node cannot forward the data to the next hop along the primary route due to node mobility or link failure, the pre-discovered backup path is rapidly exploited to reroute data packets without causing disruption to data transmission. FTCARP provides a fast route recovery mechanism and improves the communication reliability in the network, but it incurs a considerable routing overhead to discover primary and backup routes.

3.4.2 Multi Radio Interfaces

This section reviews multichannel routing protocols where each node is equipped with multiple radio interfaces. This enables each node to transmit concurrently using distinct channels in different transceivers at the same time, and hence network performance can be significantly improved. Multichannel routing protocols in this category can be further classified based on the number of discovered paths, into single-path and multipath multichannel routing protocols.

3.4.2.1 Single-Path Multichannel Routing

Lee *et al.* [108] propose an extension to the well-known proactive DSDV [21] to support multichannel communication in wireless ad hoc networks, named DSDV-MC. DSDV-MC aims to increase the network capacity by enabling concurrent transmission in multiple channels. Each node in DSDV-MC is equipped with two half-duplex radio interfaces. To minimise the effect of periodic updates in proactive routing protocols, DSDV-MC divides the network layer into a dedicated control plane and a data plane. Routing updates, channel information and control packets are sent via the dedicated control channel, while the data packets are sent via data channels. In DSDV-MC, nodes periodically advertise routing information, topology changes, channel information and switching via the control channel. Exchanging current channel information enables neighbour nodes to assign a unique channel and reduce interference. DSDV-MC adopts a receiver-based channel assignment approach where each node is assigned a channel and a transmitter switches to a receiver channel to start communication. If a node changes its receiving channel, then it must broadcast an incremental message to the entire network to update the current listening channel. DSDV-MC enables multichannel communication and reduces the required overhead for channel assignment and routing packets by utilising receiver-based channel assignment and a dedicated control channel. However, DSDV-MC is prone to a control channel bottleneck issue and it inherits a high control overhead from DSDV.

Gong *et al.* [114] propose on-demand routing and channel assignment in a multichannel MANET called Channel Assignment AODV (CA-AODV). Additionally, they propose two extensions called 2-hop CA-AODV and K-hop CA-AODV. CA-AODV aims to mitigate interference (inter-interference and intra-interference) that exists in multichannel routing protocols. They achieve this by dynamically assigning an orthogonal channel only to active neighbour nodes during a route discovery process (RREQ and RREP). CA-AODV assumes that each node in the network is equipped with two radio interfaces; one radio is fixed in the common control channel and the other is switchable between channels to deliver data packets. In 2-hop CA-AODV, neighbour nodes periodically exchange extended Hello packets, which include the home channel for this node and the active channel for its one-hop neighbour. This enables a node to determine the active channel taken by its two-hops neighbour and thus select a different channel to minimise the effect of intra-flow interference in the 2-hops neighbourhood. K-hop CA-AODV extends 2-hop CA-AODV by introducing a new control packet called (CHANNELTAKEN). In k-hop CA-AODV, nodes broadcast a CHANNELTAKEN packet to k-hops to inform them about channels that have already been taken. The proposed protocols have been shown to require fewer channels and less computation and complexity. However, they increase the overhead of channel assignment and may not respond well to a network with high node mobility.

Zhou *et al.* [134] propose an extension to the well-known reactive routing protocol AODV [19] to support multichannel communication in MANETs, called Multichannel-AODV with channel Reuse (M-AODV-R). It uses a cross-layer design approach to solve channel assignment, channel reuse and routing problems jointly. In M-AODV-R each node is equipped with two radio interfaces; the first radio interface is assigned to a common control channel by all nodes in the network and this radio interface is dedicated for control messages only, such as RREQ, RREP and Hello, and the other radio interface is dedicated to data transmission and can switch between data channels to transmit data packets. M-AODV-R adopts distributed dynamic channel assignment where nodes exchange channel usage information periodically via Hello packets. During RREQ and RREP, each node records the route and indexes of channels that have been taken so far in the same route. As RREP packets are forwarded to the source node, intermediate nodes involved in the RREP update their routing table and channel usage tables. This helps to select a route with a conflict free channel and hence mitigates interference among nodes in the same route. The M-AODV-R combines channel assignment, reuse and routing information and helps to mitigate the inter-flow interference on a route. However, it uses only one transceiver for data packet transmission, while the other transceiver is dedicated to control packets, which underutilises available network's resources.

Zhou [135] proposes a routing and interface assignment algorithm for a Multi-Channel Multi-Interface (MCMI) routing protocol in MANETs. In MCMI a dedicated radio interface is assigned to a common control channel on each node in order to exchange control packets, coordinate channels and discover neighbours. The proposed algorithm considers both the number of hops between the source and the destination, and the effects of adjacent hop interference. MCMI consists of two decoupled steps: route selection and interface assignment. The first step aims to find a best path between the source and the destination. A best path is considered as the path with the shortest hop count and the smallest effect from adjacent hop interference. Once the best path is selected, a channel is assigned to the radio interface using the Viterbi algorithm for each hop in the path with the aim of minimising adjacent hop interference. In order to establish a route with minimum adjacent interference, each node in MCMI floods the entire network with topology control information about its neighbourhood of two hops. This information enables each node to build and maintain a global knowledge of the entire network, including the available channels and the number of radio interfaces at each node. Although the proposed algorithm can reduce interference among adjacent hops, it requires a high overhead for topology construction and maintenance, and may suffer in a network with high node mobility.

3.4.2.2 Multipath Multichannel Routing

Lee *et al.* [10] propose a Reliable Hybrid Multipath Routing (RHMP) protocol to enhance the reliability of communication in a tactical ad hoc network. RHMP assumes that the number of radio interfaces is the same as the number of available channels and they are assigned to a distinct channel. RHMP is a hybrid routing protocol that uses proactive-like routing for route discovery and reactive-like routing for route recovery and maintenance. In order to achieve the long distance cover for the tactical wireless ad hoc network, RHMP periodically discovers multiple routes towards every node in the network. A new packet called Periodic Route Discovery Message (PRDM) is transmitted every time interval. The time intervals are reconfigured dynamically depending on the link quality and node mobility. The best discovered route will be picked as the master route. RHMP finds a node and channel disjointed routes to avoid routing loop problems. If a link failure is detected for any of the master routes, the second highest rated alternative route is selected as the master route. However, if no alternative route is available, then the protocol rediscovers a new route as in a reactive routing protocol by transmitting an On-demand Route Recovery Message (ORRM). The RHMP protocol is shown to be efficient in a network with low node densities and low degrees of node mobility. However, increasing node density or mobility can significantly increase the maintenance overhead, affecting overall network performance.

Kok *et al.* [115] extend the well-known multipath AOMDV [80] to enhance network performance by supporting multichannel communication using multiple radio interfaces. It is named Extended AOMDV for Multi-interface Multi-Channel networks (EAOMDV-MIMC). EAOMDV-MIMC assumes that all nodes in the network have multiple homogeneous radio interfaces. Unlike other related works, EAOMDV-MIMC does not assign channels to nodes, but rather lets nodes utilise all the available channels they are tuned to. To allow the discovery of multiple links or node-disjointed paths in each channel, EAOMDV-MIMC establishes a route discovery process in all available channels. When a broken link is detected and cannot be repaired, the node broadcasts RERR on all available channels. Nodes estimate the channel condition (i.e. congested or free) by monitoring the interface queuing delay for each radio interface corresponding to each channel. Based on that estimation, the node forwards the data packets via the channel with the smallest expected queuing delay and smallest expected contention. The authors also extend EAOMDV-MIMC to propagate the estimated channel condition for each radio interface with the view to improving next-hop selection. The extended version is called EAOMDV-MIMC-PM, where the estimated channel conditions for each channel are piggybacked on data packets. Neighbour nodes overhearing this packet can retrieve its estimated channel condition information and make better next-hop selections. EAOMDV-MIMC improves network performance by discovering multiple paths in multiple channels, but it increases routing overheads considerably.

Gharavi [137] propose a Dual-channel/Dual-path Routing (DDR) protocol to improve the transmission of real-time information (video traffic) over multi-hop ad hoc links. DDR is an extension to the well-known reactive routing protocol DSR [20] to support multipath multichannel routing. DDR assumes that each node can be assigned two non-overlapping channels and can listen to them at the same time. In DDR the route discovery process is performed in a single channel. However, it modifies the RREQ process in DSR to enable intermediate nodes to rebroadcast a duplicate RREQ, which has a smaller hop count compared to a previously received RREQ. Thus, a source can discover multiple routes to any destination. The source node selects the best two routes (with the least hop count, the lowest power budget and smallest number of joint nodes) in two different channels for data transmission. Then the source transmits two data streams using two different channels, which eliminates inter-flow interference.

3.5 Discussion

The multichannel protocols are designed to exploit available channels with the scope of enhancing the network performance. To accomplish the benefits of utilising multiple channels in wireless networks, three issues need to be addressed: 1) the availability of radio interface (single radio or multi radios) per node, which is concerned with the capability of the wireless device to transmit and/or receive at the same time; 2) The channel assignment mechanism, which is concerned with assigning a channel to the radio interface, and facilitating channel negotiation and agreement on which channel should be used for data transmission; 3) The routing mechanism, which is concerned with finding and maintaining a route between source and destination nodes and routing data packets to their destination.

In the following sections different approaches to design and implement the multichannel routing protocol are discussed.

3.5.1 Number of Radio Interfaces

The number of radio interfaces per node plays an important role in designing a multichannel routing protocol. A large number of the proposed solutions assume that each node in the network is equipped with multiple half-duplex radio interfaces (NICs). Equipping each node with multiple radio interfaces enables each node to transmit and receive simultaneously, using different non-overlapping channels over different radio interfaces. This can provide concurrent communication among adjacent nodes, enhance spatial reuse, utilise the available bandwidth efficiently, mitigate the issues of multichannel hidden terminals and deafness and hence improve network performance and capacity. Although utilising multiple radio interfaces can significantly improve network capacity and facilitate communication in a multichannel wireless network, it produces a higher cost in terms of hardware equipment and power consumption which is not generally desirable in small battery powered wireless devices such as nodes in MANETs. Furthermore, it cannot be directly implemented in the majority of current communication devices, such as laptops and PDAs, as they tend to be equipped with a single transceiver. Additionally, to incorporate multiple radio interfaces into a single device, they need to be separated by enough distance to avoid interference between them inside the node, which may not be practical. For example, radio interfaces should be at least 38cm apart, according to [138] or operate in different frequency bands (2.4GHz and 5GHz) [139] to avoid interference between the radio interfaces inside the node. Although using a busy-tone radio interface can prevent collision for data packets and is simpler to implement than using a full data packet interface, it still increases the cost of hardware and power consumption as it requires extra dedicated hardware. Additionally, no data packets are expected to be transmitted using this extra hardware.

Equipping each node with a single radio interface enables the nodes to either transmit/receive or listen to a single channel at any given time. Single radio multichannel solutions can be implemented in the majority of wireless devices without any changes to the existing hardware and without increasing the cost of hardware or power consumption, as in the multi radio solutions. Nodes can switch between channels to transmit or receive and this can still allow concurrent communication among adjacent nodes operating in different non-overlapping channels, enhancing the spatial reuse compared with a single-channel network, utilising the available bandwidth efficiently and hence improving the network performance and capacity. However, the proposed protocols exploit a single radio interface to implement multichannel communication, and this may not fully utilise the available bandwidth as efficiently as the multi-radio solutions does. Additionally, as all nodes are equipped with a single transceiver and are only aware of communication in the current listening channel, when a node switches to a new channel, it may not be aware of ongoing communication in the new channel and therefore it may inadvertently act as a multichannel hidden terminal and suffer also from deafness problems.

Although equipping each node in the network with multiple radio interfaces may increase concurrent communication in the network, it is more expensive to realise in terms of hardware cost and expected power consumption. In contrast, single radio multichannel routing solutions are more practical and applicable to existing wireless devices without increasing hardware cost or power consumption. Additionally, utilising multiple channels over a single transceiver can still improve the network capacity and performance, as shown in [105, 104, 88].

Based on the above discussion and for the aforementioned reasons, this thesis focuses on designing multichannel routing protocols where each node is equipped with a single half-duplex transceiver as it is more practical, the costs of hardware and power consumption are less than for multiple transceivers and it is more applicable to the majority of existing communication devices.

3.5.2 Channel Assignment

Selecting an appropriate channel assignment approach for MANETs where all nodes are equipped with a single transceiver is challenging. Different channel assignment approaches have different trade-offs in terms of the overall achievable performance, the design complexity and the expected overhead to realise them.

A large number of multichannel routing and MAC protocols depend on a common control channel and/or time synchronisation to support channel assignment in the multichannel network. Clock synchronisation is a difficult task to accomplish in a large-scale decentralised infrastructure-less dynamic network such as a MANET. Utilising a common control channel can greatly facilitate channel assignment and negotiation. Additionally, it can support broadcast and reduce the routing overhead associated with exchanging control packets (RREQ and RREP) and also help to maintain local connectivity (Hello). On the other hand, as all nodes are exchanging control packets in a single common channel, this channel may suffer from control channel saturation problems [6] as well as multichannel hidden terminal, deafness and channel switching delay. Furthermore, dedicating part of the available bandwidth (one channel, for example) exclusively to the control packets and negotiation will reduce the number of channels available for data communication by about one third, in the case of utilising three non-overlapping channels in IEEE 802.11b at 2.4GHz. Additionally, it may require tight time synchronisation to ensure that all nodes are listening to the control channel at the same time, which can be hard to achieve in a large-scale MANET.

With regard to different channel assignment approaches that have been discussed in section 3.3.1, a static channel assignment approach is considered to be the easiest approach to implement, whereas dynamic channel assignment is the most complex and the semi-dynamic approach is in-between [140].

A static channel assignment approach may suffer from inter-path interference among nodes inside the cluster sharing the same channel. Additionally, it is not suitable for a network with dynamic topology changes because of the network partitioning issue, as nodes cannot communicate with neighbours operating in different channels. In contrast, the dynamic channel assignment approach can significantly reduce inter- and intra-path interference, but a common control channel or time synchronisation may be required to coordinate channel selection, which is difficult to achieve in decentralised networks such as MANETs. Additionally, it requires strict channel negotiation, coordination and switching before any data transmission, which is costly in terms of channel assignment, channel switching overheads such as channel switching latency, and energy consumption [141, 142]. A semi-dynamic approach is more flexible than a static channel assignment approach as it allows nodes to switch their channel to another node's channel and thus communicate with their neighbours operating in different channels; it also alleviates the network partitioning issue. Additionally, it requires less strict channel coordination compared with a dynamic channel assignment approach, as only the transmitter or receiver is required to switch to another node's channel for communication. However, it may still suffer from inter-path interference, and multichannel hidden terminal and deafness problems [140].

Based on the above discussion and for the aforesaid reasons, this thesis chooses to avoid using a common control channel or time synchronisation and also chose to adopt a semi-dynamic approach to achieve channel assignment and coordination.

3.5.3 Multichannel Routing

Different routing strategies have been proposed to enhance routing functionality in the multichannel wireless ad hoc network. The majority of these solutions, discussed in section 3.4, were an extension to the well-known single-channel routing protocols (which have been discussed in section 2.5) to support multichannel communication in MANETs. This section discusses different approaches to support multichannel routing protocols in wireless ad hoc networks; namely, considering channel assignment and routing protocol jointly or disjointly, and considering the number of discovered paths per destination (single path or multipath) [143].

A joint channel assignment and routing approach, where channel assignment and routing are closely associated together and routing plays a role in channel assignment may optimise selection of channel and routing, improve the load balance and reduce the interference volume [143]. However, this approach increases the design complexity and channel assignment overhead. Additionally, it may require a common control channel, time synchronisation or extra control packets to perform channel assignment and routing cooperatively.

A disjointed channel assignment and routing approach carries out the channel assignment and routing in a segregated manner. Multichannel routing protocols belonging to this category are mainly concerned with assigning orthogonal channels to neighbour nodes or paths. Considering multichannel selection and routing separately simplifies multichannel protocol design and also enables a better conceptual understanding of the impact of each component (channel assignment and routing) separately. However, disjointed channel assignment and routing approach may still suffer from interference issues.

With regard to the number of discovered paths per destination, single-path and multipath multichannel routing protocols were proposed as discussed in section 3.4.

Single-path multichannel routing protocols discover and maintain a single route between source and destination nodes, then the discovered route is used for data transmission. Unlike single-path single-channel routing protocols, a single-path multichannel routing protocol may offer simultaneous communication among adjacent nodes operating in different channels and therefore can improve the network performance and capacity. However, discovering a single route to any destination may make the routing protocol unreliable, as route failure due to unpredictable node mobility, link condition, and multichannel hidden terminal and deafness issues could cause a transmission failure. Additionally, the delay time to recover from a broken link may not be acceptable in some delay-sensitive applications [144]. Increasing node density, mobility or offered load in the network may increase the occurrence of the route failure and hence degrade network performance sharply.

In contrast with single-path multichannel routing protocols, the multipath multichannel routing protocols can discover and maintain multiple (node and channel disjointed) routes between source and destination nodes. The multiple discovered paths can be used simultaneously to transmit data packets along multiple channels or one path can be used for data transmission and the remaining paths as alternative paths to recover quickly from a broken link. Multipath multichannel routing protocols can confer additional advantages to the routing protocol such as enhancing route reliability, resilience and load balancing, increasing network throughput and capacity, reducing the delay to recover from a broken link and interference, and also improving fault-tolerance in the MANET's routing protocols [144, 145]. However, the disadvantage of discovering multiple paths in multiple channels is that it increases the associated routing overhead of discovering and maintaining multiple routes, which will increase energy consumption. Additionally, as each node is only equipped with a single transceiver, it may not have an up-to-date view of all discovered paths in different channels.

Based on the above discussion and for the aforementioned reasons, this thesis chose to adopt a dis-jointed channel assignment and routing approach. Although considering channel assignment and routing jointly can further improve the network performance, investigating the problems separately can reduce design complexity and allow for a better conceptual understanding of the impact of each component.

3.6 Conclusions

Utilising multiple non-overlapping channels may reduce interference, contention and collisions and enable multiple concurrent communication among adjacent nodes, thus improving network performance and capacity. Meanwhile, it introduces new challenges or worsens existing challenges in wireless ad hoc networks. This chapter has highlighted the expected benefits and challenges of utilising multiple channels in communication in MANETs.

The chapter has provided a literature review of different approaches to implementing and incorporating multichannel communication in MANETs from different aspects. Proposed solutions can be categorised based on the number of transceivers per node, into single/multi radio multichannel protocols, or based on the adopted channel assignment approach, into static, dynamic and semi-dynamic approaches, or based on the number of discovered paths per destination into single/multipath routing protocols. A thorough discussion of these three aspects was presented and the adopted approach of this research was identified.

This research considers a wireless ad hoc network where all nodes are equipped with a single half-duplex transceiver. A semi-dynamic channel assignment approach is adopted in this thesis without reliance on a common control channel or time synchronisation. The thesis investigates the impact of the single-path multichannel routing protocol in Chapter 5 on network performance. Then, a new multipath multichannel routing protocol is proposed in Chapter 6 to enhance reliability, error resilience and fault tolerance in MANETs. This is followed by study of a cross-layer MAC mechanisms in Chapter 7 to enhance communication reliability in the multipath multichannel routing protocols further.

Chapter 4

Methodology

4.1 Introduction

This chapter describes in detail and justifies the methodology used to undertake this research. A brief description of the chosen routing protocol and cross-layer design approaches in the wireless network is given. Different system modelling techniques used in the wireless network research community are briefly discussed and then the selection of the network simulator (NS-2) is justified. NS-2 is a free open-source discrete-event simulator, and it is one of the most widely used network simulator tools in the network research community.

The organisation of this chapter is as follows: Section 4.2 discuss the selected routing protocol. Section 4.3 describes different cross-layering design techniques. In Section 4.4, a discussion of different system modelling techniques is presented, together with a justification of the selected models. Section 4.5 describes the multi-channel extension to NS-2. Section 4.6 describes the simulation approach, environments, assumptions and the performance evaluation metrics. Section 4.7 summarises the chapter.

4.2 Routing Protocols

Designing a robust routing protocol is a vital task to realise workable MANETs in the future. A significant amount of research has already been devoted to further advancing their routing protocols. Based on the number of utilised channels in the network, routing protocols can be categorised into single channel protocols such as that mentioned in section 2.5 and multichannel protocols such as that mentioned in section 3.4. Each category can be further sub-categorised based on the number of discovered paths per destination into single/multipath routing protocols.

Reactive routing protocols are designed to suit networks with high density and high node mobility, which makes them a fertile area for research. Therefore, this thesis focuses on studying and analysing the behaviour of reactive routing protocols under different routing configurations, namely, reactive single channel single path, single channel multipath, multichannel single path, and multichannel multipath routing protocol.

4.2.1 Selection Criteria

Reactive or on-demand routing protocols start a discovery process to discover a route between a source and destination nodes whenever the source has data to send to a destination and does not have a valid route towards the destination. The discovered route is maintained as long as the source has data to send. The source node starts the discovery process by flooding RREQ packets throughout the network. The destination node, or an intermediate node which has a valid fresh route to the destination, replies to the source node with a route reply (RREP) packet. Upon receiving a RREP from the source node, a route is established and the source node starts transmitting data packets. A route maintenance procedure maintains the established route as long as it is required. When node/link failure is detected along an active route, a route repair/recovery process is started to repair the broken link and resume data transmission.

In this study, the well-known reactive routing protocol (AODV) [19] is chosen. AODV is a simple and widely used reactive routing protocol for MANETs. Ad hoc On-demand Distance Vector (AODV) is a single-path routing protocol that has been extensively studied and used as a reactive routing protocol in mobile ad hoc networks. It was developed in 2003 in Nokia Research Centre, University of

California, Santa Barbara and the University of Cincinnati. Extensions to AODV have been proposed in Chapters 5 and 6 to support multichannel single path and multichannel multipath routing techniques respectively.

4.3 Cross-Layer Designs

The standardisation of communication systems into a layered protocol stack helps to reduce network design complexity, enables fast development of interoperable systems and improves the design of communication protocols [33]. Interacting between layers in these standards only occurs between neighbouring layers. However, due to the lack of coordination among layers, the overall performance of such an architecture can be limited. The unique characteristics of wireless network communication, such as the shared communication medium, interference, propagation environment, mobility and limited bandwidth, introduce new challenges. For instance, when a transmission error is detected in a wired network, reducing the bit rate immediately can help to reduce packet loss as the collision is reduced and then the bit rate can be increased slowly when no more errors are detected. With regard to wireless networks, this solution is not practical as a significant packet loss is usually caused by interference, fading, collisions, noise, etc. Therefore, reducing the bit rate might not solve the problem as in wired networks, but only lead to a reduction in the throughput and increase the time it takes to recover from the error.

To overcome this limitation, a careful modification to the layering of protocol stacks has been proposed, namely cross-layer design. The main idea of using cross-layering design is to allow coordination, interaction and optimisation among non-adjacent layers while maintaining the functionality associated with the original layers [146]. Jurdak [147] has proposed the following definition for a cross-layer design approach: "*The design of algorithms, protocols, or architectures that exploit or provide a set of interlayer interactions that is a superset of the standard interfaces provided by the reference layered architecture.*" Due to the unique characteristics of MANETs, which are mentioned in 2.4.2 and the limitation of coordination in the layered approach, a cross-layer design is considered a useful technique to improve the performance of wireless networks, including MANETs. More detailed information about cross-layer designs can be found in [33, 32, 147, 148, 149, 150]

4.3.1 Cross-Layer Approaches

Srivastava *et al.* [148] categorise proposals to implement cross-layer interaction in the literature into three categories as in Figure (4.1 [148]).

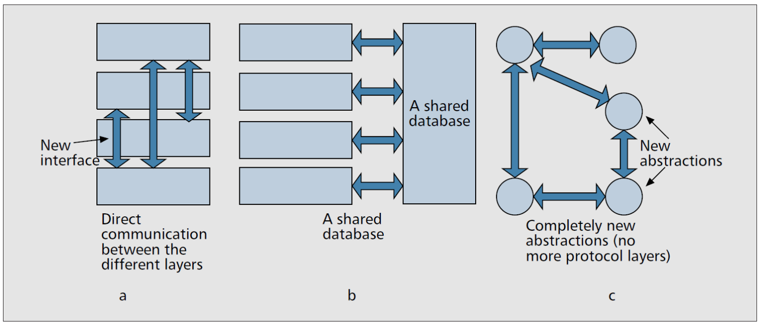

Figure 4.1: Cross-layer architecture

- **Direct Communication between Layers:** This approach enables direct information sharing and exchange between non-neighbouring layers during runtime as shown in Figure (4.1 (a)). Direct communication between different layers can be accomplished by either passing information in packet headers (downward direction only) or by using layer triggers or signalling as in [151]. Practically speaking, a shared variable allows the visibility of variables between layers (upward or downward) at runtime. Layer triggers issue a predefined signal, which notifies of special events between different protocols at different layers. A direct communication approach can be further categorised based on the direction of the information flow into:
  - **Upward cross-layering:** when the higher layer protocol (i.e. Routing) access information from a lower layer protocol (i.e. PHY or MAC).
  - **Downward cross-layering:** when the lower layer protocol (i.e. PHY or MAC) access information from a higher layer protocol (i.e. Routing).
- **A Shared Database Across Layers:** In this approach a common database made to be accessible between all layers (see Figure 4.1 (b)). The shared

database is considered to be a new layer that provides a service of storage and sharing information. Also, this approach provides common methods to insert/retrieve data to/from the database. However, this approach requires careful design of the interaction between the shared database at different layers.

- **Completely New Abstractions:** In this approach a novel organisation of the protocol is proposed that does not use the layering scheme as illustrated in Figure (4.1 (c)). This approach provides greater flexibility and interactions between the building blocks of the protocol. However, a careful design is essential to avoid *spaghetti-like* code and may also require a completely new system implementation.

4.3.2 Selection Criteria

Direct communication between layers is one approach to implement interaction across different layers. The main advantage of this approach over others is its simplicity and the potential to solve some issues and improve the performance of MANETs. In our implementation, we use this approach to implement the cross-layer by using the downward technique. More specifically, a new field in the common packet header was added to enable a runtime information sharing between the routing and MAC layers. This information enables the multichannel MAC layer protocol to determine which channel to switch to and start communication. Furthermore, we enable layer triggers between the MAC and routing layers to enable a node to check the validity of its routing information towards a destination node or to invoke an alternative route. Further details of the used cross-layer technique, will be given in Chapters 7.

4.4 System Modelling

Despite extensive research on MANETs, few examples of real implementation are exist. This is mainly due to the unique nature of MANETs and the wide possiblity of applications. Researchers are still working to propose, evaluate and validate different algorithm designs to realise such a network. Performance evaluation is required during network design, implementation and building to assess the applicability of the proposed solutions. Different approaches used to evaluate the network performance include testbed and system modelling [152, 153].

A testbed approach uses a real network system which requires real devices, monitoring of the network and then extraction of data [152]. Testbeds help to understand network behaviour and functionality in a real situation. However, implementing a real experiment on a testbed is difficult because: it is difficult to monitor, has limited support of mobility, is expensive and time consuming and lacks re-producibility.

A system modelling approach uses a simple representation of a real system to organise, evaluate and understand the network system and therefore predict how the system might behave without implementing it. Various parameters and often some simplifications are applied to study the behaviour of the system. Issariyakul *et. al.* [154] classify system modelling into two approaches: an analytical approach and a simulation approach. An analytical modelling approach describes the system mathematically to provide a better understanding of the system. An analytical result is derived mainly from mathematical proof and is considered valid as long as its assumptions, parameters and conditions are accurate. Analytical modelling techniques such as Queuing Network Model (QNM), Generalised Stochastic Petri Net (GSPN) and Petri Net (PN) [155] help in studying the performance of communication systems and understanding the effect of different parameters and their interactions in network systems. Most of the analytical models used in MANETs ignore node mobility by assuming a static node [156]. This is mainly due to the high complexity involved in incorporating random mobility of nodes in analytical modelling [157]. However, node mobility is one of the main characteristics in MANETs that cannot be ignored, as discussed in section 2.4.2. Therefore, analytical modelling may be more suitable to evaluate the performance of a small and static network.

A network simulation approach uses a software tool to simulate network behaviour and to provide a better understanding of the behaviour of different models. Simulation introduces a means to study large and complex systems and to determine their feasibility before implementing them. Usually simulation requires fewer simplifications and assumptions compared to an analytical model, as almost all the system specification details are incorporated into the simulation model. Simulation is widely used and accepted in the research community as a valid tool to study and evaluate proposed protocols under different conditions and environments. It is usually used before implementing the proposed solution in a real system. A network simulation approach is used in this thesis to model the system and study proposed solutions.

4.4.1 Network Simulators

Numerous network simulators have been developed and used to study and evaluate network performance, including MANETs. Due to the high cost involved in realising a real ad hoc network, simulation has become a very popular alternative in the MANET research community. Network simulators can be distinguished based on their cost as free open-source network simulators such as NS-2 [158], NS3 [159], OMNet++ [160] or as commercially produced simulators such as MATLAB [161], OPNET [162] and QualNet [163]. Each type of simulator has its strengths and weaknesses. Kasch *et. al.* [164] suggest factors that need to be considered to select the most appropriate simulator; these include the simulation platform, type of simulation tool and the support of user friendly interfaces. Table 4.1 reports on a comparative study of different simulators [165].

Network simulation tools usually depend on a simulation clock (time-dependent) to track simulation events with simulation time chronologically. Time-dependent simulation can be further divided into time-driven and event-driven simulation [154]. A time-driven simulation performs events at fixed intervals of time. On the other hand, an event-driven simulation performs events based on the next event time rather than at fixed time intervals. Therefore, in event-driven simulation, events with the smallest timestamps are retrieved and executed from an event list, and then the simulation clock advances to the associated timestamp for the next event.

Table 4.1: Comparison of Different Network Simulators

Simulator	Language	Pros	Cons
MATLAB	C++	• Excellent graphical support. • Excellent facility for debug.	• Processing speed is slow. • Exceptional programming skills are required.
OPNET	C / C++	• Large number of customers. • Professional support. • Excellent documented.	• Relatively expensive but there is a special price for universities. • More suitable for network managers than for researcher.
QUALNET	C++	• Easy to use and learn . • Animation capabilities. • There is support for distributed computing and multiprocessor systems.	• Installation problems on Linux. • Slow Java-based user interface. • It is costly.
OMNET++	C++	• Easy to trace a bug. • Simulates power consumption problems.	• Limited routing protocols available. • No compatibility (not portable).
NS3	C++ Python scripts.	• Free and Open Source. • It is a new simulator; NS-3 is not an extension of NS-2.	• Windows platform are lightly supported as some ns-3 aspects depend on Unix / Linux support. • Limited visual aid.
NS2	C++ OTcl scripts	• Free and Open Source. • Extendable • Support various types of networks and protocols. • Have some visualisation tools. • Large community supporter • well documented.	• Takes long time to learn. • Difficult to trace a bug. • Very limited visual aid.

4.4.2 Selection Criteria

This thesis reports on extensive simulation work conducted using the network simulator version-2 (NS-2) [158]. NS-2 was chosen as it is a widely used and accepted network simulator tool in the network research community. Furthermore, NS-2 is a free, open-source and readily extendable. Therefore, researchers tend to extend the implementation of NS-2 to include their own model and study its simulation performance. According to [166], 54% of research on MANETs is conducted using NS-2 as a simulation tool to develop and evaluate the network performance of the proposed protocols. Furthermore, NS-2 is a discrete-event-driven simulator that supports various network types, such as wired, wireless and satellite. For these reasons, NS-2 was selected as a simulation tool to develop and analyse proposed MANET protocol solutions.

4.4.3 NS-2 Simulator

NS-2 is an open-source discrete-event-driven simulator that was developed in 1995 by Lawrence Berkeley Laboratory at the University of California. Initially, NS-2 only supported wired networks. Then a Monarch project at Carnegie Mellon University (CMU) provided a wireless extension to NS-2 to support wireless communication and node mobility models.

NS-2 is implemented over two programming languages: C++ and the Object-oriented Tool command language (OTcl). The core of NS-2 is written using C++, which specifies the internal mechanism of the simulation, while the scripting language OTcl is used as a user interface to construct and configure the network environment. NS-2 combines the advantages of both languages to provide a robust, fast and adaptable simulation environment. It uses C++, which provides fast execution at runtime. It uses OTcl to change the network configuration quickly without the need to recompile the simulator. NS-2 has all the essential features for network simulation, including abstraction, visualisation, emulation, and traffic and movement scenario generation files. It adopts a network layer approach and supports a wide range of protocols and models in each layer, such as (UDP, TCP. AODV, DSR, DSDV, AOMDV, IEEE 802.11, IEEE 802.11Ext, energy models ... etc.)

The NS-2 simulator includes several radio propagation models that support propagation delay, capture effects, and carrier sense models. For instance, it supports a free space propagation model, a two-ray ground reflection model and a shadowing propagation model [167]. The default characteristics of radio models are similar to a commercial Lucent WaveLAN technology with a nominal transmission range of 250 meters, an omnidirectional antenna and a nominal bit rate of 2Mb/sec.

4.4.4 Mobility Model

A MANET is a style of wireless network where nodes can move arbitrarily and the topology can change unpredictably. Node mobility is one of the main causes of frequent link failure in MANET, which can lead to serious network performance degradation. The mobility model describes the movement of mobile nodes by record-ing changes in node direction, velocity and acceleration over time.

Utilising a realistic mobility model to mimic expected node movement patterns is vital to study the behaviour of proposed protocols in real-life-like situations. Different mobility models can be used to support random node mobility in ad hoc networks [168] such as: *Random Walk (RW), Random Direction Mobility (RDM) and Random Waypoint mobility model (RWP)* as shown in Figure 4.2.

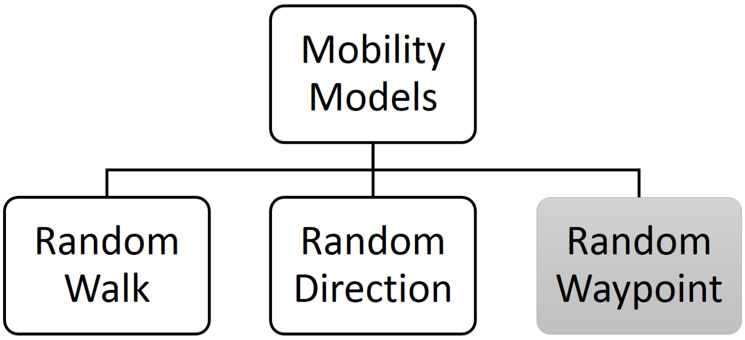

Figure 4.2: Mobility Models

The Random Waypoint mobility model is used widely in simulation studies to assess the performance of routing protocols in MANETs [169, 170]. In this mobility model, each node moves independently of others. At the beginning of the simulation, each node is placed randomly within the defined simulation area and remains stationary for a specific pause time (t) of seconds. Then a node selects a random destination within the simulation area and starts moving towards it with a speed (s) selected from a uniform distribution $[0, Vmax]$ where $Vmax$ is the maximum speed that the node can reach. Once the node has reached the selected destination, it pauses for a constant time (t) again. Then the node chooses another random destination and repeats the same process until the simulation terminates. With regard to the pause time (t) parameter, when it is set to zero that means that the node will be moving dynamically from one destination to another without pausing in between.

In this thesis, we choose the Random Waypoint mobility model as the mobility model for the following reasons. It is able to mimic unpredictable node movements and dynamic topology changes in MANETs. Dynamic topology changes cause frequent link failures, which provide a suitable context in which to simulate the proposed routing solutions in the subsequent chapters and monitor their reaction in highly dynamic mobile scenarios. Furthermore, the Random Waypoint mobility model is already built in NS-2.

4.4.5 Random Scenario Generation

NS-2 supports two types of mobility model, deterministic and random mobility models [154]. A deterministic mobility model enables the programmer to control node movement and destination during the simulation time. This type of mobility is suitable to study the behaviour of a small network where node movement is known beforehand. However, as the number of nodes in the scenario increases, it is difficult to specify the movement for all nodes. On the other hand, a random mobility model provides a wide range of scenarios, which provides a better test of the network's behaviour. However, it does not allow the programmer to control or review the movement of nodes.

NS-2 provides an independent utility called *setdest*, which is written in C++ to create deterministic mobility scenarios. The topology (node movement) file defines the network area, simulation time and mobility model. The created scenarios represent a fully random controllable movement of nodes and should be included in the simulation script before starting the simulation. *Setdest* can be found in this directory *ns/indep-utils/cmu-scen-gen/setdest*

NS-2 supplies another utility file called *cbrgen.tcl*, which is written in Tcl, to create traffic-related scenarios. *Cbrgen.tcl* models both TCP and Constant Bit Rate (CBR) traffic. The traffic generator file defines the characteristic of the data communication that is going to be used, the data packet size, type, send rate and the number of connections in the scenario. The created scenarios are included in the simulation script before starting the simulation. The drawback of this utility file is its lack of randomness when creating connections between nodes, as highlighted by [171]. More specifically, the chosen destination for a connection depends on the source node ID. For instance, if the source node ID is smaller than 50, then the chosen destination for a connection will be *n+1*, while it will be *n+2* if the source node ID is smaller than 75. Abdallah [171] has modified the traffic generation file in NS-2 to randomly choose a destination for connections, regardless of the source ID. In this thesis, we used the modified *Cbrgen.tcl* file by [171] to randomise the selection of destinations in the simulated scenarios more fully. This utility can be found in the directory *ns/indep-utils/cmu-scen-gen/cbrgen.tcl*.

A Constant Bit Rate (CBR) is an application layer component traffic generator that is used to generate constant data traffic every fixed interval. It is usually used to send data to an end-system, which requires a predictable response time and a specific amount of bandwidth during the lifetime of the connection. In this thesis, the CBR traffic model was used to evaluate the performance of the proposed algorithms under a constant transmission.

4.5 Multichannel Extension in NS-2

Although NS-2 is the most widely used simulation tool to validate and evaluate network performance, the native implementation of NS-2 only supports the legacy single channel IEEE 802.11 MAC DCF protocol. Due to the limitation of the legacy IEEE 802.11 MAC protocol (discussed in Chapter 3) and the availability of multiple channels in the defined IEEE 802.11 PHY, much research has been conducted on the utilisation of multiple channels. In order to realise and evaluate the performance of these solutions, several extensions have been proposed such as Hyacinth's [172], Ramon's [173] and Maheshwari's [112]. However, most of these extensions consider multiple radio interfaces rather than a single radio interface.

Maheshwari *et al.* [112] propose a multichannel MAC protocol called xRDT where each node is equipped with two radio interfaces. The main purpose of xRDT [112] is to improve network performance by utilising multiple channels. They incorporate the semi-dynamic channel assignment of the Receiver Directed Transmission protocol (RDT). We chose the multichannel xRDT over other possibilities because it uses the same working mechanisms as RDT protocol. However, it uses an extra radio interface (busy tone) and sends an extra control message (DTC) to address the multichannel hidden terminal and deafness problems existed in the RDT communication scheme. The xRDT develop a multichannel MAC protocol using an old version of NS-2 (version NS-2.27). Further details are discussed in Chapter 5.

This work benefited from an implementation of the multichannel MAC protocol in xRDT to implement our own multichannel MAC (RDT-MAC) protocol. However, there are significant differences between xRDT and RDT-MAC; RDT-MAC is implemented using a single radio interface rather than two radio interfaces. This reduces the hardware and power consumption cost and the design complexity. Additionally, RDT-MAC is implemented using the latest version of NS-2 (version NS-2.35).

Although RDT-MAC can run independently of any upper layer protocol, it was decided to link it somehow with the routing layer protocol, called RDT-AODV. RDT-AODV is our own extension to the AODV routing protocol to adopt the RDT communication scheme. More details regarding RDT-AODV will be given in section 5.3.1. This is because this work focuses on enhancing the performance of the reactive routing layer protocol by utilising multiple channels. Practically speaking, the routing protocol mechanisms (route discovery, data forwarding and route maintenance) have been modified to address multiple channels. Furthermore, the calculation of the receiver node's home channel is done in the routing layer and then passed to the MAC layer protocol to be used for contention and transmission. An extensive simulation was done to validate the implementation of the proposed MAC and routing protocols and to compare them with xRDT. Further details and the analysis of RDT-MAC and RDT-AODV will be discussed in Chapter 5.

4.5.1 Channel Assignment Approach

Different strategies for channel assignment were presented in section 3.3.1.

In this thesis a semi-dynamic channel assignment is chosen as the main approach for channel assignment for the following reasons: first, as multiple channels are used over a single radio interface as most wireless devices do, channel negotiation becomes a costly task. Second, it is difficult to implement time synchronisation in a decentralised network such as MANETs to negotiate a channel. Third, using a common control channel for negotiating or exchanging control packets could cause a bottleneck problem in the common channel and also waste a considerable proportion of already scarce available bandwidth. Unlike a fixed channel assignment approach, a semi-dynamic channel assignment approach can reduce the network partitions and provide adaptability to dynamic network conditions [174]. A well-known semi-dynamic channel assignment approach called the Receiver Directed Transmission (RDT) protocol is adopted in this research.

4.5.2 Network Model

While there are different approaches to design and support a multichannel network, this research has adopted a RDT communication scheme proposed by Shacham *et al.* [12]. In RDT, each node in the network is assigned a channel called a *quiescent channel*. Nodes listen to their *quiescent channel* when they are not transmitting. Channel assignment is either well-known in advance to all nodes in the network or can be obtained from node addresses. In this model all orthogonal channels available in the network are used for data transmission which is a more desirable design in a resource constrained network with a limited number of channels. More details of RDT are given in section 5.2.1.

The multichannel routing protocols proposed in the next chapters are based on the following principles. First, no channel negotiation is required as the receiver node's home channel is known in advance. Second, no tight time synchronisation is necessary. In MANETs clock synchronisation is a difficult task to achieve due to the absence of centralisation and unpredictable topology change. Finally, no common control channel is required. Exchanging control packets to negotiate the communication channel over a common control channel could cause channel bottlenecks and also underutilise available bandwidth.

4.6 Simulation Approaches

The NS-2 simulator [158] is used in this thesis as the main tool to implement and evaluate the performance of various protocols under different environments. NS-2 was run under the Linux CentOS 7.6 operating system. Experiments were conducted on a ***bwlf*** server of clusters of 32 machines. Each machine in the ***bwlf*** cluster has 8

Intel processors 2.0 GHZ, 12 GB RAM, 4 MB cache memory size and 1 TB hard disk size. We used this number of machines because the proposed solutions are examined under different environment settings and consequently, a high number of scenarios have been produced. Therefore, these scenarios were distributed between different machines, with the same specifications, to reduce the time required for simulation as well as to overcome the issue of limited storage size, caused by the huge file size of each scenario.

All experiments in the subsequent chapters were carried out and compared using NS-2 simulation. Table 4.2 shows the different MAC and routing protocols used in this thesis to produce the results in their corresponding chapters.

Table 4.2: Mac and Routing Protocols used in this thesis

Chapter	Protocol	MAC protocol	Routing protocol	Number of radio interface	Number of channel
CH.5	AODV	IEEE 802.11	AODV	One	One
	xRDT	XRDT	AODV	Two	Three
	RDT-AODV	RDT-MAC	RDT-AODV	One	Three
CH.6	AOMDV	IEEE 802.11	AOMDV	One	One
	RMMMC	RDT-MAC	RMMMC	One	Three
CH.7	RIVC	RDT-MAC (with RIVC)	RMMMC	One	Three
	MB	RDT-MAC (with MB)	RMMMC	One	Three
	RIVC-MB	RDT-MAC (with RIVC-MB)	RMMMC	One	Three

All reported protocols in Table 4.2 have been implemented and tested using the latest version of NS-2 (version NS-2.35), with the exception of the Extended Receiver Directed Transmission multichannel MAC protocol (xRDT), which was originally developed using version NS-2.27. Performance analysis of all protocols was conducted using AWK scripts [175]. Each data point in the graphs presented in the simulation results in this thesis is the mean of 25 distinct runs obtained from 5 different random traffic scenarios and 5 different random movement scenarios.

4.6.1 Simulation Environments

Identical traffic and movement scenarios were used throughout this thesis to ensure fair comparisons between different protocols. For simulation purposes all connections were set to start transmitting data packets at a random time between 0 and 100 seconds and to stay active until the end of the simulation. This is to ensure that all connections are running for the most of the simulation time. User Datagram Protocol (UDP) was used with a CBR as the connection model in the simulation. Since no feedback control mechanism is required in UDP, the generated traffic (CBR) is constant regardless of how the network is run. Twenty random source-destination connections of CBR traffic were simulated as it is important to challenge the routing protocols with constant offered loads and environmental conditions. The data packet size was *512 bytes* and the generation rate was *4 packets/second*. The simulation area was set to 1000 $m\times$ 1000 m and the simulation time was 300 seconds for all experiments. The default common parameters in NS-2 were followed for radio model, power and threshold levels, such that the transmission range was 250 m and the carrier sensing range was 550 m. The two-ray ground reflection model was used as the radio propagation model. The Random Waypoint model was used as the node mobility model.

Table 4.3: Simulation Experiments

Number of Protocol (P)	Network Density (D)	Node Mobility (M)	Number of Connections (C)	Number of Scenario Iterations (I)
AODV AOMDV xRDT RDT-AODV RMMMC RIVC MB RIVC-MB	50 100 150 200 250 300	1 5 10 15 20 25 30	10 15 20 25 30 35 40	5 different mobility scenarios * 5 different traffic scenarios
8	6	7	7	25
No of experiments with different network density ($P * D * I$)			8 * 6 * 25 = 1200 Runs	
No of experiments with different node mobility ($P * M * I$)			8 * 7 * 25 = 1400 Runs	
No of experiments with different connections ($P * C * I$)			8 * 7 * 25 = 1400 Runs	
Total number of all experiments = 1200 + 1400 + 1400 = **4000 Runs**				

In order to study the behaviour of the proposed protocols under various conditions, extensive experiments were conducted using different simulation settings (see Table 4.3). The number of nodes, node speeds and connections were varied to study the impact of the node density, mobility and number of source-destination pairs (referred to as connections) with respect to the protocol performance.

- **Impact of Network Density**

  The impact of node density on network performance was studied. Various numbers of mobile nodes (from 50 to 300 nodes) were deployed randomly over a 1000 $m\times$ 1000 m area. They represent a range of networks from low density (sparse) to highly dense. As the number of nodes increases in the network, more interference, contention and collision are expected, which leads to multiple link failures. Each node moves dynamically (pause time is zero) with a random speed between [0,10] m/sec.

- **Impact of Node Mobility**

  The impact of node mobility on network performance was studied where the node mobility is incremented gradually from 1 m/sec to 30 m/sec to evaluate the impact of node mobility on networks where nodes are moving from a very low to a very high speed. All of the nodes move dynamically (pause time is zero). Increasing node mobility causes frequent topology changes, which lead to higher link breakages and stresses the routing protocol. Since a multichannel network mainly aims for a dense network, 200 mobile nodes were deployed randomly over a 1000 $m\times$ 1000 m area.

- **Impact of Number of Connections**

  The impact of increasing the number of connections on the network performance was studied. Various numbers of connections (from 10 - 40 connections) in each scenario represent networks with different loads (low to high load). Increasing the number of connections may increase the contention and collisions in the wireless medium. Since a multichannel network mainly aims for a dense network, 200 mobile nodes were deployed randomly over a 1000 $m\times$ 1000 m

area. Each node moved dynamically (pause time was zero) with a random speed of between [0,10] *m/sec*.

The general simulation parameters used to conduct all the experiments in this thesis are listed in Table 4.4.

Table 4.4: General Simulation Parameters

Simulation Parameters	**Value**
Network area	1000 $m\times$ 1000 m
Simulation time	300 *sec*
Propagation model	Two Ray Ground
Mobility model	Random WayPoint
Maximum Speed	10 *m/sec*
Pause time	0 *sec*
Traffic type	CBR
Data packet size	512 *bytes*
Send rate	4 *packets/sec*
Interface queue length	150
MAC layer protocol	IEEE 802.11 DCF
Channel bandwidth	2 *Mbps*
Number of iterations	25 *iterations*
Density	
Number of nodes	50, 100, 150, 200, 250, 300
Mobility	
Number of nodes	200
Maximum Speed	1, 5, 10, 15, 20, 25, 30 *m/sec*
Pause time	0 *sec*
Offered load	
Number of nodes	200
Number of connections	10, 15, 20, 25, 30, 35, 40

To establish the results' statistical confidence, several random topologies are run for each simulation. The provided statistics in this thesis were collected using a 95% confidence level and over 25 randomly generated topologies. For the sake of clarity and tidiness, samples of the mean, standard deviation and confidence intervals have been provided in Appendix A. The provided confidence interval in Appendix A represents the upper and lower error estimation values from the mean. As the provided confidence interval was found to be fairly small in almost all cases and to not obscure the data representation in the graphs, we chose to only include samples of the confidence interval in tables in Appendix A.

4.6.2 Assumptions

The following assumptions, which are widely used in the literature [176] have been adopted in this study to conduct the experiments.

- The number of mobile nodes remains fixed during the simulation time.
- All nodes are equipped with a single half-duplex radio transceiver such that it can only transmit or receive at any given time, but not both simultaneously.
- A node's transceiver has N non-overlapping (orthogonal) channels of equal bandwidth. A non-overlapping channel means that simultaneous transmission among adjacent nodes utilising different channels does not cause interference.
- The number of available channels is known to all nodes in advance.
- Each node is assigned a home channel that is well-known to other nodes.
- The channel switching overhead is negligible since rapid channel switching will become feasible in the future with improved hardware.
- There is no other network presence other than the nodes of the multichannel network.

4.6.3 Evaluation Metrics

Several metrics may be used to evaluate the network performance. However, the focus here is on the following metrics to examine the performance of different protocols under different network conditions:

Packet Delivery Ratio (PDR): The ratio of data packets that are successfully received by destinations compared to the number of data packets that are generated by sources during the simulation time. We prefer to use the PDR over the throughput as we are interested in measuring the total number of delivered data packets to their destination rather than the rate of successful packet delivery over the wireless channel per second.

Route Discovery Latency (RDL): The average delay between initiating the RREQs from the source node and the first received corresponding RREP (measured in milliseconds). This metric measures the efficiency of the route discovery mechanism in the routing protocol to discover a route to any destination.

End-to-End Delay (EED): The average time taken for a data packet to be transmitted across the network from source to destination (measured in seconds). EED includes all types of possible delays, including buffering data during the route discovery process, interface link queuing, retransmission delay at the MAC and propagation delay times.

Routing Overhead: The total number of routing packets (RREQ, RREP, RERR and Hello) generated/forwarded by the routing protocol during the simulation time. All packets sent or forwarded (at each hop) to the network layer are routing overhead. When comparing protocols with different routing packet sizes, the total routing overhead is calculated based on the packet size (measured in Kbytes).

Collision Rate: The total number of dropped (routing and data) packets caused by collisions in the MAC layer per unit of simulation time. This metric measures the collision for routing and data packets because they are sharing the same medium.

Data Dropped Packets: The total number of dropped data packets in the routing layer during the simulation time. This includes all types of reasons to drop data packets, including the link layer callback (CBK), no/invalid route (NRTE), Time To Live (TTL), interface queue (IFQ) and route loop (loop).

Data Dropped Packets Caused by No Route: The total number of dropped data packets in the routing layer caused by no/invalid route (NRTE) during the simulation time.

Data Dropped Packets Caused by MAC Retransmission: The total number of dropped data packets at the MAC layer, caused by exceeding the maximum retry limit (denoted as RET) during the simulation time.

Note that the aforementioned evaluation metrics are not completely independent. For instance, lower PDR means that the EED metric is evaluated with fewer samples.

Thus, with a lower PDR, samples may have less delay and not reflect the actual delay time.

4.7 Conclusions

This chapter presents and justifies the methodology used to carry out this research. The reactive routing protocol AODV was chosen in this study. The main functions of the employed routing protocol (AODV) are described and explained to provide a content for the new extensions. Different cross-layer approaches were described to explain and justify the method used in Chapter 5 and 7. Furthermore, a list of the system modelling techniques used in the research community have been given and discussed and then the selection of the simulation approach was justified. The NS-2 simulator was picked to implement and evaluate the performance of the proposed multichannel protocols and to compare their performance with different protocols. After that, the details of the multichannel support in NS-2 were provided along with the used channel assignment mechanism. Finally, the simulation approach, assumptions and evaluation metrics were described in detail.

Chapter 5

Performance Evaluation of Receiver Directed Transmission

5.1 Introduction

Utilising multiple channels in communication can increase wireless ad hoc network capacity. In multichannel wireless networks nodes can operate in more than one non-overlapping channel. Therefore, multiple pairs of nodes can concurrently communicate within carrier sensing range of each other using different channels. This should enhance the spatial reuse, reduce contention and collision in each channel and increase the number of transmissions, thereby increasing network capacity.

Because more than one channel is available and nodes only use one at a time, transmitter and receiver nodes need to be tuned to the same channel before they can communicate. Proposed protocols in the literature [177, 178, 179] usually achieve this by either using a separate control radio interface/channel, or by enabling nodes to switch to a pre-defined channel at a pre-determined time to perform channel negotiation. Consequently, these approaches require either an additional radio interface/channel or tight time synchronisation to perform channel negotiation.

The Receiver Directed Transmission (RDT) communication scheme uses a clever approach to implement multichannel wireless network, bypassing channel negotiation without requiring an additional control radio interface/channel or time synchronisation. The aim of the majority of the proposed protocols that use RDT as their communication scheme is to address the anticipated multichannel hidden terminal and deafness and broadcast support problems. However, the proposed solutions usually require extra hardware, tight time synchronisation or a common control channel. This increases costs for extra hardware and power consumption, and possibly underutilises some of the already scarce bandwidth. Although different solutions have been proposed to address the anticipated issues in RDT schemes, no work, to the author's knowledge, has been proposed to evaluate the performance of RDT schemes with a single transceiver, without relying on a common control channel or time synchronisation under different network conditions.

This chapter reports a performance evaluation of a multichannel RDT scheme where each node is equipped with only a single radio interface without relying on a common control channel or time synchronisation. Additionally, it investigates the effect of varying node density, mobility and number of connections in the network on RDT protocol performance. The NS-2 simulator is used to evaluate the performance of the multichannel single radio RDT scheme under different network conditions and to compare its performance with different protocols.

The rest of this chapter is organised as follows: Section 5.2 describes the communication architecture of RDT schemes along with works related to RDT schemes. Section 5.3 describes the working processes of the RDT-AODV and RDT-MAC protocols. In section 5.4, performance evaluation results are given. Section 5.5 summarises presents and a conclusion.

5.2 Communication Architecture of the RDT

This section describes the communication architecture of the RDT scheme, which is used in this thesis as the main approach to support multichannel networks. Then a review of relevant protocols that use the RDT scheme as the main communication approach to implement a multichannel network is presented.

5.2.1 Receiver Directed Transmission (RDT) Protocol

In RDT every node is assumed to be equipped with a single half-duplex radio interface. In addition, every node is assigned "or selects", a well-known *quiescent channel* (or home channel) which it always tunes to when it is idle. In this research we use the terms *quiescent channel* and home channel alternatively to refer to the same thing. When a node has a packet to transmit to a node operating in a different channel, the transmitter node must switch its interface to the receiver node's *quiescent channel* and then transmit following the CSMA/CA mechanism as in a single channel MAC protocol. Following a successful transmission, the transmitter node switches its radio interface back to its own *quiescent channel*. The same process is repeated until the packet reaches its final destination.

Shacham *et al.* [12] assume that in a dense network (high number of neighbours), each node satisfies two conditions: 1) each node has routing information for at least one neighbour on every channel; and 2) the set of nodes in each channel constitutes a connected graph. Furthermore, the protocol assumes that the selection and the distribution of the *quiescent channel* to the neighbouring nodes is performed by a separate mechanism. These assumptions simplify the approach greatly in the sense that it is no longer necessary for the communicating pair to negotiate which channel to use beforehand. Shacham *et al.* [12] only evaluated the proposed multichannel architecture (RDT) theoretically using an analytical model.

As all nodes in RDT are assumed to be equipped with a single half-duplex transceiver, nodes can only listen to one channel at any given time. Therefore, a node may not have the actual state of the channel (idle/busy) it intends to transmit in. Consequently, a node may inadvertently act as a hidden terminal, causing collision for an ongoing transmission in different channels from its own. Furthermore, if the intended receiver is not listening in its *quiescent channel* (engaged in another transmission in a different channel), the transmitter node may conclude that the link to the intended receiver has broken and experience the deafness problem.

5.2.2 Related Work

Based on RDT communication schemes several protocols have been introduced to implement a multichannel wireless network and address expected issues in RDT schemes, namely multichannel hidden terminal, deafness and broadcast support issues. Proposed solutions in the literature usually require an extra radio interface or a common control channel, or depend on time synchronisation.

Maheshwari *et al.* [112, 180] propose the Extended Receiver Directed Transmission (xRDT) protocol to address potential issues in RDT, namely the multichannel hidden terminal and deafness problems. xRDT addresses the multichannel hidden terminal problem by using a busy tone interface. In xRDT every node is equipped with two radio interfaces; one is for data packets, while the other works as a busy tone to notify potential transmitting nodes about the current state of the channel. Let us assume that for each data channel Ch_i there is a different busy tone called BCh_i. When a node receives a data frame on channel Ch_i, it tunes its busy tone interface related to this channel BCh_i until it successfully receives the frame. This forces all potential transmitter nodes on channel Ch_i to defer their transmissions and not contend to this channel while the busy tone is on. This helps to inform other nodes located in the receiver's transmission range about the current state of the receiver's channel and therefore prevents the multichannel hidden terminal problem. Furthermore, xRDT introduces a notification mechanism to alleviate the deafness problem. When node A is transmitting on a different channel, any transmission intended for node A will fail and therefore, the transmitter node will increment the contention window exponentially. To alleviate the deafness problem, xRDT enables the deaf node when it returns to its *quiescent channel* to broadcast a Data Transmission Complete (DTC) message. The DTC will wake up all backed-off potential transmitter nodes and inform them that the receiver node is back listening to its home channel. Consequently, the potential transmitter will halt its back-off and start contending to use the medium. The proposed notification message does not prevent the deafness from occurring, it only helps the potential transmitter to halt its back-off and start contending to use the medium. Furthermore, the authors enabled the selection of the *quiescent channel* of a node to change periodically based on the traffic load in this channel. However, no further details are provided in [180] about the used distribution mechanism of the new *quiescent channel*.

Although xRDT addresses the multichannel hidden terminal problem and helped to eliminate the deafness problem, it does require an extra radio interface to transmit and receive the busy tone, which is complex to engineer and more expensive to realise in terms of hardware costs and power consumption. Furthermore, xRDT uses an extra radio interface just as a busy tone notifier whereas it could be used as a second data interface to enhance the network throughput. Moreover, they used an extra control overhead (DTC) to only alleviate the deafness problem.

Jain *et al.* [181, 182] propose an anycast extension to the RDT protocol to alleviate the deafness problem using only a single radio interface. They achieve this by exploiting path diversity (multipath provided by routing protocol) in the transmission channel. The routing protocol AOMDV [80] is modified to maintain multiple paths in each channel in the network and to provide multiple node addresses to the MAC layer protocol. When a node has data to send, it switches its radio interface to the receiver node's *quiescent channel* and multicasts an RTS frame to multiple next-hop receivers, which are provided by the routing protocol, in that channel and then it waits to receive a CTS control frame. Receiving a CTS from any one of the next-hop nodes indicates the channel reservation and hence the transmitter starts transmitting the data packet to the node that sent a CTS frame. If a CTS is not received from any next-hop nodes, the transmitter retries sending the RTS up to six times. Anycast RDT alleviates the deafness problem by negotiating access to the medium with multiple next-hop nodes instead of with a single node. This parallel negotiation increases the probability of success even if some nodes are operating in a different channel.

Wang *et al.* [183], propose a dual default channel switching mechanism (D-RDT) MAC protocol using a single radio interface in order to address the multichannel hidden terminal problem and the missing receiver problem in RDT. In D-RDT each node has two default channels rather than one, namely the default control channel and the default data channel. All nodes keep listening to their default control channel. When a transmitter node A has data to send to node B, node A switches its radio interface to the default control channel of node B and exchanges control packets RTS/CTS. Upon successful exchange of RTS/CTS, the transmitter and the receiver nodes will switch their radio interfaces to the default data channel of the receiver node and start transmitting data packets. Following a successful communication both nodes will switch back to their default control channel and broadcast a DTC packet to notify the backed-off potential transmitting nodes. However, if ACK frame has not been received, the transmitter node A will turn its radio interface back to the default control channel of node B and establish the communication again until the packet is successfully received or the maximum retry count is reached.

The main idea of the D-RDT protocol is to eliminate the collision between the control and data frames and hence reduce the occurrence of the multichannel hidden terminal problem. However, the problem of deafness still exists. Furthermore, a considerable delay may occur from the excessive channel switching, especially in the NIC, which takes about 150 to 200 μsec [100, 101] to reset the Voltage Control Oscillator (VCO), which may increase the deafness time for the transmitter and degrade network performance.

Wang *et al.* [184], propose an RDT Split-time Multichannel MAC protocol (RSM) to address the multichannel broadcast support problem that exists in RDT. They use a split-time mechanism and require time synchronisation to support broadcasting. RSM splits the working time of nodes into a synchronising period, broadcasting period and data-transmitting period. All nodes are required to switch their channel to the common control channel during a synchronisation period. Then nodes transmit their own time beacon after a random back-off window. Receiver nodes accept the information and update their local time and therefore all nodes in the network are synchronised to the same time. During the broadcasting period nodes with a broadcast packet start broadcasting after a random back-off time window to avoid collision. Then the data transmission period starts, which follows the RDT communication scheme.

Although the RSM protocol supports broadcasting in the RDT protocol, it requires a tight time synchronisation and uses a common control channel, which wastes some of the scarce available bandwidth. Furthermore, the common control channel may act as a bottleneck and become congested.

Hwang *et al.* [185] propose a receiver-centric multichannel MAC (RcMAC) protocol to utilise multiple channels while reducing unnecessary channel switching. The RcMAC protocol requires only a single transceiver and consists of two phases, a channel selection phase performed in a dedicated control channel and a data transmission phase performed in the corresponding data channel. In RcMAC, if the sender and receiver are on the control channel, then they will negotiate which channel to use to transmit the data. On the other hand, if the receiver is not listening to the control channel, then the sender will perform receiver-centric channel switching, with the support of neighbours listening to the control channel. RcMAC enables the sender node to gather the channel information of its intended receiver asynchronously and with the aid of its neighbour listening on the control channel, without requiring explicit channel negotiation and hence reducing the amount of unnecessary channel switching.

However, RcMAC uses a dedicated control channel. Hence some of the available bandwidth will not be used to exchange data packets. Furthermore, the transmitter node may rely on out-dated information from its neighbour, which will increase the delay in finding out the current receiving channel of the receiver node.

Tytgat *et al.* [186] propose a new channel selection metric called Received Signal to Interference Strength-based Threshold (ReSIST), which is specifically designed for the RDT protocol. The aim of this metric is to reduce the interference between different wireless technologies (e.g. IEEE 802.11(WiFi) and IEEE 802.15.4(ZigBee)). Furthermore, they implemented RDT and verified their metric in a testbed using two different settings. In the first setting RDT scans all the channels at the beginning of the experiment, then selects the best channel as the *quiescent channel*. This channel does not change during the experiment. In the second setting RDT dynamically switches the *quiescent channel* selection during the experiment, based on the interference level with other wireless technologies (e.g. select channel with least average Packet Error Rate (PER)). This is accomplished by periodically measuring the interference level on different channels and using this information to build a PER channel ranking table. Tytgat *et al.* [186] show that RDT is capable of coping with dynamic environments provided that it has relevant information about all available channels.

Table 5.1: Related Works based on RDT scheme

Protocol	Transceiver#	Home Channel#	Control Channel	Sync	Aims
xRDT [112]	2	1	no	no	To address multichannel hidden terminal and deafness problems
Anycast RDT [181]	1	1	no	no	To alleviate deafness in RDT using multicast RTS
D-RDT [183]	1	2	no	no	To address multichannel hidden terminal and missing receiver problems
RSM [184]	1	1	yes	yes	To support broadcast in RDT scheme
RcMAC [185]	1	1	yes	no	To reduce unnecessary channel switching
ReSIST [186]	1	1	no	no	To reduce interference among different wireless technologies and dynamically select *quiescent channel in RDT*

Table 5.1 summarises the main attributes of some of the related works that use the RDT scheme as their main communication scheme. From the above table it is noticeable that most of the proposed protocols aim to address anticipated issues in RDT communication scheme, namely the multichannel hidden terminal, deafness and broadcast support problems. However, these issues are not exclusive to the multichannel RDT protocol; they are common in other multichannel protocols utilising a single transceiver. It is worth mentioning that the hidden terminal problem is also common in wireless networks where a single channel is deployed, as explained in 2.6.1. Furthermore, the table shows that the proposed solutions usually require extra hardware, tight time synchronisation or common control channels, which increase the cost of hardware and power consumption, and also underutilise some of the already scarce bandwidth.

Although different approaches have been proposed to address the anticipated issues in the RDT scheme, no works, to the author's knowledge, have been proposed to evaluate the performance of the RDT scheme with a single transceiver without relying on a common control channel or time synchronisation under different network conditions (different density, node mobility and connections). Therefore, the aim of this chapter is to evaluate the performance of a multichannel RDT communication scheme using only a single radio interface and without relying on a control channel or time synchronisation. Additionally, it investigates the effect of varying the network density, mobility and connections on RDT protocol performance.

5.3 Multichannel RDT Protocol

The RDT communication scheme facilitates channel assignment and negotiation without using a control channel, time synchronisation or extra hardware. Each node in RDT is assigned a well-known *quiescent channel* at network initialisation, which the node listens to when not transmitting. The channel assignment could be accomplished by using a separate mechanism derived from node addresses. In this research, node addresses are adopted as the means of channel assignment. This makes it easier for all the nodes in the network to know other node's *quiescent channel* by using the following equation 5.1.

$$(\mathrm{DesH}_{ch} = N_{id} \bmod T_{ch}) \tag{5.1}$$

where:

$DesH_{ch}$ is the *quiescent channel* of this node N_{id},

N_{id} is the IP address of the node,

T_{ch} is the total number of available non-overlapping channels in the network

5.3.1 RDT-AODV

A slight modification is made to the standard AODV routing protocol to support the multichannel RDT communication scheme. The modified version of AODV is referred to as RDT-AODV from here on. A new field is added to the control packets in AODV to help the MAC layer determine which channel to switch to and contend in. Furthermore, the routing discovery and maintenance procedures are performed in the destination node's *quiescent channel*. Similar to AODV, RDT-AODV discovers and maintains only a single path between the source and destination. Therefore, RDT-AODV is considered to be a single-path multichannel routing protocol.

In RDT-AODV when the source node S has data to send to the destination node D, node S calculates the $DesH_{ch}$ of node D using the equation 5.1 and includes D's home channel in the packet's header. This to help the MAC layer determine (cross-layer interaction) which channel to contend in and transmit the packet to. Then, node S broadcasts the RREQ packet in the corresponding channel (channel 1 in this case), as shown in Figure 5.1. In Figure 5.1 the letter inside the circle represents the node ID and the number represents the node's home channel (*quiescent channel*). Following a successful transmission node S tunes its radio interface back to its own home channel. Standard AODV route discovery procedures are carried out/retried in the destination node's home channel until the RREQ reaches its destination node or an intermediate node with a fresh route to the destination. In these cases a RREP packet will be unicast in the reverse route to the source node S.

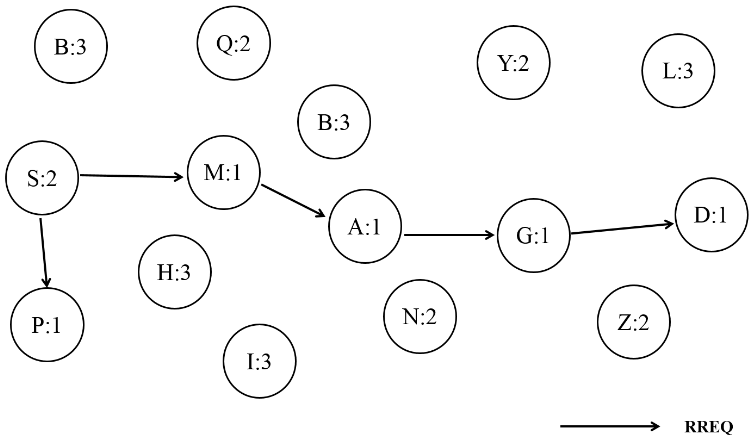

Figure 5.1: Route Request process in RDT-AODV

The RREP will be unicast in the next hop node's home channel. In this case, the RREP will be unicast through nodes G and A in channel 1 as shown in Figure 5.2. However, node M has to switch its radio interface to the next hop node's home channel, node S and transmit the packet. Upon receiving the RREP at node S, the route is established and the source starts forwarding data packets following the same mechanism.

In RDT-AODV only a few channel switches may occur during the route discovery process and data forwarding. Therefore, RDT-AODV has fewer channel switches

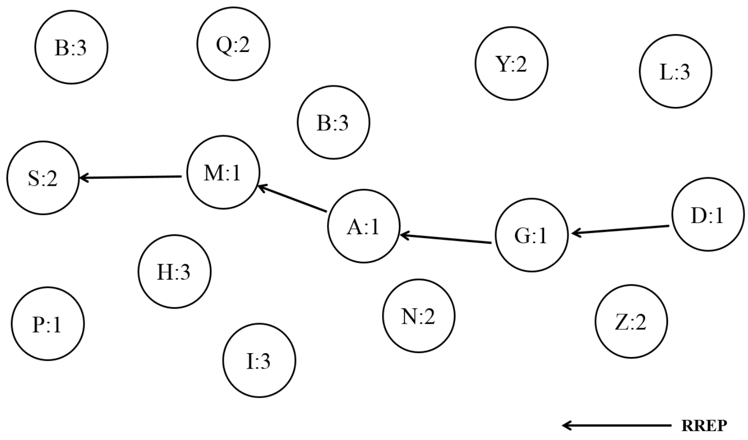

Figure 5.2: Route Reply process in RDT-AODV

compared with the previously mentioned protocols in section 5.2.2. This is because there is no need for channel negotiation in RDT-AODV before communication starts and only a single route discovery is performed in the destination home channel. Furthermore, once the route is established, only the source node may need to switch its channel, just for the duration of this transmission, and then the data packets travel through the intermediate nodes without channel negotiation or switching.

The multichannel wireless network is mainly aimed at a highly dense network, and in a dense network it is more likely that every node finds at least one neighbour operating in every channel. However, in a sparse network or where no neighbour is operating in the destination home channel, the problem of network partitioning may occur.

5.3.2 RDT-MAC

A slight modification was made to the standard single channel IEEE 802.11 MAC DCF protocol to support the multichannel RDT communication scheme. The modified version of the IEEE 802.11 MAC DCF is referred to as RDT-MAC from here on. In 802.11 DCF all overhearing nodes invoke the virtual carrier sensing mechanism, set their NAV and back-off from contending on the medium for the duration of this communication. However, as there is more than one channel available in the network, multiple NAVs corresponding to each channel are required. This NAV is denoted as a channel NAV or CNAV. Therefore, all overhearing nodes in RDT-

MAC set their CNAV corresponding to the channel they hear the transmission from. Apart from that RDT-MAC deploys similar mechanisms to those in 802.11 DCF, such as optional access mode (RTS/CTS), exponential back-off identical inter-frame spacing, collision avoidance strategies, recovery procedure and retransmission limits, which are discussed in 2.3.

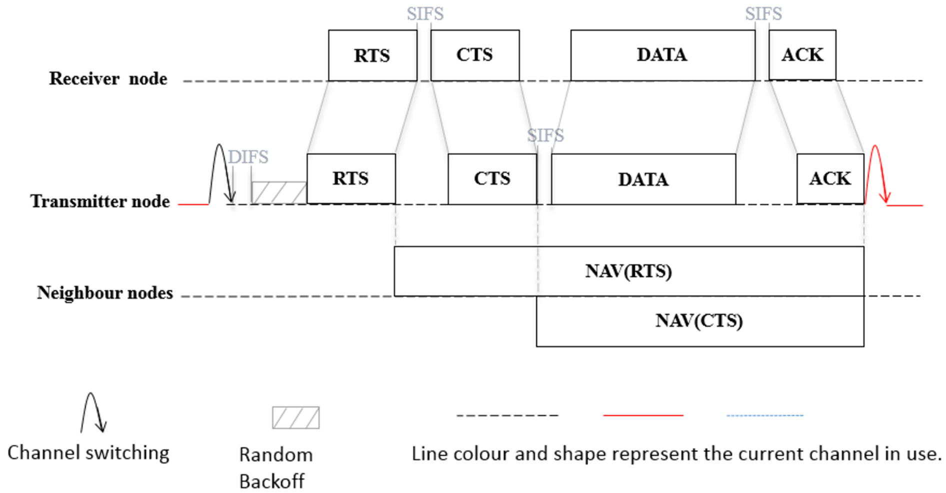

Figure 5.3: Working flow of RDT-MAC

Figure 5.3 illustrates the workflow of the RDT-MAC protocol to access the medium and transmit the data packet. In RDT-MAC in order to transmit a packet to the next-hop receiver, the transmitter node must switch its channel to the receiver node's home channel. Then it performs the CSMA/CA mechanism as in IEEE 802.11 DCF in this channel. If the transmitter finds the channel busy, then it should back-off from contending on the medium as in the regular MAC protocol. If the back-off procedure is completed successfully and the medium is still free, the transmitter performs the RTS/CTS handshake with the receiver node. All overhearing nodes in the respective channel invoke their CNAV and back-off from contending on the medium. After a successful transmission the transmitter node will switch back to its own home channel, setting the contention window to the minimum value and selecting a random back-off. The same procedure is repeated for the next transmission.

Note that nodes cannot participate in any transmission in the respective channel while their CNAV is set. However, nodes are able to switch and contend for transmission in different channels for which the CNAV is not set. This increases the capability of concurrent transmission in different channels and can potentially increase network throughput. However, due to the capability of nodes with a single half-duplex transceiver to listen to only a single channel at a time, the node may not have updated knowledge of the current state of the new channel. This may inadvertently make the transmitter node act as a hidden terminal, causing collisions for ongoing communication in the new channel. Additionally, it can suffer from the deafness problem if the intended receiver is engaged in another transmission in a different channel. Again, these issues are not exclusive to the RDT-MAC protocol but are common in other multichannel protocols utilising a single transceiver.

5.4 Performance Evaluation

The NS-2 simulator [158] was used to implement and evaluate the performance of the proposed protocol under different network conditions. The number of nodes, mobile speeds and number of connections were varied to study the impact of the node density, mobility and number of connections (offered load), respectively on RDT-AODV protocol performance. Details of the simulation settings used in this chapter were explained in 4.6. The performance metrics used to evaluate the performance of the protocols compared in this chapter were given in 4.6.3.

The main goal of this performance evaluation study is to assess the impact of using multiple channels with a single transceiver (RDT-AODV) and to compare this with single channel single transceiver (AODV) and a multichannel multi-transceiver (xRDT) protocols. Additionally, it aims to study the impact of multichannel hidden terminal and deafness problems on a multichannel single transceiver RDT-AODV protocol under different network conditions.

5.4.1 The Compared Protocols

The simulation results reported in this chapter are for the following protocols:

AODV: This is a well-known reactive routing protocol that is widely used and extensively studied in MANETs. AODV [19] is a single-path routing protocol that is designed to operate in a single channel network. AODV is used in this thesis as a standard benchmark. More details about AODV and its working mechanism were provided in 2.5.1.2.

xRDT: This is a multichannel MAC protocol proposed by Maheshwari *et al.* [112, 180] to address potential issues in RDT, namely the multichannel hidden terminal and deafness problems. xRDT requires two radio interfaces, one for data packets and one that works as a busy tone interface to notify the potential transmitting nodes about the current state of the channel. This enables the protocol to address the multichannel hidden terminal problem. Furthermore, xRDT alleviates the deafness problem by enabling the deaf node to broadcast DTC when it is back on its own home channel. xRDT is a single-path multichannel protocol using multiple radio interfaces per node that is designed to operate in multichannel networks.

RDT-AODV: Shacham *et al.* [12] propose a multichannel communication scheme based on a *quiescent channel* model called RDT. Shacham *et al.* evaluated their proposal theoretically. In contrast, this thesis implements and evaluates the RDT scheme with AODV (RDT-AODV) using a network simulation (NS-2). RDT-AODV [187] represents our implementation of the RDT communication scheme with AODV routing protocol. Furthermore, RDT-AODV uses the modified multichannel RDT-MAC as the MAC layer protocol. RDT-AODV is a single-path multichannel routing protocol using a single radio which is designed to operate in a multichannel network.

Table 5.2: Differences Between the Compared Protocols

Protocol	**Routing**	**Mac**	**Transceiver#**	**Channel#**
AODV	AODV	802.11 DCF	1	1
xRDT	AODV	xRDT	2	3
RDT-AODV	RDT-AODV	RDT-MAC	1	3

The differences between the compared protocols used in this chapter are shown in Table 5.2. Unlike xRDT, the AODV and RDT-AODV protocols consider a network where every node is equipped with only a single half-duplex transceiver. Although xRDT assumes that each node in the network is equipped with two radio interfaces, it uses only one radio interface for data packets while the other radio works as a busy tone notifier. With regard to the number of utilised channels xRDT and RDT-AODV consider the same number of channels (3 non-overlapping channels), whereas AODV uses only a single channel despite the availability of multiple channels in wireless communication standards.

Although there are differences among the compared protocols as shown in Table 5.2, there are significant similarities in the operating mechanisms. For instance, the route discovery, maintenance and data forwarding mechanisms for all reported protocols are similar and they follow the AODV routing protocol. Furthermore, the similar CSMA/CA mechanisms were used in all reported protocols with exception of the multichannel MAC protocols (xRDT and RDT-MAC) where a different NAV object was introduced for each channel CNAV. We chose the multichannel xRDT for comparison against RDT-AODV rather than other multichannel protocols because it uses the same working mechanisms as the RDT protocol. However, xRDT uses an extra radio interface (busy tone) and sends an extra control message (DTC) to address the multichannel hidden terminal and deafness problems that exist in the RDT communication scheme. From the above comparison, it is fair to compare the performance of AODV, xRDT and RDT-AODV protocols.

5.4.2 Impact of Network Density

The simulation settings used to study the impact of network density on the network performance were explained in details in 4.6.1. Twenty source-destination connections of CBR traffic were simulated with a data packet size of 512 bytes and a generation rate of 4 packets/second. Each node moves dynamically with a random speed between [0,10] m/sec.

5.4.2.1 Collision Rate

Figures 5.4 and 5.5 show the effect of network density on the collision rate for the compared protocols. It can be seen in Figure 5.4 that the collision rate of the single channel single radio AODV significantly increases as the network density increases. This is mainly due to increase in interference and contention in a single medium shared between all nodes. AODV uses a simple flooding approach to send broadcast packets (RREQ) which neither employ channel reservation nor acknowledgement mechanisms at the MAC layer. As the number of nodes in the network increases, the number of neighbour nodes rebroadcasting the RREQ increases (see Figure 5.7). This cause the broadcast storm problem [188] and increases the chance of collision between simultaneous transmissions. On the other hand, multichannel protocols (RDT-AODV and xRDT) have significantly lower collision rates compared with that of AODV. This is due to the fact that using multiple non-overlapping channels divides the collision domain into multiple collision domains and hence less interference and contention and fewer packet collisions occur in each domain (channel). However, as the number of nodes in each collision domain likely be higher than the available channels in networks, multiple nodes may be allocated to the same collision domain and hence increase the collision probability.

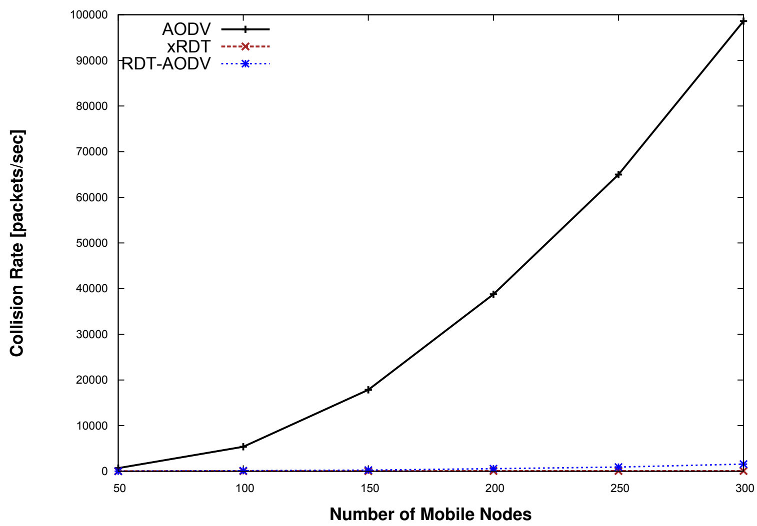

Figure 5.4: Collision rate vs. network density

To clearly distinguish the impact of network density on the collision rate in multichannel protocols and for better resolution, Figure 5.5 has been provided. Figure 5.5 shows that the collision rate of RDT-AODV increases as the network density increases. This is perhaps due to the increased occurrence of the multichannel hidden terminal issue in RDT-AODV. Additionally, as the number of nodes in the network increases, the number of nodes in each collision domain increases. Thus, it may increase the possibility of collision with neighbour nodes sharing the same collision domain. On the other hand, xRDT shows little effect from an increase in network density. The reasons for xRDT's superiority are that it addresses the multichannel hidden terminal issue and alleviates deafness problems.

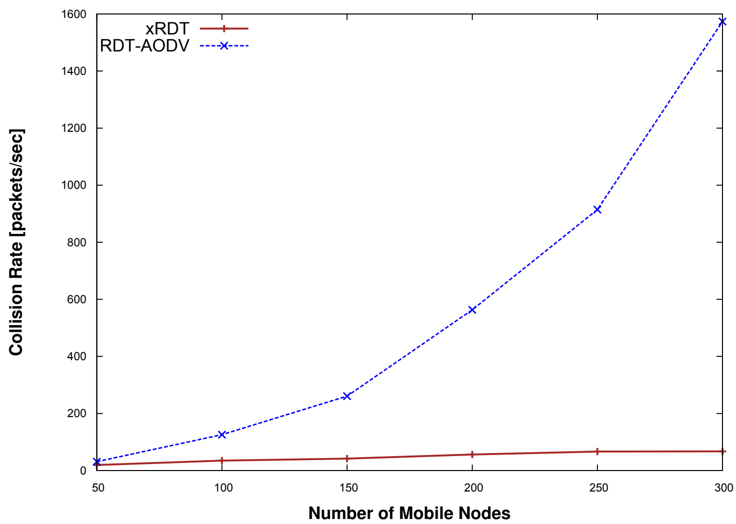

Figure 5.5: Collision rate for xRDT and RDT-AODV vs. network density

5.4.2.2 Routing Overhead

Figure 5.6 depicts the routing overhead for the compared protocols versus the network density. The figure shows that the routing overhead of the single channel single radio AODV is the highest compared with other protocols in all network densities. This is due to many factors including the participation of almost all nodes in the network in route discovery/recovery processes, a high volume of interference, contention and collisions in a single common channel. This increases the probability of collision in a single medium (see Figure 5.4). Increasing the contention and collision causes more frequent link failure, which necessitates route re-discovery (flooding the network with RREQ) leading inevitably to an increase in the routing overhead.

On the other hand, there is a steady increase in routing overhead for the multichannel protocols as the network density increases. Although xRDT uses two radio interfaces and addresses the multichannel hidden terminal and deafness problem, it has a higher routing overhead compared with RDT-AODV. This may be due to frequent changes in the *quiescent channel* of the receiver nodes in xRDT, which make the transmitter unaware of the current *quiescent channel* of the receiver node and hence, a higher number of RREQ packets are sent for route discovery or repair, as can be seen in Figure 5.7.

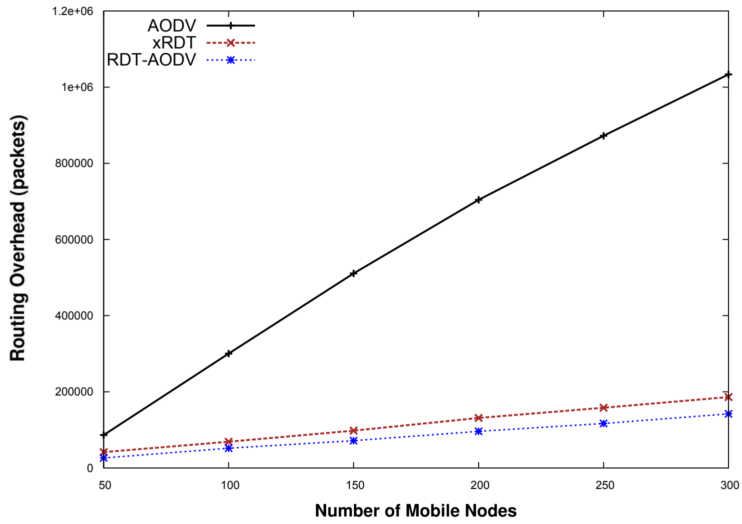

Figure 5.6: Routing overhead vs. network density

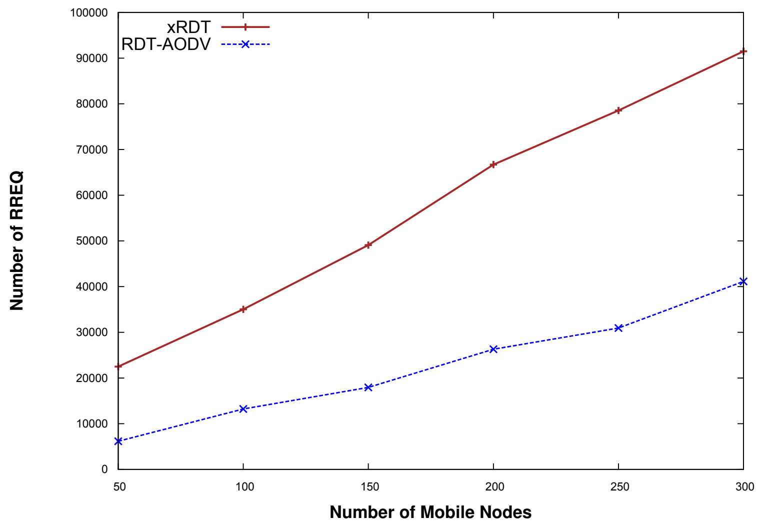

Figure 5.7: Route Request overhead for xRDT and RDT-AODV vs. network density

5.4.2.3 Data Drops

Figure 5.8 shows the impact of network density on the number of dropped data packets in the routing layer for the compared protocols. The number of dropped data packets in AODV increases as the network density increases. Again, this is because of the high collision rate and routing overhead in a single shared medium, which may cause channel congestion. On the other hand, a multichannel single radio RDT-AODV has reduced the number of data drops noticeably compared with a single channel single radio AODV. This is due to the availability of multiple non-overlapping channels that help to reduce the collision and routing overhead in RDT-AODV compared with that in AODV. Furthermore, in a low-density network, the number of dropped data packets decreases in RDT-AODV as network density increases. This may be due to poor network connectivity in RDT-AODV at low network density (network partitioning). xRDT has the least number of dropped data packets in comparison with other compared protocols. This is due to the availability of multiple channels and the ability of xRDT to address the multichannel hidden terminal and deafness problems along with reducing the traffic load in a heavily loaded channel.

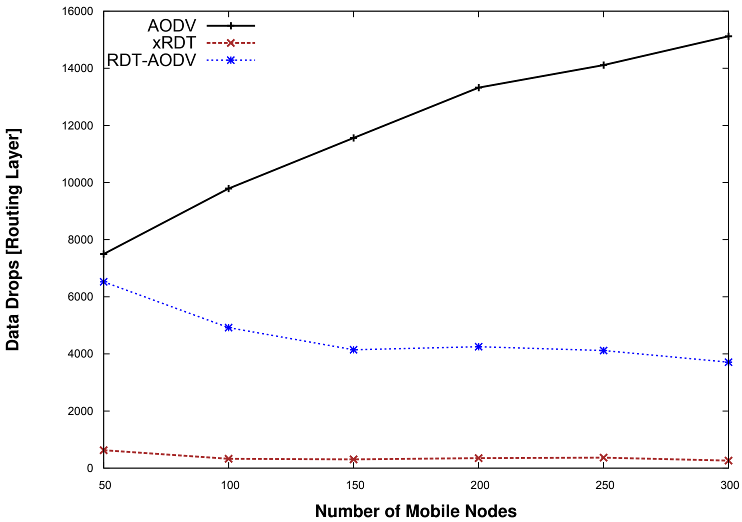

Figure 5.8: Data drops vs. network density

5.4.2.4 Delay

Figures 5.9 and 5.10 show the impact of increasing network density on the end-to-end delay for data packets in the compared protocols. It can be seen in Figure 5.9 that the delay in the single channel single radio AODV is significantly higher than that in the multichannel protocols. This is mainly due to increase in interference, contention and collision in a single shared medium, along with an increase in network density. On the other hand, multichannel protocols have reduced the delay significantly compared with AODV. This is because more than one medium is being used for contention, which reduces the interference, collisions and time to access the medium. Furthermore, the channel model (*quiescent channel*) used in RDT-AODV and xRDT facilitates the channel assignment and avoids channel negotiation, which helps to reduce the end-to-end delay.

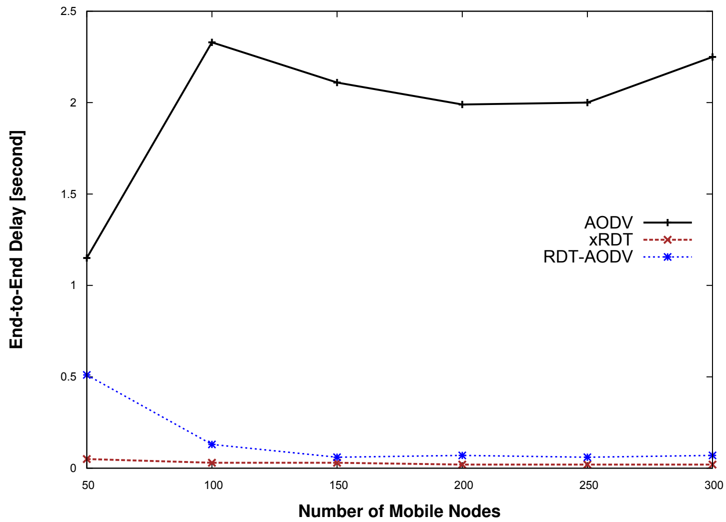

Figure 5.9: End-to-end delay vs. network density

To clearly distinguish the impact of network density on the delay in the multichannel protocols and for better resolution, Figure 5.10 has been provided. Figure 5.10 shows that, in a low-density network, RDT-AODV has a noticeably higher delay than xRDT. This is probably due to poor network connectivity, which is caused by network partitioning, and the hidden terminal and deafness problems in RDT-AODV. However, as the network density increases, both protocols show a stable performance with superiority to xRDT. This superiority is due to the ability of xRDT to solve the multichannel hidden terminal and deafness problems, which reduce the collision rate and consequently the end-to-end delay.

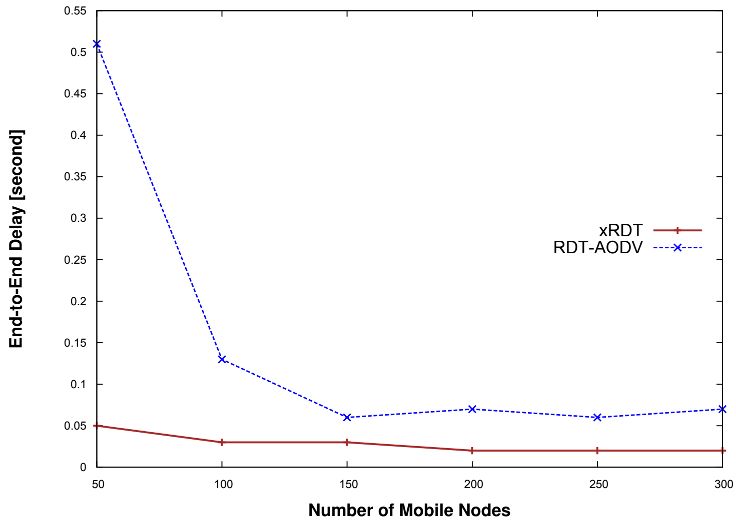

Figure 5.10: End-to-end delay for xRDT and RDT-AODV vs. network density

5.4.2.5 Packet Delivery Ratio (PDR)

Figure 5.11 shows the impact of network density on the PDR for the compared protocols. In a low-density network the standard single channel single radio AODV has an acceptable PDR around 60%. However, as the network density increases, the PDR for AODV decreases drastically to the point where less than 10% of the data packets sent by source nodes are successfully received by destination nodes. This is mainly due to the increased interference, contention and collisions in a single shared medium as network density increases. In contrast, the PDR of RDT-AODV increases as the network density increases and it seems that the network density has no negative impact on its performance. Although RDT-AODV assumes the same number of transceivers at each node as does AODV, it achieves a significantly higher PDR. This is mainly due to the utilisation of multiple channels for communication in RDT-AODV. As expected, xRDT has the highest PDR among compared protocols regardless of network density. It has a PDR around 21% higher than that of RDT-AODV in a highly dense network (300 nodes). This is mainly due to xRDT's capability to address the multichannel hidden terminal and deafness problems that exist in RDT-AODV. However, this comes with the higher hardware costs and energy consumption. The confidence interval values for the compared protocols are given in Table A.1 in Appendix A.

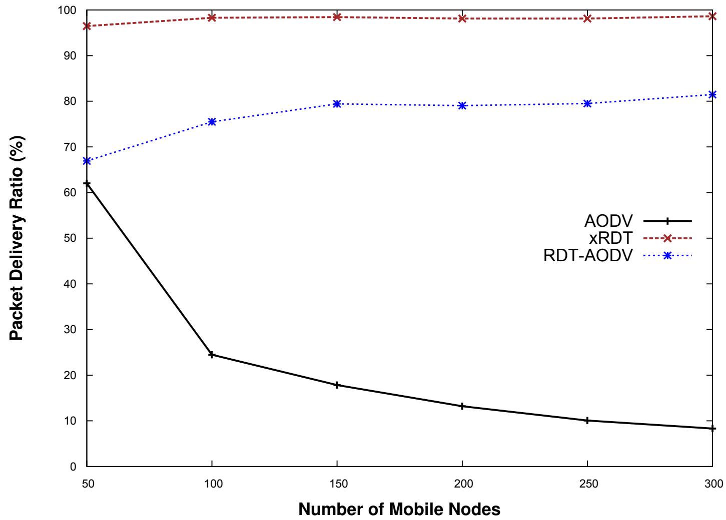

Figure 5.11: Packet delivery ratio vs. network density

Based on the results provided in this section, the following observations can be made:

- The performance of the single channel single radio AODV protocol decreased drastically as the network density increases. This is caused by increase in interference, contention and collision, along with the hidden terminal issue, in a single shared medium as network density increases.

- Utilising multiple channels can significantly improve the network capacity even in highly dense networks. This is because concurrent communication increases and the collision domain is divided into smaller collision domains.

- The multichannel single radio RDT-AODV protocol can significantly increase the network capacity compared with the single channel single radio AODV protocol without requiring extra hardware, control channels or time synchronisation. Furthermore, the multichannel hidden terminal and deafness problems have little/no effect on RDT-AODV performance, even with an increase in network density. However, the performance of RDT-AODV is affected slightly by network partitioning at low network density.

- The multichannel multi-radio xRDT protocol showed superior performance among the compared protocols regardless of network density. This is due to its ability to address the multichannel hidden terminal and deafness problems that exist in RDT-AODV. However, implementing xRDT requires higher hardware costs, and battery consumption.

5.4.3 Impact of Node Mobility

The simulation settings used to study the impact of node mobility on the network performance were explained in 4.6.1. Twenty connections of CBR traffic were simulated with a data packet size of 512 bytes and a generation rate of 4 packets/second. The number of mobile nodes in the network was 200 nodes.

5.4.3.1 Collision Rate

Figures 5.12 and 5.13 show the effect of node mobility on the collision rate for the compared protocols. It can be seen in Figure 5.12 that the collision rate of the single channel single radio AODV is significantly increased as the node speed increases from 1 to 5 m/sec. When node speed is 1 m/sec, the changes to network topology and the occurrence of link breakage are few. Therefore, the necessity for route re-discovery is reduced. However, as node mobility speed increases to 5 m/sec, the network topology changes more frequently, which increases the frequency of link breakage and therefore extra routing overhead is required to repair/rediscover a new route and hence the collision. However, as the node speed increases, the collision rate for AODV does not seem to be greatly affected. This may be because of link breakage occurrence after the speed of 5 m/sec is slightly increased, and therefore, there is a slight increase in the routing overhead (see Figure 5.14). On the other hand, multichannel protocols have significantly lower numbers of collisions than AODV, as can be seen in Figure 5.12.

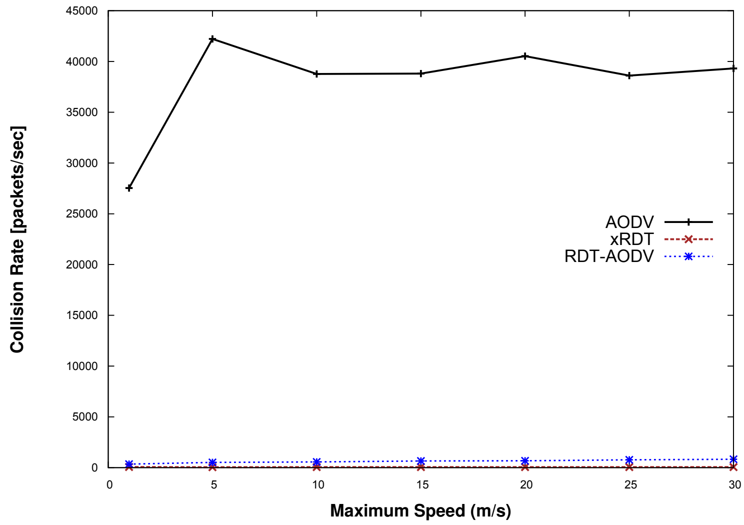

Figure 5.12: Collision rate vs. node mobility

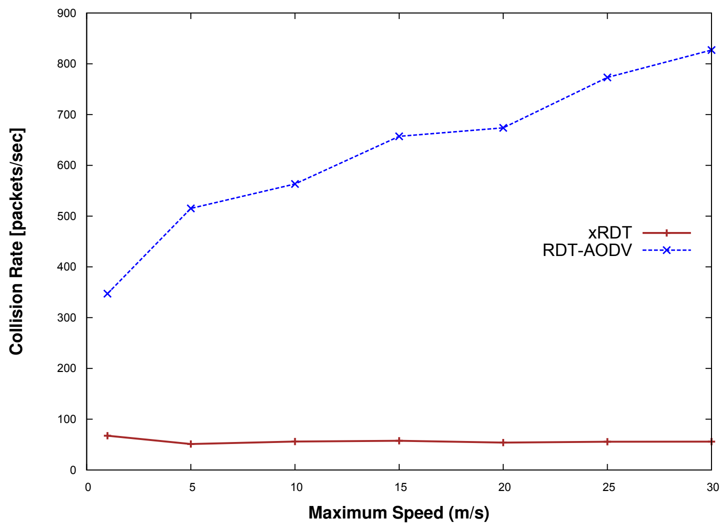

Figure 5.13: Collision rate for xRDT and RDT-AODV vs. node mobility

To distinguish the impact of node mobility on the collision rate in the multichannel protocols and for better resolution, Figure 5.13 has been provided. The collision rate of RDT-AODV steadily increases as the node speed increases. This is due to the increase in link breakage and the consequent routing overhead, which ultimately increases the contention and collision in the medium. Despite the increase in node mobility and the consequent link breakage and overhead, xRDT shows stable performance. This may be because it solves the multichannel hidden terminal and deafness problems, which contribute to keeping the occurrence of collisions low even with an increase in routing overhead.

5.4.3.2 Routing Overhead

Figure 5.14 presents the routing overhead for the compared protocols versus node mobility. The figure shows that the routing overhead of single channel single radio AODV is higher than that of the compared multichannel protocols. The routing overhead of AODV increases steadily with the increase of node mobility. This is due to frequent network topology changes as node mobility increases, which leads to frequent link breakage and an extra level of activity to repair or discover a new route (RREQ flooding). Similarly, the routing overhead of multichannel protocols increases as the node mobility increases, but with a significantly lower overhead compared with a single channel protocol. This is mainly due to the availability of multiple channels and to the fact that a smaller proportion of the total number of nodes in the network are involved in the route discovery and repair activities.

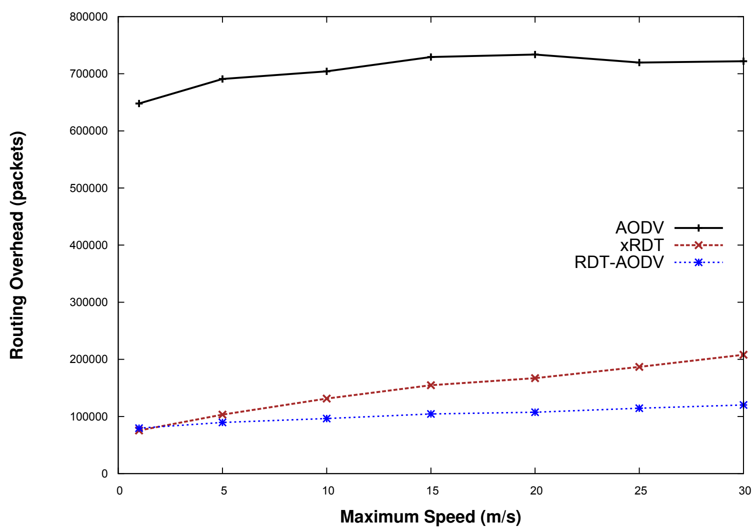

Figure 5.14: Routing overhead vs. node mobility

Although xRDT uses two radio interfaces and addresses the multichannel hidden terminal and deafness problems, it has a higher routing overhead than RDT-AODV. This may be caused by frequent changes in the *quiescent channel* channel of nodes in xRDT, along with the increase in node speed, which makes the transmitter node unaware of the current *quiescent channel* of the receiver node and hence, a higher number of RREQ packets flood into the network to discover/repair a route, as can be seen in Figure 5.15.

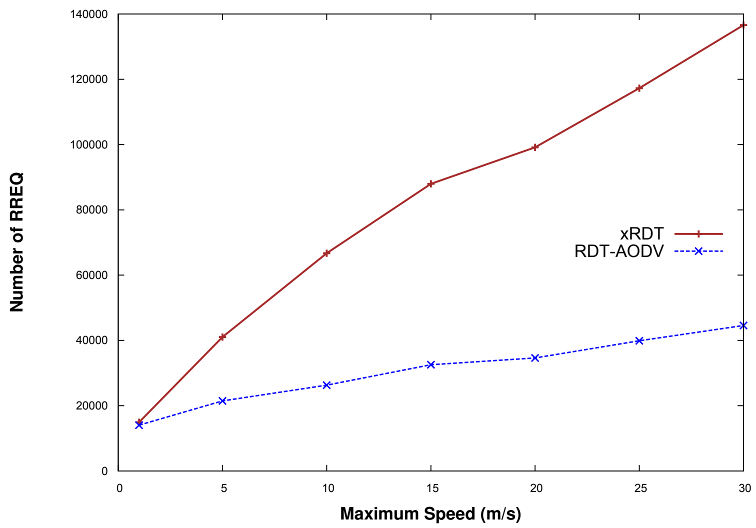

Figure 5.15: Route Request overhead for xRDT and RDT-AODV vs. node mobility

5.4.3.3 Data Drops

Figure 5.16 shows the impact of node mobility on the number of dropped data packets in the routing layer for the compared protocols. The number of dropped data packets in AODV increases as node mobility increases. This is probably due to increase in channel congestion caused by a higher routing overhead to repair broken links and a consequent increase in the collision rate in a single shared medium. On the other hand, the multichannel single radio RDT-AODV has reduced the data drops noticeably compared with single channel single radio AODV. This is due to the availability of multiple non-overlapping channels, which help to reduce the collision and overhead produced from repairing broken links in RDT-AODV, compared with AODV. Furthermore, the number of dropped data packets increases steadily in RDT-AODV as node mobility increases, which is perhaps caused by frequent changes in network topology and corresponding route recovery process which increases the frequency of multichannel hidden terminal occurrence. xRDT has the lowest number of dropped data packets and is only slightly affected by node mobility in comparison with the other compared protocols. This is due to the lower rate of collisions in xRDT compared with other protocols and its ability to address the multichannel hidden terminal and deafness problems compared with RDT-AODV.

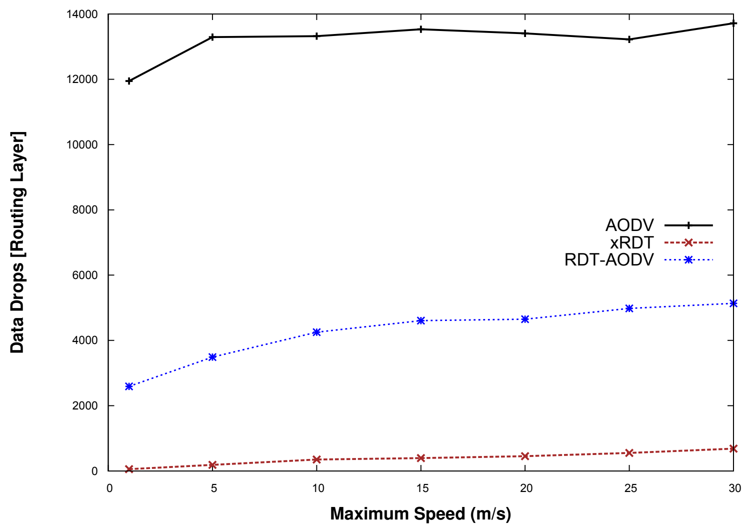

Figure 5.16: Data drops vs. node mobility

5.4.3.4 Delay

Figures 5.17 and 5.18 show the impact of increasing node mobility on average end-to-end delay for data packets in the compared protocols. It can be seen in Figure 5.17 that the delay in single channel single radio AODV is significantly higher than that in the multichannel protocols. The delay of AODV fluctuates mildly as node speed increases. It depends on the ability of AODV to repair broken links and deliver data packets. On the other hand, multichannel protocols incur significantly less delay in delivering data packets to their destination, compared with the single channel protocol. This is due to the smaller number of overheads and collisions occurring in multichannel protocols in response to route discovery or repair.

To distinguish the impact of node mobility on delay in the multichannel protocols and for better resolution, Figure 5.18 has been provided. Figure 5.18 shows that the delay of RDT-AODV increases as node mobility increases. This is likely to be due to the increase in the frequency of link failure as node mobility increases, which requires more rediscovery of other routes to destination Which increase the routing overhead and multichannel hidden terminal problem. On the other hand, xRDT is not affected by an increase in node mobility, which again is due to its ability to address the multichannel hidden terminal and deafness problems regardless of the increase in routing overhead. It is worth mentioning that the difference in the delay time to deliver data packets between RDT-AODV and xRDT is rather small compared with that of AODV.

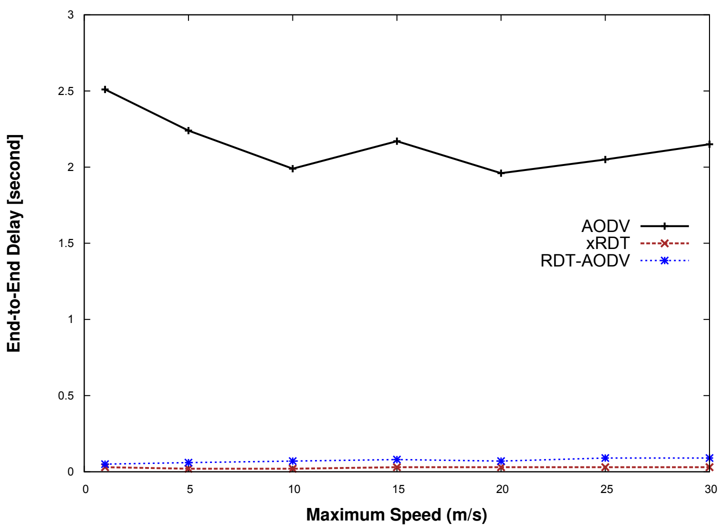

Figure 5.17: End-to-end delay vs. node mobility

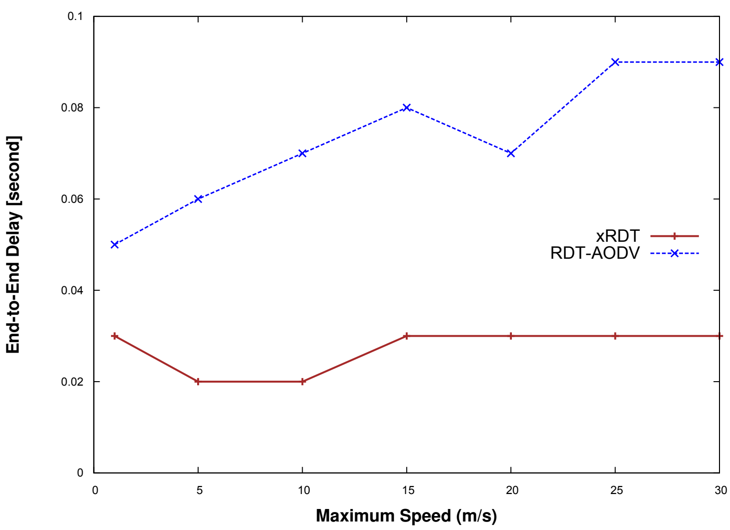

Figure 5.18: End-to-end delay for xRDT and RDT-AODV vs. node mobility

5.4.3.5 Packet Delivery Ratio (PDR)

Figure 5.19 shows the impact of increasing node mobility on the PDR for the compared protocols. The PDR for single channel single radio AODV is very low and slightly decreases as the node mobility increases. However, node mobility does not seem to have a dramatic impact on the delivery of data packets in AODV. It seems that the major impact of this low PDR performance is related to the high degree of interference and collisions in a single channel network. On the other hand, the PDR for multichannel single radio RDT-AODV is high compared with that of AODV. The node mobility seems to cause a slight steady decrease (by about 14% from speed 1 to 30 m/sec) in the PDR for RDT-AODV. xRDT has the highest PDR among the compared protocols regardless of node mobility. As node mobility increases, there is a slight decrease in the PDR of xRDT. This is mainly due to xRDT's capability to address the multichannel hidden terminal and deafness problems that exist in RDT-AODV. However, this comes with higher hardware costs and energy consumption. In contrast, multichannel single radio RDT-AODV achieves a noticeably high PDR compared with a single channel single radio AODV. The confidence interval values for the compared protocols are given in Table A.2 in Appendix A.

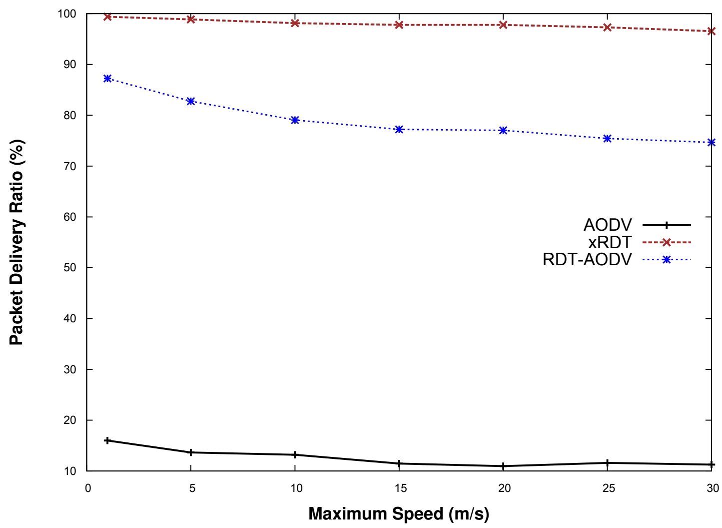

Figure 5.19: Packet delivery ratio vs. node mobility

Based on the results provided in this section, the following observations can be made:

- The performance of the single channel single radio AODV protocol slightly decreases as node mobility increases.

- Utilising multiple channels can significantly improve network capacity even in a highly dense mobile network. This is due to increasing concurrent communication and dividing the collision domain into smaller collision domains.

- The multichannel single radio RDT-AODV protocol can significantly increase the network capacity compared with the single channel single radio AODV protocol without requiring extra hardware, control channels or time synchronisation. Furthermore, the multichannel hidden terminal and deafness problems have little effect on RDT-AODV's performance, even with an increase in node mobility. Increasing node mobility causes frequent topology changes and link failures and hence increasing routing overhead. However, node mobility shows little effect on RDT-AODV performance.

- The multichannel multi-radio xRDT protocol illustrates superior performance among the compared protocols regardless of node mobility speed. This is due to its ability to address the multichannel hidden terminal and deafness problems that exist in RDT-AODV. However, implementing xRDT requires higher hardware costs and battery consumption.

5.4.4 Impact of Number of Connections

The simulation settings used to study the impact of number of connections on the network were explained in 4.6.1. A different number of connections of CBR traffic were simulated with a data packet size 512 bytes and generation rate of 4 packets/second. Each node moves dynamically with a random speed between [0,10] m/sec. The number of mobile nodes in the network was 200 nodes.

5.4.4.1 Collision Rate

Figures 5.20 and 5.21 show the effect of increasing network density on the collision rate for the compared protocols. Figure 5.20 shows clearly that the collision rate of the single channel single radio AODV is the highest among the compared protocols and that it increases as the number of connections increases. This is likely to be due to increase in interference, contention and collision in a single shared medium, along with an increased possibility of hidden terminal problems as the number of connections increases. On the other hand, multichannel protocols have significantly reduced the number of collisions compared with AODV, as can be seen in Figure 5.20. This may be due to utilising more than one medium for contention and communication, which reduces the probability of collisions.

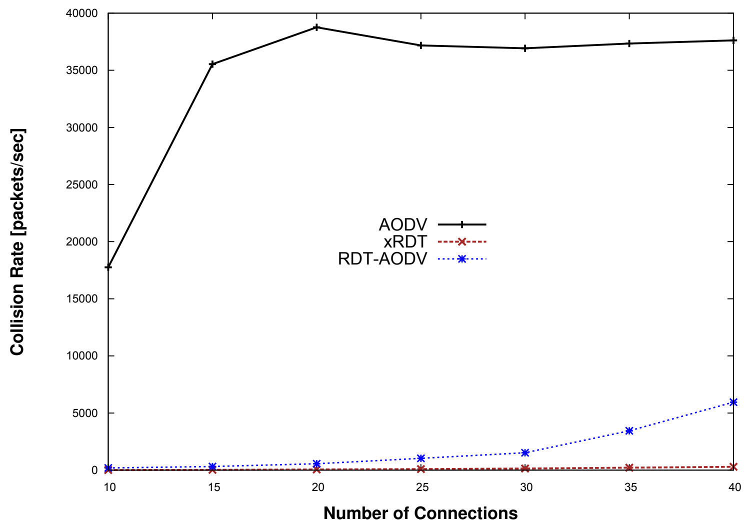

Figure 5.20: Collision rate vs. number of connections

To distinguish the impact of the number of connections on the collision rate in the multichannel protocols and for better resolution, Figure 5.21 has been provided. The collision rate of RDT-AODV steadily increases as the number of connections increases from low to medium (10 to 30 connections). A noticeable increase in the collision rate occurs as the network load increases (after 30 connections). This is perhaps due to increased occurrence of multichannel hidden terminal and deafness problems, which ultimately increase the link breakage rate and routing overhead (as can be seen in Figure 5.22). The collision rate of xRDT slightly increases as the number of connections increases. This may be because of its capability to solve the multichannel hidden terminal and deafness problems, which directly contribute to keeping the occurrence of collisions low, even with an increased number of connections.

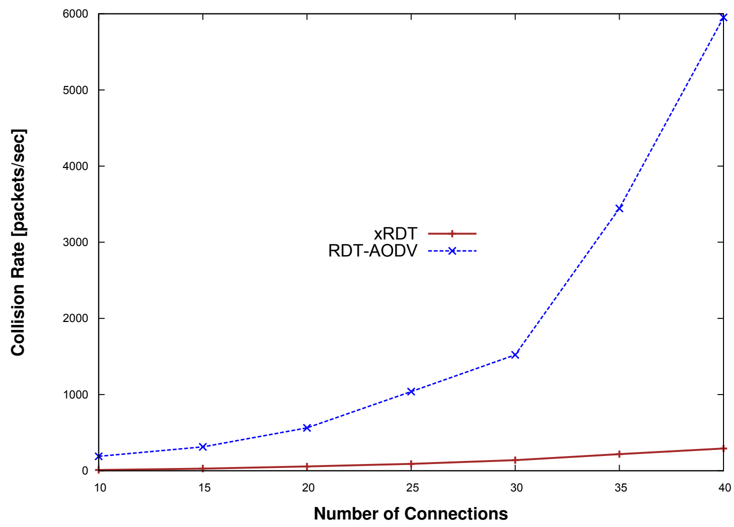

Figure 5.21: Collision rate for xRDT and RDT-AODV vs. number of connections

5.4.4.2 Routing Overhead

Figure 5.22 depicts the routing overhead for the compared protocols versus the number of connections. The figure shows that the routing overhead of the single channel single radio AODV is higher than the multichannel protocols and increases linearly with the increasing number of connections. This is could be due to many factors, including the increased number of hidden nodes, which inadvertently increase contention and cause collisions in the ongoing communication, and participation of all nodes in the route discovery/recovery process, which inevitably means extra routing overhead. Similarly, the routing overhead of the multichannel protocols increases as the number of connections increases, but with a significantly lower overhead. This may be explained by the availability of multiple channels and the fact that only nodes listening to the destination *quiescent channel* are involved in the route discovery/recovery process.

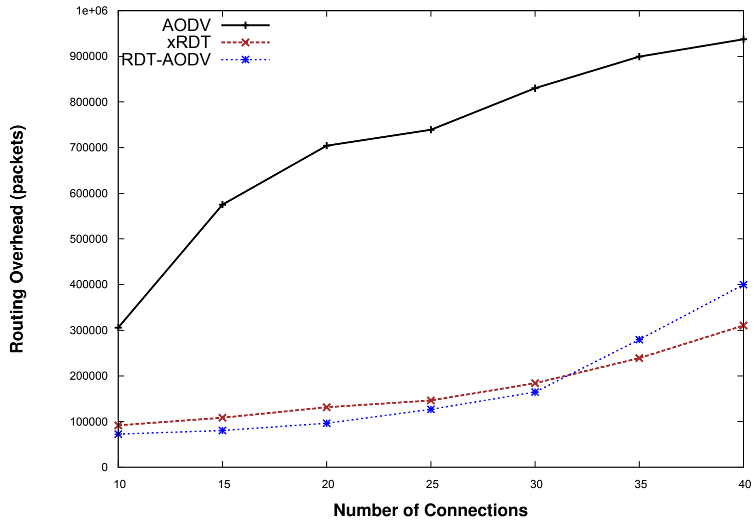

Figure 5.22: Routing overhead vs. number of connections

RDT-AODV shows a lower routing overhead compared with xRDT in a low to medium offered load (10 to 30 connections). This may be because the multichannel hidden terminal problem and deafness are not severe (indicated by the number of collisions, see Figure 5.21) at a low and medium number of connections. As a result, fewer RREQ packets are generated, as shown in Figure 5.23. As the number of connections increases, more nodes need to switch their radio interfaces to the receiver node's *quiescent channel*. As the transmitter node does not have the current state of the new channel, the node may inadvertently act as a hidden terminal node. Consequently, this will increase the collision rate (as shown in Figure 5.21). As a result more link breakages will occur, leading to an extra level of activity to repair or discover a new route (RREQ flooding), as can be seen in Figure 5.23. On the other hand, the routing overhead for xRDT is higher than for RDT-AODV at low to medium offered load. This is because of frequent changes in the *quiescent channel* of nodes in xRDT, which make the transmitter node unaware of the current *quiescent channel* of the receiver node and hence, a higher number of RREQ packets are sent for route discovery/repair, as can be seen in Figure 5.23. As the number of connections increases, the multichannel hidden terminal becomes more pronounced in RDT-AODV, and therefore it has higher routing overhead then xRDT.

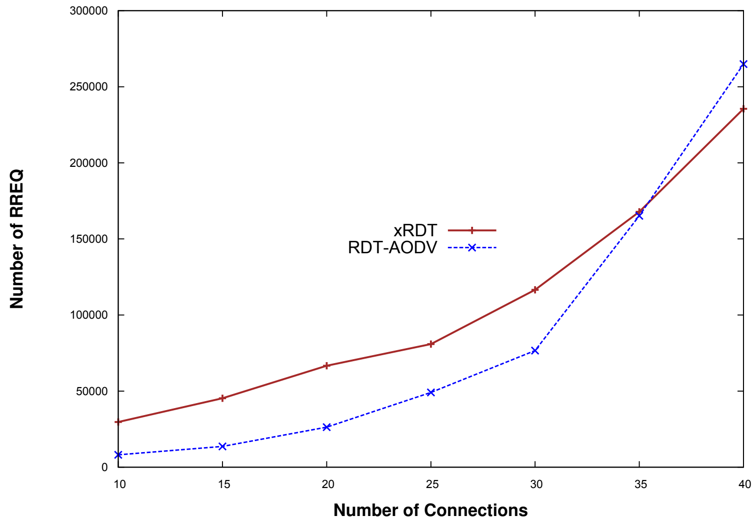

Figure 5.23: Route Request overhead for xRDT and RDT-AODV vs. number of connections

5.4.4.3 Data Drops

Figure 5.24 shows the impact of the number of connections on the number of dropped data packets in the routing layer for the compared protocols. The number of dropped data packets in the single channel single radio AODV increases linearly as the number of connection increases. This is because of the increased interference, contention and collision rates and overhead, along with a hidden terminal problem in a single shared medium. On the other hand, the multichannel single radio RDT-AODV has reduced data drops noticeably in comparison with AODV. This is due to the availability of multiple non-overlapping channels, which helps to reduce the collisions and overhead in RDT-AODV compared with AODV. At low to medium numbers of connections, the amount of dropped data in RDT-AODV increases linearly. However, in a network with a high offered load (over 30 connections), a significant increase is observed. This is because the high number of connections make the multichannel hidden terminal problem more pronounced. xRDT is least affected by dropped data packets, despite the increase in the number of connections in comparison with other compared protocols. This is due to the availability of multiple channels and the ability of xRDT to address the multichannel hidden terminal and deafness problems compared with RDT-AODV.

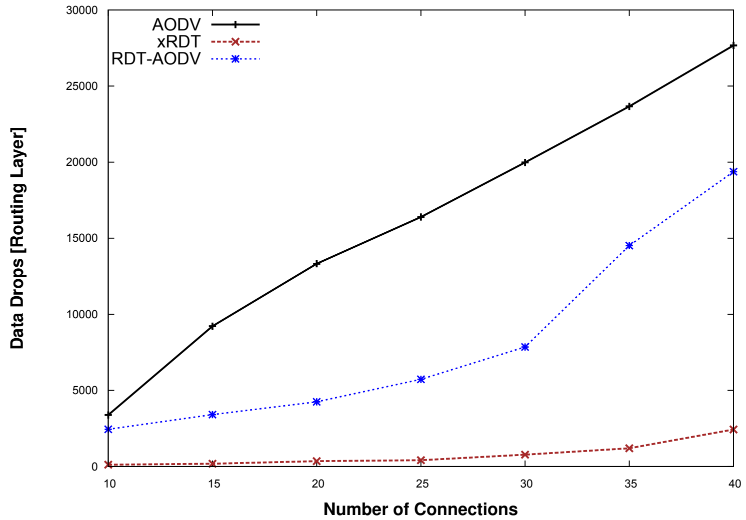

Figure 5.24: Data drops vs. number of connections

5.4.4.4 Delay

Figures 5.25 and 5.26 show the impact of increasing the number of connections on the end-to-end delay for data packets in the compared protocols. It can be seen in Figure 5.25 that the delay in single channel single radio AODV is significantly higher than that in the multichannel protocols in all cases. This is mainly due to the increase in the interference, contention and collision in a single shared medium, along with the increase in hidden terminal nodes. On the other hand, multichannel protocols have significantly less delay compared with a single channel AODV because there is more than one medium for contention, which will reduce interference, collisions and time required to access the medium.

Figure 5.26 shows the delay for xRDT and RDT-AODV. At a small to medium number of connections, the difference between xRDT and RDT-AODV is rather small. However, with the increased number of connections, the delay for RDT-AODV jumps significantly. Again, this is mainly due to the increased occurrence of the multichannel hidden terminal issue as the number of connections increases, which increases the number of collisions (as in Figure 5.21) and necessitates more route re-discovery processes (as in Figure 5.23). All these factors increase the delay for RDT-AODV at a high network offered load.

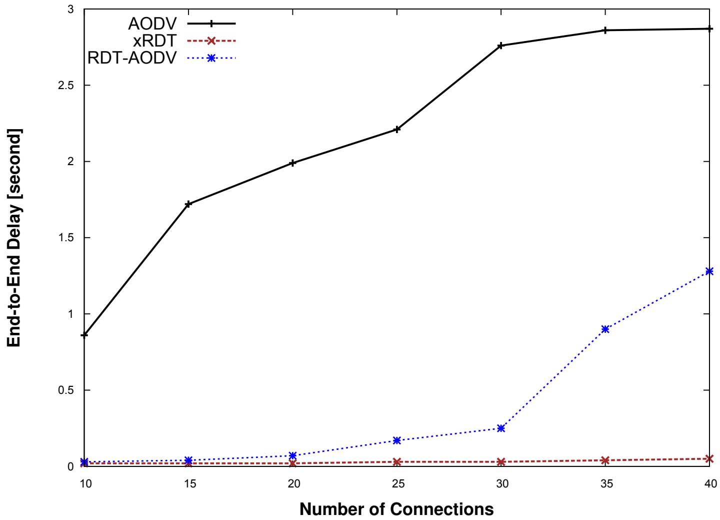

Figure 5.25: End-to-end delay vs. number of connections

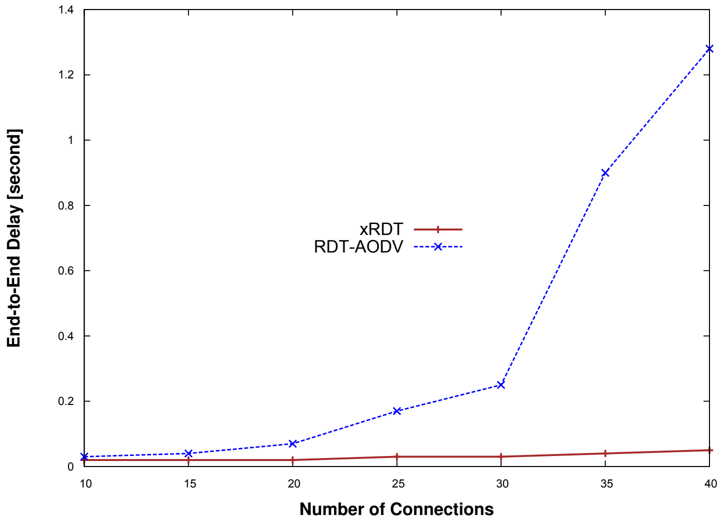

Figure 5.26: End-to-end delay for xRDT and RDT-AODV vs. number of connections

5.4.4.5 Packet Delivery Ratio (PDR)

Figure 5.27 shows the impact of the number of connections on the PDR for the compared protocols. With a low number of connections (10 connections), the performance for single channel AODV is acceptable (at around 60% of PDR). However, as the number of connections increases, the PDR for AODV decreases dramatically to the point where less than 10% of the sent data packets are successfully received by destination nodes. This is mainly due to the increased interference, contention and collision, along with an increase in the hidden terminal and exposed node problems as the number of connections increases. On the other hand, the multichannel protocols have better PDR than AODV in all cases.

With regard to the RDT-AODV, increasing the number of connections seems to have no negative impact on its performance with low to medium offered load (from 10 to 30 connections). However, a noticeable decrease in PDR occurs in networks with a high number of connections (35 and 40 connections). This is mainly due to the increased occurrence of the multichannel hidden terminal problem, which causes an increase in collision rates and the routing overhead. With regard to xRDT, it shows very little decrease as the number of connections increases. This is because of its ability to address the multichannel hidden terminal and deafness problems. However, this comes with higher hardware cost and energy consumption. In contrast, the multichannel single radio RDT-AODV achieves a significantly higher PDR than a single channel single radio AODV. The confidence interval values for the compared protocols are given in Table A.3 in Appendix A.

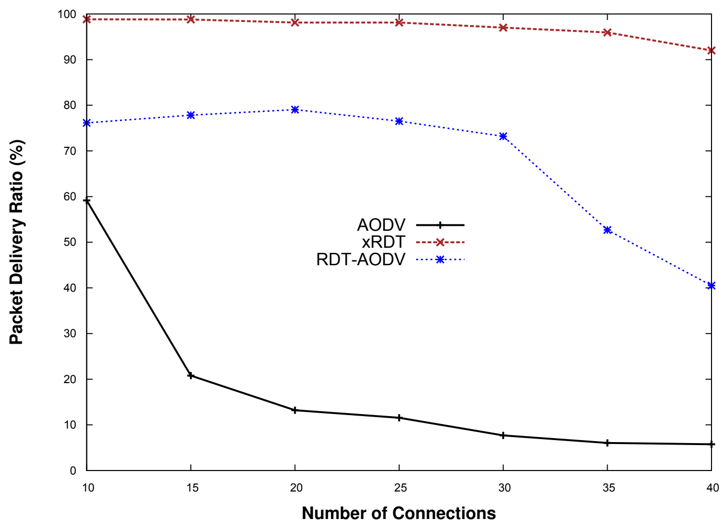

Figure 5.27: Packet delivery ratio vs. number of connections

Based on the results provided in this section, the following observations can be made:

- The performance of the single channel single radio AODV protocol decreases drastically as the number of connections increases. This is because of the increased interference, contention and number of collisions, along with the hidden terminal and exposed node problems in a single shared medium.

- Utilising multiple channels can significantly improve the network capacity, even in networks with a high number of connections. This is due to increasing concurrent communication and dividing the collision domain into smaller collision domains.

- The multichannel single radio RDT-AODV protocol can significantly increase the network capacity compared with the single channel single radio AODV protocol without requiring extra hardware, control channels or time synchronisation. With a low to medium number of connections, the multichannel hidden terminal and deafness problems have little effect on RDT-AODV performance.

  However, the performance of RDT-AODV was noticeably affected as the number of connections increased. This is due to the increased occurrence of multichannel hidden terminal and deafness problems.

- The multichannel multi-radio xRDT protocol has superior performance among the compared protocols, regardless of the network offered load. This is due to its ability to address the multichannel hidden terminal and deafness problems that existed in RDT-AODV. However, implementing xRDT requires higher hardware costs and battery consumption.

5.5 Conclusions

Utilising multiple channels in communication can increase the wireless ad hoc network capacity by enabling concurrent communication among adjacent nodes using different non-overlapping channels. Furthermore, it can decrease the levels of interference, contention and collision by providing more than one medium for communication.

Different approaches were proposed to utilise multiple channels in wireless networks. The Receiver Directed Transmission (RDT) protocol is one of them. RDT uses a clever approach to implement the multichannel wireless network, bypassing channel negotiations without requiring an additional control radio interface/channel or time synchronisation. Several protocols have been proposed based on RDT to implement a multichannel network and overcome the expected issues in RDT namely the multichannel hidden terminal, deafness and lack of broadcast support. However, these solutions usually depend on extra hardware (xRDT), a control channel (RcMAC) or time synchronisation (RSM).

Using the network simulator NS-2, this chapter has evaluated the performance of a multichannel RDT using a single radio interface without extra hardware, a control channel or time synchronisation. The performance of RDT-AODV was evaluated against the single channel single radio AODV and multichannel multi-radio xRDT. This is important to evaluate the performance of the protocol practically rather than theoretically.

To evaluate the protocols under different network conditions, an extensive simulation was performed by varying the network density, mobility and number of connections. The simulation results suggest that increasing network density has no or little effect on RDT-AODV performance. However, RDT-AODV suffered from network partitioning in networks with low node density. With regard to the impact of node mobility on RDT-AODV, increasing the node mobility has little effect on the protocol's performance. With regard to the impact of the number of connections, the performance of RDT-AODV degraded noticeably as the number of connections in the network increased. This is mainly due to the increased occurrence of multichannel hidden terminal and deafness problems.

From the results and discussion provided in this chapter, it seems that RDT-AODV has the ability to implement multichannel MANETs and improve the network performance without extra hardware, common control channel or time synchronisation. Furthermore, RDT-AODV performs better than the standard single channel single radio AODV in all reported network configurations. The results suggest that the network density and mobility have little/no impact on RDT-AODV performance. However, increasing the offered load in the network (number of connections) has a negative impact on RDT-AODV as multichannel hidden terminal and deafness issues become more pronounced.

Based on the reported results and discussions in this chapter, the RDT-AODV seems to be suitable for the implementation of multichannel MANETs, especially when a low to medium network offered load is required by applications.

Chapter 6

Multipath Multichannel Routing Protocol

6.1 Introduction

In Chapter 5 an extensive study was reported on that evaluated the performance of the Receiver Directed Transmission (RDT) communication scheme. Unlike other proposed protocols based on RDT, the RDT-AODV and RDT-MAC protocols, which follow the RDT communication scheme were implemented without requiring extra hardware, a common control channel or time synchronisation. Using the NS-2 simulator, the results reported in Chapter 5 show that utilising RDT with a single transceiver, without relying on a common control channel or time synchronisation, can significantly improve the network capacity compared with a single channel network. However, the performance of RDT-AODV was affected in a major way by an increase in the offered load (number of connections) in the network, due to increased occurrence of multichannel hidden terminal and deafness problems.

This chapter introduces a multipath extension to the multichannel RDT-AODV routing protocol called Route Migration over Multiple link failure in MultiChannel routing protocol (RMMMC). RMMMC is a novel fault-tolerant multipath multichannel routing protocol. It aims to improve reliability and resilience to link failure and provide fault-tolerance to multichannel routing protocols in MANETs. The route discovery and recovery algorithms in RDT-AODV are modified to support multipath functionality in RMMMC.

The RMMMC protocol forms multiple node and channel disjointed paths in multiple channels towards any destination. The route discovery procedure is modified from RDT-AODV's to initiate two distinct route discovery processes in two different channels which should help to eliminate co-channel interference. A new routing packet type called Multi-Hop PAth (MHPA) packet is introduced to announce a possible alternative path in a different channel. Data packets are delivered using only one of the paths. The second path is used as a recovery path when link failure is detected. Furthermore, a new route recovery mechanism is proposed that lets nodes detect link failure to reroute the data packets via the alternative route regardless of the failure location. RMMMC can handle multiple link failures. Additionally, RMMMC improves local connectivity in the multichannel routing protocol by enabling a node to broadcast a Hello packet on all available channels alternatively in a Round Robin manner.

The NS-2 simulator is used to emulate the proposed multipath multichannel routing protocol and to evaluate its performance with different protocols under different network conditions. The rest of this chapter is organised as follows: Section 6.2 describes the new proposed RMMMC routing protocol in detail. Section 6.3 discusses its performance evaluation in different network environments. Section 6.4 presents a summary and conclusion for this chapter.

6.2 The Multipath Multichannel Routing Protocol

Initialising multiple paths in multiple channels can bring the following benefits to a single path multichannel routing protocol:

- First, it increases the probability of discovering a route to a destination, which is important in a multichannel network where every node is equipped with a single half-duplex transceiver.
- Second, it improves the fault-tolerance of the routing protocol, which is achieved by utilising extra discovered paths to deliver data between the source

and destination when link failure is detected.

- Third, when a link becomes a bottleneck and congested due to a heavy load, utilising multiple paths in multiple channels can balance the load by rerouting the traffic via pre-discovered alternative paths in a different channel.

- Fourth, it can increase aggregate bandwidth utilisation of the network by splitting and routing the data destined for the same destination via different paths in different channels.

- Fifth, it can easily provide node and channel disjointed routes, which are considered to be the highest degree of disjointedness (as discussed in section 2.5.2.2).

- Finally, it can reduce recovery delay when link failure is detected by utilising pre-established alternative routes instead of initiating a new route re-discovery process.

Therefore, initialising multiple paths over multiple channels can improve the reliability, and increase error resilience and fault-tolerance in the multichannel routing protocol in MANETs.

Utilising multiple paths over multiple channels can benefit the routing protocols as discussed earlier; however it brings different challenges to those in multipath single channel protocols. For instance, the approach used to support channel assignment and negotiation, the frequency of channel switching and awareness of activities in different channels are all important factors that need to be rethought when designing a multipath multichannel routing protocol.

RMMMC [189] extends the multichannel single-path RDT-AODV routing protocol (which is presented in Chapter 5) to support multiple paths in multiple channels. RMMMC combines multiple paths and channels during the route discovery process to increase the probability of discovering multiple disjointed routes to any destination. Therefore, more than one route in different channels is constructed between each source and destination node. The discovered routes in RMMMC are node and channel disjointed paths, which is the highest degree of disjointedness (as discussed in section 2.5.2.2). In RMMMC, the best discovered path is used for data packet transmission while the other path works as an alternative path and is used to recover from the broken link when detected. Additionally, RMMMC supports route accumulation during the route discovery phase (RREQ and RREP). The intermediate nodes involved in the active route are informed about the full multi-hop path available in the other channel (the full multi-hop alternative route in the alternative channel) via the newly introduced routing control packet (MHPA). Hence, intermediate nodes are aware of the full multi-hop path in a different channel which increases their chances of recovering from a broken link. When a link failure is detected, the node that detects the link failure will steer (detour) data packets on to the backup route (data migration) by selecting a neighbour node from the alternative path.

A local repair mechanism in AODV, AOMDV and RDT-AODV routing protocol is invoked if a broken link is closer to the destination than to the source. In contrast, RMMMC activates a multichannel local repair mechanism where the link failure can be repaired regardless of its location, provided that an alternative pathway is available.

RMMMC improves the resilience of the multichannel routing protocols by providing a full multi-hop alternative path in different channels to handle multiple link failures. To accomplish this, significant changes have been made to route discovery and recovery in RDT-AODV; namely improving local connectivity, and introducing a new route discovery procedure and multichannel local repair mechanisms. With regard to the MAC protocol used, RMMMC uses the multichannel RDT-MAC protocol, which is presented in Chapter 5 as a means of supporting the multichannel communication in MANETs. Similar to RDT-AODV, RMMMC assumes that each node in the network is equipped with a single half-duplex radio interface, as most current wireless devices are. Thus, a node can only listen to one channel at a time.

The following sections describe the working process of RMMMC in detail. Section 6.2.1 explains how the proposed protocol supports local connectivity. Section 6.2.2 specifies modifications made to routing table management. Modified routing control packets are presented in Section 6.2.3. A detailed description of the new route discovery and recovery procedures are given in Sections 6.2.4 and 6.2.5 respectively.

6.2.1 Improving Local Connectivity

A wide variety of reactive and proactive routing protocols in single channel MANETs [20, 70, 19, 80] use Hello packets to discover their neighbours and maintain local connectivity [190, 191]. In such an approach nodes advertise their presence by periodically broadcasting a one-hop Hello packet every $HELLO\_INTERVAL$. Absence of receipt of several Hello packets from a neighbour that exceed the $ALLOWED\_HELLO\_LOSS$ threshold is taken to mean that the link with that neighbour has been lost and it is removed from the neighbour list and no further data is forwarded to it.

In multichannel MANETs where each node is equipped with a single transceiver support for neighbour discovery and maintenance of local connectivity without deploying a common control channel is a challenging task. Different possible approaches to maintaining local connectivity in multichannel networks come with different costs. The following are some of the possible solutions to support neighbour discovery and to maintain local connectivity in a multichannel network:

- Broadcast Hello packet in all available channels every $HELLO\_INTERVAL$. This will maintain a good local connectivity knowledge and is a more accurate reflection of the current state of the network topology. However, this approach is expensive as the node is required to switch its channel as frequently as every $HELLO\_INTERVAL$, which risks increasing the frequency of the deafness problem and degrading network performance.

- Broadcast the Hello packet in a dedicated control channel. This will reduce the routing overhead related to broadcasting the Hello packet as all neighbour nodes will receive a copy of the Hello packet. However it requires a common control channel and tight time synchronisation.

- Broadcast the Hello packet only in the current listening channel. This will reduce the Hello packet overhead, but the node would be unaware/disconnected from its neighbour nodes operating in different channels.

- Broadcast the Hello packet alternately in all available channels in a Round Robin manner every $HELLO\_INTERVAL$. This will reduce the Hello routing overhead. However, the freshness of local connectivity information may not be update or reflect the current state of the network topology.

From the discussion above, it seems that different approaches to supporting local connectivity in multichannel networks come with different costs. Thus, there should be a trade-off between the produced overhead and the accuracy of maintaining local connectivity knowledge [192]. Selecting an appropriate approach to support neighbour discovery depends on many factors, such as application requirements [193], node mobility patterns [194] and the application's link failure sensitivity.

The RMMMC protocol supports neighbour discovery and local connectivity by enabling nodes to broadcast periodically a Hello packet successively in a Round Robin manner over all available channels every $HELLO\_INTERVAL$. The $HELLO\_INTERVAL$ (every 0.9 *sec*) and the $ALLOWED\_HELLO\_LOSS$ (5 packets) parameters in RMMMC are modified to find a compromise between the Hello overhead and the freshness of neighbour knowledge. It is worth mentioning that at very high node mobility, local connectivity may not be updated on time and therefore may not reflect the current state of the network.

In Figure 6.1 let it be assumed that there are three available channels in the network and that the letter inside the circle represents the node ID and the number represents the node's home channel (*quiescent channel*). Therefore, the home channel for nodes S and Q is channel 2. To support local connectivity, for instance, node S broadcasts a Hello message in $Channel1$ in the first interval. Thus, nodes M and B are made aware of node S's presence. Then, in the second interval, node S broadcasts a Hello message in $Channel2$, and so on. This enables nodes to interconnect with their neighbours operating in different channels while reducing the routing overhead caused by a Hello packet.

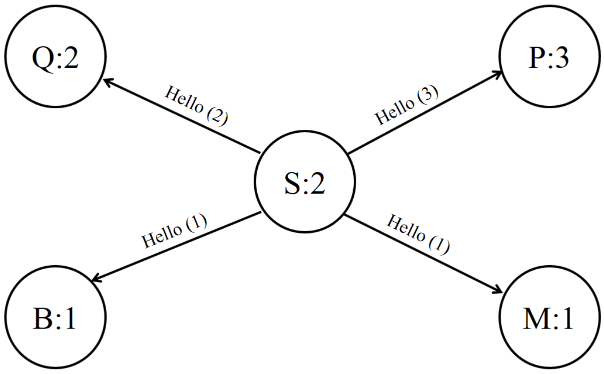

Figure 6.1: Support local connectivity in RMMMC

6.2.2 Modifications of the Routing Table

To support the new mechanisms in RMMMC, only a few fields have been added to the original routing table. Furthermore, a new routing table called alternative routing table' was introduced.

Routing Table:

The following fields are added to the original routing table:

- *rt_accumulated_no* : the number of addresses in the accumulated path.
- *rt_pri_path*[] : accumulated addresses for any routing entry.

Alternative Routing Table:

RMMMC introduces a new routing table called the alternative table to maintain information related to the alternative path. This enables a node that detects link failure to reroute a data packet using an alternative node in a different channel. To ensure the freshness of routing information in the alternative table, RMMMC used the same ageing techniques and timers as in the original routing table.

The alternative routing table contains the following fields:

- *Destination* : the IP address for the final destination node.
- *Expiry_time* : the lifetime of the route entry.
- *al_accumulated_no* : the number of addresses in the accumulated path.
- *al_backup_path*[] : accumulated addresses for the alternative path.

A routing entry in the alternative routing table is created/updated in the following cases:

- Source or Destination node: When the node acquires two entries in different channels (an entry in the routing table and an entry in the alternative table).
- Intermediate node: When the node receives Multi-Hop PAth packet (MHPA), which includes the full multi-hop alternative path in the alternative channel.

6.2.3 The Modified Routing Control Packets

As RMMMC supports route accumulation function during route discovery, a few changes are required to the RREQ and RREP packet frame formats. Furthermore, a new routing control packet called the Multi-Hop PAth (MHPA) packet is introduced to provide a full multi-hop alternate path in an alternative channel.

The Extended Route Request and Route Reply Packets:

In contrast to the AODV and RDT-AODV protocols, the RMMMC routing protocol supports route accumulation during a route discovery phase. Therefore, the RREQ and RREP packet formats and how the protocol handles them are modified as follows:

- *accumulated_no* : the number of hops in the accumulated path.
- *accumulated_path*[] : the IP addresses for the accumulated path.
- *flags* : whether RREQ/RREP are sent in original (primary) or alternative (backup) routes.

RMMMC uses part of the reserved fields in the RREQ and RREP packets to implement *accumulated_no* and flags fields as shown in Figures 6.2 and 6.3, respectively. This keeps the packet size down. Additionally, a new field called *accumulated_path*[] is added to RREQ and RREP packets. Figures 6.2 and 6.3 show the new packet format for RREQ and RREP, respectively. In order to have a more precise calculation of the new RREQ and RREP packets, the calculation of the size of these packets is modified in the simulator before the node sends RREQ or RREP, in order to reflect the actual size of the transmitted packet. The size of packets in this case depends on the number of IP addresses (hops) included in the *accumulated_path*[].

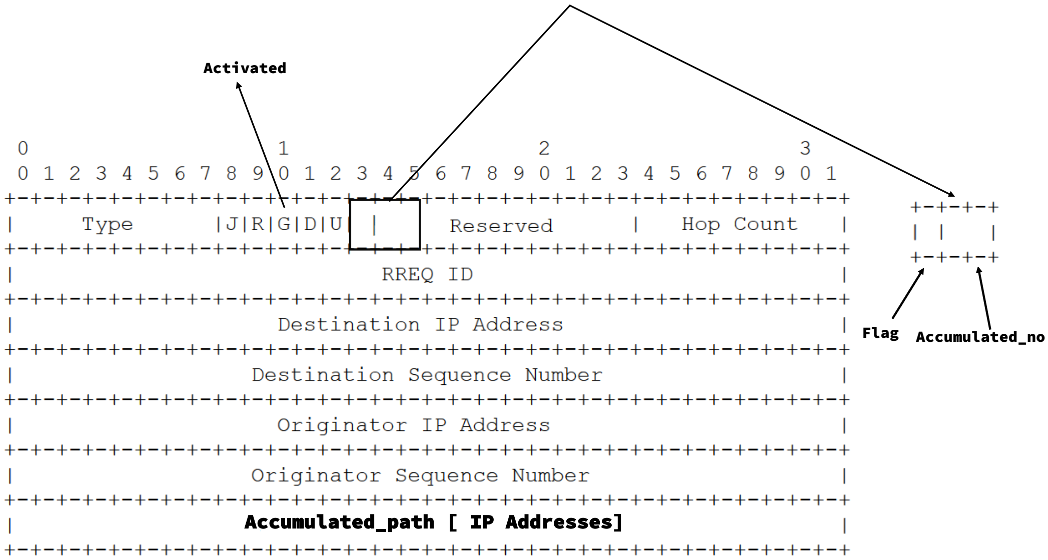

Figure 6.2: The extended RREQ packet in RMMMC

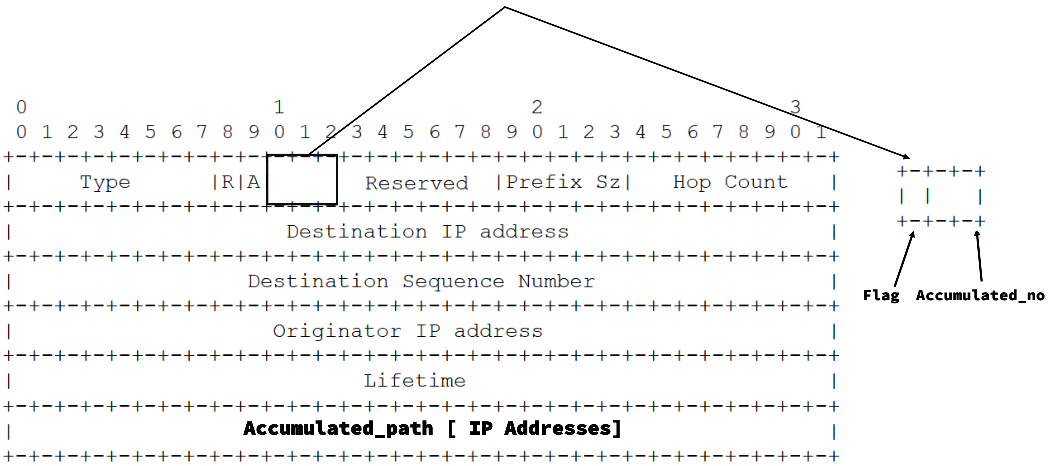

Figure 6.3: The extended RREP packet in RMMMC

Multi-Hop PAth packet (MHPA):

RMMMC introduces a new routing control packet called the MHPA packet. The format of the MHPA packet is similar to the modified RREP packet, but it has different functionality. The MHPA is used to create/update a route entry in the alternative routing table at the intermediate nodes. The destination node only creates and sends this packet when it creates or updates its two routing entries for any destination (an entry in the routing table and an entry in the alternative table). Furthermore, it is used to announce to all intermediate nodes involved in discovered paths the existence of an alternative path in a different channel.

6.2.4 The Proposed Route Discovery Mechanism

RMMMC introduces a new routing discovery mechanism to support multipaths in a multichannel wireless ad hoc network. The proposed protocol initiates multiple route discovery processes for any destination in multiple channels. Additionally, it supports route accumulation during the route discovery process (RREQ and RREP). Furthermore, it introduces a new multichannel route recovery mechanism where any node detecting a link failure, regardless of its location, can divert the data packets along an alternative path in an alternative channel.

Determining the optimal number of discovered paths per destination is not a trivial task. Increasing the number of discovered paths may increase the probability of finding an alternative route and reducing the delay to recover from the link failure, but also creates an extra overhead to establish and maintain these routes. Since the proposed multipath multichannel routing protocol in this chapter aims to improve fault-tolerance and enhance the reliability of routing in multichannel MANETs, the protocol only considers two routes per destination: one works as the primary route and the other is considered as a backup route. This strikes a compromise between increasing the routing overhead, contention and collisions caused by the route discovery and maintenance mechanisms, and the expected benefits from the extra discovered paths. Furthermore, for a network with three non-overlapping channels, discovering two paths in two different channels per destination means involving around two-thirds of the entire network in the route discovery process.

6.2.4.1 The Route Accumulation Approach

RMMMC supports route accumulation during the route discovery process (RREQ and RREP packets). The *accumulated_path*[] is used to provide a full multi-hop alternative route to recover from the broken link. This gives a node that detects the link failure more options for recovering from the broken link and should generally increase the probability of recovering from link failure. To achieve this, the frame formats of RREQ and RREP packets have been modified to support route accumulation functionality as explained in section 6.2.3. This lets each node acquire a multi-hop path for any entry in its routing table. For instance, in Figure 6.4, the source node S includes its address in the *accumulated_path*[] before broadcasting the RREQ. Neighbour nodes M and Q, which receive the RREQ should create/update a route entry to node S with the *accumulated_path* $\{S\}$. Then nodes M and Q will append their own addresses in the *accumulated_path*[] and re-broadcast the RREQ in their own home channel, and so on as can be seen in Figure 6.4. Thus, when the destination node D receives the RREQ packet from node C, the *accumulated_path*[] would be included in the RREQ packet as $\{S - M - B - C\}$. The same concept of route accumulation is applied to the RREP packet. Therefore, each node involved in any route acquires the multi-hop path between itself and any destination in its routing table.

It is worth mentioning that the concept of route accumulation is also used in other routing protocols such as DSR [20]. However, there are differences between the proposed accumulation path mechanism in RMMMC and in DSR. DSR adopts the source routing mechanism where the source node includes a list of hops to be followed by the intermediate nodes, while RMMMC adopts a hop-by-hop routing mechanism. Furthermore, the *accumulated_path* in RMMMC aims to provide an alternative path in a different channel to recover from the broken link.

6.2.4.2 Route Request Process

In RMMMC a source node initiates the route discovery process by broadcasting two RREQ packets in two different channels. The first RREQ is broadcast in the destination home channel (original route) with the primary flag, as in the RDT-AODV protocol, while the second RREQ is sent in a different channel (alternative route) with the backup flag. The RMMMC handles the RREQ packet via the destination and intermediate nodes as follows:

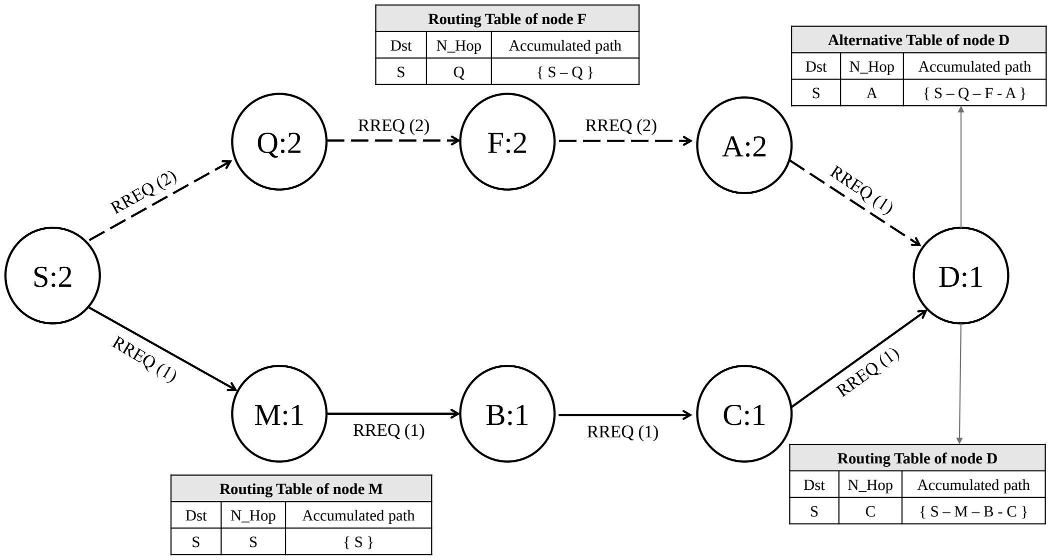

Figure 6.4: Route Request (RREQ) process in RMMMC

- Destination node: When a destination node receives a RREQ packet, it will create/update a routing entry based on the RREQ flag (primary or backup). If the RREQ flag is primary, then a route entry would be created/updated in the routing table. On the other hand, if the RREQ flag is backup, then it will create/update an entry in its alternative table.

- Intermediate node: Intermediate nodes receiving a RREQ packet in either route should create/update a route entry in their routing table regardless of the RREQ flag. All nodes in the original (primary) and alternative (backup) routes rebroadcast the RREQ in their own home channel, with the exception of when a node is in the alternative route (RREQ flag is backup) and then the final destination is in its neighbour's table (which has been discovered from the local connectivity as explained in section 6.2.1). In this case, the intermediate node should switch its radio interface to the destination node's home channel and rebroadcast the RREQ. This is required to enable the destination node to receive and reply to the RREQ and establish a route. Furthermore, intermediate nodes in the original route that receive a RREQ with a backup flag will ignore this packet. This is important for constructing a node and channel disjointed path and to enable only the destination node to establish two distinct paths for each source node. For instance, in Figure 6.4, nodes

M, B, C, Q, F will rebroadcast the RREQ in their own home channels. However, node A finds that node D is in its neighbour's table, therefore it should switch its channel to node $D's$ home channel and rebroadcast the RREQ. This RREQ will only be processed by the destination node; the intermediate node (node C) will ignore this RREQ as it is sent from the alternative channel (with a backup flag while node C is listening to the destination node home channel).

6.2.4.3 Route Reply Process

The Route Reply (RREP) packet is unicast along the reverse route of the RREQ when the destination node or an intermediate node with a fresh route towards the destination receives the RREQ. As there are two RREQs broadcast on two different channels, there will be two RREP packets unicast to the source node along two different channels. This would enable multiple paths to be established to any destination. The RMMMC handles the RREP packet as follows:

- Destination node: When the destination node receives the RREQ, it updates its corresponding table depending on the RREQ flag, as explained earlier, and then sends the RREP to the source node via the node that it received the RREQ from. This ensures that the shortest two forwarding paths constructed between any source and destination are node and channel disjointed paths. For instance, in Figure 6.5, node D will send an RREP via node C in $Channel1$ and another RREP via node A in $Channel2$. The RREP deploys the same route accumulation mechanism as explained earlier.

- Intermediate node: When an intermediate node with a fresh route to the destination receives the RREQ, it sends an RREP to the source node with its accumulated path to the destination. For instance, in Figure 6.5, if node B has a fresh route towards node D, then node B will send RREP to node S, including its accumulated path to the destination node D plus its own address as follows: $\{D - C - B\}$.

- Generating Gratuitous RREP: In order to enable the destination node to acquire the full multi-hop path to any source node, the source node should set the Gratuitous RREP flag $'G'$ in the RREQ packet, which is already defined in standard AODV. Therefore, intermediate nodes receiving a RREQ with a $'G'$ flag (see Figure 6.2) with a fresh route to the destination will unicast RREP to the RREQ originator with its accumulated path to the destination. Additionally, it will unicast a gratuitous RREP to the destination node along its accumulated path to the source node.

Let us assume node B in Figure 6.5 receives a RREQ from S and has a fresh route towards node D. In this case, node B will send a RREP to node S, including its *accumulated_path* to the destination node D as $\{D - C - B\}$. Additionally, it will send a gratuitous RREP to node D including its *accumulated_path* to the source node S as $\{S - M - B\}$. Note that the same process explained here is also applied to the alternative routes.

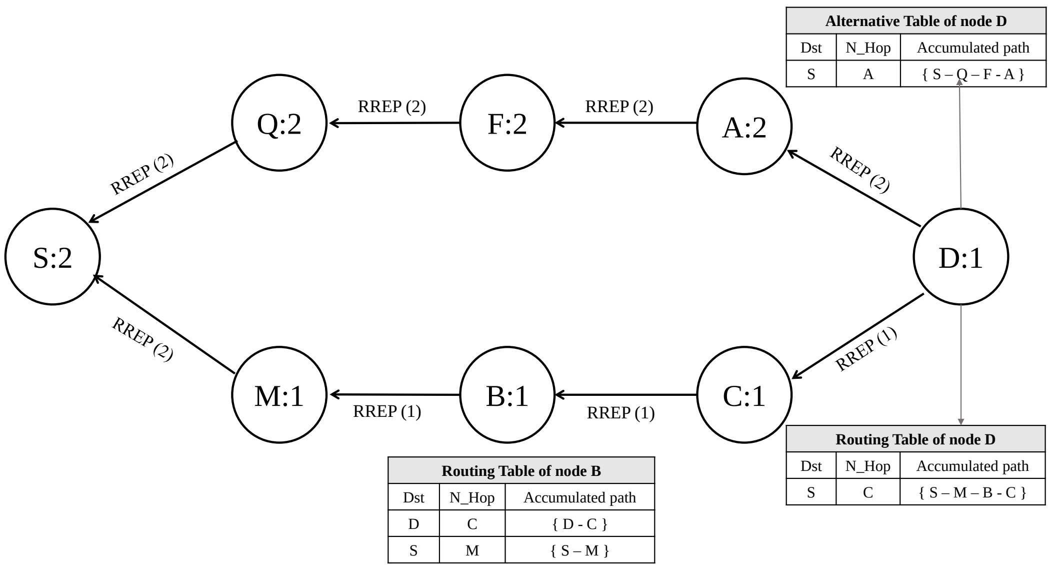

Figure 6.5: Route Reply (RREP) process in RMMMC

6.2.4.4 Advertise the Multi-hop Alternative Path

In RMMMC only the destination node sends a MHPA packet to inform intermediate nodes about a possible multi-hop alternative route in a different channel, which can be used to recover from a link failure when it is detected. The RMMMC packet will be initiated by the destination node whenever two entries for any node in its routing tables (an entry in the routing table and an entry in the alternative table) are created or updated. This would help to improve the freshness of the multi-hop alternative route at intermediate nodes and, therefore, the usefulness of the provided alternative paths.

Figure 6.6 shows the process of sending an MHPA packet in RMMMC. Let us assume that the destination node D has built two full multi-hop paths towards node S, namely, $path1\,\{S - M - B - C\}$ in its routing table and $path2\,\{S - Q - F - A\}$ in its alternative table. In this case node D will send two MHPA packets to node S as follows:

First, node D will apply the **Least Hop First Algorithm (LHF)** [195] to both paths. This is to enable the intermediate node that detects the link failure to search for and select the least hop count (nearest to the destination) first. So, after applying the LHF algorithm to the *accumulated_path*[], the order of nodes for $path1$ will be $\{C - B - M - S\}$ and for $path2$ it will be $\{A - F - Q - S\}$.

Second, node D will unicast the two MHPA packets to node S in two different routes. $Path1$ will be unicast to the next hop in the opposite route (*node A*) in channel 2 and $path2$ will be unicast to the next hop in the opposite route (*node C*) in channel 1. This is to provide intermediate nodes involved in the forwarding path with a full multi-hop path in the alternative channel.

Intermediate nodes that receive the MHPA packet will only update their alternative route and then forward the packet to their next hop in their routing table towards the destination of this packet (node S in this example). Node D will send an MHPA whenever it receives a fresher route to any destination in either of its routing tables. Although this may increase the routing overhead, it is important to improve the freshness of the multi-hop alternative routes at intermediate nodes.

6.2.4.5 Traffic Allocation

RMMMC combines multiple paths with multiple channels to improve the route discovery process and fault-tolerance in multichannel routing protocols in MANETs. Therefore, data traffic will be forwarded using only one path with the shortest hops

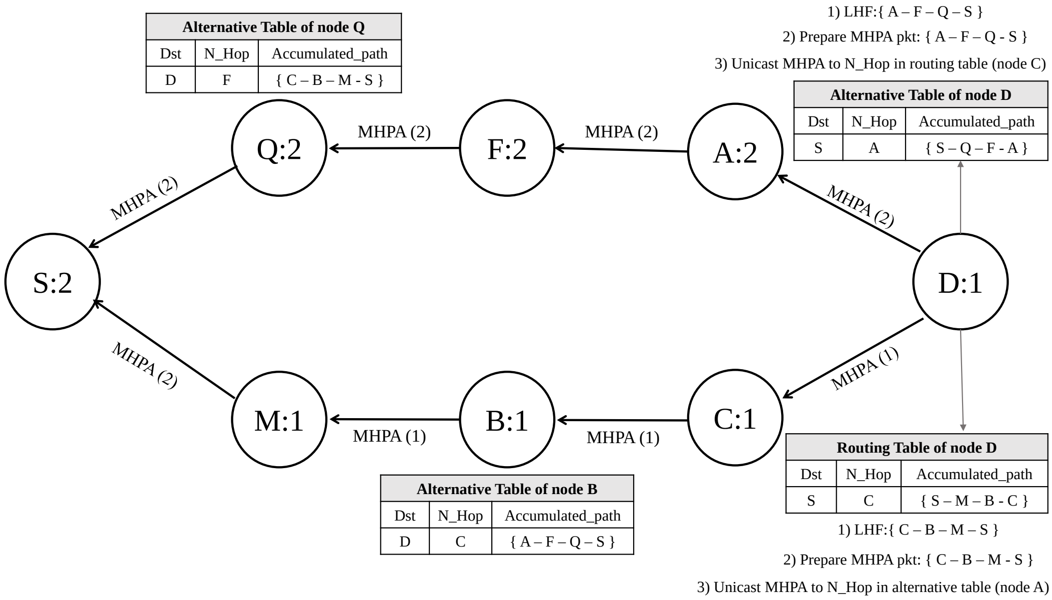

Figure 6.6: Multi-Hop PAth (MHPA) packet in RMMMC

to the destination; the other discovered path will only be used as a backup path to recover from a broken link when it is detected.

6.2.5 The Proposed Route Recovery Mechanism

When a link failure is detected in the AODV, AOMDV and RDT-AODV protocols, the node that detects the failure will run the local repair algorithm if the location of the failure is closer to the destination than to the source node. In this case, the node will broadcast a RREQ packet with a limited Time-To-Live (TTL). If the route is repaired (node receives RREP) before the TTL expires, then the node will forward the data packet via the newly discovered route. Otherwise, the node will drop the data packets affected, invalidate the route and send a Route ERRor (RERR) packet to the source node to re-initiate a new route discovery process. Hence, the delay and overhead to recover from the broken link in the network may increase.

In contrast, the proposed routing recovery mechanism in RMMMC can recover from a broken link anywhere in the route regardless of the failure location, provided that a valid alternative node is available. Furthermore, RMMMC does not require the broadcasting of a RREQ when a link failure is detected as intermediate nodes involved in the routes are provided with the full multi-hop path of an alternative path in a different channel. Furthermore, as two route discoveries are initiated per destination during the route discovery process, initiating another route discovery when a link failure is detected and cannot be repaired, will substantially increase the routing overhead and collisions and may affect the performance of the routing protocol. Finally, if the broken link cannot be repaired due to network topology changes, then initiating a new route discovery by source node may be more desirable, in order to establish a new route that reflects the current state of the network topology. This may reduce the routing overhead caused by repairing a broken link and also improves the resilience of the multichannel routing protocol to handle multiple link failures.

In RMMMC when a node detects a link failure (either by link layer feedback or the absence of several Hello packets), it will follow the following procedure: firstly, it will search for a route entry related to the final destination in its alternative table. If node finds a valid alternative route entry in its alternative table, then it will compare the provided *accumulated_path*[] field with its neighbour table. The provided *accumulated_path*[] is ordered using the Least Hop First (LHF) algorithm to enable a node search and to select a backup node with the shortest path towards the destination first. If the node finds any node from the *accumulated_path*[] that also exists in the neighbour table, then this node will switch its radio interface to the alternative node's home channel and reroute the data packet to this node. On the other hand, if the node does not have a valid alternative route or none of its neighbours are in the multi-hop alternative path, then the node will drop the data packet and initiate RERR as in the original AODV protocol.

Note that during the design of RMMMC, it was decided not to initiate a RREQ with limited TTL when a link failure is detected, as is the case in AODV, AOMDV and RDT-AODV, but rather to invalidate the route, drop the data packets and send the RERR to the upstream node. This reduces the overhead caused by local repair, as if the route is not repaired, then the node has to send the RERR to the source, which ultimately starts a new route discovery process. Additionally, frequent link breakage may also indicate changes to the network topology, hence the pre-established multi-hop routes may not reflect the current state of the network.

Therefore, re-establishing fresh routes to the destination might be desirable to ensure the freshness of primary and alternative routes. However, this may come with a slightly higher routing overhead.

Figures 6.7 and 6.8 illustrate the workflow of route recovery in RMMMC. Let us assume that node M detects that the link between node M and B is broken (either by absence of several Hello packets or by link layer notification) can be seen in Figure 6.7. In this case, node M will check its alternative routing table to D. Let us assume that it finds the following *accumulated_path* $\{A - F - Q - S\}$ towards node D; node M will compare the accumulated alternative path $\{A - F - Q - S\}$ with its neighbour table. Node M does not find node A in its neighbour table, but finds node F is in its neighbour table. In this case, node M will switch its channel to node F's channel and reroutes the data packets for D to node F. Therefore, node M uses its alternative route to recover from the broken link without initiating a new route discovery process.

Let us assume that there is another link failure between node F and node A (see Figure 6.8). In this case, node F will check its alternative routing table to D. If there is an entry in its alternative table, then it will compare the *accumulated_path* $\{C - B - M - S\}$ with its neighbour table. Node F finds that node C is in its neighbour table. In this case, node F will switch its channel to node C's channel and reroute the data packets for D to node C. Therefore, the proposed algorithm can handle multiple link failures by rerouting data packets via pre-established alternative routes in different channels.

6.3 Performance Evaluation

The NS-2 simulator [158] was used to implement and evaluate the performance of the proposed protocol under different network conditions. The number of nodes, speeds and connections have been varied to study the impact of node density, mobility and number of connections (offered load) respectively on RMMMC performance. Details of the simulation settings used in this chapter are explained in section 4.6. The metrics used to evaluate the performance of the compared routing protocols in

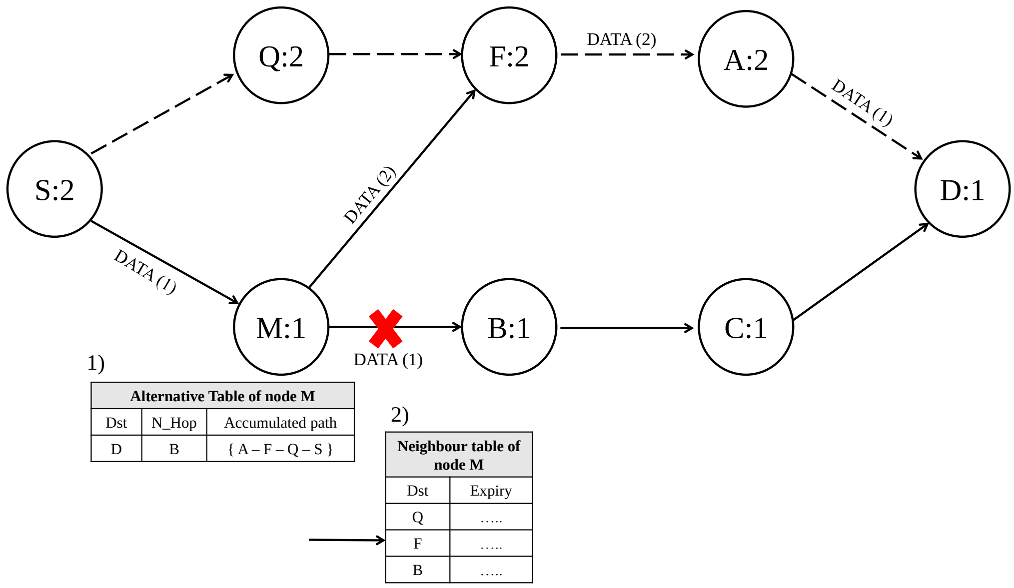

Figure 6.7: Handling link failures in RMMMC (case 1)

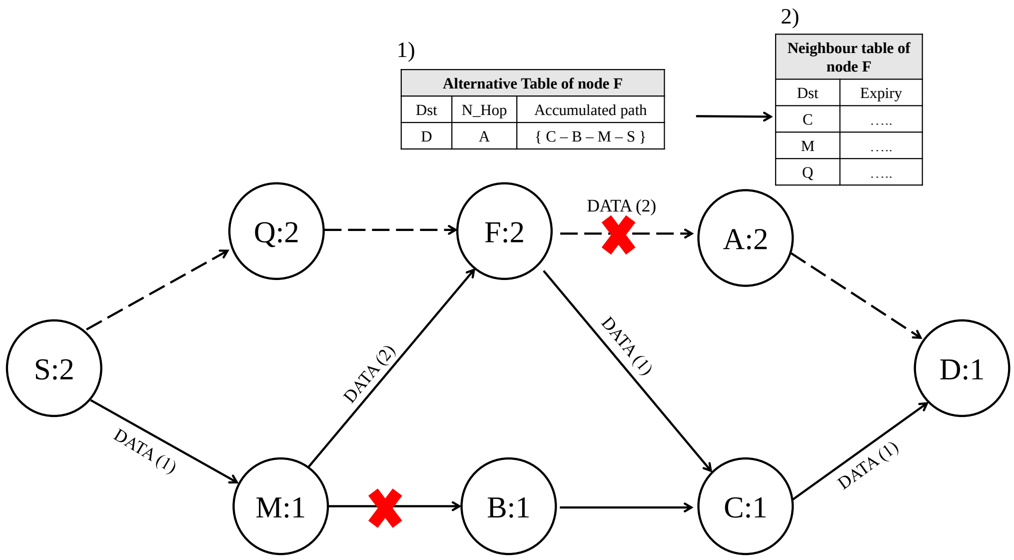

Figure 6.8: Handling link failures in RMMMC (case 2)

this chapter are given in section 4.6.3.

The main goal of this study is to evaluate the performance of the proposed multipath multichannel routing protocol RMMMC and to compare its performance with the single-path multichannel RDT-AODV and the multipath single channel AOMDV routing protocols. Extensive simulation experiments were conducted to compare the performance of the three routing protocols under different network conditions to understand better the impact of each environment on protocols performance.

6.3.1 The Compared Protocols

The simulation results reported in this chapter are for the following protocols:

AOMDV: This is an extension to the single-path AODV routing protocol to provide multiple loop-free and node/link disjointed paths per route discovery. AOMDV [80] is designed to provide efficient route recovery from a link failure, and to improve the fault-tolerant property in the routing protocol in MANET. During route discovery, AOMDV discovers and maintains multiple links and/or node disjointed paths. When link failure is detected, the protocol switches to a different path, which avoids re-initiating a new route discovery process. New route discovery is initiated when all cached paths to a specific destination have failed. Route maintenance in AOMDV is similar to that of AODV, except that the RERR in AOMDV is generated when all cached paths towards a destination have failed. More details about AOMDV and its working mechanism are provided in 2.5.2.

RDT-AODV: This is a single-path multichannel routing protocol that was studied and evaluated in Chapter 5. It uses the modified multichannel RDT-MAC as the MAC layer protocol as described in section 5.3.2.

RMMMC: This is an extension to the RDT-AODV routing protocol. It was designed to support multiple paths over multiple channels in MANETs. RMMMC [189] is designed to improve the route discovery process in a single-path multichannel routing protocol by discovering and maintaining multiple paths in multiple channels. Furthermore, it provides a new multichannel route recovery mechanism where a node can recover from broken links by rerouting data along a pre-discovered path in a different channel. RMMMC is a multipath routing protocol designed to operate in multichannel networks.

Table 6.1 shows the differences between the compared routing protocols used in this chapter. AOMDV constructs an unlimited number of nodes or link disjointed routes using only a single-route discovery process. All discovered routes share the same channel. Furthermore, if no cached routes are available, a local repair with a limited scope (RREQ) is initiated if the broken link is closer to the destination than to the source node. Otherwise, the node will drop its unroutable data packets

Table 6.1: Differences Between the Compared Routing Protocols

Protocol	**Mac**	**paths#**	**Disjointedness**	**Channels#**	**Route Recovery**
AOMDV	802.11 DCF	not limited	node/link	1	(local repair). Use cached routes if available. If not, broadcast RREQ if failure is closer to destination than to source. If not repaired, then drop and send RERR to source node
RDT-AODV	RDT-MAC	1	-	3	(local repair). If failure closer to destination than to source, broadcast RREQ. If not repaired, then drop and send RERR to source node
RMMMC	RDT-MAC	2	node and channel	3	(multichannel repair). Use cached routes in different channels to reroute data. If no alternative available, then drop and send RERR to source node

and send RERR upstream to source node. On the other hand, RMMMC constructs two node and channel disjointed routes using two route discovery processes in two different channels. Furthermore, if no alternative route is available in RMMMC, then node will drop unroutable data packets and send RERR upstream to source node without initiating a RREQ packet. With regard to the number of utilised channels, RMMMC and RDT-AODV use the same number of channels (3 non-overlapping channels), whereas AOMDV uses only a single channel despite the availability of multiple channels in wireless communication standards.

Although there are differences among the compared routing protocols, as shown in Table 6.1, there are also similarities in the operating mechanisms. For instance, all of the compared protocols consider a network where every node is equipped with only a single half-duplex transceiver. Similar CSMA/CA mechanisms were used in all reported protocols, with the exception of the multichannel MAC protocols (RMMMC and RDT-MAC) where a different NAV object is introduced for each channel CNAV.

6.3.2 Impact of Network Density

The simulation settings used to study the impact of network density on the network performance were explained in 4.6.1. Twenty connections of CBR traffic were simulated with a data packet size of 512 bytes and a generation rate of 4 packets/second. Each node moves dynamically with a random speed between [0,10] m/sec.

6.3.2.1 Collision Rate

Figure 6.9 illustrates the average collision rate in the MAC layer for the compared protocols as network density increases. It can be seen in the graph that the collision rate of the multipath single channel AOMDV significantly increases as network density increases. This is mainly due to the increase in interference and contention in a single medium shared among all the nodes. On the other hand, the multichannel routing protocols RMMMC and RDT-AODV significantly decreased the number of collisions compared with AOMDV by about 77% and 89%, respectively. This is because using multiple non-overlapping channels divide the collision domain into multiple collision domains and hence, less interference and contention and fewer collisions will occur in each domain (channel). Furthermore, only some of the total number of nodes in the network are involved in route discovery and recovery in multichannel routing protocols.

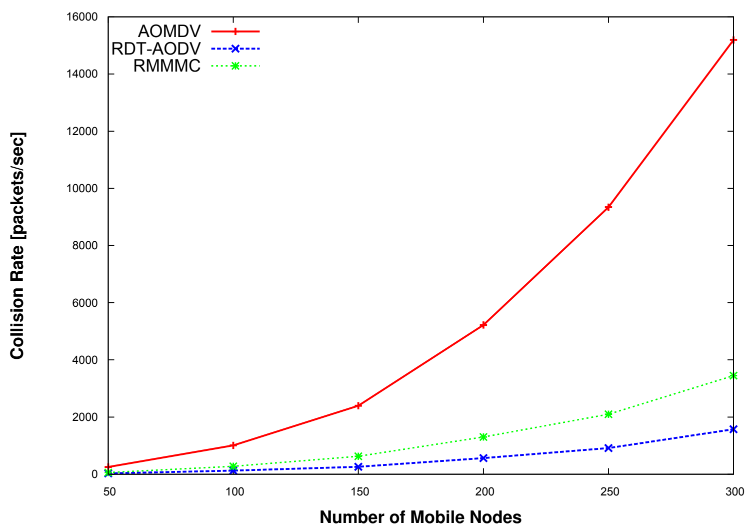

Figure 6.9: Collision rate vs. network density

With regard to the multichannel routing protocols, Figure 6.9 shows that the collision rate of the multipath RMMMC is almost double that of the single-path RDT-AODV as network density increases. This is mainly because RMMMC initiates two route discoveries per destination rather than a single-route discovery as in RDT-AODV. Since the control and data packets uses the same physical medium, increasing the number of control packets will increase the collision probability. Therefore, as the number of nodes in the network increases, the number of mobile nodes involved in the route discovery increases, which increases the collision rate.

6.3.2.2 Routing Overhead

Figures 6.10 and 6.11 1illustrate the impact of increasing network density on the routing overhead in terms of number of transmitted packets and bytes respectively. The figures show that the routing overhead increases almost linearly for all protocols as the network density increases. Although AOMDV initiates a single-route discovery per destination and uses multiple paths to recover from the broken links, the routing overhead for AOMDV is higher than for the multichannel routing protocols. This may be due to many factors, including participation of all nodes in the network in route discovery/recovery processes. It also increases the probability of collision in a single medium (see Figure 6.9). Additionally, increasing contention and collision in the medium may increase the frequency of link failure, which may necessitate more frequent route re-discovery (flooding the network with RREQ), leading to increases in the routing overhead. Comparing the overhead of AOMDV with that of AODV (which was reported in Figure 5.6), it is clear that AOMDV has significantly reduced the routing overhead due to the availability of multiple paths in AOMDV, which reduce the need to re-initiate route discovery.

Regarding the multichannel routing protocols, the multipath RMMMC had a slightly higher routing overhead than the single-path RDT-AODV. Although RMMMC doubles the number of discovery processes per destination and introduces a new control packet (MHPA), Figure 6.10 shows that at a network density of 300 nodes, the routing overhead of RMMMC is only increased by approximately 12%

compared with RDT-AODV. This may indicate that the availability and use of an alternate route has reduced the necessity of re-initiating route discovery in response to any failure. Furthermore, RMMMC is capable of repairing multiple broken links anywhere in the route regardless of their location.

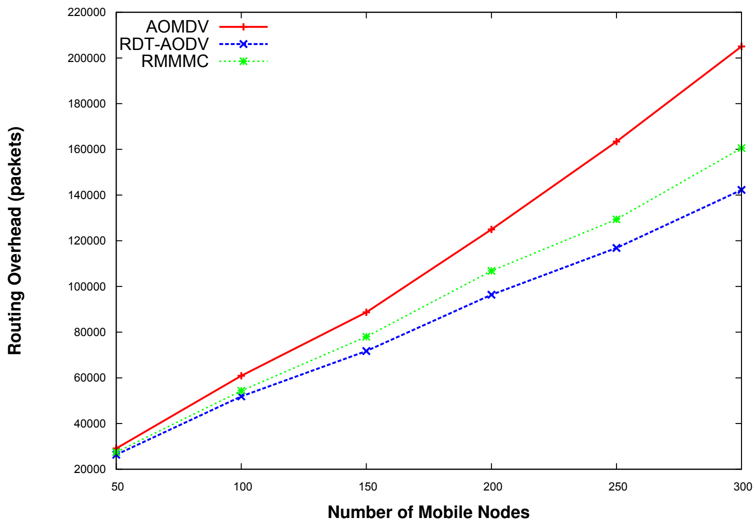

Figure 6.10: Routing overhead vs. network density

Figure 6.11 shows the routing overhead in terms of transmitted bytes for the three routing protocols. Similar performance behaviour for the compared protocols, in terms of transmitted bytes incurred routing overhead can be seen in Figure 6.11. Although Figure 6.10 shows that the increase in routing overhead of RMMMC is about 12% compared with RDT-AODV in terms of number of transmitted packets, Figure 6.11 shows that RMMMC increases the routing overhead in terms of transmitted bytes by approximately 27% compared with RDT-AODV. This increase is expected and is due to the increase in packet size in RREQ and RREP and the newly introduced packet MHPA in the multipath RMMMC protocol. In RMMMC as the number of nodes in the network increases, so does the number of intermediate nodes in the path, and hence the *accumulated_path*[] size increases.

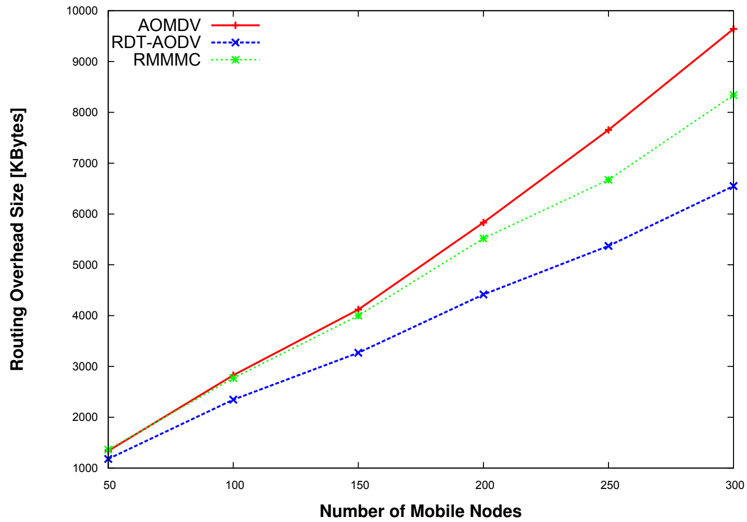

Figure 6.11: Routing overhead (in terms of bytes) vs. network density

6.3.2.3 Route Discovery Latency (RDL)

Figure 6.12 shows the average delay time (in milliseconds) in discovering a route between source and destination nodes, denoted as RDL, for the compared protocols against increases in network density. It can be seen in the graph that the multipath single channel AOMDV has significantly less RDL (which is better) to discover a route to any destination compared with the multichannel routing protocols. This is due to the fact that all nodes in the network are listening to a single channel and therefore they are aware of the route to other nodes in the network. In contrast, nodes in RDT-AODV and RMMMC are not deploying a common control channel, are prone to the deafness issue and are also expected to listen to their own channel while idle, and therefore, may not be able to participate in route discovery for nodes listening to different channels than them. Thus, the RDL in multichannel routing protocols is higher than in AOMDV.

With regard to the multichannel routing protocols, RMMMC reduces the RDL in the network with 300 nodes by approximately 51% in comparison with RDT-AODV. This is because RMMMC initiates multiple route discoveries per destination in different channels, which increases the probability of discovering a route to the destination.

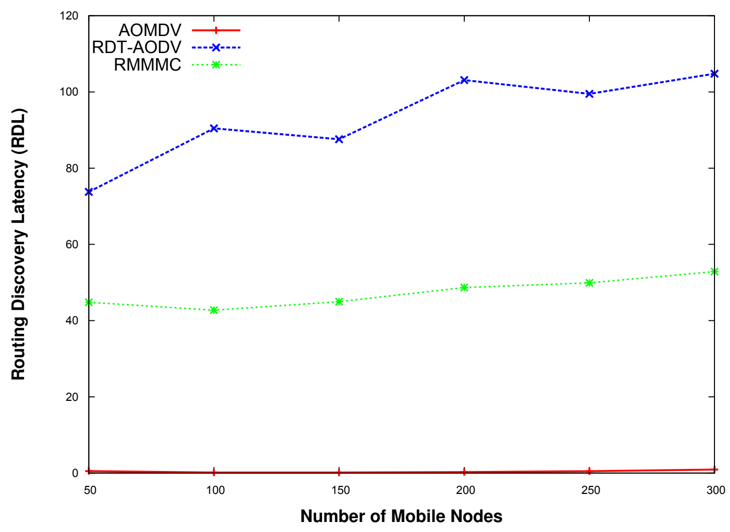

Figure 6.12: Route Discovery Latency vs. network density

6.3.2.4 Data Drops

Figure 6.13 shows the total number of dropped data packets in the routing layer for the compared routing protocols as the network density increases. Note that this performance metric represents the total number of dropped data packets in the routing layer which include the dropped data packets due to link layer callback (CBK), no/invalid route (NRTE), Time-To-Live (TTL), interface queue (IFQ) and route looping (loop).

As can be seen in Figure 6.13, AOMDV has the highest number of dropped data packets among the compared protocols and the number of dropped packets increases as network density increases. This is mainly due to the high volume of contention and collision in a single shared medium. On the other hand, the number of dropped data packets in the multichannel routing protocols is significantly less than in AOMDV. This is due to utilising multiple non-overlapping channels in communication.

With regard to the multichannel routing protocols Figure 6.13 shows that the multipath RMMMC has noticeably reduced the number of dropped data packets at all densities compared with single-path RDT-AODV. For instance, at a network density of 300 nodes, RMMMC reduced the number of dropped data packets by approximately 54% compared with RDT-AODV. This is mainly due to the capability of RMMMC to discover multiple routes and use the pre-discovered alternate route to recover from a broken link.

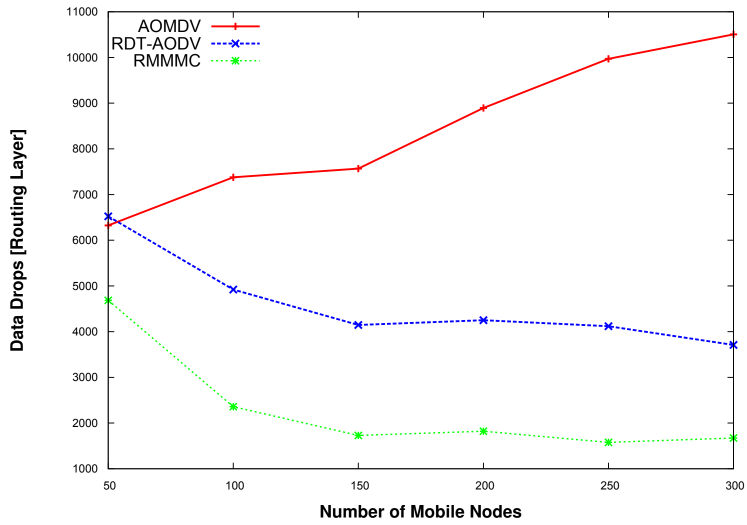

Figure 6.13: Data drops vs. network density

6.3.2.5 Data Dropped Packets Caused by No Route

To distinguish the total number of dropped data packets due to no/invalid route (denoted as (NRTE)) out of the total number of dropped data packets, Figure 6.14 has been provided. This allows a better assessment of the efficiency of using pre-discovered alternative routes. Figure 6.14 shows that number of dropped data packets due to NRTE in the multichannel single-path RDT-AODV is the highest among the compared routing protocols. This may be due to changes in network topology (as the node moves with a speed of 10 m/sec) and the absence of alternative routes when link breakage is detected in RDT-AODV. In contrast, the multipath routing protocols (AOMDV and RMMMC) have significantly reduced the number of dropped data packets due to NRTE. This is perhaps because of the availability of multiple routes to any destination, which can be used to recover from a broken link when link failure is detected.

With regard to the multipath routing protocols (AOMDV and RMMMC), Figure 6.14 suggests that in a sparse network (50 nodes, for example), the number of dropped data packets due to NRTE is very high in RMMMC, which may be related to poor network connectivity. However, as the network density increases (e.g. 300 nodes), RMMMC reduces the NRTE by approximately 49% compared with AOMDV. This is perhaps due to the availability of multiple nodes in the *accumulated_path*[] and the fact that changes to the network topology are not quickly significant. Therefore, the multi-hop alternate path can still provide recovery from a broken link.

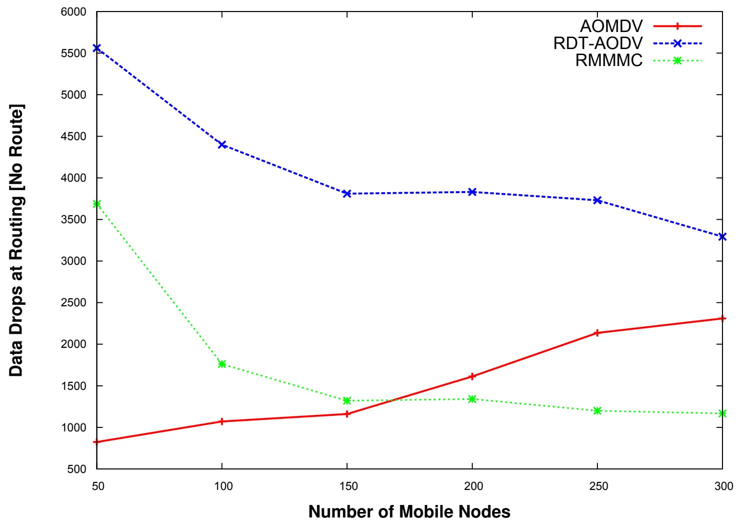

Figure 6.14: Data drops (NRTE) vs. network density

6.3.2.6 Delay

Figures 6.15 and 6.16 demonstrate the impact of increasing network density on the end-to-end delay for data packets in the compared protocols. It can be seen in Figure 6.15 that the delay in the multipath single channel AOMDV is significantly higher than that in the multichannel routing protocols. Despite the availability of multiple paths in AOMDV, the delay increases as the network density increases. This is mainly due to the increase in interference, contention and collision in a single shared medium along with the increase in network density. On the other hand, multichannel protocols have reduced the delay significantly compared with AOMDV. This is due to the utilisation of more than one medium for contention, which reduces the interference, number of collisions and access time to the medium.

To distinguish the impact of network density on delay in the multichannel protocols and for better resolution, Figure 6.16 is provided. Figure 6.16 shows that in a network with low density RMMMC slightly reduces the delay compared with RDT-AODV. This is due to multiple route discoveries in RMMMC, which increase the probability of establishing a route to a destination and reduce the risk of network partitioning that exist in RDT-AODV. As the network density increases, the delay for both protocols is stable and rather similar to each other.

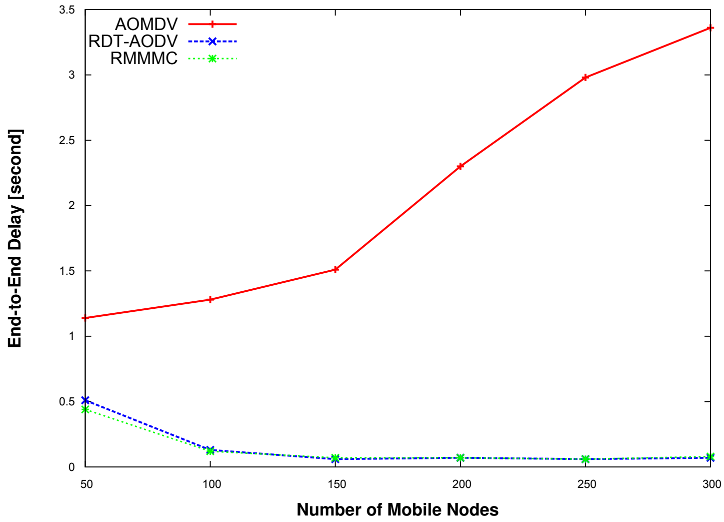

Figure 6.15: End-to-end delay vs. network density

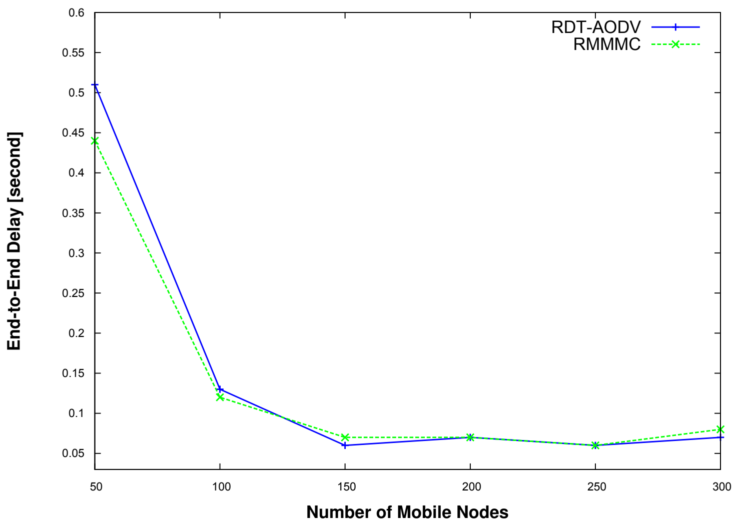

Figure 6.16: End-to-end delay for RDT-AODV and RMMMC vs. network density

6.3.2.7 Packet Delivery Ratio (PDR)

Figure 6.17 shows the impact of network density on the PDR for the three routing protocols. In a low-density network (50 nodes) the multipath single channel AOMDV has an acceptable PDR around 67%. However, as network density increases, the PDR for AOMDV decreases noticeably despite the availability of multiple paths, to the point where less than 43% of the data packets sent by source nodes are received by destination nodes. This is mainly due to increase in interference, contention and collisions in a single shared medium as network density increases. On the other hand, the multichannel routing protocols improve the PDR significantly compared with AOMDV, which is due to utilising multiple non-overlapping channels for communication.

With regard to the multichannel routing protocols, the multipath RMMMC improves the PDR at all network densities compared with single-path RDT-AODV. This is due to the capability of RMMMC to find and use alternative routes in case link failure is detected. However, the performances of both protocols were almost the same in networks with very high density (300 nodes). This is probably due to the increasing number of collisions (see Figure 6.9) and greater overhead (see Figures 6.10, 6.11) in the RMMMC protocol. The confidence interval values for the compared protocols are given in Table A.4 in Appendix A.

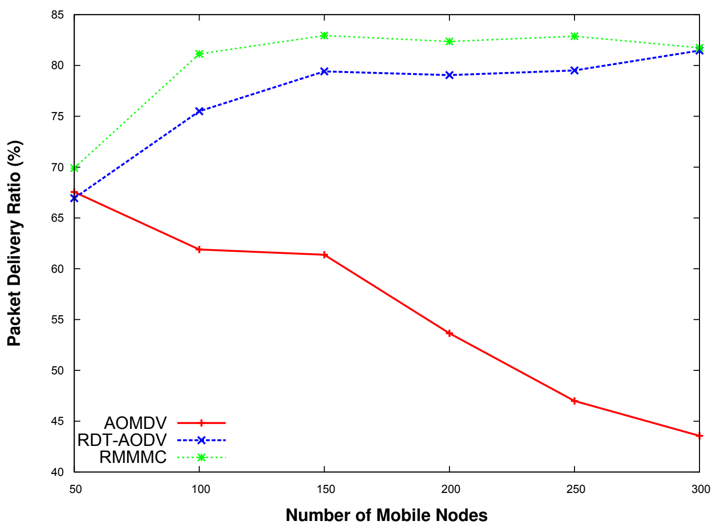

Figure 6.17: Packet Delivery Ratio vs. network density

Based on the discussion of results provided in this section, the following observations can be made:

- The performance of the multipath single channel AOMDV routing protocol is affected greatly as network density increases, despite its capability to find and use multiple paths to recover from a broken link. This is due to increase in interference, contention and collisions along with the hidden terminal issue in a single shared medium as network density increases.
- Utilising multiple channels can significantly improve network capacity even in a highly dense network. This is due to increasing concurrent communication and dividing the collision domain into smaller collision domains.
- The multipath multichannel RMMMC routing protocol improves network performance in many respects in comparison with the single-path multichannel RDT-AODV protocol. This due to the new route discovery and recovery capability provided, which enables the discovery of multiple node and channel disjointed routes between source and destination nodes. Furthermore, discovering multiple paths in RMMMC helps to mitigate network partitioning at low network density found in RDT-AODV.

6.3.3 Impact of Network Mobility

The simulation settings used to study the impact of node mobility on the network performance were explained in 4.6.1. Twenty connections of CBR traffic were simulated with a data packet size of 512 bytes and a generation rate of 4 packets/second. The number of mobile nodes in the network was 200 nodes.

6.3.3.1 Collision Rate

Figure 6.18 shows the impact of increasing node mobility on the collision rate in the MAC layer for the three routing protocols. The Figure 6.18 shows that the collision rate of the multipath single channel AOMDV significantly increases as the node speed increases from 1 to 5 m/sec. When the node speed is 1 m/sec, changes to the network topology are few and consequently there is little link breakage. Therefore, the necessity for initiating route re-discovery is reduced. However, as node mobility increases to 5 m/sec, network topology changes become more frequent, which increase the frequency of link breakage and therefore extra routing overhead is required to repair/rediscover new routes. The graph also shows that the collision rate for AOMDV increases slightly in line with increasing node mobility. Again, this may be due to the increase in link breakage occurrence, and therefore, extra routing overhead being required to repair/re-discover a new route (see Figure 6.19), which ultimately increases collisions in the medium. On the other hand, multichannel routing protocols have significantly reduced the collision rate compared with AOMDV, which is credited to utilising multiple non-overlapping channels and dividing the collision domain into smaller collision domains.

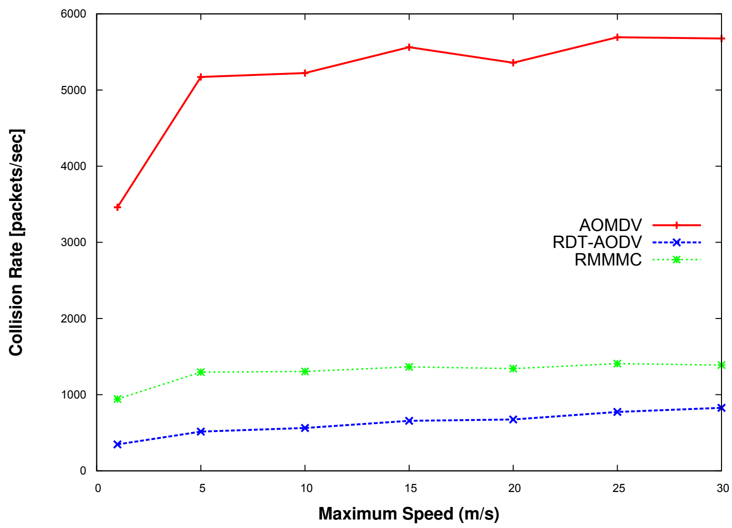

Figure 6.18: Collision rate vs. node mobility

With regard to the multichannel routing protocols, increasing the node mobility has little impact on the collision rate (as shown in Figure 6.18). Since the control and data packets share the same physical medium, increasing the control packets in RMMMC (doubling the amount of route discovery) will increase the contention and collision probability in the medium. Therefore, it is expected that the collision rate of RMMMC will be higher than that of RDT-AODV. Although the multipath RMMMC doubles the route discovery processes per destination, RMMMC increases the number of collisions in the network with node mobility of 30 m/sec by 67% compared with RDT-AODV. This indicates that the number of route re-discoveries (routing overhead) performed by RMMMC is less than that of RDT-AODV in response to any link failure, as we will see in section 6.3.3.2.

6.3.3.2 Routing Overhead

Figures 6.19 and 6.20 show the impact of increasing node mobility on the routing overhead in terms of number of transmitted packets and bytes, respectively. It is clear in Figure 6.19 that the routing overhead rises almost linearly as the node mobility increases. As node mobility increases, the network topology changes more frequently. Therefore, pre-discovered routes may not reflect the current state of the network, and hence more link breakage occurs. The routing overhead for the multipath single channel AOMDV is the highest among the compared protocols. This may be because of the participation of all the nodes in the single shared medium in the route discovery and repair process. Additionally, extra routing packets are transmitted (RREQ with limited TTL) as link breakage is detected and cannot be repaired.

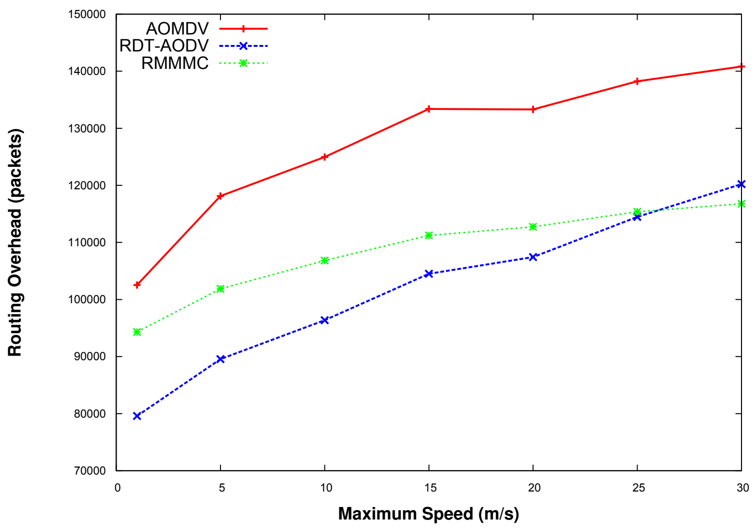

Figure 6.19: Routing overhead vs. node mobility

With regard to the multichannel routing protocols, the routing overhead is less than that of AOMDV. In a network with low node mobility speed (1 m/sec), RM-

MMC increases the routing overhead by 18% compared with that of RDT-AODV, despite introducing two route discoveries per destination. This also indicates that utilising pre-discovered alternative path help to reduce the number of transmitted routing packets. The difference in routing overhead between RMMMC and RDT-AODV, in terms of the number of packets, decreases as the mobility speed increases to the point where RMMMC produces less routing overhead by 2% compared to RDT-AODV. This change is directly related to the method used by each protocol to handle the broken link. As in RDT-AODV, a broken link is repaired by initiating a RREQ with limited TTL. In the case of high mobility a higher rate of link breakage would occur and the routing overhead would increase. The routing overhead would increase as the frequency of link breakage, which is caused by node mobility, increases. On the other hand, RMMMC repairs a broken link by rerouting the data packet through pre-discovered paths. Therefore, fewer routing packets are transmitted in response to link failure. However, as node mobility increases, the network topology keeps changing and therefore more pre-discovered paths fail to reflect the current state of the network. Thus, more route errors may be an issue (as can be seen in Figure 6.21). This also affects the packet delivery ratio of RMMMC (as will be seen in section 6.3.3.7).

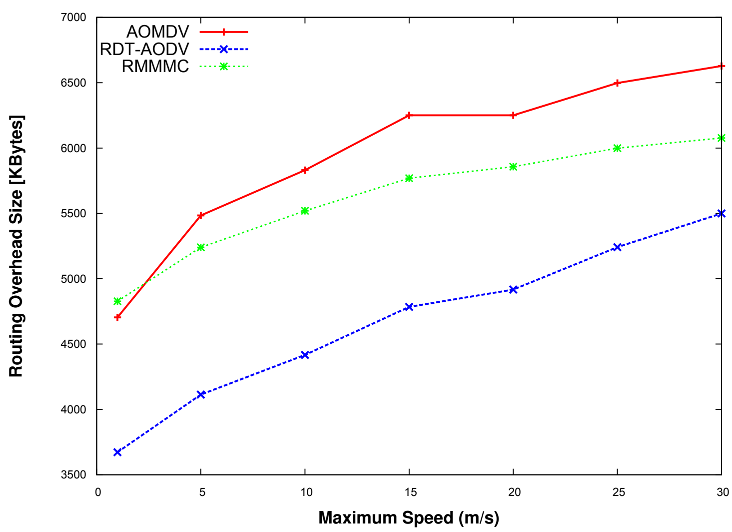

Figure 6.20: Routing overhead (in terms of bytes) vs. node mobility

Figure 6.20 shows the routing overhead of the three routing protocols in terms of the transmitted bytes. Although the number of routing packets produced in RM-MMC is less than that in RDT-AODV at high speed (30 m/sec, as shown in Figure 6.19), the produced routing overhead in terms of transmitted bytes is always higher in RMMMC with all reported speeds. This is related to the increase in RREQ and RREP packets sizes (depending on the number of hops in the $accumulated\_path[]$) and the newly introduced MHPA packets. This justifies why the collision rate of RMMMC (as shown in Figure 6.18) is higher than that of RDT-AODV, even when the number of transmitted routing packets in RMMMC is less.

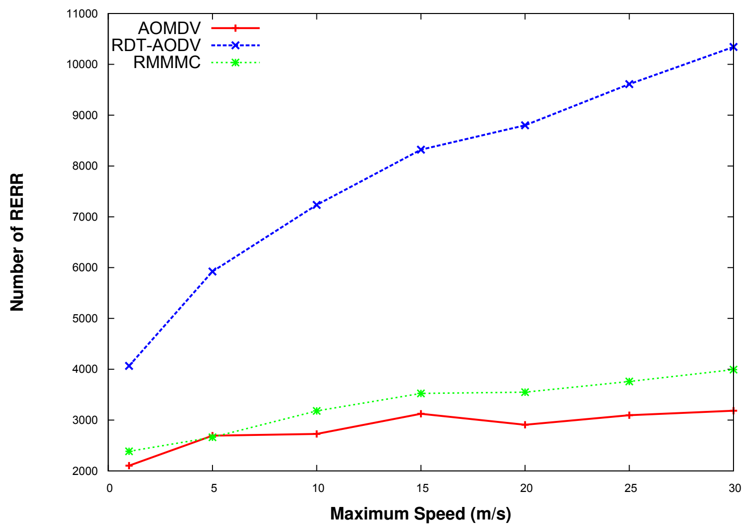

Figure 6.21: Route Error vs. node mobility

6.3.3.3 Route Discovery Latency (RDL)

Figure 6.22 shows the average delay time to discover a route between source and destination nodes for the compared protocols against increases in node mobility in the network. It can be seen in the graph that the multipath single channel AOMDV has significantly less RDL than the multichannel protocols. This is due to the fact that all nodes in the single channel network are listening to the same channel and therefore become rapidly aware of route changes to other nodes in the network. In contrast, nodes in RDT-AODV and RMMMC are not deploying a common control channel, are prone to the deafness issue and are also expected to listen to their own channel while idle, and therefore may not be able to participate in route discovery belonging to nodes listening to different channels than them. Thus, the RDL in multichannel routing protocols is higher than that of AOMDV.

With regard to the multichannel routing protocols, RMMMC reduces the RDL in the network with high mobility (30 m/sec) by 54% in comparison with that of RDT-AODV. This is due to initiating multiple route discoveries in different channels in RMMMC, thereby increasing the probability of discovering a route to the destination.

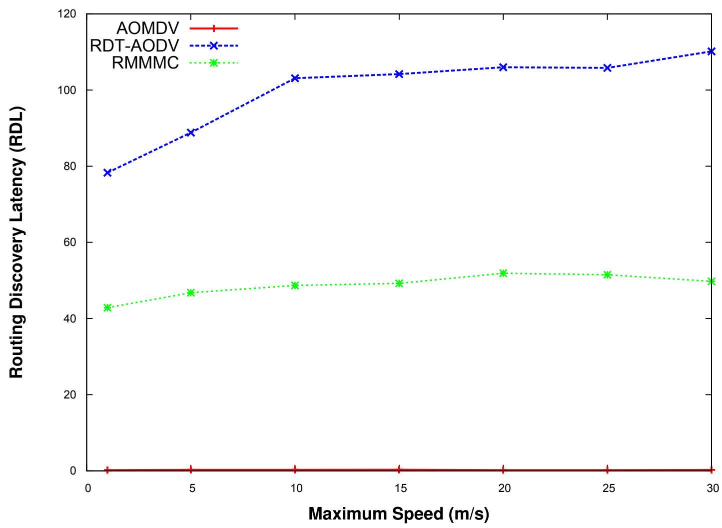

Figure 6.22: Route Discovery Latency vs. node mobility

6.3.3.4 Data Drops

Figure 6.23 presents the total number of dropped data packets in the routing layer for the compared protocols as node mobility in the network increases. As can be seen in Figure 6.23, AOMDV has the highest number of dropped data packets compared with the other protocols. This is mainly due to the high volume of interference, contention and collision in a single shared medium along with increase in node mobility speed. On the other hand, the dropped data packets in multichannel routing protocols are significantly lower than in AOMDV, which is due to utilising multiple non-overlapping channels in communication.

With regard to the multichannel routing protocols, the multipath RMMMC reduces the number of dropped data packets with all the node mobility speeds compared with single-path RDT-AODV. For instance, in a network with node speed of 30 m/sec, RMMMC reduces the number of dropped data packets by 59% compared with RDT-AODV. This is mainly due to the capability of RMMMC to discover multiple routes in different channels and use a pre-discovered alternative route to recover from a broken link.

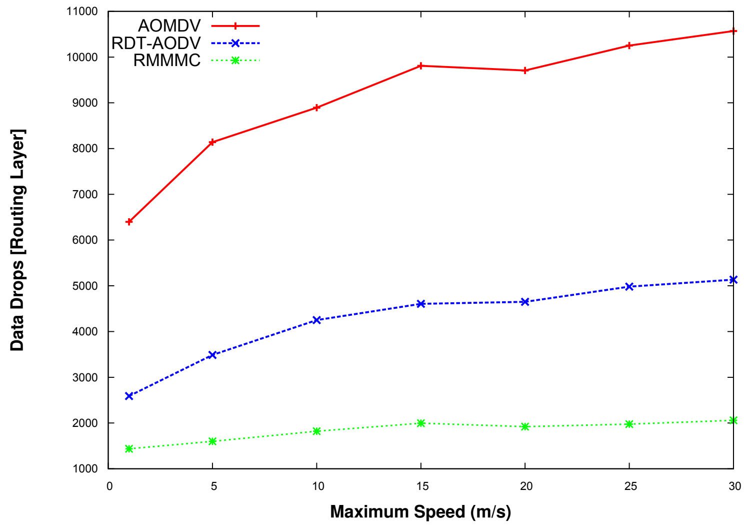

Figure 6.23: Data drops vs. node mobility

6.3.3.5 Data Dropped Packets Caused by No Route

To distinguish the total number of dropped data packets due to no/invalid route (denoted as (NRTE)) out of the total number of dropped data packets, Figure 6.24 has been provided. It allows a better assessment of the efficiency of using pre-discovered alternative routes. Figure 6.24 shows that the number of dropped data packets due to NRTE in multichannel single-path RDT-AODV significantly increases as the node mobility increases. This is due to fast changes in the network topology and the absence of alternative routes in RDT-AODV. On the other hand, the multipath routing protocols (AOMDV and RMMMC) have a significantly lower number of dropped data packets due to NRTE compared with RDT-AODV. This is due to the availability of backup routes to any destination.

The Figure 6.24 also suggests that in a network with low mobility (1-5 m/sec), RMMMC has noticeably lower number of dropped data packets due to NRTE compared with AOMDV. This is perhaps due to the availability of multiple nodes in the *accumulated_path*[] and the fact that changes to the network topology are not significant. However, as node mobility increases, the network topology changes more frequently. Therefore, pre-discovered routes in RMMMC may not reflect the current state of the network. Hence, NRTE increases noticeably as the node mobility increases. It is worth mentioning that the availability of an unlimited number of alternative paths and the route repair mechanism in AOMDV play a vital role in stabilising the number of dropped data packets due to NRTE as network mobility increases.

To overcome this issue in the multipath multichannel RMMMC, a new cross-layer MAC mechanism called Route Information validity Check (RIVC) is proposed in Chapter 7. RIVC aims to detect early routes with invalid route information during the RTS/CTS exchange and reroute data early via an alternative route which has valid route towards the final destination.

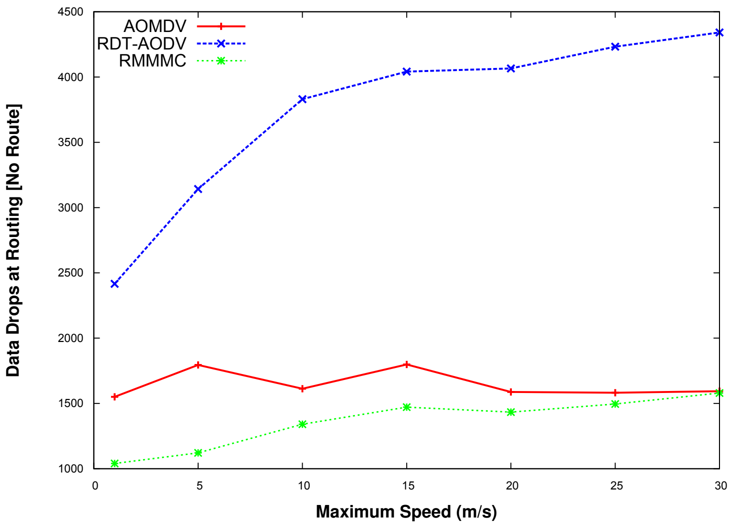

Figure 6.24: Data drops (NRTE) vs. node mobility

6.3.3.6 Delay

Figures 6.25 and 6.26 demonstrate the impact of increasing node mobility on the end-to-end delay for data packets for all the three routing protocols. It can be seen in Figure 6.25 that the delay in the multipath single channel AOMDV is significantly higher than that of the multichannel protocols. This is perhaps because of the high contention and collision in a single shared medium, along with the increase in routing overhead as link breakage increases. Surprisingly, the delay in AOMDV decreases as the node mobility increases. This is perhaps due to the ability of AOMDV to discover multiple routes during the route discovery process and to repair the broken link using discovered paths. Therefore, as node mobility increases, more link breakage will be incurred, and thus more route re-discoveries will be performed (increasing the freshness of alternative routes in the network), which helps to reduce the delay in delivering the data packets. On the other hand, multichannel protocols incur significantly less and more stable delays in comparison with AOMDV. This is due utilising the pre-discovered paths to recover from the broken link when detected along with a smaller overhead and number of collisions that occur in multichannel protocols in response to route discovery or repair.

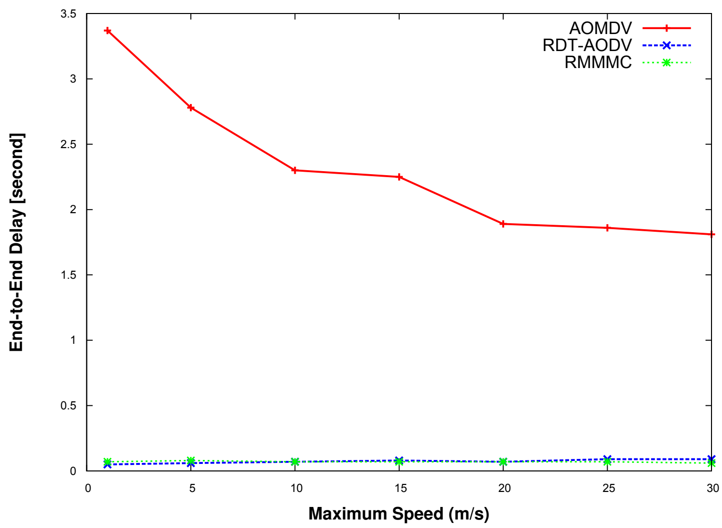

Figure 6.25: End-to-end delay vs. node mobility

To distinguish the impact of increasing node mobility on the delay in the multichannel protocols and for better resolution, Figure 6.26 has been provided. Figure 6.26 shows that the delay in the single-path RDT-AODV slightly increases as the node mobility increases. This is perhaps due to the increase in frequency of link failure as node mobility increases, which requires more time to re-discover another route to the destination. On the other hand, the multipath RMMMC is not affected by the increase in node mobility, which may relate to its capability to find and use alternative routes if link failure is detected. The difference in delay to deliver data packets between the multichannel routing protocols RDT-AODV and RMMMC is clearly rather small compared with that of AOMDV.

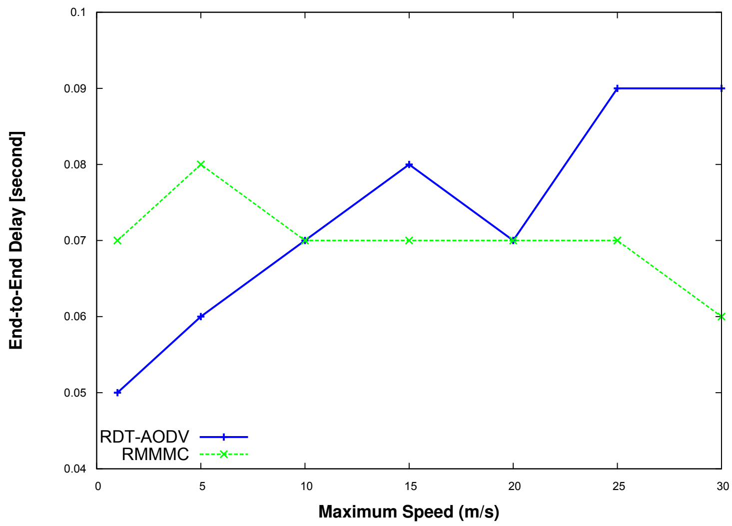

Figure 6.26: End-to-end delay for RDT-AODV and RMMMC vs. node mobility

6.3.3.7 Packet Delivery Ratio (PDR)

Figure 6.27 shows the impact of node mobility on the PDR for the compared routing protocols. In a network with low node movement (1 m/sec), the multipath single channel AOMDV has an acceptable PDR at around 64%. However, as node mobility in the network increases, the PDR for AOMDV decreases noticeably, despite the availability of multiple paths, to the point where around 46% of the data packets sent by source nodes are successfully received by destination nodes. This is mainly due to increase in link breakage as node mobility increases, which causes extra routing overhead, interference, contention and collisions in a single shared medium. On the other hand, the multichannel routing protocols improve the PDR significantly compared with AOMDV, which is due to using multiple non-overlapping channels in communication.

With regard to the multichannel protocols, the multipath RMMMC has better PDR than the single-path RDT-AODV at low to medium node mobility (1-15

m/sec). In contrast, as node mobility increases (e.g. 30 m/sec), the PDR of RMMMC decreases to 67%. In comparison with RDT-AODV, as node mobility increases, the PDR of RMMMC decreases to the point where it has 9% less PDR than RDT-AODV. In addition, the graph reveals that as node mobility increases from 1 to 30 m/sec, the PDR of RMMMC declines by 26%, whereas it declines by 14% for RDT-AODV. This decline in the PDR in RMMMC may be related to the availability/validity of alternative routes at low to medium node mobility, which is higher than when node mobility rapidly increases. On the other hand, RDT-AODV shows a small decrease as node mobility increases, which may be due to the route recovery mechanism used where the node uses local repair (RREQ with limited TTL). However, this increases the routing overhead to repair or re-discover a new route (as can be seen in Figure 6.19). The confidence interval values for the compared protocols are given in Table A.5 in Appendix A.

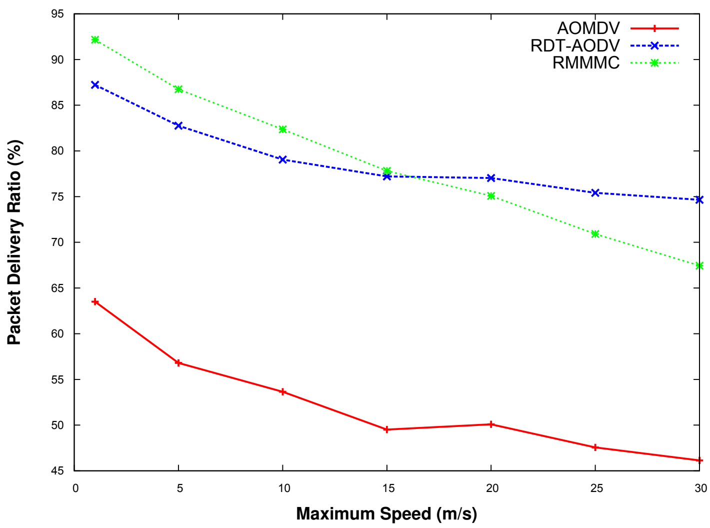

Figure 6.27: Packet Delivery Ratio vs. node mobility

Based on the discussion of results provided in this section, the following observations can be made:

- The performance of the multipath single channel AOMDV routing protocol is affected greatly as network mobility increases, despite its ability to find and use multiple paths to recover from a broken link. This is due to the increased interference, contention and number of collisions, along with the hidden terminal issue, in a single shared medium as node mobility increases.

- Utilising multiple channels can significantly improve network capacity even in a network where nodes move rapidly. This due to increasing concurrent communication and dividing the collision domain into smaller collision domains.

- The multipath multichannel RMMMC routing protocol improves the performance in some aspects in comparison with the single-path multichannel RDT-AODV protocol. Major improvement is noticed in a network with low to medium node mobility (1 -15 m/sec) which is due to the proposed route discovery and recovery mechanisms. However, as node mobility increases beyond that, a steady decrease is observed in RMMMC performance. This is perhaps due to frequent changes in the network topology, which means that the pre-discovered multipaths in different channels do not reflect the current state of the network. Hence, more link breakage occurs and cannot be repaired. When designing RMMMC, it was decided not to initiate a local repair (broadcasting RREQ with limited scope), as in RDT-AODV and AOMDV, when the node does not have a valid alternative with which to repair the broken link. This was mainly to keep the overhead down to repair the broken link. Additionally, it enables the source node to rebuild two routes, which reflect the current state of the network.

- The performance of single-path multichannel RDT-AODV seems to be less affected by node mobility than RMMMC. This may be because of the deployed route recovery mechanism in RDT-AODV (broadcasting RREQ with a limited scope), which enables a node that detects a link breakage to repair the link locally and transmit data through the newly discovered route.

6.3.4 Impact of Number of Connections

The simulation settings used to study the impact of number of connections on the network performance were explained in 4.6.1. A different number of connections of

CBR traffic were simulated with a data packet size of 512 bytes and a generation rate of 4 packets/second. Each node moves dynamically with a random speed between [0,10] m/sec. The number of mobile nodes in the network was 200 nodes.

6.3.4.1 Collision Rate

Figure 6.28 shows the effect of increasing the network load (number of connections) on the collision rate in the MAC layer for the compared protocols. It can be clearly seen in Figure 6.28 that the collision rate of the multipath single channel AOMDV is the highest among the compared protocols and it increases as the network load increases, despite the availability of multiple paths to recover from broken links. This may be because of the increase in the interference, contention and collisions in a single shared medium, along with the increased possibility of hidden terminal problem occurrence as the number of connections increases. On the other hand, the multichannel protocols (RDT-AODV and RMMMC) significantly reduce the number of collisions compared with AOMDV when the network has a high number of connections (40 connections, for example) by 56% and 78%, respectively. This is again due to their multichannel nature, which divides the collision domain into smaller collision domains.

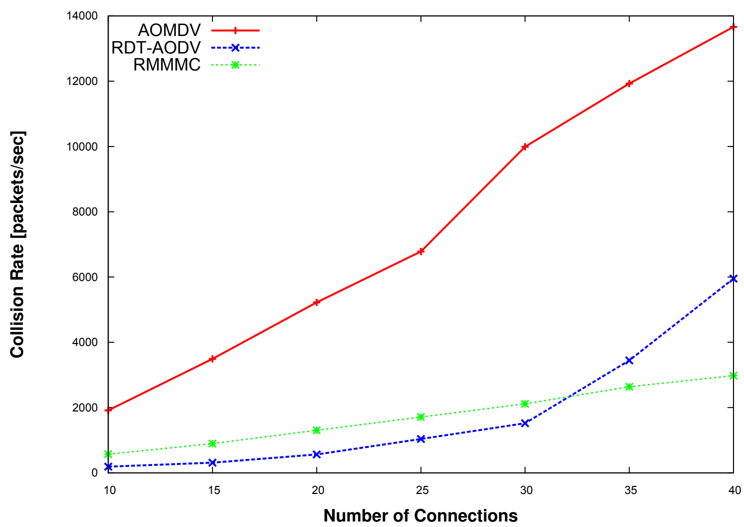

Figure 6.28: Collision rate vs. number of connections

Regarding the performance of the multichannel routing protocols in a network with low to medium connections (10 - 30 connections), RMMMC shows a higher number of collisions than RDT-AODV. This is related to the higher routing overhead (double the route discoveries) produced with RMMMC at low and medium connection loads (as we will see in Figures 6.29 and 6.30). However, in a network with a high number of connections, the multichannel hidden terminal and deafness issues increase, which in turn increase the frequency of link breakage. As a result, the routing overhead to maintain or discover a new route increases, which leads to an increase in collisions in the network. Interestingly, in a network with a high offered load, the collision rate of multipath RMMMC is significantly reduced by 49% compared with that of the single-path RDT-AODV. This is due to the availability and use of the pre-discovered alternative path in RMMMC, which helps to reduce the number of route re-discoveries in response to any fault.

6.3.4.2 Routing Overhead

Figures 6.29 and 6.30 show the impact of increasing the number of connections on the routing overhead in terms of the number of transmitted packets and bytes, respectively. Figure 6.29 shows that, at a low offered load, the routing overhead for all protocols is relatively small and not significant with superiority to multichannel routing protocols. As the network load increases, the routing overhead of AOMDV increases noticeably. This may be due to the participation of all nodes in the single shared medium in the route discovery and repair process.

With regard to the multichannel routing protocols the difference in routing overheads with low to medium (10 - 25 connections) is relatively small, despite doubling the number of route discoveries in RMMMC. As the number of connections increases in the network, the contention to access the medium increases, which increases the possibility of the occurrence of multichannel hidden terminal and deafness problems and collisions. This may lead to frequent link breakage. With this in mind, the single-path RDT-AODV responds to the link failure by repairing (broadcasting RREQ with limited scope) or initiating a new route discovery, which increases the contention and collision in the medium (see Figure 6.28) and leads to an increase in routing overhead. On the other hand, RMMMC responds to link failure by utilising the pre-discovered paths in a different channel to repair the broken link without increasing the level of contention in the medium. In a network with a high number of connections (40 connections, for example) the routing overhead of the single-path multichannel RDT-AODV increases significantly, to the extent that the produced overhead is higher by 25% and 99% than those of the multipath single channel AOMDV and the multipath multichannel RMMMC, respectively.

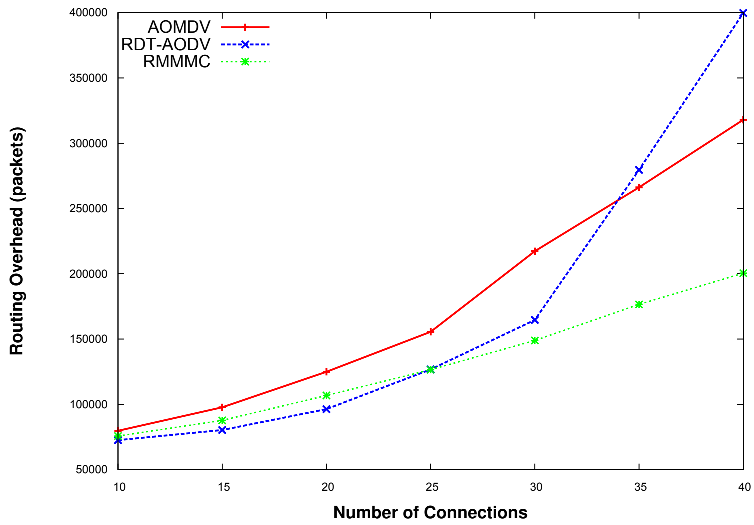

Figure 6.29: Routing overhead vs. number of connections

Similar to the routing overhead pattern in Figure 6.29, Figure 6.30 shows the routing overhead of the compared protocols in terms of transmitted bytes. Figure 6.30 suggests that in a network with a high number of connections (40 connections, for example), RMMMC has reduced the routing overhead (in term of bytes) by 29% and 43% compared with AOMDV and RDT-AODV, respectively. This is mainly due to the availability and use of the pre-discovered multiple paths to recover from the broken link without initiating new route repair processes.

It is worth mentioning that in spite of the RDT-AODV initiating a single-route discovery per destination and a small number of nodes operating in the destination home channel being involved in the routing process, the routing overhead in terms of number of packets and bytes is considerably higher than that of AOMDV and RMMMC at a high number of connections. This is mainly due to the bad effect of the multichannel hidden terminal and deafness problems in RDT-AODV and to the used local repair mechanism, which increases contention and possibility of the multichannel hidden problem. Meanwhile, RMMMC shows more scalability and robustness to an increase in the network connections (offered load).

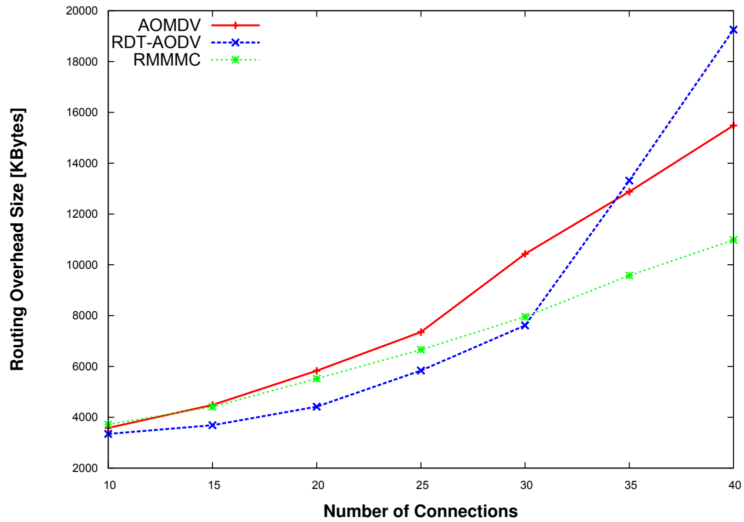

Figure 6.30: Routing overhead (in terms of bytes) vs. number of connections

6.3.4.3 Route Discovery Latency (RDL)

Figure 6.31 shows the average delay time to discover a route between source and destination nodes for the three routing protocols against increases in network connections. It can be seen in Figure 6.31 that the multipath single channel AOMDV has significantly less RDL than the multichannel protocols. This is due to the fact that all nodes in the single channel network are listening to the same channel and therefore are aware of the routes to other nodes in the network. In contrast nodes in RDT-AODV and RMMMC are not deploying a common control channel, are prone to the deafness issue and are also expected to listen to their own channel while idle, and therefore may not be able to participate in route discovery with nodes listening to different channels than them. Thus, the RDL in multichannel routing protocols is higher than that of AOMDV.

With regard to the multichannel routing protocols, RMMMC reduced the RDL in a network with 40 connections by 53% in comparison with RDT-AODV. This is due to initiation of multiple route discoveries in different channels in RMMMC, thereby increasing the probability of discovering a route to the destination.

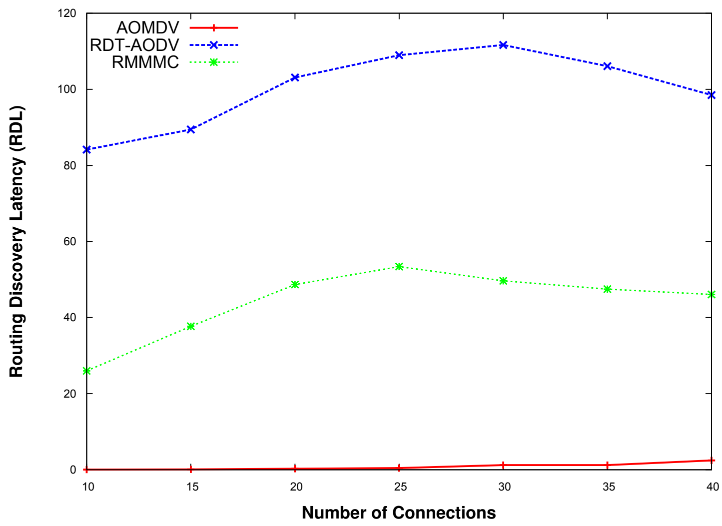

Figure 6.31: Route Discovery Latency vs. number of connections

6.3.4.4 Data Drops

Figure 6.32 shows the total number of dropped data packets in the routing layer for the compared routing protocols as the network offered load increases. As can be seen in Figure 6.32, AOMDV has the highest number of dropped data packets compared with the other routing protocols. This is mainly due to the high volume of interference, contention and collisions in a single shared medium. On the other hand, the numbers of dropped data packets in the multichannel routing protocols are significantly lower than in AOMDV. This is due to using multiple channels in communication.

With regard to the multichannel routing protocols, the multipath RMMMC reduces the number of dropped data packets with all number of connections compared with single-path RDT-AODV. For instance, in a network with 40 connections, RMMMC reduces the number of dropped data packets by 58% compared with RDT-AODV. This is mainly due to the capability of RMMMC to discover multiple routes and use a pre-discovered alternative route to recover from a broken link.

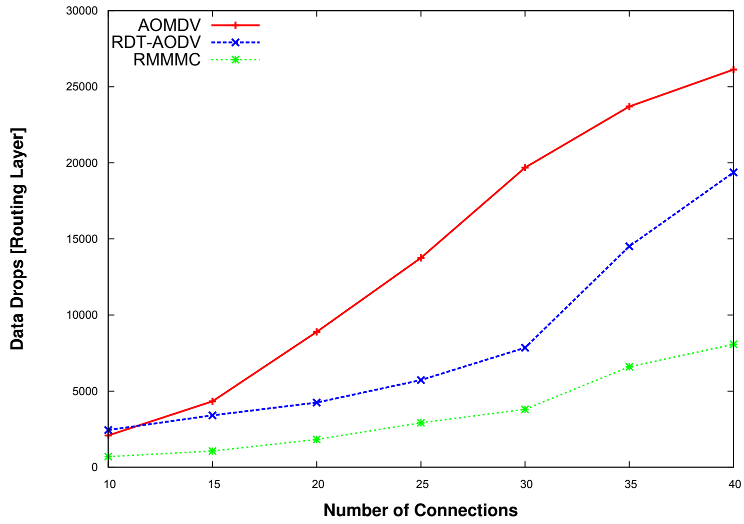

Figure 6.32: Data drops vs. number of connections

6.3.4.5 Data Dropped Packets Caused by No Route

To distinguish the total number of dropped data packets due to no route (denoted as (NRTE)) out of the total number of dropped data packets, Figure 6.33 has been provided. This allows a better assessment of the efficiency of using pre-discovered alternative routes. Figure 6.33 shows that in a network with a low number of connections (10 -15 connections), the NRTE of the multipath AOMDV is very low compared with the multichannel protocols. This is probably due to the low rate of contention and collision in the medium. However, as the network load increases, there is a steady increase in the NRTE of AOMDV, which is due to the increase in contention and collisions in the medium. In contrast, the single-path multichannel RDT-AODV significantly reduces the number of dropped data packets due to NRTE in a network with high load in comparison with AOMDV, because of its multichannel nature. Discovering multiple routes to any destination and utilising the multichannel route recovery without incurring extra overhead in RMMMC helps to reduce the number of dropped data packets due to NRTE with all offered loads in comparison with RDT-AODV.

With regard to the multipath routing protocols (AOMDV and RMMMC), Figure 6.33 suggests that increasing the number of connections in the network will increase the number of dropped data packets due to NRTE for both protocols. However, the increase in network connections has less impact on RMMMC than on AOMDV. For instance, as network connections increase (40 connections), RMMMC reduces the data dropped packets due to NRTE by 56% compared with AOMDV. This is perhaps due to the availability of multiple nodes in the *accumulated_path*[] in different channel and the fact that the changes to the network topology are not rapidly significant (10 m/sec). Therefore, the provided multi-hop alternative path can still recover from a broken link.

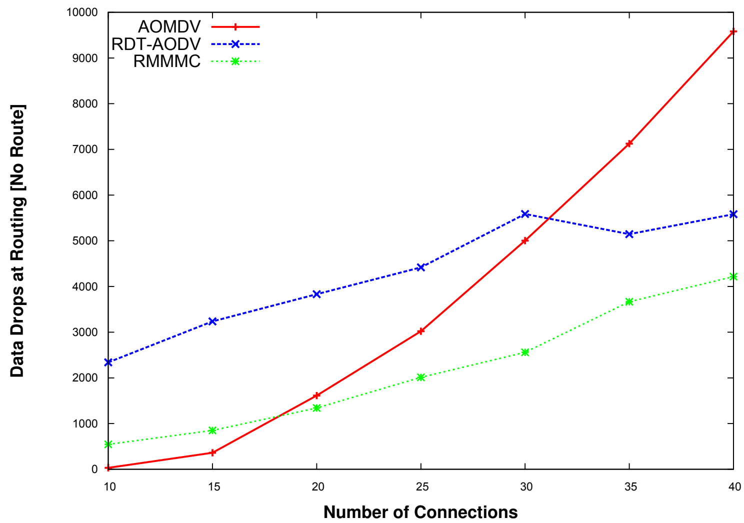

Figure 6.33: Data drops (NRTE) vs. number of connections

6.3.4.6 Delay

Figures 6.34 and 6.35 show the impact of increasing the number of connections in the network on the end-to-end delay for the compared routing protocols. It can be seen in Figure 6.34 that the delay of the multipath single channel AOMDV is low in a network with light offered load (10 - 15 connections). However, as the number of connections increases, the delay in AOMDV increases dramatically, despite the availability of multiple paths in AOMDV to recover from the broken link. This is perhaps due to the increase in the interference, contention and number of collisions, along with the increase in hidden and exposed problems in a single shared medium. On the other hand, multichannel routing protocols reduce the delay significantly compared with AOMDV in all cases. This is due to utilising more than one medium for contention, which reduces the interference, collisions and access time to the medium.

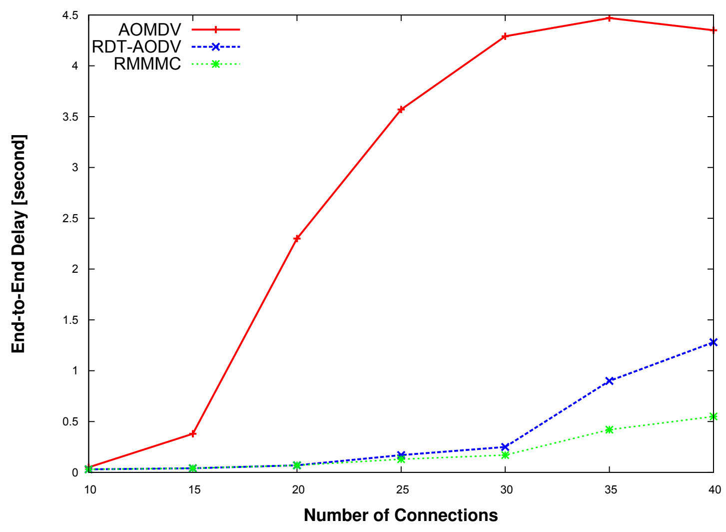

Figure 6.34: End-to-end delay vs. number of connections

To distinguish the impact of network load on the delay in the multichannel routing protocols and for better resolution, Figure 6.35 has been provided. Figure 6.35 shows that, with a low to medium offered load (10 - 30 connections), the delays of both protocols are relatively similar. However, as the number of connections increases, the delay for the single-path RDT-AODV dramatically increases, which is again related to the increase in multichannel hidden terminal and deafness issues in RDT-AODV. On the other hand, the multipath RMMMC significantly reduces the delay in the network with 40 connections by 57% compared with RDT-AODV. This is mainly because RMMMC improves route discovery and can use a pre-established alternative route in a different channel to recover from a broken link, rather than re-initiating a new route discovery process.

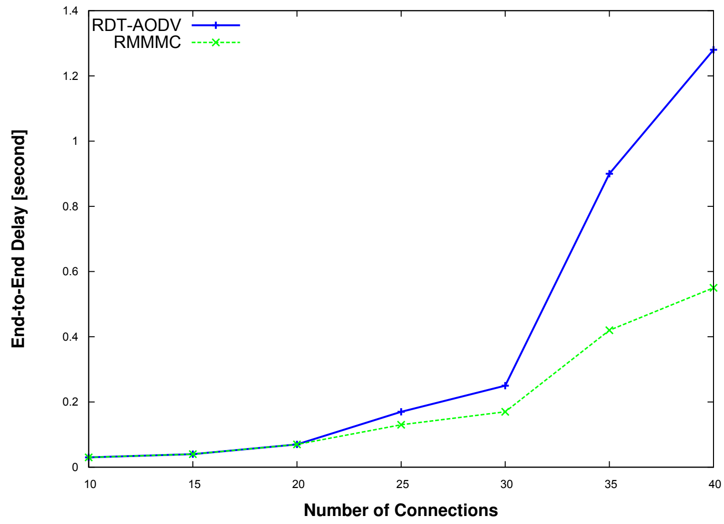

Figure 6.35: End-to-end delay for RDT-AODV and RMMMC vs. number of connections

6.3.4.7 Packet Delivery Ratio (PDR)

Figure 6.36 shows the effect of the number of connections in the network on the PDR for the compared routing protocols. In a network with a low number of connections (10 connections), the multipath single channel AOMDV has a very good PDR at around 79% which is about 4% better than RDT-AODV. This is due to the low degree of contention and collision and the availability and use of multiple routes. However, as the number of connections in the network increases, the PDR for AOMDV decreases drastically, despite the availability of multiple paths, to the point where around 16% of the data packets sent by source nodes are successfully received by destination nodes. This is mainly due to the increase in interference, contention and collisions in a single shared medium as the number of connections in the network increases. On the other hand, the multichannel routing protocols improve the PDR significantly compared with AOMDV, which is due to using multiple non-overlapping channels in communication.

With regard to the multichannel routing protocols, the multipath RMMMC improve the PDR with all numbers of connections in the network compared with the single-path RDT-AODV. This is due to the capability of RMMMC to discover and use alternative routes if link failure is detected. For instance, RMMMC increases the PDR in a network with a high load (40 connections) by 47% compared with RDT-AODV.

It is worth mentioning that at low to medium network loads (10 - 30 connections), RDT-AODV shows good PDR performance. However, as the number of connections in the network increases after 30 connections, a significant drop in PDR takes place, as can be seen in Figure 6.36. This is mainly due to an increase in the multichannel hidden terminal and deafness problems, which lead to an increase in the collision rate (as can be seen in Figure 6.28), and consequently increase the routing overhead (as can be seen in Figure6.28), which ultimately affects the PDR. The confidence interval values for the compared protocols are given in Table A.6 in Appendix A.

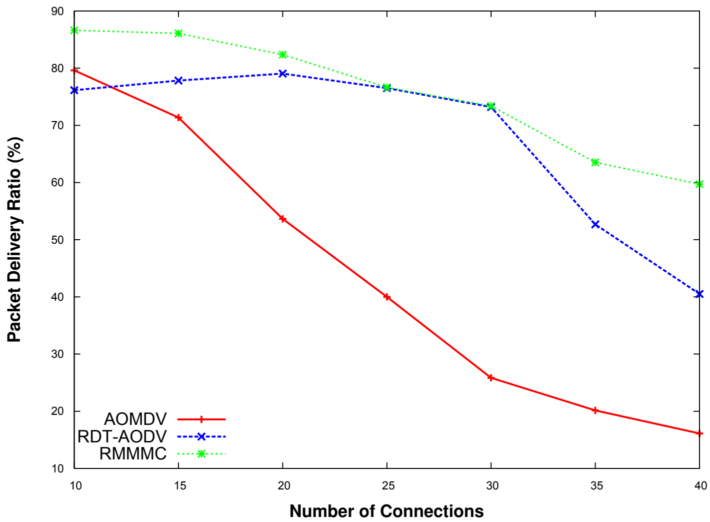

Figure 6.36: Packet Delivery Ratio vs. number of connections

Based on the discussion of results provided in this section, the following observations can be made:

- The performance of the multipath single channel AOMDV routing protocol is affected greatly by increasing the number of network connections, despite its capability to find and use multiple paths to recover from a broken link. This is due to an increase in interference, contention and collisions, along with the hidden terminal issue, in a single shared medium as network connections increase.

- Utilising multiple channels can significantly improve network capacity, even in a network with a high load. This is due to increasing concurrent communication and dividing the collision domain into smaller collision domains.

- The multipath multichannel RMMMC routing protocol improves network performance in all aspects in comparison with the single-path multichannel RDT-AODV protocol as network connections increase. The improvement in performance is clearer as network load increases. This is mainly due to the discovery and use of multiple node and channel disjointed paths when the contention and congestion in a channel increase. Moreover, new route discovery and recovery in RMMMC help to improve the performance of the routing protocol without incurring extra overhead in the already congested medium.

- As the number of connections in the network increases, the issues of multichannel hidden terminals, deafness and channel congestion increase. One of the reasons why RMMMC outperforms RDT-AODV as network connections increase is the use of the multichannel route recovery mechanism, where data packets are rerouted along pre-discovered routes in different channels without incurring extra routing overhead.

6.4 Conclusions

This chapter has presented a multipath multichannel routing protocol to enhance the performance of the single-path multichannel routing protocol presented in Chapter 5. The proposed routing protocol (RMMMC) aims to improve the reliability, resilience to link failures and fault tolerance of multichannel routing protocols in MANETs. To achieve this, RMMMC introduces the following changes to the multichannel RDT-AODV routing protocol: 1) improves the route discovery mechanism by establishing multiple node and channel disjointed paths in different channels, which increase the probability of discovering a route to any destination; 2) supports a route accumulation function during route discovery; 3) supports a multihop alternative path announcement by using MHPA packets; 4) supports neighbour discovery and local connectivity maintenance by enabling a Hello packet to be sent periodically in different channels in a Round Robin manner; and finally, it modifies the route recovery mechanism to enable a node that detects link failure to repair the broken link, regardless of the failure location, using a provided pre-discovered alternative route in a different channel without initiating a RREQ with limited scope.

Using the NS-2 simulator, the performance of the proposed multipath multichannel RMMMC is compared with the previous single-path multichannel RDT-AODV and the well-known multipath single channel AOMDV under different network conditions. The simulation results suggest that discovering multiple paths in different channels in RMMMC improves network performance, as network density increases compared with other protocols, and it also mitigates network partitioning issues that exist in RDT-AODV. With regard to the impact of node mobility, the proposed protocol shows superior performance in a network with low to medium node mobility (1-15 m/sec). However, in a network with higher node mobility, the performance of RMMMC is lower than that of RDT-AODV. This is mainly due to rapid changes to network topology, which means that the pre-discovered alternative path may no longer reflect the current state of the network. Hence, there are more un-repaired broken links which degrade protocol performance. With regard to the impact of increasing the number of connections in the network, RMMMC shows superior performance compared with the other routing protocols. This is mainly because of the proposed multipath multichannel route discovery and recovery mechanisms. As the network load increases, multichannel deafness and congestion increase in the network, However, utilising a pre-discovered alternative route in a different channel to recover from the broken link without incurring extra overhead, helps to recover from the broken link by rerouting the data along a different channel.

Based on the reported results and discussions in this chapter, the RMMMC shows the potential to improve the reliability and fault tolerance of the multichannel routing protocol. However, the performance of the RMMMC was significantly affected as node mobility increased. This is perhaps due to the fact that each node can only monitor activities in the channel it listens on as it is only equipped with a single transceiver and rapid topology changes, which mean that the pre-discovered alternative paths may no longer reflect the existing network topology, make it slower to recover from broken links. Therefore, two cross-layer MAC mechanisms are proposed in Chapter 7 to improve the reliability of communication in multipath multichannel routing protocols (the Route Information Validity Check (RIVC)) and also to balance the load in congested links (the Modified Backoff (MB)).

Chapter 7

Cross-layer Multipath Multichannel MAC Protocol

7.1 Introduction

Utilising multiple paths in multiple channels can improve network performance by enabling a node to reroute data along pre-discovered paths seamlessly when link failure is detected. Rerouting data packets via an alternative path in a different channel can help to repair a broken link (as explained in Chapter 6) without incurring extra delay or overhead caused by a new route discovery process. However, due to frequent network topology changes and the fact that each node can only monitor activities in one channel at a time as it is equipped with a single transceiver, the availability and validity of the route at the new receiver (intermediate node) cannot be guaranteed. Depending on a stale/invalid route for data transmission or to recover from a broken link could cause a data packet to be dropped, increase the delay to recover from a broken link and degrade network performance.

To mitigate the occurrence of this issue and to improve the reliability of communication in multipath multichannel routing protocols, a novel cross-layer MAC mechanism called Route Information Validity Check (RIVC) is proposed in this chapter. RIVC modifies the working mechanism of RTS/CTS handshake in the multichannel RDT-MAC to forecast invalid route information at a receiver node (intermediate node), providing early invalid route detection and early switchover to an alternative path in a different channel, if possible, at the MAC layer level.

In the IEEE 802.11 DCF standard, the absence of a corresponding acknowledgement frame (CTS/ACK) for a transmitted frame (RTS/DATA) signals a collision with another transmission and the possibility that the intended receiver has not received the frame. Hence, a transmitter should initiate an error recovery process by retransmitting the failed frame after observing back-off rules. The transmitter should retry transmitting the frame until the transmission is successful, or until the relevant retry limit is reached, whichever occurs first. However repeating retransmission in the MAC protocol can increase contention and collision in a busy medium and hence cause congestion in the channel. In a multipath multichannel network, when a broken link is detected, the transmitter might try to recover from it using the alternative path in the backup channel. This motivated the proposal of a Modified Back-off (MB) mechanism. The MB mechanism enables a transmitter node to invoke an alternative path in the alternative channel, if available, when the retry count reaches a pre-defined threshold criterion. It would help to load balance traffic and reduce contention in a busy medium.

This chapter introduces two new extensions to the multichannel MAC (RDT-MAC) protocol, namely Route Information Validity Check (RIVC) and Modified Back-off (MB) mechanisms, which aim to improve the reliability of communication in multipath multichannel routing protocols. The design and implementation of each mechanism is carried out separately to understand better the impact of each mechanism and then both are combined in one multichannel MAC protocol which is denoted RIVC-MB. Both mechanisms utilise cross-layer interaction between the MAC and routing layers to check route information validity and provide an alternative node to communicate with at the MAC layer level.

The NS-2 simulator is used to implement the proposed multichannel MAC (RIVC, MB and RIVC-MB) mechanisms and to evaluate their performance under different network conditions. The rest of this chapter is organised as follows. In Section 7.2 the RIVC mechanism is presented. Section 7.3 introduces the MB mechanism. Section 7.4 presents the RIVC-MB mechanism. Section 7.5 discusses the performance evaluation of the proposed mechanisms under different network environments. Section 7.6 presents a summary and conclusion for this chapter.

7.2 Route Information Validity Check (RIVC)

The proposed RIVC mechanism [196] aims to mitigate the issue of transmitting/rerouting a data packet to a node that has stale (invalid) route information towards a final destination. This would improve communication reliability in the multipath multichannel routing protocols and only enable data packets with valid routes to occupy the medium.

The optional access mode Request-To-Send/Clear-To-Send (RTS/CTS) handshake in the multichannel RDT-MAC protocol has been modified to support early invalid route detection and early handover. The modified version of RDT-MAC is referred to as RIVC from here on. The RTS/CTS mechanism in the multichannel RDT-MAC has been modified to enable the transmitter to check route information validity at the receiver node while exchanging RTS/CTS frames. If the receiver does not have a valid route towards the final destination, then the transmitter node should be informed to invoke the alternative path in a different channel, if available. This would enable early stale/invalid route detection, an early switchover and ensure only data packets with valid route information occupy the medium.

The RIVC mechanism adds an extra check (which utilises a cross-layer interaction between the MAC and routing layers) while the transmitter and the receiver are exchanging modified RTS/CTS frames with the aim of optimising the use of the medium and enabling only data packets with valid routing information to be transmitted and consume bandwidth on the medium. This check is important as only data packets with valid routing information will be processed in the routing layer protocol and forwarded to their final destination. Furthermore, RIVC enables a transmitter node that is informed about the invalidity of the route at the receiver node (the early invalid route detection feature) to consult its own routing layer protocol (alternative routing table) and reroute data packets along an alternative route (this is the early handover feature), if available. Additionally, RIVC would reduce the number of dropped data packets due to no/invalid routes to be transmitted/rerouting, which unduly consume bandwidth on the medium.

The proposed RIVC mechanism provides the following benefits to the network:

- Improves the reliability of data transmission/rerouting to an alternative route in a different channel.
- Provides early invalid route detection and early switchover to the alternative route.
- Utilises existing RTS/CTS frames with a slight modification to check route validity at intermediate nodes towards the final destination.
- Reduces the risk of transmitting/rerouting a data packet that has an invalid route, occupies the medium, and wastes node and network resources.

7.2.1 MAC Control Frames

IEEE 802.11 DCF specifies the control frames RTS/CTS that reserve the medium, alleviate the hidden terminal problem, and improve the reliability of communication in the wireless medium. Furthermore, it provides faster collision inference and validation of the transmission path's existence (as discussed in 2.3.3).

The RIVC mechanism introduces an extra check while nodes are exchanging RTS/CTS frames to support route validity checking and early rerouting. In order to support this functionality, slight modifications to the RTS and CTS frame formats are introduced.

- **RTS frame:** In the RTS frame, one field is added as shown in Figure 7.1.
  - *Final destination address:* This is the address of the final destination node of the data packet. Including this field enables the receiver of the RTS frame (intermediate node) to check the validity of its route information towards the final destination.
- **CTS frame:** In the CTS frame, one field is added as shown in Figure 7.2.

Bytes	2	4	6	6	6	4
	Frame control	Duration ID	Address 1 Receiver address	Address 2 Transmitter address	Address 3 Final destination address	FCS

Figure 7.1: New RTS frame structure in RIVC

– *Validity flag:* This indicates the validity of the routing information at the receiver node. Based on this flag, the transmitter node will decide whether to continue transmitting the data packet (receives the CTS with valid flag) or invoke the alternative route (receives the CTS with invalid flag), if possible. Furthermore, the *validity flag* in the CTS frame will help neighbour nodes, which hear this CTS, to decide whether to back-off from contending within the medium (overhearing the CTS with a valid flag) or not (overhearing the CTS with invalid flag).

Bytes	2	4	6	1	4
	Frame control	Duration ID	Address 1 Receiver address	Validity	FCS

Figure 7.2: New CTS frame structure in RIVC

7.2.2 Cross-Layer Interaction between MAC and Routing Layers

Different approaches to implementing cross-layer interaction in wireless networks are discussed in section 4.3. This study adopts a direct communication between layers approach, more specifically a downward cross-layering approach where the lower layer (MAC) accesses information in a higher layer (routing) during run time.

The proposed RIVC mechanism utilises cross-layer interaction between the MAC and routing layers to provide early invalid route detection while nodes exchange RTS/CTS frames. Furthermore, it provides for an early switchover to reroute the data via the alternative route, if available.

Cross-layer interaction between the MAC and the routing layers is not supported in the native implementation of NS-2 simulator or in the OSI network layer architecture 2.4.1. Hence, the implementation of NS-2 (NS-2.35) was modified to support cross-layer interaction between the MAC and routing layers. Practically speaking, layer triggers (signalling) are used to notify the MAC layer protocol about the validity/availability of a route in the routing layer protocol.

In the proposed mechanism the MAC protocol interacts (consults) with the multipath multichannel routing protocol (RMMMC) in the following two cases:

- When the receiver node receives an RTS, it checks its route information validity in the routing table towards the final destination before sending a CTS back to the transmitter node with a flag indicating route validity towards the final destination.
- When the transmitter receives the CTS with an invalid flag, it checks for an alternative node from its alternative table in the routing layer.

The proposed mechanism in the MAC layer is not intended as a substitute for a network layer routing protocol. Routing protocols are still required to discover and maintain the multiple paths between source and destination nodes. However, utilising the proposed MAC mechanism should improve transmitting/rerouting reliability in a multipath multichannel routing protocol. Note that the routing protocol (RMMMC in this case) is responsible for discovering and maintaining routes and also providing the IP address for the alternative node to the MAC protocol. Hence, the MAC protocol can use the provided alternative node for data rerouting.

7.2.3 Working Process of RIVC

The process of handling the modified RTS/CTS frames in the RIVC mechanism at the transmitter, receiver and neighbour nodes is as follows:

1. **The transmitter node:** Switches its interface to the receiver node's home channel and transmits the modified RTS frame, which includes the final destination address *(address 3)* in Figure 7.1.

2. **The receiver node:** When the receiver node receives the RTS frame, it checks its routing table (cross-layer interaction) to determine the validity of its routing information towards the final destination (*address 3* in the RTS frame). If the receiver node has valid routing information, then it sends the CTS with a valid flag, which signifies the validity of its routing information towards the final destination. On the other hand, if its routing information towards the final destination is invalid, then the receiver node sends CTS with an invalid flag. Figure 7.3 shows the working flow of the receiver node when receiving the modified RTS frame.

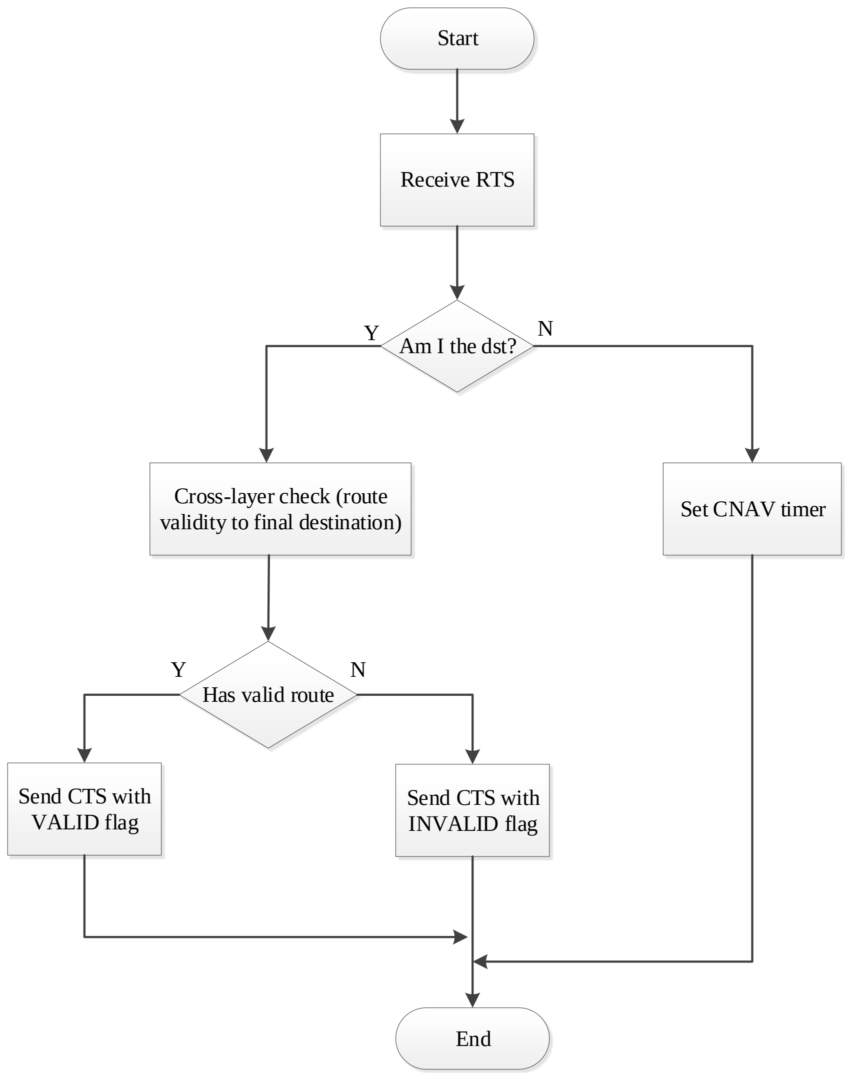

Figure 7.3: RTS process at the receiver side (intermediate node) in RIVC

3. **The transmitter node:** When the transmitter node receives the CTS frame,

it checks the *validity flag* as shown in Figure 7.4. If the flag is valid, which signifies that the receiver node has valid routing information towards the final destination, then the transmitter node sends the data frame as in the IEEE 802.11 DCF, which is illustrated in Figure 7.5. On the other hand, if the flag in the CTS is invalid, then the transmitter node can conclude that the route at the receiver node (next-hop) towards the final destination is invalid (this is the early detection feature) and, hence, try to reroute the data packet via its alternative route, if available.

In this case, the transmitter checks its alternative table in the routing layer (cross-layer interaction) to see if it has a valid alternative node in the alternative channel. If the transmitter does not have a valid alternative route, then it drops the data packet and notifies the upper layer (as can be seen in Figures 7.4 and 7.6). This provides an early invalid route detection feature. On the other hand, if the transmitter has a valid alternative node (this is the early rerouting feature), then the transmitter updates the receiver field in the RTS *(Address 1)* and the next-hop address in the data frame to the new receiver's address (alternative node IP address provided by the routing protocol), calculates the alternative node's home channel using equation 5.1, switches its interface to the respective channel, resets the CW value to the minimum *(CWmin)* as it is contending/operating on a new channel, and then exchanges RTS/CTS frames as shown above.

If the new receiver (alternative node) has a valid route towards the final destination (sent the CTS with valid flag), then the transmitter transmits the data packet to the alternative node as shown in Figure 7.7. On the other hand, if the receiver has an invalid route towards the final destination, then the transmitter receives a CTS with an invalid flag. In this case, the transmitter node can conclude that all its available routes (primary and alternative) towards the final destination are invalid and hence drop the data packet and notify the upper layer (routing layer), as illustrated in Figure 7.8.

4. **The neighbour nodes:** When neighbour nodes overhear the RTS frame in

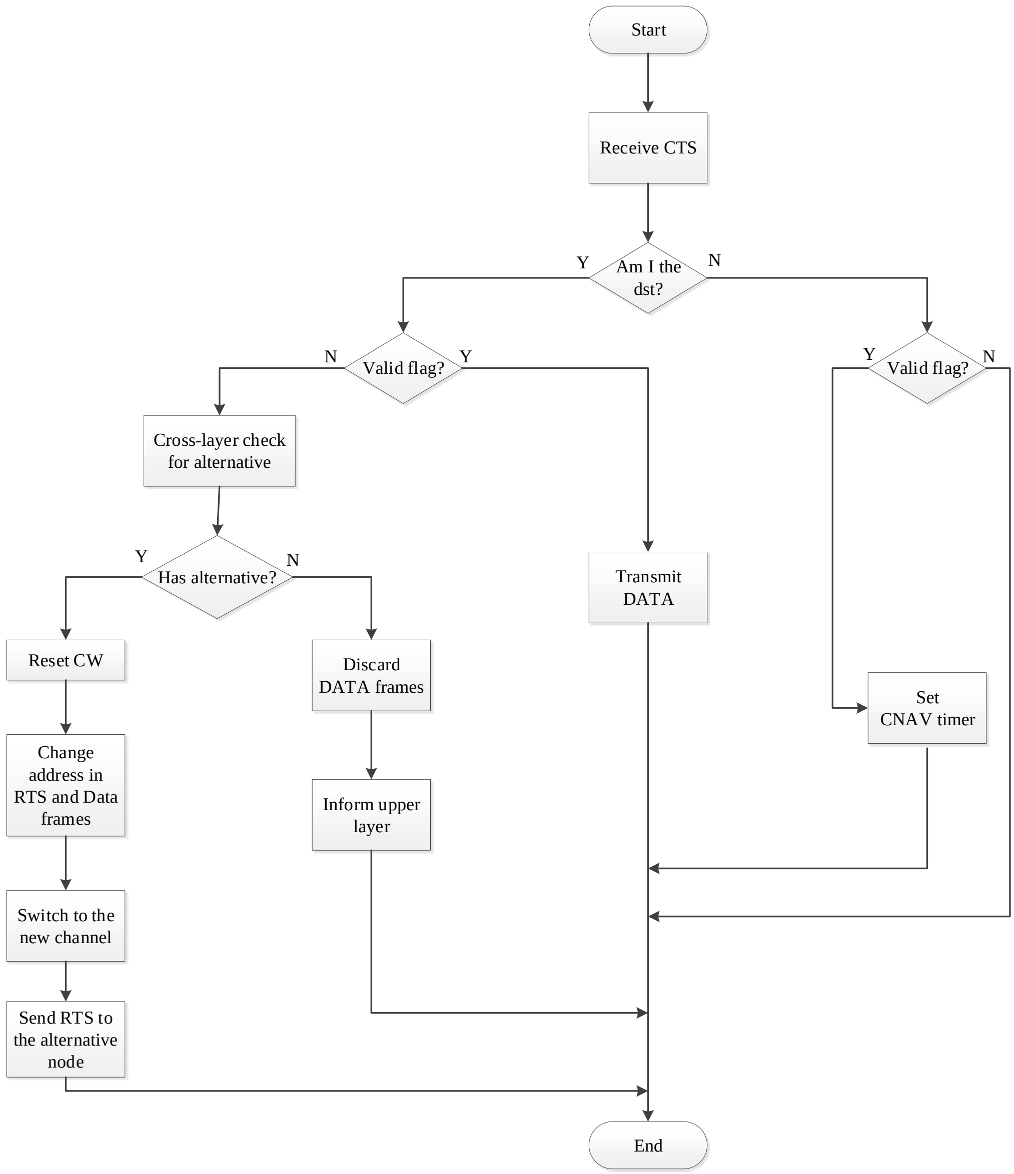

Figure 7.4: CTS process at the transmitter side in RIVC

RIVC, they should back-off from contending on the medium and should set their CNAV timer as in the RDT-MAC protocol. However, when neighbour nodes overhear the CTS frame in RIVC, instead of setting their CNAV blindly, they should check and act according to the provided *validity flag* as shown in Figure 7.4. If the flag in the CTS is valid, then neighbour nodes should back-off from contending on the medium and set their CNAV timers as in RDT-MAC. On the other hand, if the flag in the CTS is invalid, then neighbour nodes should not back-off from contending on the medium as no further communication will follow from the transmitter node. Thus, neighbour nodes that have data to send are not unduly prevented from contending to access the medium.

Note that the RIVC mechanism only seeks to assure that the next-hop node still has valid routing information towards the final destination. However, it does not guarantee that the actual wireless links in the next 2-hops still exist, as it is difficult and costly to track link connectivity of mobile nodes in a decentralised infrastructure-less network such as a MANET.

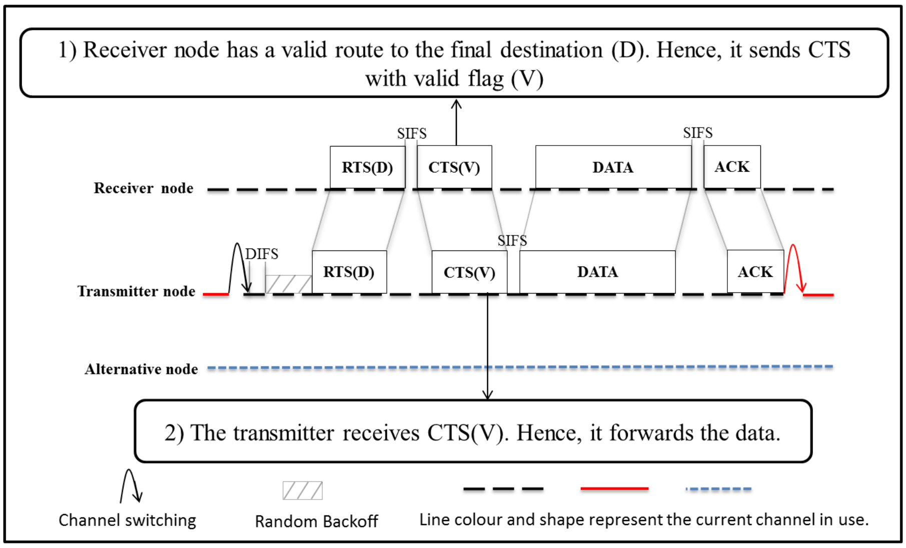

Figure 7.5: RTS/CTS exchange in RIVC. Case: the receiver has valid route information

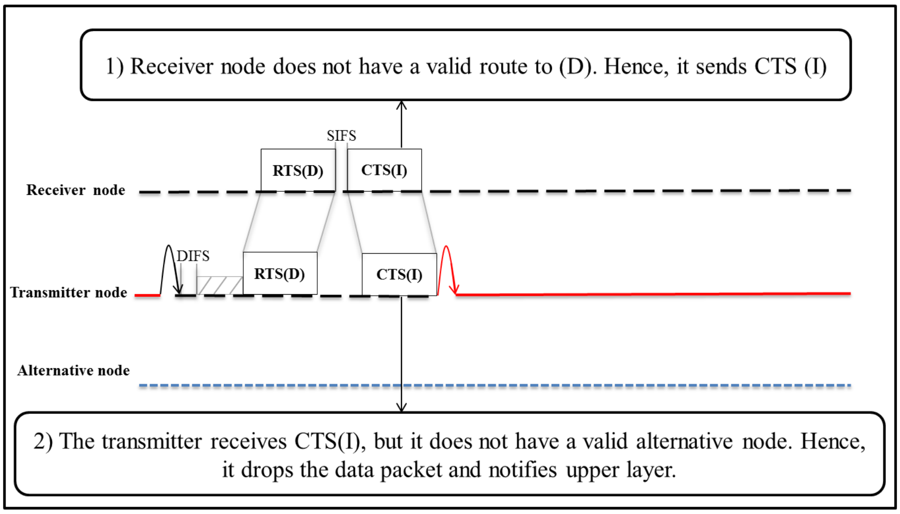

Figure 7.6: RTS/CTS exchange in RIVC. Case: receiver has an invalid route and the transmitter does not have a valid alternative node

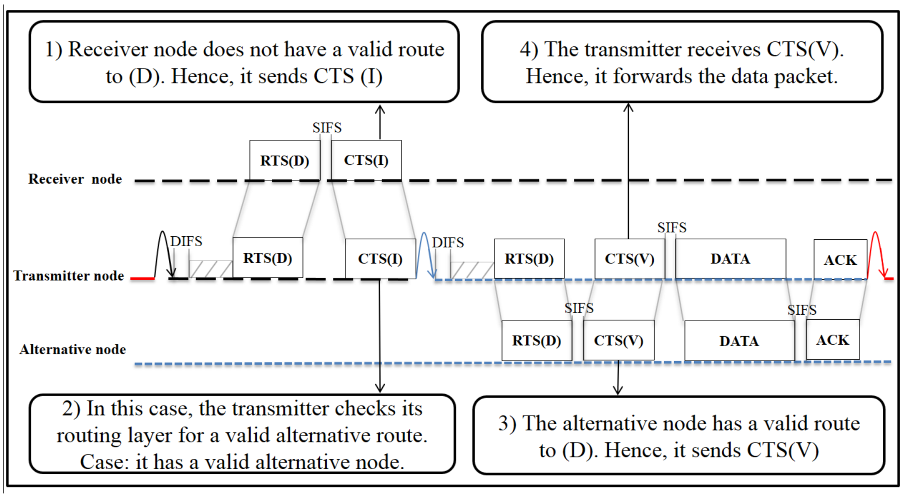

Figure 7.7: RTS/CTS exchange in RIVC. Case: receiver has invalid route information and the transmitter has a valid alternative route with valid route information

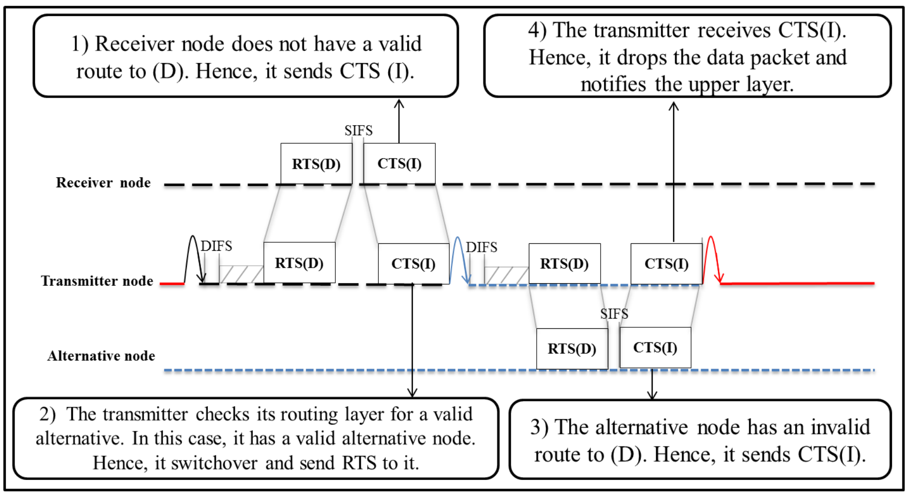

Figure 7.8: RTS/CTS exchange in RIVC. Case: receiver has invalid route information, and the transmitter has a valid route, but the alternative has invalid route information

7.3 Modified Back-off (MB)

The carrier sense mechanism in the original IEEE 802.11 DCF invokes the back-off procedure when it finds that the medium is busy or when the transmitter node transmits a frame and does not receive a corresponding frame (CTS/ACK). In these cases the transmitter node increments the retry counter in series and the Contention Window *(CW)* exponentially, and backs off from contending on the medium during this time. After the back-off timer reaches zero, the transmitter node will try to recover from the error by retransmitting the frame again (as discussed in section 2.3.4).

Campbell *et al.* [197, 198] propose a MultiChannel Distributed Coordination Function called MC-DCF to improve the overall throughput in a Wireless Sensor Network (WSN) and to reduce medium-access delay. In MC-DCF the back-off algorithm of the IEEE 802.11 DCF is modified to invoke channel switching when the pre-defined threshold is reached. The retry counter is used as a threshold. When the threshold is reached (after the third retry count), the transmitter node should switch to another channel and sense the medium.

When a node has data to send, the CW will be set to the initial value of ($CWmin$) and the node can transmit after observing the backoff rules. The CW value will increment in series every time an unsuccessful attempt is made to transmit, which causes an increment in the retry counter as well. The retry counter will reach its threshold after the third retry attempt. In this case, the transmitter will switch its channel to another channel and sense if the new channel is free. If the new channel is free, then the transmitter node may transmit the frame. If the new channel is busy, then the transmitter node should switch to yet another channel. If all channels are busy, then the transmitter should revert to a random back-off timer. MC-DCF was proposed originally for a sensor network where all the nodes are static. Furthermore, it only considers a single-hop static network where source nodes send data towards the sink and hence there is little need for a routing protocol to route data packets.

Motivated by the idea of channel switching when the pre-defined threshold number is reached in MC-DCF, the MB mechanism is proposed. MB is an extension to the multichannel RDT-MAC protocol to provide load balance and reduce contention in a busy medium by benefiting from pre-discovered alternative routes. The modified version of RDT-MAC is referred to as MB from here on.

The back-off procedure in the multichannel RDT-MAC protocol (which was presented in Chapter 5) is modified (MB) [196] to invoke the pre-discovered alternative route in a different channel (cross-layer interaction), if available, when the pre-defined threshold is reached (after the third retry count as in MC-DCF). This threshold is referred to as a Channel retransmission Retry Limit (CRL) from here after. The CRL threshold is based on the retry count value and will be reached after the third retransmission follows the initial transmission, as can be seen in Figure 7.9. Unlike MC-DCF, MB is designed to work in multi-hop MANETs and benefits from pre-discovered routes provided by the multipath multichannel routing protocol (RMMMC, which was presented in Chapter 6).

It is worth mentioning that, as no extra information is required to implement the MB mechanism, the MAC control frame in MB has not been modified and it is same as that in the RDT-MAC protocol.

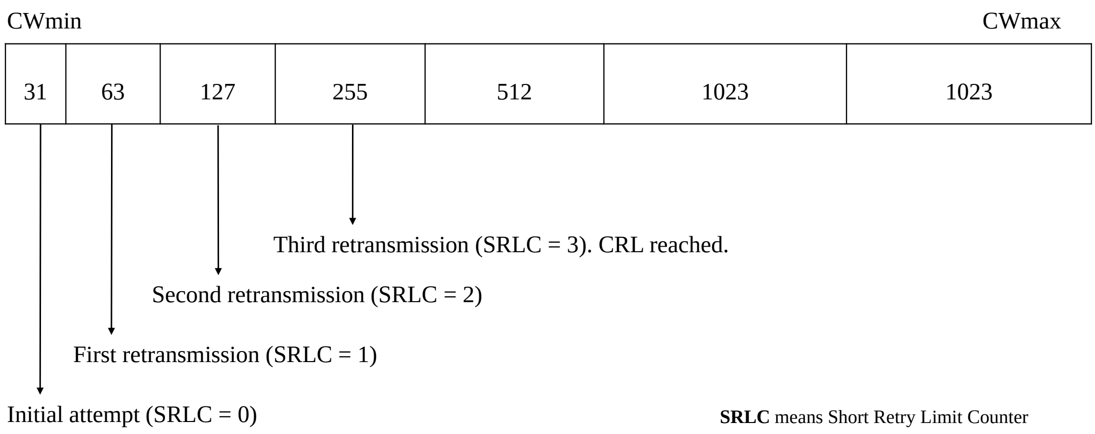

Figure 7.9: Contention window with defined threshold in MB mechanism

7.3.1 Cross-Layer Interaction between MAC and Routing Layers

As mentioned earlier in section 7.2.2, NS-2 does not support cross-layer interaction between MAC and the routing layers. However, NS-2 can be modified to support such interaction with the aim of improving network performance.

The proposed MB mechanism interacts (consults) with the multipath multichannel (RMMMC) routing protocol in the following case:

- When the retry counter reaches the pre-defined threshold (CRL), the transmitter node consults its alternative table in the routing layer for an alternative route in a different channel.

7.3.2 Working Process of MB

Figure 7.10 illustrates the working process of the MB mechanism. In MB, when a node transmits a frame and does not receive a corresponding acknowledgement frame (CTS/ACK), it increments the retry counter and the CW values and transmits again after observing the medium access rules.

- If the retry counter value is less than the CRL threshold, then the transmitter node continues its attempts to transmit the frame in the current channel, as in the RDT-MAC.
- On the other hand, if the retry counter value has exceeded the CRL threshold, then the transmitter node checks its alternative table in the routing layer (cross-layer interaction) to determine if it has a valid alternative route.
- If the transmitter does not have a valid alternative route, then the transmitter continues the retransmission and the back-off procedure in the current channel, as in the RDT-MAC protocol.
- On the other hand, if the transmitter has a valid alternative, then the transmitter updates the destination address field in the RTS ($Address1$) and the next-hop address in the data frame to the new receiver's address (alternative node IP address which is provided by the routing protocol), calculates the alternative node's home channel (using equation 5.1) and switches its interface to that channel for communication. Also, the transmitter resets the CW value to the minimum *(CWmin)* as it is contending/operating in a new channel. Then the transmitter exchanges RTS/CTS frames with the new receiver at the new channel according to the RDT-MAC.

Note that when the transmitter node finds an alternative node and switches its channel to the new receiver's home channel, it should not reset the retry counter and should not change the address of the data packet's final destination.

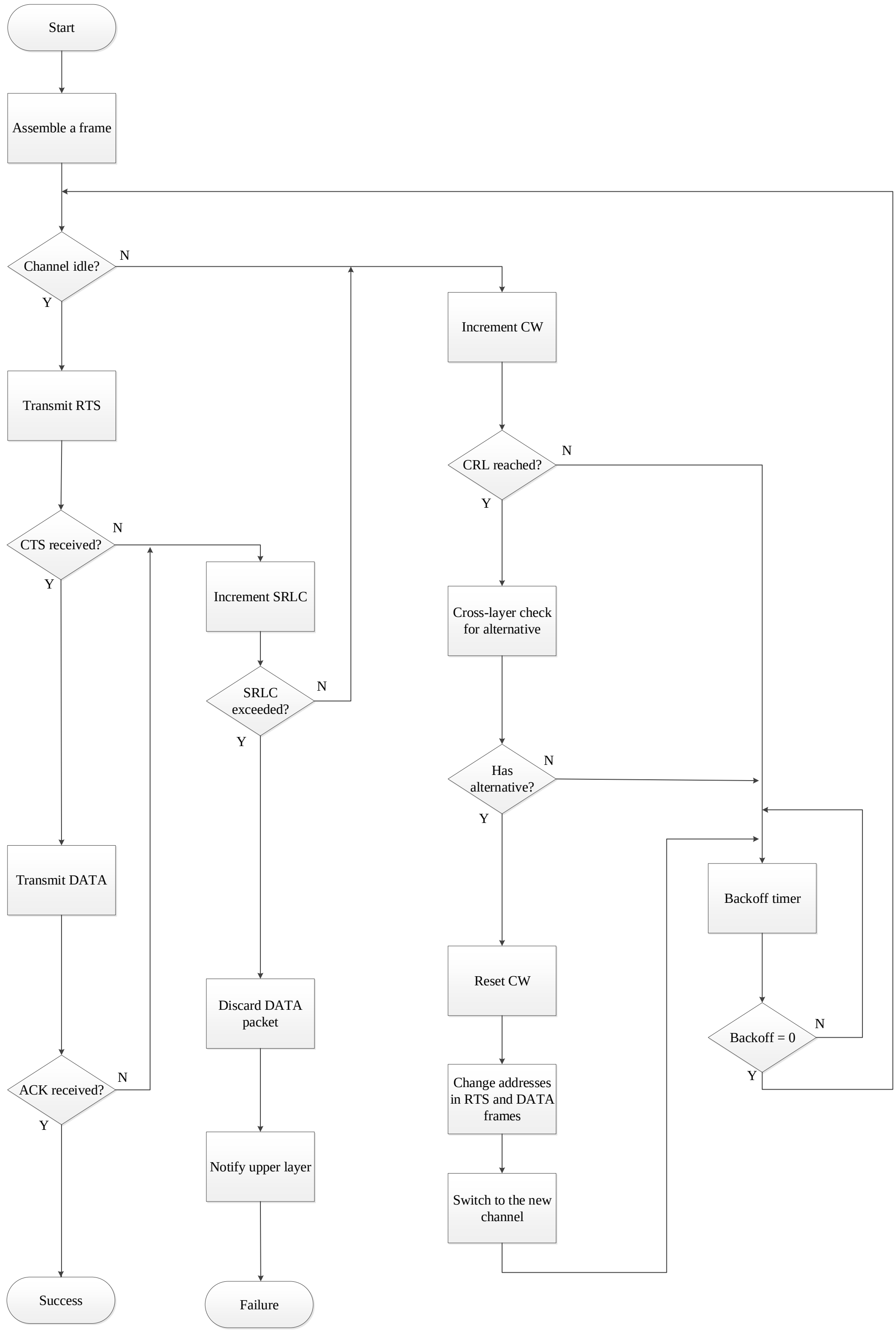

Figure 7.10: Working process of MB mechanism

7.4 Route Information Validity Check-Modified Backoff (RIVC-MB)

The working mechanisms of RIVC (presented in section 7.2) and MB (presented in section 7.3) have been combined together to work as one mechanism. The combined mechanisms are referred to as RIVC-MB [196] from here on. RIVC-MB aims to investigate the benefit of combining both mechanisms in one protocol. It utilises a cross-layer interaction between the MAC and routing layers.

The MAC control frames (RTS and CTS) in the RIVC-MB mechanism have been modified according to that in RIVC (as explained in section 7.2.1). RIVC-MB supports the cross-layer interaction between the MAC and routing layers as stated in sections 7.2.2 and 7.3.1.

7.4.1 Working Process of RIVC-MB

Figure 7.11 illustrates the working process of the RIVC-MB mechanism. When a node has data to send, it has to observe the medium access rules before contending on the medium as in RDT-MAC. If the medium is free, the transmitter sends RTS (which includes the final destination address ($Address3$)).

- Upon receiving the RTS, the receiver should check its route information validity towards the final destination and then transmit a CTS back to the transmitter with either a valid or invalid flag.

- Upon receiving the CTS, the transmitter should check the *validity flag* and act accordingly. If the *validity flag* in the CTS is valid, then the transmitter node should transmit data as in RDT-MAC.

- If the *validity flag* in the CTS is invalid, then the transmitter should consult its own alternative table in the routing layer to check if it has a valid alternative node. If the transmitter has a valid alternative node, then the address of the receiver node in the RTS and the data would be updated to the new receiver's address (alternative node). On the other hand, if the transmitter does not have a valid alternative, then it should drop the data packets and notify the upper layer about the link failure.

- If the transmitter transmits the RTS or data frames and does not receive the corresponding frame (CTS or ACK), then the transmitter has to increment the retry counter. Then it checks if the retry counter exceed the Short Retry Limit Counter (SRLC).

- If the retry count exceeds the SRLC, then the transmitter should drop the data packet and notify the upper layer.

- If the retry count does not exceed the SRLC, then the transmitter should increment the retry counter and CW values and then check if the retry counter has exceeded the CRL threshold.

- If the retry counter does not exceed the CRL, then the transmitter should back-off as in RDT-MAC and retry when the back-off reaches zero.

- If the retry counter has exceeded the CRL, then the transmitter should consult its own alternative table in the routing layer to check if it has a valid alternative node.

- If the transmitter does not have a valid alternative node, then it should continue transmitting data as in the RDT-MAC without changing the receiver node.

- If the transmitter has a valid alternative, then it should update the receiver addresses in RTS and next-hop in data frames, reset the CW, switch to the new receiver's channel and reroute the data packet to the new receiver.

- Unlike MB, the new receiver in RIVC-MB has to check the validity of its routing information towards the final destination before sending the CTS back.

- If the new receiver (alternative node) has valid routing information towards the final destination, then it should send the CTS with a valid flag. In this case, the transmitter node will reroute the data to this node, as shown in Figure 7.12.

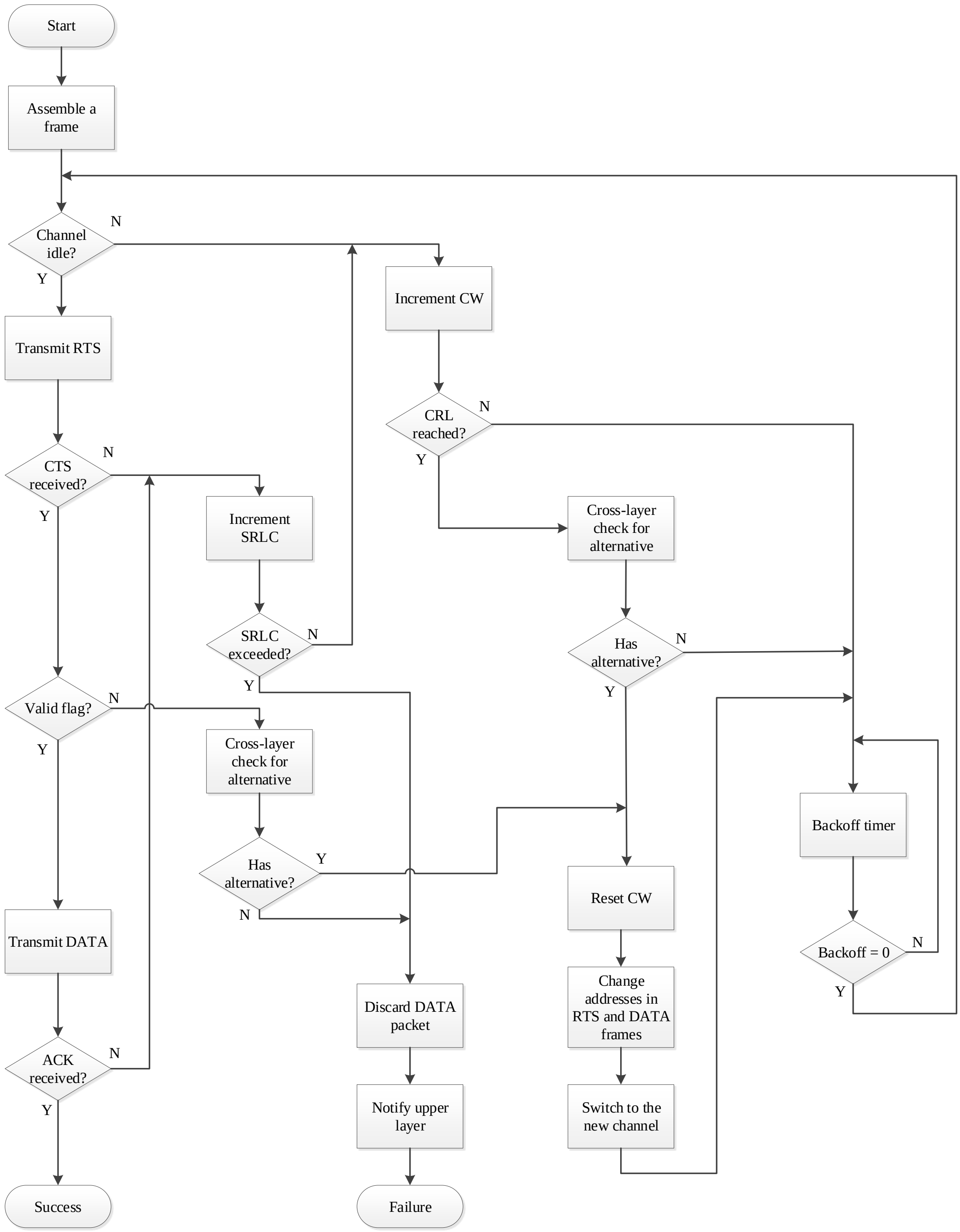

Figure 7.11: Workflow of RIVC-MB mechanism

- If the new receiver node (alternative node) does not have valid routing information towards the final destination, then it should send the CTS with an invalid flag. In this case, the transmitter node should drop the data packet and notify the upper layer, as shown in Figure 7.13.

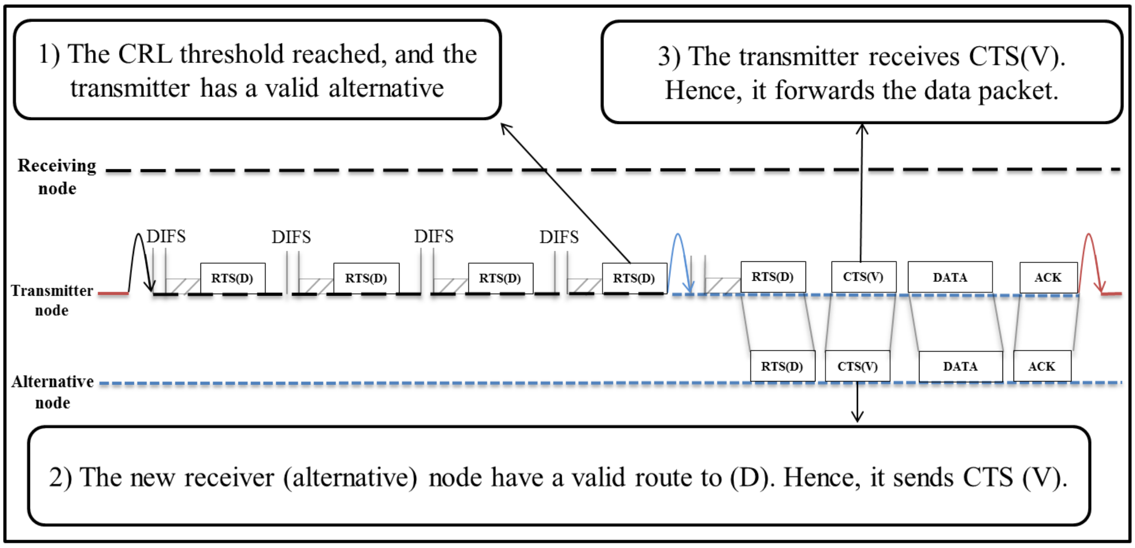

Figure 7.12: The retry counter exceeds the CRL and the transmitter has a valid alternative route with valid route information in RIVC-MB

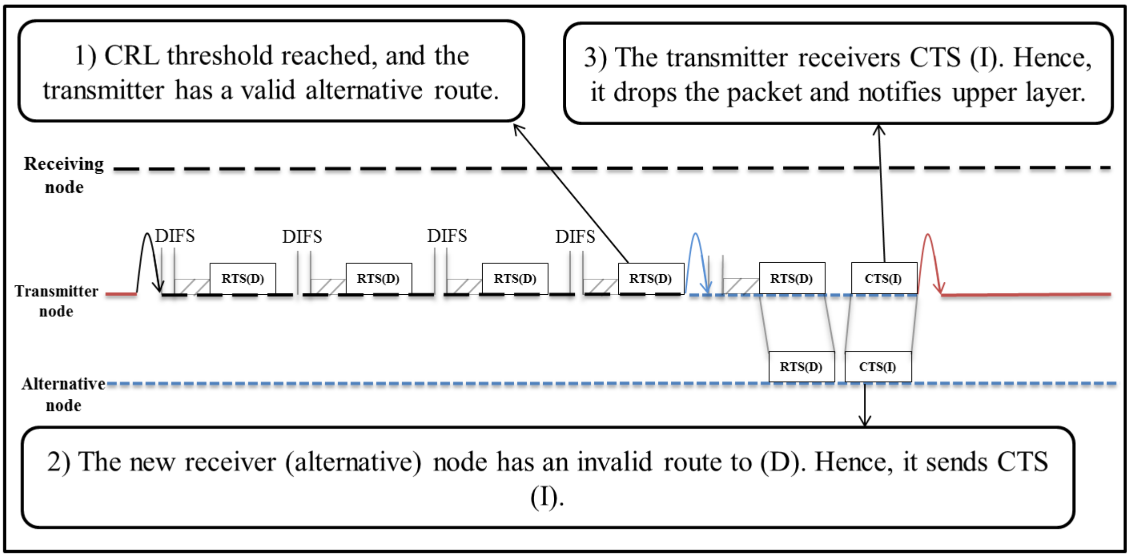

Figure 7.13: The retry counter exceeds the CRL and the transmitter has a valid alternative route, but the alternative node does not have a valid route information in RIVC-MB

Enabling the transmitter node to check route information validity before any transmission/rerouting is important, especially when the transmitter reroutes the data packet via a different path that is in a different channel. Furthermore, enabling the transmitter node to invoke the alternative route following repeated unsuccessful transmissions may reduce contention in the primary channel. Using RIVC along with the MB mechanism ensures route validity at intermediate nodes. Additionally, it reduces the number of dropped data packets due to an invalid route from unduly consuming bandwidth in the medium.

7.5 Performance Evaluation

The NS-2 simulator [158] was used to implement and evaluate the performance of the proposed mechanisms in this chapter. The number of nodes, mobile speeds and number of connections were varied to study the impact of the node density, mobility and number of connections (offered load), respectively, on the proposed MAC mechanisms. Details of the simulation settings used in this chapter were explained in section 4.6. The performance metrics used to evaluate the performance of the protocols compared in this chapter are given in section 4.6.3.

The main goal of this study is to evaluate the performance of the proposed MAC mechanisms (RIVC, MB and RIVC-MB) against the multipath multichannel routing protocol, RMMMC, as an example. Extensive simulation experiments were conducted to compare the performance of the proposed MAC mechanisms under different network conditions, to understand better the impact of each environment on the protocols' performance.

7.5.1 The Compared Protocols

The simulation results reported in this chapter are for the following protocols:

RMMMC: This is an extension to the RDT-AODV routing protocol to support multiple paths over multiple channels in MANETs. RMMMC [189] is designed to improve the reliability and fault-tolerance of the multichannel routing protocol by establishing multiple routes to any destination. Furthermore, it provides a multichannel route recovery mechanism where a broken link can be repaired using a pre-discovered alternative route, regardless of the location of the link breakage.

RMMMC is a multipath multichannel routing protocol that is designed to operate in a multichannel network (presented in Chapter 6). RMMMC uses the multichannel RDT-MAC as its MAC layer protocol (presented in section 5.3.2).

RIVC: This is an extension to the multichannel RDT-MAC protocol to improve the reliability of communication in the multipath multichannel routing protocols and to mitigate the number of dropped data packets due to no/invalid routes. It provides early invalid route detection and early handover to pre-discovered routes. RIVC takes the multipath multichannel RMMMC (presented in Chapter 6) as its routing protocol.

MB: This is an extension to the multichannel RDT-MAC protocol to reduce contention in the wireless medium. It enables the transmitter to reroute data through pre-discovered routes when the retry count reaches a threshold criterion. MB takes the multipath multichannel RMMMC (presented in Chapter 6) as its routing protocol.

RIVC-MB: This is an extension to the multichannel RDT-MAC protocol and it combines the working mechanisms of RIVC and MB in one protocol. It takes the multipath multichannel RMMMC (presented in Chapter 6) as its routing protocol.

Table 7.1 shows the differences among the compared protocols used in this chapter. All the compared protocols in this chapter employ the same routing protocol, which is the multipath multichannel RMMMC routing protocol. However, each of them has a different version of the multichannel RDT-MAC protocol (RIVC, MB and RIVC-MB) with a different goal.

Table 7.1: Differences among the compared protocols

Protocol	**Routing**	**MAC**
RMMMC	RMMMC	RDT-MAC
RIVC	RMMMC	RDT-MAC (with RIVC mechanism)
MB	RMMMC	RDT-MAC (with MB mechanism)
RIVC-MB	RMMMC	RDT-MAC (with RIVC-MB mechanism)

The following subsections evaluate the effect of the proposed MAC mechanisms (MB, RIVC and RIVC-MB) on the multipath multichannel routing protocol (RMMMC).

7.5.2 Impact of Network Density

The simulation settings used to study the impact of increasing network density on the network performance were explained in 4.6.1. Twenty source-destination connections of CBR traffic were simulated with a data packet size of 512 bytes and a generation rate of 4 packets/second. Each node moves dynamically with a random speed between [0,10] m/sec.

7.5.2.1 Data Drops

Figure 7.14 shows the effect of MB, RIVC and RIVC-MB mechanisms on the RM-MMC total number of dropped data packets in the routing layer as node density increases. Note that this performance metric represents the total number of dropped data packets in the routing layer, which includes the data packets dropped due to link layer callback (CBK), no/invalid route (NRTE), Time-To-Live (TTL), interface queue (IFQ) and route looping (loop).

As can be seen in Figure 7.14 MB has the highest number of dropped data packets in the routing layer among all the compared protocols in all the reported network densities. This is mainly due to the adopted method of rerouting data to an alternative route, if available, when the retry count reaches a pre-defined threshold (CRL) and a new receiver node (alternative node) does not have a valid route towards the destination node.

With regard to the RIVC and RIVC-MB mechanisms, Figure 7.14 shows that the number of dropped data packets is reduced when the network density varies between 50 and 250 nodes. However, in a highly dense network (300 nodes), the number of dropped data packets in RIVC and RIVC-MB is slightly higher than in RMMMC, 11% and 8%, respectively. The reason for reducing the total number of dropped data packets in RIVC and RIVC-MB in most network densities may be related to their ability to discover early on an invalid route and reroute data via an alternative route, if available. However, in a highly dense network, rerouting data in a different channel may increase the occurrence of multichannel hidden terminals and dropped data packets.

To allow a better assessment of the efficiency of using the proposed mechanisms and to distinguish the total number of dropped data packets due to NRTE out of the different possible reasons for dropping data packets in the routing layer, section 7.5.2.2 has been provided.

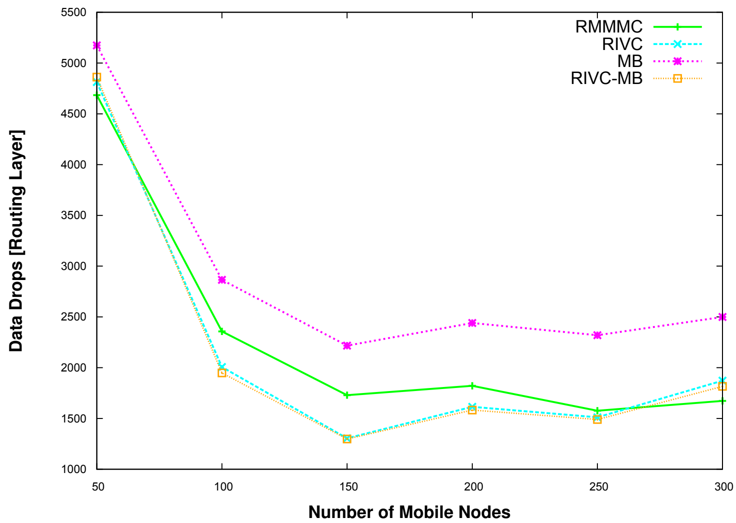

Figure 7.14: Data drops vs. network density

7.5.2.2 Data Dropped Packets Caused by No Route

Figure 7.15 shows the effects of the proposed mechanisms on the total number of dropped data packets due to NRTE in the compared protocols as network density increases. A node may drop a data packet due to no/invalid route (NRTE) in the following situations: 1) if a node cannot discover a route to a destination and the number of route discovery retries has exceeded the pre-defined limit ($RREQ\_RETRIES$); 2) a node receives a RREP to forward and it does not have a valid route to the destination node of this packet (the source node in this case); and 3) a node receives a data packet to forward to a destination when it does not have a valid route towards the final destination node. In the first two cases the node only drops the data packets while in the third case the node must drop the data packets and send an RERR to notify the source node.

To identify the exact reason behind data packets being dropped due to NRTE from the three cases, the implementation and the trace file of the compared protocols are modified. The results of different reasons for dropping data packets due to NRTE are provided in Table 7.2. As all nodes in the network are mobile and move with a random speed of 10 m/sec, the network topology changes dynamically. This may increase the frequency of link breakage and may cause the pre-discovered alternative route to fail to reflect the current state of the network. Hence, the receiver node may drop the data packets due to NRTE.

Figure 7.15 shows that in a network with low node density (50 nodes), all compared protocols have a significantly high number of dropped data packets due to NRTE. This is mainly due to the poor network connectivity, network partitioning and the high frequency of dropping data packets due to exceeding the RREQ limit, as can be seen in Table 7.2.

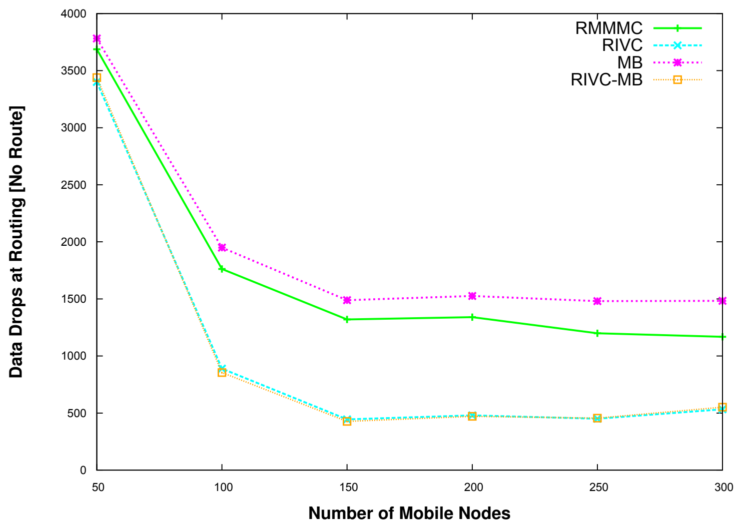

Figure 7.15: Data drops (NRTE) vs. network density

As network density increases, network connectivity improves and consequently, the number of dropped data packets due to exceeding the RREQ limit or receiving RREP, while having an invalid route, significantly decreases as shown in Table 7.2. At the same time, the number of dropped data packets due to receiving data packets while the node has NRTE increases.

Table 7.2 shows that at medium to high network density, the major reason for dropping data packets is receiving data packets while the node has NRTE towards the final destination. As the RMMMC and MB protocols do not employ any mechanism to avoid/minimise this issue, the number of dropped data packets due to receiving data while the node has NRTE is significantly higher than in RIVC and RIVC-MB. In contrast, the proposed mechanisms RIVC and RIVC-MB have successfully reduced the number of data packets dropped for this reason. There are two reasons for this: the capability of RIVC and RIVC-MB to check and detect early on an invalid route before any transmission/rerouting process; and the capability of the proposed mechanisms to reroute the data packets early on to an alternative route when the primary route is determined to be invalid. If the primary and alternative routes have invalid route information, then the transmitter can drop the data packets early and inform the source node about the broken link.

It is worth mentioning that in most of the routing protocols such as RMMMC, RDT-AODV, AODV and AOMDV, when a node receives a data packet while it has no/invalid route towards the final destination, it drops the data packet and sends a RERR to the source. In contrast, the proposed mechanisms of RIVC and RIVC-MB help to avoid/reduce this case by trying to reroute the data packets using pre-discovered alternative routes, when the transmitter node is informed about the invalidity of the route at the receiver node. Additionally, the number of data packets dropped due to receiving data packets, while the node has NRTE for RIVC and RIVC-MB (reported in Table 7.2), is detected early and prevented from being unnecessarily transmitted in the medium for one-hop, thereby reducing the number of data packets with an invalid route that unduly consume bandwidth in the medium.

Table 7.2: Details of dropped data packets due to NRTE vs. network density

Protocol	**Number of nodes**	**Exceed RREQ limit OR receive RREP while has no route**	**Receive data while has no route**	**Total of dropped data packets due to NRTE**
RMMMC	50	2620	1067	3687
	100	388	1373	1761
	150	72	1247	1319
	200	32	1308	1340
	250	42	1156	1198
	300	24	1143	1167
RIVC	50	2821	579	3400
	100	441	443	884
	150	107	337	444
	200	48	431	479
	250	40	410	450
	300	30	522	552
MB	50	2680	1101	3781
	100	401	1548	1949
	150	111	1377	1488
	200	41	1484	1525
	250	41	1439	1480
	300	22	1460	1482
RIVC-MB	50	2782	657	3439
	100	464	390	854
	150	105	322	427
	200	37	434	471
	250	45	409	454
	300	34	517	551

7.5.2.3 Data Dropped Packets Caused by MAC Retransmission

Figure 7.16 shows the total number of dropped data packets in the MAC layer due to exceeding the retransmission limit (denoted as RET) for the compared protocols. This performance metric was chosen to measure the impact of the proposed mechanisms on reducing the number of dropped data packets in the MAC layer due to exceeding the retry limit. As expected, the MB mechanism reduce the total number of dropped data packets due to RET with all network densities, compared with other protocols. For instance, at the network density of 300 nodes, MB reduces the total number of dropped data packets due to RET in comparison with RMMMC, RIVC and RIVC-MB by approximately 47%, 17% and 17%, respectively. This is due to its ability to reroute the data packets to the pre-discovered alternative route in the MAC layer, where the alternative route is available, before the retry count limit is exceeded. Hence, there are fewer dropped data packets due to RET.

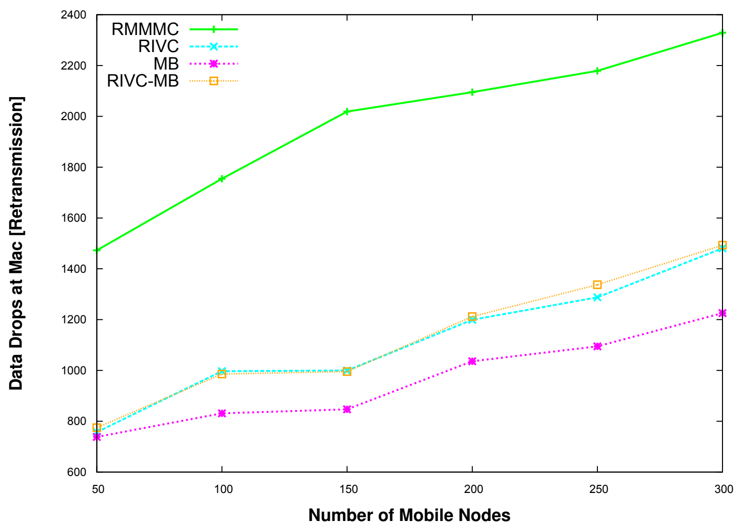

Figure 7.16: Data drops at MAC (RET) vs. network density

With regard to RIVC and RIVC-MB, they reduce the total number of dropped data packets due to RET in comparison with RMMMC by 36% and 35%, respectively. This is mainly due to their capability to discover an invalid route early on during the RTS/CTS exchange and the possibility of terminating the retransmission earlier when the receiver node has NRTE. Although RIVC-MB is a combination of the RIVC and MB mechanisms, the total number of dropped data packets due to RET in RIVC-MB is higher than that of MB by approximately 21%. This is perhaps due to differences in the working processes of the RIVC-MB and MB mechanisms. In other words in the RIVC-MB mechanism the RIVC check is expected to have the initial impact in the communication, when nodes are exchanging RTS/CTS frames, while the MB mechanism starts working after several unsuccessful retransmission attempts and when the retry count reaches the pre-defined threshold (after the third retry).

7.5.2.4 Delay

Figure 7.17 demonstrates the impact of the increasing network density on the average end-to-end delay for data packets for all the compared protocols. It can be seen in Figure 7.17 that all compared protocols have a similar trend in delay. In a low density network, all protocols have a relatively high delay (between 0.42 and 0.44 *sec* to deliver a data packet from the sender to the receiver). This is caused by poor network connectivity and network partitioning. As network density increases, all protocols show a relatively stable delay with RMMMC being superior to the other proposed mechanisms. This superiority of RMMMC may be related to unsuccessful attempts in the proposed mechanism to reroute the data when the receiver node has an invalid route or when the retry count reaches the pre-defined threshold.

It is worth mentioning that in a network with 300 nodes the difference in the delay between RMMMC and the other proposed mechanisms is relatively small. For instance, at a network density of 300 nodes, the differences in delay between RMMMC and the proposed mechanisms MB, RIVC and RIVC-MB are around 0.02, 0.04 and 0.04 *sec*, respectively. As delay in this research was measured as the average time to deliver a data packet between the source and the destination, increasing the number of delivered data packets (as we will see in Figure 7.18) may cause a slight increase in the delay.

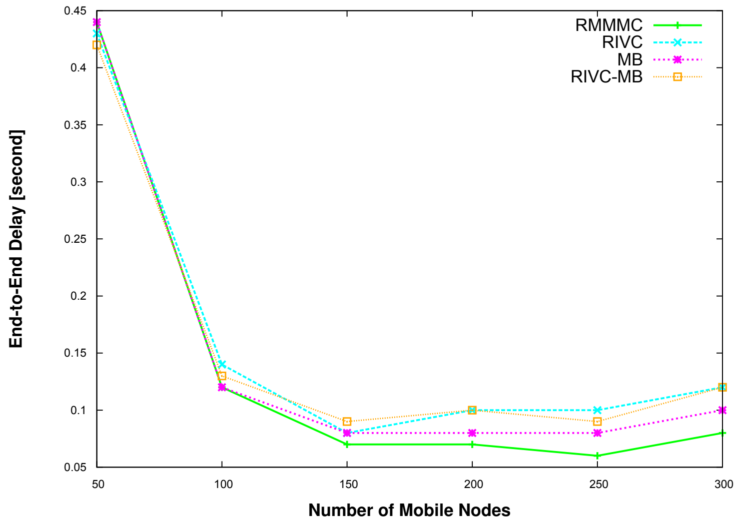

Figure 7.17: End-to-end delay vs. network density

7.5.2.5 Packet Delivery Ratio (PDR)

Figure 7.18 shows the impact of network density on the PDR for the compared protocols. The figure shows that the other proposed mechanisms improve the PDR with all network densities in comparison with the RMMMC protocol.

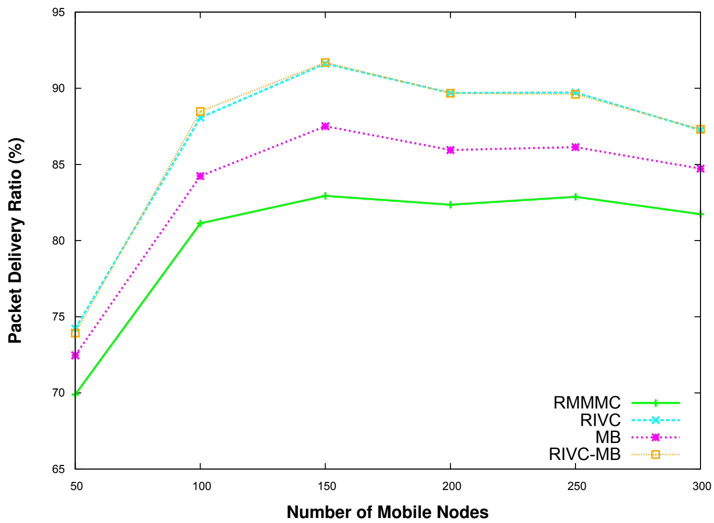

Figure 7.18: Packet Delivery Ratio vs. network density

For instance, in a highly dense network (300 nodes, for example), the proposed mechanisms MB, RIVC and RIVC-MB have improved the PDR in comparison with RMMMC by 3%, 6% and 6%, respectively. The mechanism employed in MB helps to improve the PDR as the node has the ability to find and reroute data when the retry count reaches the pre-defined threshold. With regard to the RIVC and RIVC-MB mechanisms, the increase in the PDR is mainly due to their capability to detect an invalid route early on and to reroute early. The confidence interval values for the compared protocols are given in Table A.7 in Appendix A.

Based on the discussion of results provided in this section, the following observations can be made:

- The proposed mechanisms (MB, RIVC and RIVC-MB) improve the PDR with all network densities.
- The MB mechanism reduces the number of dropped data packets due to RET in the MAC layer. This is mainly due to its capability of rerouting data packets via an alternative route when the retry count reaches the pre-defined threshold. However, MB increases the number of dropped data packets due to NRTE and the delay, which may be caused by rerouting data when the retry threshold is reached and by using a route with invalid routing information.
- The RIVC mechanism significantly helps to reduce the number of dropped data packet due to NRTE and RET. This is accomplished by enabling the transmitter to detect an invalid route early on and to try to reroute the data to an alternative node that has a valid route towards the final destination. Additionally, this mechanism helps to improve communication reliability of the multipath multichannel routing protocols.
- The RIVC-MB mechanism seems to have similar performance to the RIVC mechanism. This may be because the working process of RIVC occurs before each transmission/rerouting while the MB mechanism works only when the retry count reaches the pre-defined threshold. Given the extra complexity incurred by incorporating RIVC and MB in one protocol (RIVC-MB) with no gain to the network performance, it is not advisable to combine them.

7.5.3 Impact of Network Mobility

The simulation settings used to study the impact of node mobility on the network performance were explained in 4.6.1. Twenty connections of CBR traffic were simulated with a data packet size of 512 bytes and a generation rate of 4 packets/second. The number of mobile nodes in the network was 200 nodes.

7.5.3.1 Data Drops

As node speed increases, the network topology changes more frequently. Due to the frequent changes to the network topology and the fact that each node can only monitor activities in the respective listening channel as it is equipped with a single transceiver, the availability and validity of the route at the new receiver (intermediate node) cannot be guaranteed.

Figure 7.19 shows the effect of the MB, RIVC and RIVC-MB mechanisms on the RMMMC total number of dropped data packets in the routing layer as node mobility increases. As node mobility increases, the network topology changes more frequently. This may increase the frequency of link breakage and mean that a pre-discovered alternative route does not reflect the current state of the network. Hence, the number of dropped data packets may increase and network performance decreases.

Figure 7.19 shows that the MB has the highest number of dropped data packets in the routing layer among all the compared protocols at all reported node speeds. This is perhaps due to the increase in changes to the network topology along with the adopted method of rerouting the data packets to an alternative route when the retry count reaches the pre-defined threshold (CRL) and the new receiver (alternative node) does not have a valid route towards the final destination node.

With regard to the RIVC and RIVC-MB mechanisms, Figure 7.19 shows that in a network with low to relatively high node mobility (1 - 20 m/sec), RIVC and RIVC-MB noticeably reduce the number of dropped data packets compared with RMMMC. However, as node mobility increases beyond that, the number of dropped data packets in RIVC and RIVC-MB is slightly higher than in RMMMC by 5% and

3%, respectively. This is perhaps due to the rapid changes to the network topology, which may affect the availability/validity of a route at intermediate nodes. Hence, more routes with invalid routes may be detected (via the RIVC mechanism) and consequently more attempts to reroute data packets would be performed by the proposed mechanisms. Although enabling the transmitter node to reroute data opportunistically via an alternative route in a different channel may increase the chance of delivering the data packets, it increases the possibility of the occurrence of multichannel hidden terminal and deafness problems in the new (alternative) channel. Therefore, the number of the dropped data packets in the routing layer may increase.

To allow a better assessment of the efficiency of using the proposed mechanisms and to distinguish the total number of dropped data packets due to NRTE out of the different possible reasons for dropping data packets in the routing layer, section 7.5.3.2 has been provided.

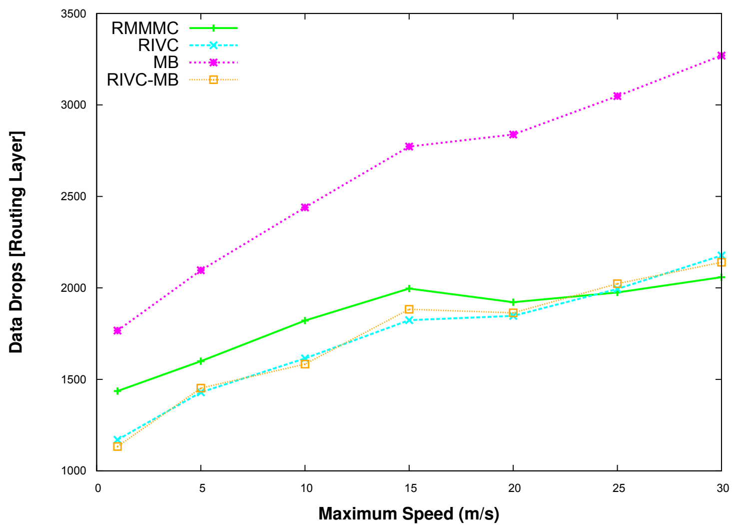

Figure 7.19: Data drops vs. node mobility

7.5.3.2 Data Dropped Packets Caused by No Route

Figure 7.20 shows the effects of the proposed mechanisms on the total number of dropped data packets due to NRTE in the compared protocols as node mobility increases. To identify the exact reason behind dropping the data packets due to

NRTE from the possible reasons mentioned in section 7.5.2.2, the implementation and the trace file of the compared protocols have been modified. The results for the different reasons for dropping data packets due to NRTE are provided in Table 7.3.

Figure 7.20 shows that the number of dropped data packets due to NRTE in the MB mechanism is the highest and it noticeably increases as the node mobility increases. This is perhaps due to the frequent changes to the network topology and hence rerouting decisions may not successfully deliver data packets to the alternative node. For instance, in a network with node speed of 30 m/sec, the number of dropped data packets due to NRTE in MB is higher than that of RMMMC, RIVC and RIVC-MB by 23%, 209% and 221%, respectively. Table 7.3 shows that the main reason behind this increase is due to receiving data packets where a node has a NRTE issue.

Figure 7.20 shows that the RIVC and RIVC-MB mechanisms significantly reduce the number of dropped data packets due to NRTE compared with RMMMC and MB with all reported node mobilities. This is caused by the mechanism employed by RIVC, which provides early invalid route detection and early rerouting to the alternative route, if possible. For instance, in a network with node speed of 30 m/sec, RIVC has reduces the number of dropped data packets due to NRTE in comparison with RMMMC and MB by 59% and 67% respectively.

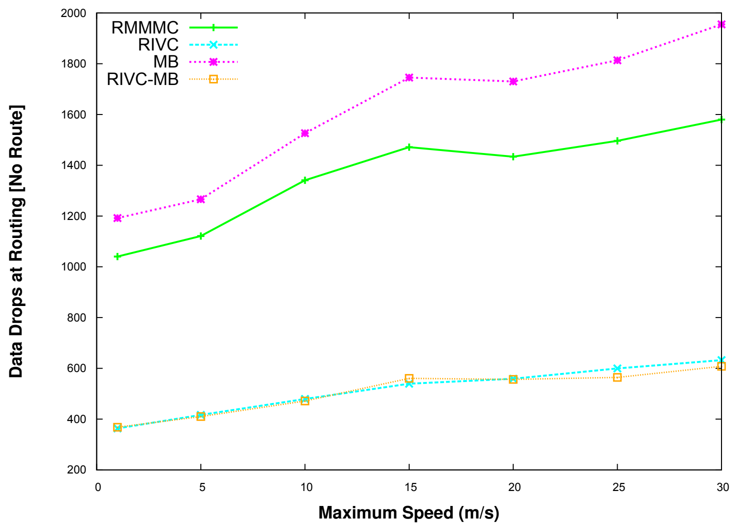

Figure 7.20: Data drops (NRTE) vs. node mobility

Table 7.3 shows that with all node speeds, the major reason for dropping data packets is receiving data packets where the receiver node has NRTE towards the final destination. As the RMMMC and MB protocols do not employ any mechanism to avoid/reduce this issue, the number of dropped data packets due to receiving data where the node has a NRTE issue is significantly higher than in RIVC and RIVC-MB. In contrast, the proposed mechanisms RIVC and RIVC-MB successfully reduce the number of dropped data packets due to receiving data where the node has a NRTE issue. This is mainly due to two reasons: the capability of RIVC and RIVC-MB to check and detect early on an invalid route before any transmission/rerouting process; and the capability of the proposed mechanisms to reroute the data packets early via an alternative route when the primary route is determined to be invalid. If the primary and alternative routes have invalid route information, then the transmitter can drop the data packets early and inform the source node about the broken link.

It is worth mentioning that the number of dropped data packets due to receiving data while node has invalid route information (NRTE) for RIVC and RIVC-MB (reported in Table 7.3) has been detected early and this has prevented the packet from unnecessarily being transmitted in the medium for one-hop. This reduces the number of data packets with an invalid route that unduly consume bandwidth in the medium.

Table 7.3: Details of dropped data packets due to NRTE vs. node mobility

Protocol	**Node mobility**	**Exceed RREQ limit OR receive RREP while has no route**	**Receive data while has no route**	**Total of dropped data packets due to NRTE**
RMMMC	1	28	1011	1039
	5	42	1078	1120
	10	32	1308	1340
	15	26	1444	1470
	20	32	1401	1433
	25	50	1445	1495
	30	51	1528	1579
RIVC	1	47	316	363
	5	63	352	415
	10	48	431	479
	15	87	452	539
	20	64	494	558
	25	64	535	599
	30	46	586	632
MB	1	34	1157	1191
	5	59	1206	1265
	10	41	1484	1525
	15	69	1675	1744
	20	55	1674	1729
	25	52	1760	1812
	30	50	1904	1954
RIVC-MB	1	48	319	367
	5	62	347	409
	10	37	434	471
	15	65	495	560
	20	71	484	555
	25	63	500	563
	30	54	553	607

7.5.3.3 Data Dropped Packets Caused by MAC Retransmission

Figure 7.21 shows the total number of dropped data packets in the MAC layer due to exceeding the retransmission limit (denoted as RET) for the compared protocols as node mobility increases. This performance metric is chosen to measure the impact of the proposed mechanisms on reducing the number of dropped data packets in the MAC layer due to exceeding the retry limit. As expected, the MB mechanism reduces the total number of dropped data packets due to RET with all node mobilities compared with other protocols. For instance, in a network with high node mobility speed (30 m/sec, for example), MB reduces the total number of dropped data packets due to RET in comparison with RMMMC, RIVC and RIVC-MB by 50%, 14% and 15%, respectively. This is due to its ability to reroute the data packets to an alternative node in the MAC layer before the retry count limit is exceeded. Hence, there are less dropped data packets due to RET. However, as node mobility increases, the probability of finding an alternative node is reduced, hence the number of dropped data packets due to RET increases.

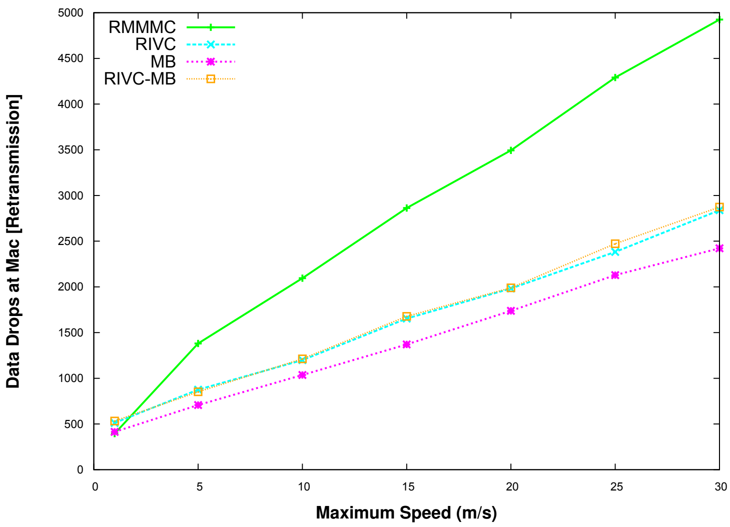

Figure 7.21: Data drops at MAC (RET) vs. node mobility

With regard to RIVC and RIVC-MB, they significantly reduce the total number of dropped data packets due to RET in comparison with RMMMC by 73% and 71%, respectively. This is mainly due to their capability of discovering an invalid route early on during the RTS/CTS exchange and the possibility of terminating the retransmission earlier when the receiver node has NRTE.

Although RIVC-MB is a combination of the RIVC and MB mechanisms, the total number of dropped data packets due to RET in RIVC-MB is higher than in MB by 18%. This is perhaps due to differences in the working process between the RIVC-MB and MB mechanisms. In other words, the RIVC mechanism is expected to have an initial impact on communication where nodes are exchanging RTS/CTS frames, while the MB mechanism is initiated after several unsuccessful retransmission attempts and when the retry count has reached the pre-defined threshold (after the third retry).

7.5.3.4 Delay

Figure 7.22 presents the effect of increasing node mobility on the end-to-end delay for data packets for the compared protocols. It can be seen in Figure 7.22 that increasing the node mobility does not have a major impact on the delay for all compared protocols, with RMMMC showing superiority. For instance, in a network with node speed of 30 m/sec, RMMMC reduces the delay in comparison with MB, RIVC and RIVC-MB by 0.03, 0.04 and 0.04 sec, respectively.

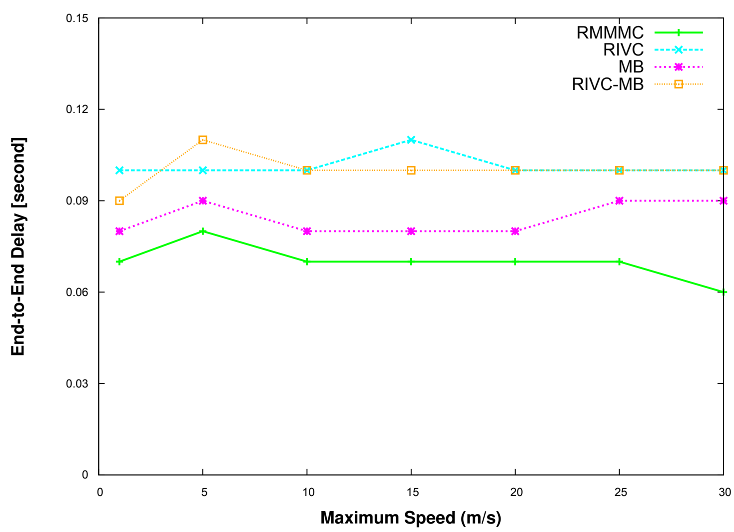

Figure 7.22: End-to-end delay vs. node mobility

As the delay in this research is measured as the average time to deliver a data packet between the source and the destination nodes, increasing the number of delivered data packets (as we will see in Figure 7.23) may cause a slight increase in the delay.

7.5.3.5 Packet Delivery Ratio (PDR)

Figure 7.23 shows impact of increasing the node mobility on the PDR for the compared protocols. In a network with low node mobility, RIVC and RIVC-MB have slightly better PDR than RMMMC and MB. As node mobility increases, the proposed mechanisms significantly increase PDR in comparison with the RMMMC protocol. For instance, in a network with high node mobility speed (for instance, 30 m/sec), MB, RIVC and RIVC-MB improve the PDR in comparison with RMMMC by 13%, 19% and 19%, respectively. The main reason for improved PDR in the MB mechanism is successful attempts to reroute data packets when the pre-defined threshold is reached. Regarding RIVC and RIVC-MB, the main reason why the PDR improves in comparison with RMMMC and MB is their capability to discover an invalid route early as node speed increases, and to reroute the data opportunistically using the pre-discovered alternative route. The confidence interval values for the compared protocols are given in Table A.8 in Appendix A.

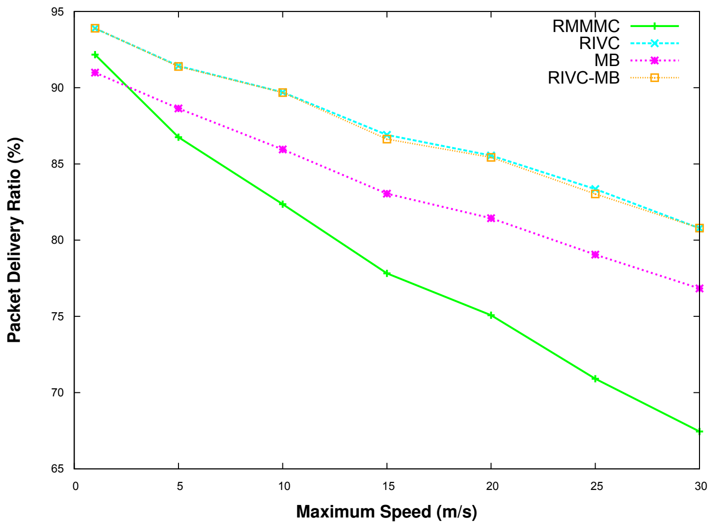

Figure 7.23: Packet Delivery Ratio vs. node mobility

Based on the discussion of results provided in this section, the following observations can be made:

- The proposed mechanisms RIVC and RIVC-MB noticeably improve the PDR with all node mobilities. This is due to their ability to detect an invalid route early and to reroute data early to an alternative route, if available. The MB mechanism improves the PDR with all mobilities, expect with a very low node mobility speed.
- The MB mechanism helps to reduce the number of dropped data packets in the MAC layer due to RET. This is mainly due to its capability to reroute the data packets to an alternative route when the retry count reaches the pre-defined threshold. However, the MB increases the number of dropped data packets due to NRTE and the delay may be caused by the unsuccessful attempts to reroute data to an alternative node when the retry threshold is reached.
- The RIVC mechanism significantly helps to reduce the number of dropped data packets due to NRTE and RET. This is accomplished by enabling the transmitter to detect an invalid route early and to try to reroute the data to an alternative node that has a valid route towards the final destination. Additionally, this mechanism helps to improve communication reliability in the multipath multichannel routing protocols.
- The RIVC-MB seems to have a similar performance to that of the RIVC mechanism. This may be due to the working process of RIVC, which occurs before each transmission/rerouting, while the MB mechanism works when the retry count reaches the pre-defined threshold. Given the extra complexity incurred by incorporating RIVC and MB in one protocol (RIVC-MB) with no gain to the network performance, it is not advisable to combine them.

7.5.4 Impact of Number of Connections

The simulation settings used to study the impact of number of connections on the network performance were explained in 4.6.1. A different number of connections of

CBR traffic were simulated with a data packet size of 512 bytes and a generation rate of 4 packets/second. Each node moves dynamically with a random speed between [0,10] *m/sec*. The number of mobile nodes in the network was 200 nodes.

7.5.4.1 Data Drops

Figure 7.24 shows the total number of dropped data packets in the routing layer for the compared protocols as the number of connections in the network increases. Increasing the number of connections in the network increases the level of interference, contention and collisions in the network, along with multichannel hidden terminal and deafness problems.

Figure 7.24 shows that the MB mechanism has the highest number of dropped data packets in the routing layer among all the compared protocols with all number of connections. As the number of connections in the network increases, the contention to access the medium increases, which increases the number of retransmissions. Therefore, the retry count reaches the pre-defined retry threshold (CRL) more frequently. Hence, the transmitter node checks its own alternative table and try to reroute data to an alternative node which is operating in a different channel more frequently. However, as nodes move dynamically with a random speed within 10 *m/sec*, the new receiver (alternative node) may move out of the communication range of the transmitter node, which would ultimately lead to unsuccessful attempts to reroute the data packets and the packets would be dropped. Additionally, as all nodes in the network are equipped with a single half-duplex transceiver, the node may not be aware of the ongoing communication in the new channel (alternative channel) and hence, may inadvertently act as hidden node, which could increase the number of collisions and data packets dropped.

With regard to the RIVC and RIVC-MB mechanisms, Figure 7.24 shows that in a network with low to medium offered load (10 - 20 connections), the number of dropped data packets in RIVC and RIVC-MB is lower than in RMMMC and MB. This is perhaps due to the lower occurrence of the multichannel and deafness problems. However, as the number of connections in the network increases beyond that, the number of dropped data packets in RIVC and RIVC-MB noticeably increases. For instance, in a network with 40 connections, the total number of dropped data packets in the routing layer in RIVC and RIVC-MB is higher than in RMMMC by 62% and 60%, respectively.

As the number of connections in the network increases and due to dynamic movement of all nodes in the network, a pre-discovered alternative route may not reflect the current state of the network. However, the RIVC and RIVC-MB mechanisms try to reroute data to a node operating in a different channel, which increases the probability of multichannel hidden terminal and deafness problems and ultimately increases the number of dropped data packets.

To allow a better assessment of the efficiency of using the proposed mechanisms, section 7.5.4.2 has been provided to distinguish the total number of dropped data packets due to NRTE out of the different possible reasons for dropping data packets in the routing layer.

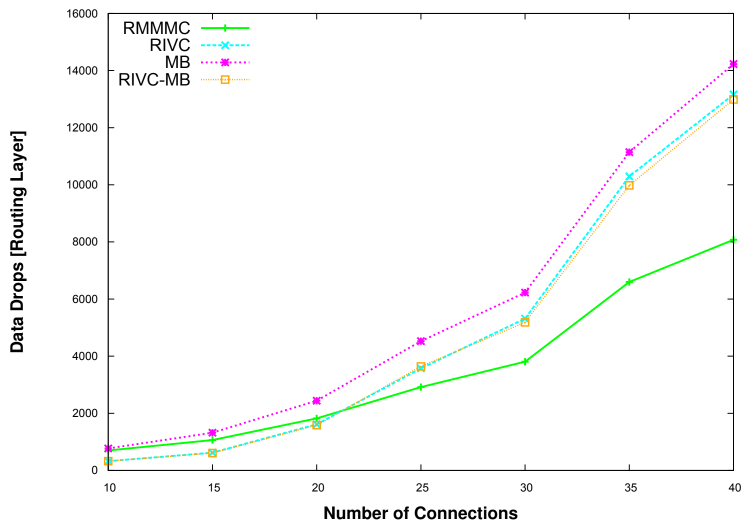

Figure 7.24: Data drops vs. network connection

7.5.4.2 Data Dropped Packets Caused by No Route

Figure 7.25 shows the effects of the proposed mechanisms on the total number of dropped data packets due to NRTE in the compared protocols as the number of connections in the network increases. To identify the exact reason behind dropped data packets due to NRTE from the possible reasons mentioned in section 7.5.2.2, the implementation and the trace file of the compared protocols have been modified. The results of different reasons for dropping data packets due to NRTE are provided in Table 7.4.

Figure 7.25 shows that the number of dropped data packets due to NRTE in the MB mechanism is the highest and linearly increases as the number of connections in the network increases. This is perhaps due to increase in the level of contention and the number of retransmissions as network connections increase. Hence, the retry count reaches the pre-defined retry threshold (CRL) more frequently. Consequently, the transmitter node may reroute the data packets to the alternative node which has no route towards the final destination. However, as nodes move dynamically, the new receiver (alternative node) may have invalid route information towards the final destination. Consequently, the number of dropped data packets due to receiving data while the node has a NRTE issue is increased as the number of connections in the network increases, as can be seen in Table 7.4.

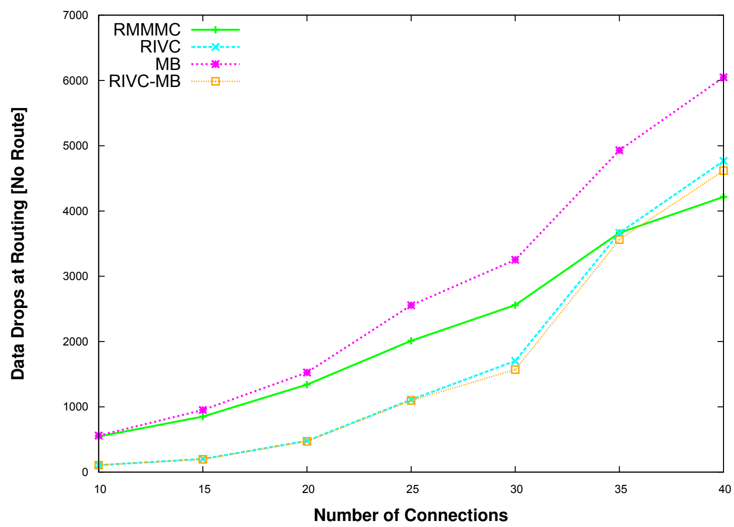

Figure 7.25: Data drops (NRTE) vs. network connection

Figure 7.25 shows that the RIVC and RIVC-MB mechanisms significantly reduce the number of dropped data packets due to NRTE compared with RMMMC and MB in a network with light to relatively high offered load (10 - 30 connections). For instance, in a network with 30 connections, the RIVC reduce the number of dropped data packets due to NRTE compared with MB and RMMMC by 47% and 33%, respectively. This is mainly caused by the adopted mechanism in RIVC where the node can detect the invalid route early and reroute data to an alternative node that has valid route information. However, in a network with high offered load (40 connections, for example), the number of dropped data packets due to NRTE in RIVC and RIVC-MB becomes higher than in RMMMC by 13% and 9%, respectively. The increase in the number of dropped data packets caused by NRTE in RIVC and RIVC-MB is due to the increase in data traffic and the increased amount of data that is rerouted to an alternative node in a different channel while the new receiver has a NRTE issue.

It is worth mentioning that the number of dropped data packets due to receiving data while a node has a NRTE issue for RIVC and RIVC-MB, which is reported in Table 7.4, is detected early and prevented from unnecessarily transmitting in the medium for one-hop, therefore reducing the number of data packets with an invalid route that unduly consume bandwidth in the medium.

Table 7.4: Details of dropped data packets due to NRTE vs. network connection

Protocol	Number of connections	Exceed RREQ limit OR receive RREP while has no route	Receive data while has no route	Total of dropped data packets due to NRTE
RMMMC	10	40	504	544
	15	18	832	850
	20	32	1308	1340
	25	97	1915	2012
	30	95	2463	2558
	35	237	3428	3665
	40	206	4008	4214
RIVC	10	5	101	106
	15	27	174	201
	20	48	431	479
	25	129	981	1110
	30	117	1587	1704
	35	243	3420	3663
	40	262	4505	4767
MB	10	6	552	558
	15	27	924	951
	20	41	1484	1525
	25	154	2402	2556
	30	108	3144	3252
	35	247	4681	4928
	40	250	5797	6047
RIVC-MB	10	4	101	105
	15	25	171	196
	20	37	434	471
	25	134	962	1096
	30	122	1447	1569
	35	316	3245	3561
	40	231	4386	4617

7.5.4.3 Data Dropped Packets Caused by MAC Retransmission

Figure 7.26 shows the total number of dropped data packets in the MAC layer due to exceeding the retransmission limit (denoted as RET) for the compared protocols as the number of connections in the network increases. This performance metric is chosen to measure the impact of the proposed mechanisms on reducing the number of dropped data packets in the MAC layer due to exceeding the retry limit. As expected, the MB mechanism reduces the total number of dropped data packets due to RET with all node mobilities compared with the other protocols. For instance, in a network with high offered load (40 connections), MB reduces the total number of dropped data packets due to RET compared with RMMMC, RIVC and RIVC-MB by 32%, 4% and 11%, respectively. This is due to its ability to reroute the data packets to an alternative node in the MAC layer before the retry count limit is exceeded. Hence, there are fewer dropped data packets due to RET. However, as the number of connections in the network increases, the contention and transmission to the medium increases, hence the number of dropped data packets due to RET increases.

With regard to RIVC and RIVC-MB, they significantly reduce the total number of dropped data packets due to RET in comparison with RMMMC by 29% and 23%, respectively. This is mainly due to their capability to discover an invalid route early during the RTS/CTS exchange and the possibility of terminating the retransmission earlier when the receiver node has a NRTE issue.

Although RIVC-MB is a combination of the RIVC and MB mechanisms, the total number of dropped data packets due to RET in RIVC-MB is higher than in MB by 13%. This is perhaps due to the differences in the working processes of the RIVC-MB and MB mechanisms. In other words, the RIVC mechanism is expected to have an initial impact on the communication while nodes are exchanging RTS/CTS frames, while the MB mechanism is initiated after several unsuccessful retransmission attempts and when the retry count reaches the pre-defined threshold (after the third retry).

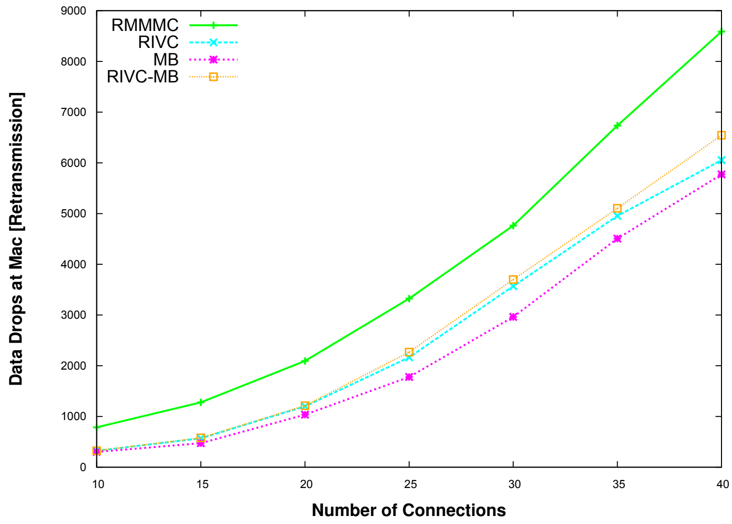

Figure 7.26: Data drops at MAC (RET) vs. network connection

7.5.4.4 Delay

Figure 7.27 demonstrates the effect of increasing the number of connections on the end-to-end delay for data packets for the compared protocols. It can be seen in Figure 7.27 that in a network with a low to medium offered load (10 - 20 connections), the delays of the compared protocols are relatively similar. As the number of connections increases, the delay for RIVC and RIVC-MB increases. This is perhaps due to the increased amount of data that is rerouted to a different channel when the transmitter is informed about the invalidity of a route or when the retry threshold (CRL) is reached.

However, it is worth mentioning that the differences among the delays of the proposed mechanisms, RIVC, RIVC-MB and RMMMC, is relatively small. For instance, in a network with high offered load (40 connections, for example), MB has the same end-to-end delay as RMMMC while the differences in delay between RMMMC and the proposed mechanisms RIVC and RIVC-MB are around 0.11 and 0.08 *sec*, respectively.

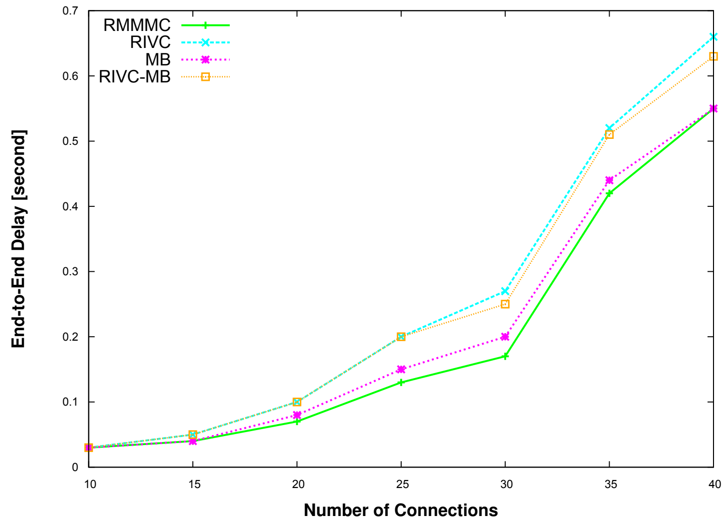

Figure 7.27: End-to-end delay vs. network connection

7.5.4.5 Packet Delivery Ratio (PDR)

Figure 7.28 shows the effect of the number of connections in the network on the PDR for the compared protocols. In a network with low connections (10 connections), the proposed mechanisms, MB, RIVC and RIVC-MB, improve the PDR in comparison with RMMMC by 5%, 10% and 10%, respectively. This is mainly due to enabling the transmitter node to reroute data packets via the pre-discovered alternative route when the route at the receiver node is invalid or when the retry count has reached the pre-defined threshold. Furthermore, the impact of the multichannel hidden terminal and deafness issues in a network with low offered load is not severe. However, as the network offered load increases, the PDR for the proposed mechanisms decreases.

In a network with a high offered load (40 connections), the PDR for MB, RIVC and RIVC-MB is slightly lower than for RMMMC by 7%, 3% and 4%, respectively. The main reason for this decrease is the increased number of unsuccessful rerouting attempts, which increase the occurrence of the multichannel hidden and deafness issues. The confidence interval values for the compared protocols are given in Table A.9 in Appendix A.

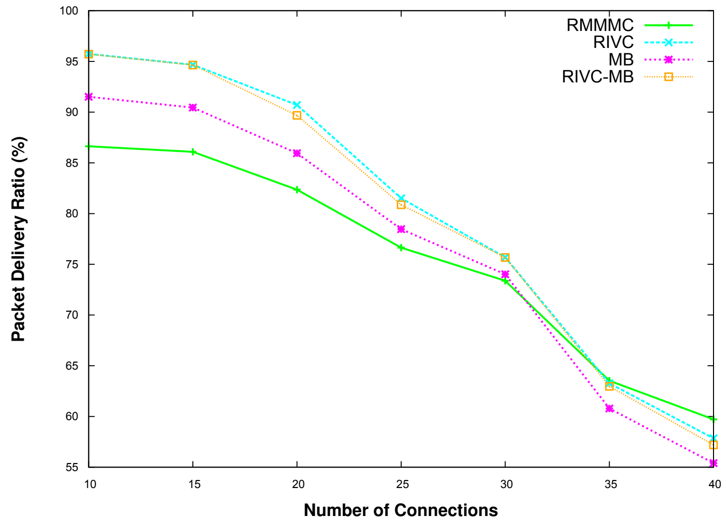

Figure 7.28: Packet Delivery Ratio vs. network connection

Based on a discussion of the results provided in this section, the following observations can be made:

- The proposed mechanisms RIVC and RIVC-MB noticeably improve the PDR in a network with low to relatively high load (10 - 30 connections). This is due to their ability to detect an invalid route early and to reroute data early to an alternative route, if available. In a network with higher offered load, the PDR of the proposed mechanisms slightly decreases below that of RMMMC. This is caused by the increased number of data packets rerouted to an alternative route in a different channel and consequently an increase in multichannel hidden and deafness issues.

- The MB mechanism helps to reduce the number of dropped data packets in the MAC layer due to RET with all number of connections. This is mainly due to its capability to reroute the data packets to an alternative route when the retry count reaches the pre-defined threshold. However, the MB increases the number of dropped data packets due to NRTE, which may be caused by unsuccessful attempts to reroute data to an alternative node that has an invalid route when the threshold is reached.

- The RIVC mechanism significantly reduces the number of dropped data packets due to NRTE at a low to relatively high load (10 - 30 connections). This is accomplished by enabling the transmitter to detect an invalid route early and to try to reroute the data to an alternative node that has a valid route towards the final destination. Additionally, this mechanism helps to improve communication reliability in the multipath multichannel routing protocols.

- The RIVC-MB mechanism seems to have a similar performance to the RIVC mechanism. This may be due to the fact that the working process of RIVC occurs before each transmission/rerouting while the MB mechanism works when the retry count reaches the pre-defined threshold. Given the extra complexity incurred by incorporating RIVC and MB in one protocol (RIVC-MB) with no gain to the network performance, it is not advisable to combine them.

7.6 Conclusions

This chapter presents two distinct MAC mechanisms that aim to enhance the reliability of communication in the multipath multichannel routing protocol and reduce contention in a busy medium. The proposed mechanisms take the multipath multichannel routing protocol (RMMMC) as their routing protocol. Due to frequent network topology changes and the fact that each node is equipped with a single transceiver and can only monitor activities in the respective listening channel, the availability and validity of the route at the new receiver (intermediate node) cannot be guaranteed. Depending on a stale/invalid route for data transmission or to recover from the broken link could cause a data packet to be dropped, increase the time it takes to recover from a broken link and degrade network performance. Both mechanisms use a cross-layer interaction between the MAC and routing layer with the aim of enhancing network performance.

The first proposed MAC mechanism (RIVC) aims to improve communication reliability in a multipath multichannel routing protocol and mitigate transmitting/rerouting data packets to a receiver that has no/invalid route (NRTE) towards the final destination node. RIVC provides an early invalid route detection and early rerouting mechanism. It uses existing RTS/CTS frames with slight modifications to enable the transmitter to check the route validity at the receiver node.

The second proposed MAC mechanism (MB) aims to reduce contention in a busy medium by enabling the transmitter node to reroute the data packet via the pre-discovered alternative route when the retry count reaches a pre-defined threshold (CRL) (after the third retry).

Using the NS-2 simulator, the performance of the proposed mechanisms is compared with the multipath multichannel routing protocol RMMMC under different network conditions. The simulation results suggest that the proposed mechanisms (MB, RIVC and RIVC-MB) improve network performance, as network density increases compared with RMMMC protocol. With regard to the impact of node mobility, the proposed mechanism shows superior performance in most of the performance metrics, as with all reported node mobility. Rapid changes to network topology mean that a pre-discovered alternative path may not reflect the current state of the network. The results suggest that the proposed mechanism RIVC manages to mitigate the issue of transmitting/rerouting data to a node that has a NRTE issue and improve communication reliability in the multipath multichannel routing protocol. With regard to the impact of increasing the number of connections in the network, the proposed mechanisms show superior performance compared with the RMMMC protocol in a network with low to relatively high load. This is mainly due to frequent rerouting of data packets to different channels in the proposed mechanism. Hence, the occurrence and impact of multichannel hidden terminal deafness issues are not very pronounced as in a network with a high load. Combining RIVC and MB mechanisms in one protocol (RIVC-MB) seems to not make any major improvement to the network performance and hence, it is recommended to not combine them to reduce the protocol complexity.

Based on the reported results and discussions in this chapter, the proposed MAC mechanisms MB, RIVC and RIVC-MB show the potential to improve communication reliability in a multipath multichannel routing protocol with RIVC proving the most promising. However, the performance of the proposed mechanisms are slightly affected by the increases in the number of connections in the network. This is perhaps due to the fact that each node can only monitor activities in their listening channel as they are equipped with a single transceiver. Also, due to rapid topology changes, frequent rerouting to different channels may increase the impact of the multichannel hidden terminal and deafness problems.

Chapter 8

Conclusions

8.1 Introduction

This thesis aims to enhance the performance of routing protocols in mobile wireless ad hoc networks (MANETs) by utilising multiple channels in communication. Utilising multiple non-overlapping channels can improve network performance by enabling adjacent nodes to communicate concurrently using different channels. This thesis investigates and studies the impact of utilising single-path and multipath multichannel routing protocols in MANETs under the constraints that each node in the network is equipped with a single half-duplex transceiver and does not rely on a common control channel or time synchronisation.

This chapter concludes the thesis. Its conclusions are presented in Section 8.2. Section 8.3 discusses the limitations of the presented works and potential future research directions.

8.2 Thesis Contributions

This research has investigated the applicability of deploying single-path and multipath multichannel routing protocols using the RDT communication scheme in MANETs under the constraints that each node is equipped with a single radio interface and does not rely on a common control channel or time synchronisation. This section details its main discoveries.

1. A analyses and investigates the performance of a single-path multichannel routing protocol based on the RDT communication scheme using a single half-duplex transceiver and without relying on a common channel or time synchronisation. The majority of multichannel protocols based on the RDT scheme aim to address the anticipated issues, namely the multichannel hidden terminal problem, the deafness problem and broadcasting support, related to the RDT scheme without studying and investigating the scheme under different network environments. They usually utilise an extra radio interface, dual home channels or time synchronisation to address these issues without a proper investigation to the scheme.

   Extensive simulation studies presented in Chapter 5 show that using the RDT communication scheme with a single transceiver, and without relying on extra hardware, a control channel or time synchronisation, can implement a multichannel MANETs and improve network performance and capacity. The results show that a single-path multichannel RDT protocol outperforms the single-path single channel AODV protocol in all reported network configurations. Another important result is that while the performance of RDT scheme is slightly affected by increasing network density and node mobility, a noticeable performance degradation takes place as the traffic load in the network increases. This is due to the issues of multichannel hidden terminals and deafness becoming more pronounced in a network with a high load.

2. A new multipath multichannel routing protocol, called RMMMC, is introduced to enhance reliability and fault-tolerance in MANETs. It can find multiple node and channel disjointed routes to destinations. RMMMC can recover from a single or multiple links failure regardless of their location seamlessly using pre-discovered backup paths and without incurring extra routing overhead or delay to repair broken links.

3. Introducing a new cross-layer multichannel MAC mechanism, called RIVC

can enhance communication reliability in multipath multichannel routing protocols using a single transceiver. RIVC supports interaction between the MAC and routing layer protocols to mitigate the issue of transmitting/rerouting data packets to intermediate nodes that have stale (out-of-date) routing towards a final destination. Thus, only data packets with valid routes are allowed to occupy bandwidth in the medium. RIVC provides early invalid route detection and early switchover to an alternative path in a different channel.

4. Introducing a cross-layer multichannel MAC mechanism called MB enhances load balancing and reduce contention in a busy channel. MB supports interaction between the MAC and routing protocols to enable a transmitter node to invoke an alternative route when the retry count in the current channel reaches a threshold.

5. The proposed multichannel solutions in this thesis are implemented and extensively evaluated using the well-known Network Simulator (NS-2). The performance of the proposed protocols are compared with the standard single-path (AODV) and multipath (AOMDV) routing protocols in MANET and the proposed protocols show a clear improvement in network performance and routing functionality. Additionally, the performance of the proposed protocols compares against a multichannel multi-radio protocol (xRDT).

8.3 Future Work

The work presented in this thesis has several limitations. they are worth studying in the future to enhance the performance of multichannel networks further. Some potential future directions are as follows:

- In Chapter 5 an in-depth investigation is performed to evaluate the performance of the multichannel RDT communication scheme. RDT assumes that the selection and distribution of all nodes *quiescent channels* is achieved via a separate mechanism. It would be interesting to investigate a distributed channel assignment mechanism which lets each node in the network become aware of other nodes *quiescent channels* while reducing the channel assignment overhead. This would enable a multichannel communication in the network without necessitating a channel negotiation or agreement.

- In Chapter 6 a multipath multichannel routing protocol is proposed to enhance reliability and fault-tolerance in MANETs. The proposed route discovery mechanism initiates two route discoveries in two different channels. However, a single multi-hop route is established in each channel. If both routes are broken and cannot be repaired, then a new route discovery process may be required which could increase the routing overhead and collisions in the network. It would be interesting to research enabling multiple route formation during any route discovery process in each channel. Thus multiple routes in each channel might be established using a single route discovery process. This would increase the availability of backup routes, increase the chance of recovering from a broken link and enhance the fault-tolerance in the MANET.

- Maintaining local connectivity in a multichannel routing protocol with a single transceiver and without deploying a common control channel or time synchronisation is not trivial. One research direction might be to investigate and design a mechanism to support local connectivity in a multichannel environment while reducing the routing overhead, collisions and energy consumption. This may require a dynamic adjustment of $HELLO\_INTERVAL$ and $ALLOWED\_HELLO\_LOSS$ parameters based on some metrics such as node velocity, the estimation of link changes or available battery life of nodes.

- This study consider the hop count as the main routing metric. However, different routing metrics could be explored to enhance routing decisions by considering the factors of interference, link quality and channel utilisation. Weighed Cumulative Expected Transmission Time (WCETT) [139], interference Aware routing metric (iAware) [199] and Weighted End-to-End Delay (WEED) [200] are examples of such routing metrics.

- In Chapter 7 a cross-layer MAC mechanism (MB) was designed to enhance load balancing and reduce contention in a busy channel. The decision to invoke an alternative channel is based on a static threshold value (CRL). It would be interesting to make the setting of the CRL threshold dynamic and based on some metrics such as the channel utilisation, node velocity or Received Signal Strength Indicator (RSSI).

- The proposed solutions in Chapters 5, 6 and 7 were evaluated using the software simulation tool NS-2. Although extensive simulations were conducted to evaluate the proposed solutions under different network conditions, further investigations could be undertaken to characterise the capability and scalability of the proposed protocols under different environments. For instance, a different node mobility model (Random Walk), a different traffic type (TCP), a larger network size or different changes to node density, mobility or connections in the network could be used to explore the performance of the proposed protocols under a wider range of conditions.

- Implementing the proposed solutions using a real environment is another interesting direction of research. This would assess the performance of the proposed solutions in the real world. However, it would require a larger outlay on wireless devices and extensive programming efforts to implement and evaluate them.

Appendix A

Comparison Data

This appendix presents samples of data used to produce the figures in this thesis. The data included in this appendix are related to the Packet Delivery Ratio (PDR) figures in Chapters 5, 6 and 7. The PDR metric was chosen as it is considered to be one of the most important metrics in this study. The data provided in the following sections represents the quantitative comparison of PDR under different network settings against different protocols.

The simulation settings used to obtain these results were explained in 4.6.1 and they are based on 25 runs, and 95% confidence level. Each row in the provided tables include number of mobile nodes, maximum node speed or number of connections), mean, Standard Deviation (StD) and the Confidence Interval (ConI).

A.1 Chapter 5

Table A.1: PDR vs. network density (related to Figure 5.11 in Chapter 5)

Node Density	**AODV**			**xRDT**			**RDT-AODV**		
	Mean	*StD*	*ConI*	*Mean*	*StD*	*ConI*	*Mean*	*StD*	*ConI*
50	62.02	6.56	± 2.57	96.46	2.09	± 0.82	66.94	5.62	± 2.20
100	24.49	4.97	± 1.95	98.29	0.81	± 0.32	75.50	4.44	± 1.74
150	17.83	4.12	± 1.61	98.43	0.81	± 0.32	79.42	3.12	± 1.22
200	13.2	4.07	± 1.59	98.12	1.21	± 0.47	79.05	4.10	± 1.61
250	10.07	3.47	± 1.36	98.13	1.78	± 0.70	79.51	2.98	± 1.17
300	8.31	3.30	± 1.29	98.63	0.54	± 0.21	81.47	3.53	± 1.39

Table A.2: PDR vs. node mobility (related to Figure 5.19 in Chapter 5)

Node Mobility	AODV			xRDT			RDT-AODV		
	Mean	*StD*	*ConI*	*Mean*	*StD*	*ConI*	*Mean*	*StD*	*ConI*
1	15.99	6.59	± 2.58	99.38	0.97	± 0.38	87.23	4.76	± 1.87
5	13.65	4.38	± 1.72	98.85	1.32	± 0.52	82.76	4.41	± 1.73
10	13.20	4.07	± 1.59	98.12	1.21	± 0.47	79.05	4.10	± 1.61
15	11.47	3.13	± 1.23	97.78	1.09	± 0.43	77.21	4.44	± 1.74
20	10.95	2.47	± 0.97	97.78	0.37	± 0.15	77.03	3.26	± 1.28
25	11.60	2.97	± 1.16	97.30	0.48	± 0.19	75.42	3.16	± 1.24
30	11.26	3.33	± 1.30	96.54	1.34	± 0.53	74.65	3.34	± 1.31

Table A.3: PDR vs. number of connections (related to Figure 5.27 in Chapter 5)

Node Connections	AODV			xRDT			RDT-AODV		
	Mean	*StD*	*ConI*	*Mean*	*StD*	*ConI*	*Mean*	*StD*	*ConI*
10	59.15	23.13	± 9.07	98.84	0.18	± 0.07	76.15	5.49	± 2.15
15	20.78	6.77	± 2.65	98.78	0.24	± 0.10	77.83	3.38	± 1.33
20	13.20	4.07	± 1.59	98.12	1.21	± 0.47	79.05	4.10	± 1.61
25	11.56	2.56	± 1	98.12	1.16	± 0.45	76.51	6.31	± 2.47
30	7.68	1.92	± 0.75	97.01	1.44	± 0.57	73.20	7.69	± 3.02
35	6.04	1.50	± 0.59	95.95	1.79	± 0.7	52.68	12.93	± 5.07
40	5.75	1.95	± 0.76	92	3.67	± 1.44	40.51	16.05	± 6.29

A.2 Chapter 6

Table A.4: PDR vs. network density (related to Figure 6.17 in Chapter 6)

Node Density	AOMDV			RDT-AODV			RMMMC		
	Mean	*StD*	*ConI*	*Mean*	*StD*	*ConI*	*Mean*	*StD*	*ConI*
50	67.55	6.24	± 2.44	66.94	5.62	± 2.20	69.90	5.21	± 2.04
100	61.89	6.08	± 2.38	75.50	4.44	± 1.74	81.14	3.88	± 1.52
150	61.38	5.98	± 2.34	79.42	3.12	± 1.22	82.94	3.63	± 1.42
200	53.65	5.16	± 2.02	79.05	4.10	± 1.61	82.36	3.01	± 1.18
250	46.99	7.35	± 2.88	79.51	2.98	± 1.17	82.88	2.71	± 1.06
300	43.56	11.92	± 4.67	81.47	3.53	± 1.39	81.74	3.77	± 1.48

Table A.5: PDR vs. node mobility (related to Figure 6.27 in Chapter 6)

Node Mobility	AOMDV			RDT-AODV			RMMMC		
	Mean	*StD*	*ConI*	*Mean*	*StD*	*ConI*	*Mean*	*StD*	*ConI*
1	63.51	10.46	± 4.10	87.23	4.76	± 1.87	92.17	3.69	± 1.45
5	56.80	8.80	± 3.45	82.76	4.41	± 1.73	86.75	3.75	± 1.47
10	53.65	5.16	± 2.02	79.05	4.10	± 1.61	82.36	3.01	± 1.18
15	49.51	7.65	± 3.00	77.21	4.44	± 1.74	77.82	3.81	± 1.49
20	50.09	5.06	± 1.98	77.03	3.26	± 1.28	75.08	3.24	± 1.27
25	47.56	5.45	± 2.14	75.42	3.16	± 1.24	70.91	3.21	± 1.26
30	46.14	4.69	± 1.84	74.65	3.34	± 1.31	67.45	3.64	± 1.43

Table A.6: PDR vs. number of connections (related to Figure 6.36 in Chapter 6)

Number of Connections	**AOMDV**			**RDT-AODV**			**RMMMC**		
	Mean	*StD*	*ConI*	*Mean*	*StD*	*ConI*	*Mean*	*StD*	*ConI*
10	79.63	3.48	± 1.37	76.15	5.49	± 2.15	86.63	4.29	± 1.68
15	71.37	7.37	± 2.89	77.83	3.38	± 1.33	86.09	2.67	± 1.05
20	53.65	5.16	± 2.02	79.05	4.10	± 1.61	82.36	3.01	± 1.18
25	39.99	6.78	± 2.66	76.51	6.31	± 2.47	76.64	4.23	± 1.66
30	25.84	4.58	± 1.80	73.20	7.69	± 3.02	73.38	2.79	± 1.10
35	20.14	4.07	± 1.60	52.68	12.93	± 5.07	63.53	5.54	± 2.17
40	16.12	2.91	± 1.14	40.51	16.05	± 6.29	59.72	4.94	± 1.94

A.3 Chapter 7

Table A.7: PDR vs. network density (related to Figure 7.18 in Chapter 7)

Node Density	**RMMMC**			**RIVC**			**MB**			**RIVC-MB**		
	Mean	*StD*	*ConI*	*Mean*	*StD*	*ConI*	*Mean*	*StD*	*ConI*	*Mean*	*StD*	*ConI*
50	69.90	5.21	± 2.04	74.23	4.96	± 1.94	72.47	4.94	± 1.94	73.93	5.04	± 1.98
100	81.14	3.88	± 1.52	88.08	4.03	± 1.58	84.24	4.20	± 1.65	88.48	3.77	± 1.48
150	82.94	3.63	± 1.42	91.62	2.53	± 0.99	87.51	3.05	± 1.19	91.69	2.42	± 0.95
200	82.36	3.01	± 1.18	89.70	3.48	± 1.36	85.95	3.07	± 1.20	89.68	3.35	± 1.31
250	82.88	2.71	± 1.06	89.73	3.29	± 1.29	86.14	2.72	± 1.06	89.61	3.13	± 1.23
300	81.74	3.77	± 1.48	87.26	3.26	± 1.28	84.73	3.50	± 1.37	87.31	3.54	± 1.39

Table A.8: PDR vs. node mobility (related to Figure 7.23 in Chapter 7)

Node Mobility	RMMMC			RIVC			MB			RIVC-MB		
	Mean	*StD*	*ConI*	*Mean*	*StD*	*ConI*	*Mean*	*StD*	*ConI*	*Mean*	*StD*	*ConI*
1	92.17	3.69	± 1.45	93.89	4.48	± 1.76	90.99	4.10	± 1.61	93.90	4.52	± 1.77
5	86.75	3.75	± 1.47	91.43	3.92	± 1.54	88.64	3.93	± 1.54	91.39	4.19	± 1.64
10	82.36	3.01	± 1.18	89.70	3.48	± 1.36	85.95	3.07	± 1.20	89.68	3.35	± 1.31
15	77.82	3.81	± 1.49	86.90	4.10	± 1.61	83.05	3.83	± 1.50	86.63	4.35	± 1.70
20	75.08	3.24	± 1.27	85.55	3.05	± 1.20	81.44	2.81	± 1.10	85.43	3.18	± 1.25
25	70.91	3.21	± 1.26	83.35	3.06	± 1.20	79.05	2.85	± 1.12	83.03	3.04	± 1.19
30	67.45	3.64	± 1.43	80.78	2.83	± 1.11	76.83	2.52	± 0.99	80.79	3.05	± 1.20

Table A.9: PDR vs. number of connections (related to Figure 7.28 in Chapter 7)

Number of Connections	RMMMC			RIVC			MB			RIVC-MB		
	Mean	*StD*	*ConI*	*Mean*	*StD*	*ConI*	*Mean*	*StD*	*ConI*	*Mean*	*StD*	*ConI*
10	86.63	4.29	± 1.68	95.74	1.37	± 0.54	91.51	1.99	± 0.78	95.71	1.39	± 0.55
15	86.09	2.67	± 1.05	94.67	1.38	± 0.54	90.45	1.72	± 0.67	94.64	1.01	± 0.39
20	82.36	3.01	± 1.18	89.70	3.48	± 1.36	85.95	3.07	± 1.20	89.68	3.35	± 1.31
25	76.64	4.23	± 1.66	81.51	3.83	± 1.50	78.46	4.11	± 1.61	80.87	4.14	± 1.62
30	73.38	2.79	± 1.10	75.69	3.58	± 1.40	74.02	3.87	± 1.52	75.67	4.02	± 1.57
35	63.53	5.54	± 2.17	62.27	7.36	± 2.89	60.79	5.36	± 2.10	62.97	5.48	± 2.15
40	59.72	4.94	± 1.94	57.85	4.58	± 1.80	55.40	4.71	± 1.85	57.20	4.40	± 1.73

References

[1] Mesut Güneş, DG Reina, JM Garcia Campos, and SL Toral. *Mobile Ad Hoc network protocols based on dissimilarity metrics.* Springer, 2017.

[2] Gaurav Khanna and Sanjay Kumar Chaturvedi. A comprehensive survey on multi-hop wireless networks: milestones, changing trends and concomitant challenges. *Wireless Personal Communications, Springer*, 101(2):677–722, 2018.

[3] Hongqiang Zhai and Yuguang Fang. Physical carrier sensing and spatial reuse in multirate and multihop wireless ad hoc networks. In *25th IEEE International Conference on Computer Communications.*, pages 1–12. IEEE, 2006.

[4] Chih-Min Chao, Hsien-Chen Tsai, and Chao-Ying Huang. Load-aware channel hopping protocol design for mobile ad hoc networks. *Wireless Networks, Springer*, 23(1):89–101, 2017.

[5] IEEE Standard for Information Technology - Telecommunications and information exchange between systems - Local and Metropolitan networks - Specific requirements - Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications: Higher Speed Physical Layer (PHY) Extension in the 2.4 GHz band. *IEEE Std 802.11b-1999*, pages 1–96, Jan 2000.

[6] Jingpu Shi, Theodoros Salonidis, and Edward W. Knightly. Starvation mitigation through multi-channel coordination in CSMA multi-hop wireless networks. In *Proceedings of the 7th ACM international symposium on Mobile ad hoc networking and computing. ACM*, pages 214–225, 2006.

[7] Piyush Gupta and Panganmala R. Kumar. The capacity of wireless networks. *IEEE Transactions on information theory, IEEE*, 46(2):388–404, 2000.

[8] Hon Sun Chiu, Kwan L. Yeung, and King-Shan Lui. Interface placement in constructing widest spanning tree for multi-channel multi-interface wireless mesh networks. In *IEEE Wireless Communications and Networking Conference*, pages 1–5. IEEE, 2009.

[9] Stephen Mueller, Rose P. Tsang, and Dipak Ghosal. Multipath routing in mobile ad hoc networks: Issues and challenges. In *Performance tools and applications to networked systems*, pages 209–234. Springer, 2004.

[10] Sung-Won Lee, Ji Yong Choi, Keun Woo Lim, Young-Bae Ko, and Byeong-Hee Roh. A reliable and hybrid multi-path routing protocol for multi-interface tactical ad hoc networks. In *Military Communications Conference*, pages 2237–2242. IEEE, 2010.

[11] Yashar Ganjali and Abtin Keshavarzian. Load balancing in ad hoc networks: single-path routing vs. multi-path routing. In *IEEE INFOCOM 2004*, volume 2, pages 1120–1125. IEEE, 2004.

[12] Nachum Shacham and Peter King. Architectures and performance of multichannel multihop packet radio networks. *IEEE Journal on Selected Areas in Communications, IEEE*, 5(6):1013–1025, 1987.

[13] Jochen H. Schiller. *Mobile communications*. Pearson education, 2003.

[14] IEEE Standard for Information Technology - Telecommunications and Information Exchange Between Systems - Local and Metropolitan Area Networks - Specific Requirements - Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications. *IEEE Std 802.11-2007 (Revision of IEEE Std 802.11-1999)*, pages 1–1076, June 2007.

[15] Hubert Zimmermann. OSI reference model–The ISO model of architecture for open systems interconnection. *IEEE Transactions on communications*, 28(4):425–432, 1980.

[16] Paul S. Henry and Hui Luo. WiFi: what's next? *IEEE Communications Magazine, IEEE*, 40(12):66–72, 2002.

[17] C. Siva Ram Murthy and B. S. Manoj. *Ad hoc wireless networks: Architectures and protocols*. Pearson Education India, 2004.

[18] Peter Rauschert, Arasch Honarbacht, and Anton Kummert. On the IEEE 802.11 IBSS and its timer synchronization function in multi-hop ad hoc networks. In *1st International Symposium on Wireless Communication Systems*, pages 304–308. IEEE, 2004.

[19] C. Perkins, E. Belding-Royer, and S. Das. Ad hoc on-demand distance vector (AODV) routing, IETF RFC 3561, IETF, 2003.

[20] David B. Johnson, David A. Maltz, and Josh Broch. DSR: The dynamic source routing protocol for multi-hop wireless ad hoc networks. In Charles E. Perkins, editor, *Ad Hoc Networking*, pages 139–172. Addison-Wesley, 2001.

[21] Charles E. Perkins and Pravin Bhagwat. Highly dynamic Destination-Sequenced Distance-Vector routing (DSDV) for mobile computers. *SIGCOMM Computer Communication Review, ACM*, 24(4):234–244, 1994.

[22] Stefano Basagni, Marco Conti, Silvia Giordano, and Ivan Stojmenovic. *Mobile ad hoc networking*. John Wiley & Sons, 2004.

[23] Chai K. Toh. *Ad hoc mobile wireless networks: protocols and systems*. Pearson Education, 2001.

[24] Guido R Hiertz, Dee Denteneer, Lothar Stibor, Yunpeng Zang, Xavier Pérez Costa, and Bernhard Walke. The IEEE 802.11 universe. *IEEE Communications Magazine, IEEE*, 48(1):62–70, 2010.

[25] Subir Kumar Sarkar, Tiptur Gangaraju Basavaraju, and C Puttamadappa. *Ad hoc mobile wireless networks: principles, protocols, and applications*. CRC Press, 2016.

[26] Pushpa R Suri and Sona Rani. Bluetooth network-the adhoc network concept. In *2007 IEEE SoutheastCon Proceedings*, pages 720–720. IEEE, 2007.

[27] Naeem Raza, Muhammad Umar Aftab, Muhammad Qasim Akbar, Omair Ashraf, and Muhammad Irfan. Mobile ad-hoc networks applications and its challenges. *Communications and Network*, 8(3):131–136, 2016.

[28] The Internet Engineering Task Force (IETF). `https://tools.ietf.org/wg/manet/` [last retrieved: February, 2019].

[29] Azzedine Boukerche. *Algorithms and protocols for wireless and mobile ad hoc networks*, volume 77. John Wiley and Sons, 2008.

[30] R. S. King. Building a Subversive Grassroots Network: How Commotion Wireless plans to enable digital communication in the face of an Internet shutdown. *IEEE Spectrum*, 2011.

[31] Marco Conti and Silvia Giordano. Mobile ad hoc networking: milestones, challenges, and new research directions. *IEEE Communications Magazine, IEEE*, 52(1):85–96, 2014.

[32] Martin W Murhammer, Orcun Atakan, Stefan Bretz, Larry R Pugh, Kazunari Suzuki, and David H Wood. *TCP/IP tutorial and technical overview*. Prentice Hall, Upper Saddle River, NJ, 1998.

[33] Dzmitry Kliazovich and Fabrizio Granelli. Introduction: Why cross-layer? Its advantages and disadvantages. *Cross Layer Designs in WLAN Systems, roubador Publishing Ltd*, pages 1–32, 2010.

[34] Leslie Jill Miller. The ISO reference model of open systems interconnection: a first tutorial. In *Proceedings of the ACM'81 conference*, pages 283–288. ACM, 1981.

[35] George Xylomenos and George C Polyzos. TCP and UDP performance over a wireless LAN. In *IEEE Conference on Computer Communications. Proceed-*

ings. 18th Annual Joint Conference of the IEEE Computer and Communications Societies., volume 2, pages 439–446. IEEE, 1999.

[36] Jonathan Loo, Jaime Lloret Mauri, and Jesus Hamilton Ortiz. *Mobile ad hoc networks: current status and future trends.* CRC Press, 2016.

[37] C. Siva Ram Murthy and B.S. Manoj. *Ad Hoc Wireless Networks: Architectures and Protocols.* Prentice Hall PTR, Upper Saddle River, NJ, USA, 2004.

[38] Sergio Verdú. Wireless bandwidth in the making. *IEEE communications Magazine, IEEE*, 38(7):53–58, 2000.

[39] Daeyoung Kim, Mary Ann Ingram, and W. Whit Smith. Measurements of small-scale fading and path loss for long range RF tags. *IEEE Transactions on Antennas and Propagation, IEEE*, 51(8):1740–1749, 2003.

[40] Martin J. Feuerstein, Kenneth L. Blackard, Theodore S. Rappaport, Scott Y. Seidel, and Howard H. Xia. Path loss, delay spread, and outage models as functions of antenna height for microcellular system design. *IEEE Transactions on Vehicular Technology, IEEE*, 43(3):487–498, 1994.

[41] David Tse and Pramod Viswanath. *Fundamentals of wireless communication.* Cambridge University Press, 2005.

[42] Aman Arora and Marwan Krunz. Interference-limited MAC protocol for MANETs with directional antennas. In *6th IEEE International Symposium on a World of Wireless Mobile and Multimedia Networks, WoWMoM'5.*, pages 2–10. IEEE, 2005.

[43] Somprakash Bandyopadhyay, Siuli Roy, and Tetsuro Ueda. *Enhancing the performance of ad hoc wireless networks with smart antennas.* Auerbach Publications, 2016.

[44] Neha Kumai, Rohit Kumar, and Rohit Bajaj. Mobile ad hoc networks and energy efficiency using directional antennas: A Review. In *International Con-*

ference on Intelligent Computing and Control Systems (ICICCS),, pages 1213–1219. IEEE, 2017.

[45] Arunesh Mishra, Vivek Shrivastava, Suman Banerjee, and William Arbaugh. Partially overlapped channels not considered harmful. In *ACM SIGMETRICS Performance Evaluation Review*, volume 34, pages 63–74. ACM, 2006.

[46] Ozlem Durmaz Incel and Pierre Jansen. Characterization of multi-channel interference. In *Proceedings of the 6th International Symposium on Modeling and Optimization in Mobile, Ad Hoc, and Wireless Networks*, pages 429–435. IEEE, 2008.

[47] Banoj Kumar Panda, Bibhudatta Dash, Rupanita Das, and Ajit Sarangi. Mobility and its impact on performance of AODV and DSR in mobile ad hoc networks. In *3rd Asian Himalayas International Conference on Internet (AH-ICI)*, pages 1–5. IEEE, 2012.

[48] Stefano Basagni, Imrich Chlamtac, Violet R Syrotiuk, and Barry A Woodward. A distance routing effect algorithm for mobility (dream). In *Proceedings of the 4th annual ACM/IEEE international conference on Mobile computing and networking*, pages 76–84. ACM, 1998.

[49] Imrich Chlamtac, Marco Conti, and Jennifer J. N. Liu. Mobile ad hoc networking: imperatives and challenges. *Ad hoc networks, Elsevier*, 1(1):13–64, 2003.

[50] G. S. Mamatha and S.C. Sharma. Analyzing the MANET variations, Challenges, Capacity and protocol issues. *International Journal of Computer Science an Engineering Survey (IJCSES)*, 1(1):14–21, 2010.

[51] Waheb A Jabbar, Mahamod Ismail, Rosdiadee Nordin, and Suki Arif. Power-efficient routing schemes for MANETs: a survey and open issues. *Wireless Networks, Springer*, 23(6):1917–1952, 2017.

[52] Song Guo and Oliver W. W. Yang. Energy-aware multicasting in wireless ad

hoc networks: A survey and discussion. *Computer Communications, Elsevier*, 30(9):2129–2148, 2007.

[53] Daniela Tulone and Samuel Madden. An energy-efficient querying framework in sensor networks for detecting node similarities. In *Proceedings of the 9th ACM international symposium on Modeling analysis and simulation of wireless and mobile systems*, pages 191–300. ACM, 2006.

[54] Priyanka Goyal, Sahil Batra, and Ajit Singh. A literature review of security attack in mobile ad-hoc networks. *International Journal of Computer Applications*, 9(12):11–15, 2010.

[55] Rashid Sheikh, Mahakal Singh Chande, and Durgesh Kumar Mishra. Security issues in MANET: A review. In *2010 7th International Conference On Wireless And Optical Communications Networks (WOCN)*, pages 1–4. IEEE, 2010.

[56] Mohamed A. Abdelshafy and Peter J.B. King. Analysis of security attacks on AODV routing. In *8th International Conference for Internet Technology and Secured Transactions (ICITST)*, pages 290–295, London, UK, 2013.

[57] Mahima Chitkara and Mohd Waseem Ahmad. Review on MANETs: Characteristics, Challenges, Imperatives and Routing Protocols. *International Journal of Computer Science and Mobile Computing*, 3(2):432–437, 2014.

[58] Diaa Ahmed and Othman Khalifa. An overview of MANETs: applications, characteristics, challenges and recent issues. *International Journal of Engineering and Advanced Technology*, 3:128, 2017.

[59] Adrian J Pullin and Colin Pattinson. A realistic battlefield model for the evaluation of MANET. In *5th Annual Conference on Wireless on Demand Network Systems and Services*, pages 81–84. IEEE, 2008.

[60] Shaik Shabana Anjum, Rafidah Md Noor, and Mohammad Hossein Anisi. Review on MANET based communication for search and rescue operations. *Wireless Personal Communications, Springer*, 94(1):31–52, 2017.

[61] Mian Tan, Ling Fang, Yue Wu, Bo Zhang, Bowen Chang, Petter Holme, and Jing Zhao. A fault-tolerant small world topology control model in ad hoc networks for search and rescue. *Physics Letters AÙĹ Elsevier*, 382(7):467–476, 2018.

[62] Husna Osman and Hamish Taylor. Towards a reference model for m-commerce over ad hoc wireless networks. In *Proceedings of E-Activity and Leading Technologies (E-ALT) Conference, IASK*, pages 223–232, 2008.

[63] Alexandros Vasiliou and Anastasios A Economides. Mobile collaborative learning using multicast MANETs. *International Journal of Mobile Communications*, 5(4):423–444, 2007.

[64] Yalong Wu, Wei Yu, Fang Yuan, Jin Zhang, Chao Lu, James H Nguyen, and Daniel Ku. A Cross-Domain Optimization Scheme for MANET Communications in Heterogeneous Networks. *EAI Endorsed Transactions on Wireless Spectrum*, 3(12):e3, 2017.

[65] Nagham H. Saeed, Maysam F. Abbod, and Hamed S. Al-Raweshidy. MANET routing protocols taxonomy. In *2012 International Conference on Future Communication Networks (ICFCN)*, pages 123–128. IEEE, 2012.

[66] Diaa Eldein Mustafa Ahmed and Othman O. Khalifa. A Comprehensive Classification of MANETs Routing Protocols. *IJCAT*, 6:141–158, 2017.

[67] Harjeet Kaur, Varsha Sahni, and Manju Bala. A survey of reactive, proactive and hybrid routing protocols in MANET: A review. *International Journal of Computer Science and Information Technologies (IJCSIT)*, 4(3):498–500, 2013.

[68] Mohammed Tarique, Kemal E. Tepe, Sasan Adibi, and Shervin Erfani. Survey of multipath routing protocols for mobile ad hoc networks. *Journal of Network and Computer Applications, Elsevier*, 32(6):1125–1143, 2009.

[69] Guangyu Pei, Mario Gerla, and Tsu-Wei Chen. Fisheye state routing: A

routing scheme for ad hoc wireless networks. In *IEEE International Conference on Communications. ICC (2000)*, volume 1, pages 70–74. IEEE, 2000.

[70] P. Jacquet, P. Muhlethaler, T. Clausen, A. Laouiti, A. Qayyum, and L. Viennot. Optimized link state routing protocol for ad hoc networks, ieee. In *Proceedings of IEEE International Multi Topic Conference (INMIC) Technology for the 21st Century*, pages 62–68, 2001.

[71] Mehran Abolhasan, Tadeusz Wysocki, and Eryk Dutkiewicz. A review of routing protocols for mobile ad hoc networks. *Ad hoc networks, Elsevier*, 2(1):1–22, 2004.

[72] Zygmunt J. Haas. A new routing protocol for the reconfigurable wireless networks. In *6th IEEE International Conference on Universal Personal Communications Record*, volume 2, pages 562–566. IEEE, 1997.

[73] Prasun Sinha Raghupathy, Prasun Sinha, Raghupathy Sivakumar, and Vaduvur Bharghavan. CEDAR: a core-extraction distributed ad hoc routing algorithm. *IEEE Journal on Selected Areas in Communications, IEEE*, 17:1454–1465, 1999.

[74] Navid Nikaein, Christian Bonnet, and Neda Nikaein. Harp-hybrid ad hoc routing protocol. In *Proceedings of international symposium on telecommunications (IST)*, pages 56–67, 2001.

[75] Jack Tsai and Tim Moors. A review of multipath routing protocols: From wireless ad hoc to mesh networks. In *ACoRN early career researcher workshop on wireless multihop networking*, volume 30, 2006.

[76] A Jayashree, GS Biradar, and VD Mytri. Review of Multipath Routing Protocols in Wireless Multimedia Sensor Network-A Survey. *International Journal of Scientific Engineering Research*, 3(7):1–9, 2012.

[77] Ender Ayanoglu, I. Chih-Lin, Richard D. Gitlin, and James E. Mazo. Diversity coding for transparent self-healing and fault-tolerant communication networks. *IEEE Transactions on communications, IEEE*, 41(11):1677–1686, 1993.

[78] Stefan Dulman, Tim Nieberg, Jian Wu, and Paul Havinga. Trade-off between traffic overhead and reliability in multipath routing for wireless sensor networks. In *IEEE Wireless Communications and Networking*, volume 3, pages 1918–1922. IEEE, 2003.

[79] Philipp Hurni and Torsten Braun. Energy-efficient multi-path routing in wireless sensor networks. In *International Conference on Ad-Hoc Networks and Wireless*, pages 72–85. Springer, 2008.

[80] Mahesh K. Marina and Samir R. Das. Ad hoc on-demand multipath distance vector routing. *Wireless Communications and Mobile Ccomputing (WCMC): Special Issue: Wireless Ad Hoc Networks: Technologies and Challenges*, 6(7):969–988, 2006.

[81] S. J. Lee and Mario Gerla. Split multipath routing with maximally disjoint paths in ad hoc networks. In *IEEE International Conference on Communications (ICC 2001)*, volume 10, pages 3201–3205. IEEE, 2001.

[82] Marc R. Pearlman, Zygmunt J. Haas, Peter Sholander, and Siamak S. Tabrizi. On the impact of alternate path routing for load balancing in mobile ad hoc networks. In *First Annual Workshop on Mobile and Ad Hoc Networking and Computing*, pages 3–10. IEEE, 2000.

[83] Sonia Waharte and Raouf Boutaba. Totally disjoint multipath routing in multihop wireless networks. In *IEEE International Conference on Communications*, volume 12, pages 5576–5581. IEEE, 2006.

[84] IEEE Standard for Information Technology - Telecommunications and Information Exchange Between Systems - Local and Metropolitan Area Networks - Specific Requirements - Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications. *IEEE Std 802.11-2007 (Revision of IEEE Std 802.11-1999)*, pages 1–1076, June 2007.

[85] Shugong Xu and Tarek Saadawi. Does the IEEE 802.11 MAC protocol work

well in multihop wireless ad hoc networks? *IEEE communications Magazine, IEEE*, 39(6):130–137, 2001.

[86] Cheikh Sarr, Claude Chaudet, Guillaume Chelius, and Isabelle Guérin Lassous. Bandwidth estimation for IEEE 802.11-based ad hoc networks. *IEEE transactions on Mobile Computing, IEEE*, 7(10):1228–1241, 2008.

[87] Jinyang Li, Charles Blake, Douglas S. J. De Couto, Hu Imm Lee, and Robert Morris. Capacity of ad hoc wireless networks. In *Proceedings of the 7th annual international conference on Mobile computing and networking*, pages 61–69. ACM, 2001.

[88] Pradeep Kyasanur and Nitin H. Vaidya. Capacity of multi-channel wireless networks: impact of number of channels and interfaces. In *Proceedings of the 11th annual international conference on Mobile computing and networking*, pages 43–57. ACM, 2005.

[89] Jaewook Shin and Hyunchol Shin. A 1.9 - 3.8 GHz fractional-N PLL frequency synthesizer with fast auto-calibration of loop bandwidth and VCO frequency. *IEEE Journal of Solid-State Circuits, IEEE*, 47(3):665–675, 2012.

[90] Senthilmurugan Sengottuvelan, Junaid Ansari, Petri Mähönen, TG Venkatesh, and Marina Petrova. Channel selection algorithm for Cognitive Radio Networks with heavy-tailed idle times. *IEEE Transactions on Mobile Computing, IEEE*, 16(5):1258–1271, 2016.

[91] Mobashir Mohammad, Manjunath Doddavenkatappa, and Mun Choon Chan. Improving performance of synchronous transmission-based protocols using capture effect over multichannels. *ACM Transactions on Sensor Networks (TOSN), ACM*, 13(2):10, 2017.

[92] Max2828/max2829 world-band transceiver ics datasheets. `https://datasheets.maximintegrated.com/en/ds/MAX2828-MAX2829.pdf`. last retrieved: April, 2019.

[93] GholamHossein EkbataniFard and Reza Monsefi. A detailed review of multi-channel medium access control protocols for wireless sensor networks. *International Journal of Wireless Information Networks, Springer*, 19(1):1–21, 2012.

[94] Rana Diab, Gérard Chalhoub, and Michel Misson. Overview on multi-channel communications in wireless sensor networks. *Network Protocols and Algorithms*, 5(3):112–135, 2013.

[95] Ridha Soua and Pascale Minet. A survey on multichannel assignment protocols in wireless sensor networks. In *Wireless Days (WD), 2011 IFIP*, pages 1–3. IEEE, 2011.

[96] Hong-jiang Lei, Gao Chao, Yong-Cai Guo, and Zhi-Zhong Zhang. Survey of multi-channel MAC protocols for IEEE 802.11-based wireless Mesh networks. *The Journal of China Universities of Posts and Telecommunications, Elsevier*, 18(2):33–44, 2011.

[97] Ozlem Durmaz Incel. A survey on multi-channel communication in wireless sensor networks. *Computer Networks, Elsevier*, 55(13):3081–3099, 2011.

[98] Jungmin So and Nitin H. Vaidya. Multi-channel MAC for ad hoc networks: handling multi-channel hidden terminals using a single transceiver. In *Proceedings of the 5th ACM international symposium on Mobile ad hoc networking and computing*, pages 222–233. ACM, 2004.

[99] Pradeep Kyasanur, Jungmin So, Chandrakanth Chereddi, and Nitin H Vaidya. Multichannel mesh networks: challenges and protocols. *IEEE Wireless Communications Magazine, IEEE*, 13(2):30–36, 2006.

[100] Jeonghoon Mo, Hoi-Sheung Wilson So, and Jean Walrand. Comparison of multichannel mac protocols. *IEEE Transactions on mobile computing, IEEE*, 7(1):50–65, 2008.

[101] Maxim 2.4 ghz 802.11b zero-if transceivers. `https://pdfserv.`

maximintegrated.com/en/ds/MAX2820-MAX2821.pdf. last retrieved: February, 2019.

[102] Shuo Wang, Qiao Li, Yule Jiang, and Huagang Xiong. Stable on-demand multipath routing for mobile ad hoc networks. In *2009 Asia-Pacific Conference on Computational Intelligence and Industrial Applications (PACIIA)*, volume 2, pages 318–321. IEEE, 2009.

[103] Ramanuja Vedantham, Sandeep Kakumanu, Sriram Lakshmanan, and Raghupathy Sivakumar. Component based channel assignment in single radio, multichannel ad hoc networks. In *Proceedings of the 12th annual international conference on Mobile computing and networking*, pages 378–389. ACM, 2006.

[104] Paramvir Bahl, Ranveer Chandra, and John Dunagan. SSCH: Slotted seeded channel hopping for capacity improvement in IEEE 802.11 ad-hoc wireless networks. In *Proceedings of the 10th Annual International Conference on Mobile Computing and Networking.*, pages 216–230. ACM, 2004.

[105] Jungmin So and Nitin H. Vaidya. A routing protocol for utilizing multiple channels in multi-hop wireless networks with a single transceiver. *University of Illinois at Urbana-Champaign*, pages 1–10, 2004.

[106] Bo Yan and Hamid Gharavi. Multi-path multi-channel routing protocol. In *Fifth IEEE International Symposium on Network Computing and Applications (NCA'06)*, pages 27–31. IEEE, 2006.

[107] Pradeep Kyasanur and Nitin H. Vaidya. Routing and interface assignment in multi-channel multi-interface wireless networks. In *IEEE Wireless Communications and Networking Conference*, volume 4, pages 2051–2056. IEEE, 2005.

[108] Unghee Lee, Scott F. Midkiff, and Jahng S. Park. A proactive routing protocol for multi-channel wireless ad-hoc networks (DSDV-MC). In *International Conference on Information Technology: Coding and Computing*, volume 2, pages 710–715. IEEE, 2005.

[109] Atul Adya, Paramvir Bahl, Jitendra Padhye, Alec Wolman, and Lidong Zhou. A multi-radio unification protocol for IEEE 802.11 wireless networks. In *First International Conference on Broadband Networks*, pages 344–354. IEEE, 2004.

[110] Shih-Lin Wu, Chih-Yu Lin, Yu-Chee Tseng, and Jang-Laing Sheu. A new multi-channel MAC protocol with on-demand channel assignment for multi-hop mobile ad hoc networks. In *International Symposium on Parallel Architectures, Algorithms and Networks*, pages 232–237. IEEE, 2000.

[111] Jaya Shankar Pathmasuntharam, Amitabha Das, and Anil K Gupta. Primary channel assignment based MAC (PCAM)-a multi-channel MAC protocol for multi-hop wireless networks. In *IEEE Wireless Communications and Networking Conference*, volume 2, pages 1110–1115. IEEE, 2004.

[112] Ritesh Maheshwari, Himansho Gupta, and Samir R. Das. Multichannel MAC protocols for wireless networks. In *3rd Annual IEEE Communications Society on Sensor and Ad Hoc Communications and Networks (SECON'06)*, volume 2, pages 393–401. IEEE, 2006.

[113] Bander H AlQarni and Ahmad S AlMogren. Reliable and energy efficient protocol for MANET multicasting. *Journal of Computer Networks and Communications, Hindawi*, 2016, 2016.

[114] Michelle X. Gong, Scott F. Midkiff, and Shiwen Mao. On-demand routing and channel assignment in multi-channel mobile ad hoc networks. *Ad Hoc Networks, Elsevier*, 7(1):63–78, 2009.

[115] Gin-Xian Kok, Chee-Onn Chow, Yi-Han Xu, and Hiroshi Ishii. EAOMDV-MIMC: A multipath routing protocol for multi-interface multi-channel mobile ad-hoc networks. *Wireless personal communications, Springer*, 73(3):477–504, 2013.

[116] Javed Abarik Torkestani and Mohammad Reza Meybodi. Channel Assignment in Wireless Mobile Ad Hoc Networks. In *Mobile Ad Hoc Networks*, pages 262–289. CRC Press, 2016.

[117] Jorge Crichigno, Min-You Wu, and Wei Shu. Protocols and architectures for channel assignment in wireless mesh networks. *Ad Hoc Networks, Elsevier*, 6(7):1051–1077, 2008.

[118] Hassen A Mogaibel, Mohamed Othman, Shamala Subramaniam, and Nor Asilah Wati Abdul Hamid. Review of channel assignment approaches in multi-radio multi-channel wireless mesh network. *Journal of Network and Computer Applications, Elsevier*, 72:113–139, 2016.

[119] Nitin Jain, Samir R. Das, and Asis Nasipuri. A multichannel CSMA MAC protocol with receiver-based channel selection for multihop wireless networks. In *10th International Conference on Computer Communications and Networks*, pages 432–439. IEEE, 2001.

[120] Ozlem Durmaz Incel. *Multi-channel wireless sensor networks: protocols, design and evaluation*. PhD thesis, University of Twente, 2009.

[121] Jenhui Chen, Shiann-Tsong Sheu, and Chin-An Yang. A new multichannel access protocol for IEEE 802.11 ad hoc wireless LANs. In *14th IEEE Proceedings on Personal, Indoor and Mobile Radio Communications,*, volume 3, pages 2291–2296. IEEE, 2003.

[122] Jingbin Zhang, Gang Zhou, Chengdu Huang, Sang Hyuk Son, and John A. Stankovic. TMMAC: An energy efficient multi-channel mac protocol for ad hoc networks. In *IEEE International Conference on Communications, (ICC'07)*, pages 3554–3561. IEEE, 2007.

[123] Asimakis Tzamaloukas and J. J. Garcia-Luna-Aceves. Channel-hopping multiple access. In *IEEE International Conference on Communications*, volume 1, pages 415–419. IEEE, 2000.

[124] Dmitri D. Perkins, Herman D. Hughes, and Charles B. Owen. Factors affecting the performance of ad hoc networks. In *IEEE International Conference on Communications (ICC 2002)*, volume 4, pages 2048–2052. IEEE, 2002.

[125] Anders Nilsson. Performance analysis of traffic load and node density in ad hoc networks. *Proceedings of 5th European Wireless 2004: Mobile and Wireless Systems beyond 3G)*, pages 24–27, 2004.

[126] Michelle X. Gong, S.R. Midkiff, and Shiwen Mao. A combined proactive routing and multi-channel MAC protocol for wireless ad hoc networks. In *2nd International Conference on Broadband Networks*, pages 444–453. IEEE, 2005.

[127] Unghee Lee, Scott F Midkiff, and Tao Lin. OSPF-MCDS-MC: A routing protocol for multi-channel wireless ad-hoc networks. In *3rd IEEE Consumer Communications and Networking Conference*, volume 1, pages 426–430. IEEE, 2006.

[128] Yali Wang and JJ Garcia-Luna-Aceves. A distributed cross-layer routing protocol with channel assignment in multi-channel MANET. In *2015 International Conference on Computing, Networking and Communications (ICNC)*, pages 1050–1054. IEEE, 2015.

[129] Shahin Vakilinia, Mohammadhossein Alvandi, Mohammad Reza Khalil Shoja, and Iman Vakilinia. Multi-path multi-channel protocol design for secure qos-aware voip in wireless ad-hoc networks. In *6th Joint IFIP Wireless and Mobile Networking Conference (WMNC)*, pages 1–6. IEEE, 2013.

[130] Marjan Radi, Behnam Dezfouli, Kamalrulnizam Abu Bakar, Shukor Abd Razak, and Tan Hwee-Pink. IM2PR: interference-minimized multipath routing protocol for wireless sensor networks. *Wireless Networks, Springer*, 20(7):1807–1823, 2014.

[131] Zamree Che-aron, Aisha Hassan Abdalla, Khaizuran Abdullah, and Wan Haslina. A Fault-Tolerant Multi-Path Multi-Channel Routing Protocol for Cognitive Radio Ad Hoc Networks. *Information Science and Applications, Springer*, 339:43, 2015.

[132] Unghee Lee and Scott F Midkiff. OLSR-MC: A proactive routing protocol for multi-channel wireless ad-hoc networks. In *IEEE Wireless Communications*

and Networking Conference, (WCNC 2006), volume 1, pages 331–336. IEEE, 2006.

[133] Reghu Anguswamy, Maciej Zawodniok, and Sarangapani Jagannathan. A multi-interface multi-channel routing (MMCR) protocol for wireless ad hoc networks. In *IEEE Wireless Communications and Networking Conference*, pages 1–6. IEEE, 2009.

[134] Jipeng Zhou, Liyang Peng, Yuhui Deng, and Jianzhu Lu. An on-demand routing protocol for improving channel use efficiency in multichannel ad hoc networks. *Journal of Network and Computer Applications, Elsevier*, 35(5):1606–1614, 2012.

[135] Yifeng Zhou. A Routing and Interface Assignment Algorithm for Multi-Channel Multi-Interface Ad Hoc Networks. *Mobile Networks and Applications, Springer*, 23(5):1318–1329, 2018.

[136] Yali Wang, Cedric Westphal, and JJ Garcia-Luna-Aceves. Using geographical coordinates to attain efficient route signaling in ad hoc networks. In *2013 IEEE 14th International Symposium on" A World of Wireless, Mobile and Multimedia Networks"(WoWMoM)*, pages 1–9. IEEE, 2013.

[137] Hamid Gharavi. Multichannel mobile ad hoc links for multimedia communications. *Proceedings of the IEEE*, 96(1):77–96, 2008.

[138] Paul Fuxjager, Danilo Valerio, and Fabio Ricciato. The myth of non-overlapping channels: interference measurements in IEEE 802.11. In *4th Annual Conference on Wireless on Demand Network Systems and Services*, pages 1–8. IEEE, 2007.

[139] Richard Draves, Jitendra Padhye, and Brian Zill. Routing in multi-radio, multi-hop wireless mesh networks. In *Proceedings of the 10th annual international conference on Mobile computing and networking*, pages 114–128. ACM, 2004.

[140] Nawaf S Mirza and Peter JB King. Would a multichannel increase ad hoc wireless network capacity? In *Proceedings of the 14th Annual PostGraduate Symposium on the Convergence of Telecommunications, Networking and Broadcasting (PGNET'14)*, pages 13–17, Liverpool, UK, 2014.

[141] Amitangshu Pal and Asis Nasipuri. DRCS: A distributed routing and channel selection scheme for multi-channel wireless sensor networks. In *2013 IEEE International Conference on Pervasive Computing and Communications Workshops (PERCOM Workshops)*, pages 602–608. IEEE, 2013.

[142] Xiaorui Wang, Xiaodong Wang, Xing Fu, and Guoliang Xing. MCRT: Multichannel real-time communications in wireless sensor networks. *ACM Transactions on Sensor Networks (TOSN), ACM*, 8(1):2, 2011.

[143] Waqas Rehan, Stefan Fischer, Maaz Rehan, and Mubashir Husain Rehmani. A comprehensive survey on multichannel routing in wireless sensor networks. *Journal of Network and Computer Applications, Elsevier*, 95:1–25, 2017.

[144] Ji Yong Choi and Young-Bae Ko. Multi-path routing with load-aware metric for tactical ad hoc networks. In *International Conference on Information and Communication Technology Convergence (ICTC)*, pages 370–375. IEEE, 2010.

[145] Oussama Souihli, Mounir Frikha, and Mahmoud Ben Hamouda. Load-balancing in MANET shortest-path routing protocols. *Ad Hoc Networks, Elsevier*, 7(2):431–442, 2009.

[146] Ning Yang, Ravi Sankar, and Jungsik Lee. Improving ad hoc network performance using cross-layer information. In *IEEE International Conference on Communications (ICC 2005)*, volume 4, pages 2764–2768. IEEE, 2005.

[147] Raja Jurdak. *Wireless ad hoc and sensor networks: A cross-layer design perspective*. Springer Science and Business Media, 2007.

[148] Vineet Srivastava and Mehul Motani. Cross-layer design: a survey and the road ahead. *IEEE Communications Magazine, IEEE*, 43(12):112–119, 2005.

[149] Lucas D. P. Mendes and Joel J.P.C Rodrigues. A survey on cross-layer solutions for wireless sensor networks. *Journal of Network and Computer Applications, Elsevier*, 34(2):523–534, 2011.

[150] Bo Fu, Yang Xiao, Hongmei Deng, and Hui Zeng. A survey of cross-layer designs in wireless networks. *IEEE Communications Surveys and Tutorials, IEEE*, 16(1):110–126, 2014.

[151] Fotis Foukalas, Vangelis Gazis, and Nancy Alonistioti. Cross-layer design proposals for wireless mobile networks: a survey and taxonomy. *IEEE Communications Surveys and Tutorials, IEEE*, 10(1), 2008.

[152] Paul Fortier and Howard Michel. *Computer systems performance evaluation and prediction.* Elsevier, 2003.

[153] Philip Heidelberger and Stephen S. Lavenberg. Computer performance evaluation methodology. *IEEE Transactions on Computers, IEEE*, (12):1195–1220, 1984.

[154] Teerawat Issariyakul and Ekram Hossain. *Introduction to Network Simulator NS2.* Springer Publishing Company, 2nd edition, 2012.

[155] Francisco J. Suárez, Pelayo Nuño, Juan C. Granda, and Daniel F. García. Computer networks performance modeling and simulation. In *Modeling and Simulation of Computer Network and Systems*, pages 187–223. Elsevier, 2015.

[156] Ahmad Ali Abdullah, Fayez Gebali, and Lin Cai. Modeling the throughput and delay in wireless multihop ad hoc networks. In *Global telecommunications conference, IEEE*, pages 1–6. IEEE, 2009.

[157] Osama Younes and Nigel Thomas. Modelling and performance analysis of multi-hop ad hoc networks. *Simulation Modelling Practice and Theory, Elsevier*, 38:69–97, 2013.

[158] The Network Simulator NS-2. `https://www.isi.edu/nsnam/ns/` [last retrieved: February, 2019].

[159] The network simulator ns-3. https://www.nsnam.org/ [last retrieved: September, 2018].

[160] Omnet++. https://omnetpp.org/ [last retrieved: September, 2018].

[161] Matlab. https://www.mathworks.com/products/matlab [last retrieved: September, 2018].

[162] Opnet. https://www.riverbed.com/products/steelcentral/opnet.html [last retrieved: September, 2018].

[163] Qualnet communications simulation. https://web.scalable-networks.com/qualnet-network-simulator-software [last retrieved: September, 2018].

[164] W. Kasch, J. Ward, and J. Andrusenko. Wireless network modeling and simulation tools for designers and developers. *Communications Magazine, IEEE*, 47(3):120–127, 2009.

[165] Haitham Adarbah. *Bandwidth and Energy-Efficient Route Discovery for Noisy Mobile Ad-Hoc Networks.* PhD thesis, De Montfort University, 2015.

[166] Saher S. Manaseer. The choice of parameter values for simulation based experiments on mobile ad hoc networks. *International Journal of Communications, Network and System Sciences, Scientific Research*, 9(04):90, 2016.

[167] Tapan K Sarkar, Zhong Ji, Kyungjung Kim, Abdellatif Medouri, and Magdalena Salazar-Palma. A survey of various propagation models for mobile communication. *IEEE Antennas and propagation Magazine, IEEE*, 45(3):pages 51–82, 2003.

[168] Tracy Camp, Jeff Boleng, and Vanessa Davies. A Survey of Mobility Models for Ad Hoc Network Research. *Wireless Communications and Mobile Computing (WCMC)*, 2:pages 483–502, 2002.

[169] William Navidi and Tracy Camp. Stationary distributions for the random waypoint mobility model. *IEEE transactions on Mobile Computing, IEEE*, (1):pages 99–108, 2004.

[170] Christian Schindelhauer. Mobility in wireless networks. In *SOFSEM 2006: Theory and Practice of Computer Science. Lecture Notes in Computer Science*, volume 3831, pages 100–106. Springer, 2006.

[171] Mohamed A. Abdelshafy. *Securing routing protocols in mobile ad hoc networks*. PhD thesis, Heriot-Watt University, 2016.

[172] Ashish Raniwala and Tzi-cker Chiueh. Architecture and algorithms for an IEEE 802.11-based multi-channel wireless mesh network. In *Proceedings IEEE 24th Annual Joint Conference of the IEEE Computer and Communications Societies.*, volume 3, pages 2223–2234. IEEE, 2005.

[173] Ramon Aguero Calvo and Jesus Perez Campo. Adding multiple interface support in NS-2. *University of Cantabria*, 2007.

[174] Lin-Huang Chang, Chia-Yu Hsu, H.F. Chang, and Tsung-Han Lee. Design and implementation of semi-dynamic multi-channel transceiver in WSNs. In *IEEE International Conference on Systems, Man and Cybernetics (SMC)*, pages 2082–2087. IEEE, 2014.

[175] Arnold D. Robbins. Gawk: Effective AWK Programming. *Boston: Free Software Foundation*, 3, 2004.

[176] Unghee Lee. *A Proactive Routing Protocol for Multi-Channel Wireless Ad-hoc Networks*. PhD thesis, Virginia Tech, 2006.

[177] Ying Qu, Bryan Ng, and Winston Seah. A survey of routing and channel assignment in multi-channel multi-radio WMNs. *Journal of Network and Computer Applications, Elsevier*, 65:120–130, 2016.

[178] Ting-Yu Lin, Kun-Ru Wu, and Guang-Chuen Yin. Channel-hopping scheme

and channel-diverse routing in static multi-radio multi-hop wireless networks. *IEEE Transactions on Computers, IEEE*, 64(1):71–86, 2015.

[179] Khaled H. Almotairi and Xuemin Sherman Shen. A distributed multi-channel MAC protocol for ad hoc wireless networks. *IEEE Transactions on Mobile Computing, IEEE*, 14(1):1–13, 2015.

[180] Ritesh Maheshwari. *Medium Access and Security Protocols for Wireless Multihop Networks*. PhD thesis, The Graduate School, Stony Brook University: Stony Brook, NY., 2009.

[181] Shweta Jain. *Efficient medium access protocols for wireless and RFID networks*. PhD thesis, The Graduate School, Stony Brook University: Stony Brook, NY., 2007.

[182] Shweta Jain and Samir R. Das. Exploiting path diversity in the link layer in wireless ad hoc networks. *Ad Hoc Networks, Elsevier*, 6(5):805–825, 2008.

[183] Mingfei Wang, Mingyang Wang, Linlin Ci, and Yongjun Xu. D-rdt: a multi-channel mac protocol for dense multi-hop wireless sensor networks. *Procedia Engineering, Elsevier*, 15:2155–2159, 2011.

[184] Mingfei Wang, Quansheng Liu, Jinyin Zuo, and Yongjun Xu. RSM: A Broadcast Available Multi-channel MAC Protocol for Wireless Sensor Networks. In *2012 Fourth International Conference on Computational and Information Sciences*, pages 1076–1079. IEEE, 2012.

[185] Jaeseon Hwang, Taewoon Kim, Jungmin So, and Hyuk Lim. A receiver-centric multi-channel MAC protocol for wireless networks. *Computer Communications, Elsevier*, 36(4):431–444, 2013.

[186] Lieven Tytgat, Opher Yaron, Sofie Pollin, Ingrid Moerman, and Piet Demeester. Analysis and experimental verification of frequency-based interference avoidance mechanisms in IEEE 802.15.4. *IEEE/ACM Transactions on Networking, IEEE*, 23(2):369–382, 2015.

[187] Nawaf S. Mirza, Mohamed A. Abdelshafy, and Peter J.B. King. Performance evaluation of Receiver Directed Transmission protocol with a single transceiver in MANETs. In *Wireless Days, 2017*, pages 241–244. IEEE, 2017.

[188] Sze-Yao Ni, Yu-Chee Tseng, Yuh-Shyan Chen, and Jang-Ping Sheu. The broadcast storm problem in a mobile ad hoc network. In *5th annual ACM/IEEE international conference on Mobile computing and networking*, pages 151–162. ACM, 1999.

[189] Nawaf S. Mirza, P. J. B. King, M. A. Abdelshafy I. Romdhani, Mohamed A., and Atif Alghamdi. Reliable multipath multi-channel route migration over multi link-failure in wireless ad hoc networks. In *IEEE 13th International Conference on Wireless and Mobile Computing, Networking and Communications (WiMob)*, pages 123–130. IEEE, 2017.

[190] Ian D. Chakeres and Elizabeth M. Belding-Royer. The utility of hello messages for determining link connectivity. In *The 5th International Symposium on Wireless Personal Multimedia Communications*, volume 2, pages 504–508. IEEE, 2002.

[191] Nisha Bhanushali, Priyanka Thakkar, and Prasanna Shete. Impact of Hello Interval on performance of AODV protocol. *International Journal of Computer Applications*, 116(23), 2015.

[192] Venkata C. Giruka and Mukesh Singhal. Hello protocols for ad-hoc networks: overhead and accuracy tradeoffs. In *Sixth IEEE International Symposium on a World of Wireless Mobile and Multimedia Networks*, pages 354–361. IEEE, 2005.

[193] Tareq Hayajna and Michel Kadoch. Analysis and enhancements of HELLO based link failure detection in wireless mesh networks. *Telecommunication Systems, Springer*, 66(3):pages 393–407, 2017.

[194] Neung-Um Park, Jae-Choong Nam, and You-Ze Cho. Impact of node speed and transmission range on the Hello interval of MANET routing protocols. In

2016 International Conference on Information and Communication Technology Convergence (ICTC), pages 634–636. IEEE, 2016.

[195] Liang Shan, Linzhen Xie, Zhengbin Li, and Anshi Xu. Partial Pre-Deflection Scheme with Least Hop First Routing for Optical Burst Switching Networks under Self-Similar Traffic. In *First International Conference on Communications and Networking in China, ChinaCom'06.*, pages 1–5. IEEE, 2006.

[196] Nawaf S. Mirza, Hamish Taylor, Mohamed A. Abdelshafy, Peter J.B. King, Imed Romdhani, and Atif A. Alghamdi. Cross-Layer Multipath Multichannel MAC protocol for MANETs. In *2018 International Symposium on Networks, Computers and Communications (ISNCC)*, pages 1–8. IEEE, 2018.

[197] Carlene Campbell, Kok-Keong Loo, Orhan Gemikonakli, Shafiullah Khan, and Dhananjay Singh. Multi-channel distributed coordinated function over single radio in wireless sensor networks. *Sensors*, 11(1):964–991, 2011.

[198] Carlene Campbell. *An efficient multichannel wireless sensor networks MAC protocol based on IEEE 802.11 distributed co-ordinated function*. PhD thesis, Middlesex University, 2011.

[199] Anland Prabhn Subramanian, Milind M Buddhikot, et al. Interference aware routing in multi-radio wireless mesh networks. In *2nd IEEE Workshop on Wireless Mesh Networks*, pages 55–63. IEEE, 2006.

[200] Hongkun Li, Yu Cheng, Chi Zhou, and Weihua Zhuang. Routing metrics for minimizing end-to-end delay in multiradio multichannel wireless networks. *IEEE Transactions on Parallel and Distributed Systems, IEEE*, 24(11):2293–2303, 2012.