



# **Bandwidth and Energy-Efficient Route Discovery for Noisy Mobile Ad-Hoc Networks**

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Submitted in fulfilment of the requirements for the  
Degree of Doctor of Philosophy

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Faculty of Technology  
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July 2015

# Abstract

Broadcasting is used in on-demand routing protocols to discover routes in Mobile Ad-hoc Networks (MANETs). On-demand routing protocols, such as Ad-hoc On-demand Distance Vector (AODV) commonly employ pure flooding based broadcasting to discover new routes. In pure flooding, a route request (RREQ) packet is broadcast by the source node and each receiving node rebroadcasts it. This continues until the RREQ packet arrives at the destination node. Pure flooding generates excessive redundant routing traffic that may lead to the broadcast storm problem (BSP) and deteriorate the performance of MANETs significantly.

A number of probabilistic broadcasting schemes have been proposed in the literature to address BSP. However, these schemes do not consider thermal noise and interference which exist in real life MANETs, and therefore, do not perform well in real life MANETs. Real life MANETs are noisy and the communication is not error free.

This research argues that a broadcast scheme that considers the effects of thermal noise, co-channel interference, and node density in the neighbourhood simultaneously can reduce the broadcast storm problem and enhance the MANET performance. To achieve this, three investigations have been carried out: First, the effect of carrier sensing ranges on on-demand routing protocol such as AODV and their impact on interference; second, effects of thermal noise on on-demand routing protocols and third, evaluation of pure flooding and probabilistic broadcasting schemes under noisy and noiseless conditions. The findings of these investigations are exploited to propose a Channel Adaptive Probabilistic Broadcast (CAPB) scheme to disseminate RREQ packets efficiently.

The proposed CAPB scheme determines the probability of rebroadcasting RREQ packets on the fly according to the current Signal to Interference plus Noise Ratio (SINR) and node density in the neighbourhood. The proposed scheme and two related state of the art (SoA) schemes from the literature ([1] and [2]) are implemented in the standard AODV to replace the pure flooding based broadcast scheme. Ns-2 simulation results show that the proposed CAPB scheme outperforms the other schemes in terms of routing overhead, average end-to-end delay, throughput and energy consumption.

# Publications

1. Haitham Y. Adarbah, Shakeel Ahmad, Bassel Arafeh and Alistair Duffy  
**“Efficient Broadcasting for Route Discovery in Mobile Ad-hoc Networks ”**  
in 2015 International Symposium on Performance Evaluation of Computer and  
Telecommunication Systems, July 2015, Chicago, IL, USA, (IEEE COMSOC),  
<http://atc.udg.edu/SPECTS2015/>
2. Haitham Y. Adarbah, Shakeel Ahmad and Alistair Duffy **“Impact of noise and  
interference on probabilistic broadcast schemes in mobile ad-hoc networks”**  
in international Computer Networks Journal (COMNET- Elsevier), Volume 88,  
Issue 9, pp 178-186, September 2015.
3. Haitham Y. Adarbah, Scott Linfoot, Bassel Arafeh and Alistair Duffy  
**“Interference-Noise Probabilistic Route Discovery Mechanism in Noisy  
MANETs”** in IEEE International Conference on Consumer Electronics (ICCE),  
January 2014, Las Vegas, US. **It has been accepted.** <http://www.icce.org/>
4. Haitham Y. Adarbah, and Scott Linfoot, **“*Analysis of Routing Overhead in  
Route Discovery Based on PHY, MAC in Noisy MANETs*”** in *IEEE  
International Conference on Consumer Electronics (ICCE),pp 373-377,  
September 2013, Berlin, Germany.*
5. Scott Linfoot, Haitham Y. Adarbah, Bassel Arafeh, and Alistair Duffy, **“Impact  
of Physical and Virtual Carrier Sensing on the Route discovery Mechanism  
in noisy MANETs**, IEEE-Transaction -Consumer Electronics Society, Volume  
59, Issue 3, pp 515-520, August 2013.

6. Haitham Y. Adarbah, Scott Linfoot, Bassel Arafeh, and Alistair Duffy, “***Effect of Physical and Virtual Carrier Sensing on the AODV Routing Protocol in noisy MANETs***, *IEEE International Conference on Consumer Electronics ICCE, January 11-14, 2013*, pp. 508–509, Las Vegas, USA
7. Haitham Y. Adarbah, Scott Linfoot, Bassel Arafeh, and Alistair Duffy, “***Impact of the Noise Level on the Route Discovery Mechanism in Noisy MANETs***,” *1st IEEE Global Conference on Consumer Electronics 2012*, 2012, pp. 710–714, Tokyo, Japan.

# Acknowledgements

I would like to express my deep gratitude to my Supervisors, Dr.Shakeel Ahmad for his supports and guidance throughout this research. His criticisms, suggestions, and frequent encouragements have been vital in improving this dissertation. My utmost gratitude also goes to Prof Alistair Duffy, Dr. Scott Linfoot, and Dr. Bassel Arafeh for their exceptional support, constant encouragement and inspiring guidance

My dearest gratitude also goes to my Sons and my Wife for her support, motivation, patience, and love. Finally, I am eternally grateful to my parents and the whole family

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# Abbreviations

<b>ABR</b>	Associativity-Based Routing
<b>ACK</b>	Acknowledgment
<b>AHBP</b>	Ad-Hoc Broadcast Protocol
<b>AODV</b>	Ad hoc On demand Distance Vector
<b>ARP</b>	Address Resolution Protocol
<b>BRG</b>	Broadcast Relay Gateways
<b>BSP</b>	Broadcast Storm Problem
<b>CAPB</b>	Channel Adaptive Probabilistic Broadcast
<b>CDS</b>	Connected Dominating Set
<b>CEDAR</b>	Core Extraction Distributed Ad Hoc Routing
<b>CGSR</b>	Cluster head Gateway Switch Routing
<b>CLASS</b>	Cross-Layer Signalling Shortcuts
<b>Cross-CBRP</b>	Cross-layer design to optimise the Cluster Based Routing Protocol
<b>CSMA/CA</b>	Carrier Sense Multiple Access with Collision Avoidance
<b>CST</b>	Carrier Sense Threshold
<b>DATA/ACK</b>	Data/Acknowledgment
<b>DCF</b>	Distributed Coordination Function
<b>DNDP</b>	Dynamic Noise-Dependent Probabilistic
<b>DP</b>	Dominant Pruning
<b>DSDV</b>	Destination Sequenced Distance Vector
<b>DSR</b>	Dynamic Source Routing
<b>DYMO</b>	Dynamic MANET On Demand
<b>FORP</b>	Flow Oriented Routing Protocol

<b>FSR</b>	Fisheye State Routing
<b>FTP</b>	File Transfer Protocol
<b>GPS</b>	Global Positioning System
<b>GSR</b>	Global State Routing
<b>HSR</b>	Hierarchical State Routing
<b>IP</b>	Internet Protocol
<b>LAR</b>	Location-Aided Routing
<b>LBR</b>	Load Balancing Routing
<b>MAC</b>	Medium Access Scheme
<b>MANET</b>	Mobile Ad hoc NETwork
<b>MPR</b>	Multi-Point Relaying
<b>NS-2</b>	Network Simulator-2
<b>OLSR</b>	Optimized Link State Routing
<b>OSI</b>	Open Systems Interconnect
<b>PAN</b>	Personal Area Network
<b>PAR</b>	Power-Aware Routing
<b>PCF</b>	Point Coordination Function
<b>PDA</b>	Personal Digital Assistant
<b>PER</b>	Packet Error Rate
<b>QoS</b>	Quality of Service
<b>RABR</b>	Route-Lifetime Assessment Based Routing
<b>RAD</b>	Random Assessment Delay
<b>RERR</b>	Route ERRor
<b>RREP</b>	Route REPly
<b>RREQ</b>	Route REQuest

<b>RTS-CTS</b>	Request-To-Send and Clear-To-Send
<b>RWP</b>	Random Way-Point
<b>SBS</b>	Scalable Broadcast Scheme
<b>SINR</b>	Signal-to-Interference plus Noise Ratio
<b>SNR</b>	Signal-to-Noise Ratio
<b>SoA</b>	state of the art
<b>SSA</b>	Signal Stability based Adaptive routing
<b>TCP</b>	Transport Control Protocol
<b>VANET</b>	Vehicular Ad Hoc Networks
<b>WLAN</b>	Wireless Local Area Network
<b>ZHLS</b>	Zone based Hierarchical Link State
<b>ZRP</b>	Zone Routing Protocol

# Chapter 1

## Introduction

This thesis addresses the Broadcast Storm Problem (BSP) in Mobile Ad-hoc Network (MANET). The main aim is to propose a novel channel adaptive probabilistic broadcasting scheme to solve the broadcast storm problem by taking into account two factors: first, the measured co-channel interference plus thermal noise, second, nodal density in the neighbourhood. The novel scheme is called a Channel Adaptive Probabilistic Broadcast (CAPB) that uses a cross layer design solution. The cross layer solution allows direct communication between nonadjacent layers, or distribution of variables among layers, while details can be found in Chapter 2.

This chapter is organised as follows: Section 1.1 presents the research motivation. Section 1.2 lists the research questions. Section 1.3 highlights the main contributions. Finally the thesis outline is presented in section 1.4

### 1.1. Motivation

Nowadays, wireless networks play a vital role in information technology. An ad-hoc network is considered as a decentralized type of wireless network. A mobile ad-hoc network (MANET) is a type of ad-hoc network where nodes are free to move around. The MANET consists of a number of mobile nodes that can connect to each other over multi-hop wireless links on an ad-hoc basis. MANETs are self-organizing, self-configuring as well as self-healing without requiring any infrastructure or central administration [3] [4].



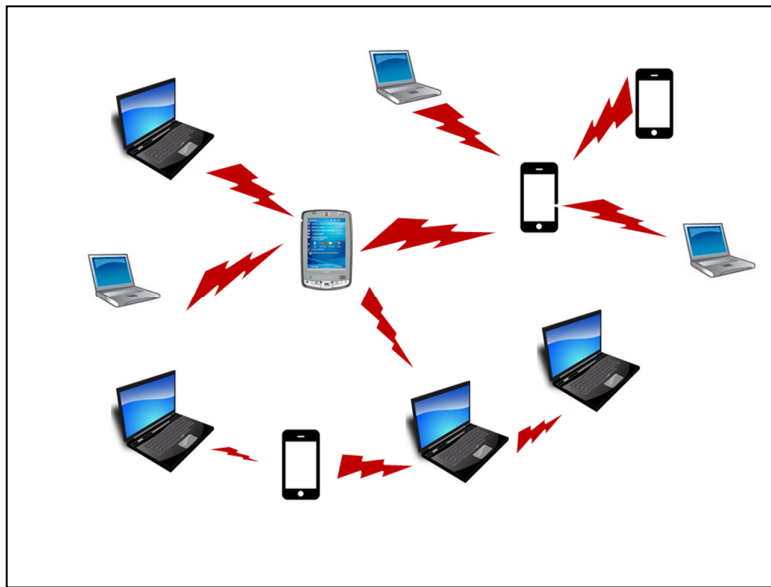


Figure 1.1: Mobile Ad hoc Networks (MANETs)

Due to limited transmission range, a mobile node may not communicate with a distant node directly. However, in MANET each node acts as a relay node. This allows a mobile node communicating with a distant node over multi-hop link. Figure 1.1 shows the typical MANET. A MANET is considered as an excellent candidate for a number of applications ranging from battlefield communication, meeting events, conferences, and emergency search-rescue operations.

MANET nodes can arbitrarily be located within an area and are free to move. The movement of MANET nodes changes the network topology dynamically. MANET nodes adapt to the changing topology by discovering new neighbours and establishing new routes to destinations [5].

When a node wants to send data to a remote node, first, it finds a set of relay nodes between itself and the remote node. The process of finding the optimal set of relay nodes between the source node and the destination node is called route discovery. Node

mobility, limited battery power and the error-prone nature of wireless links are the main challenges in designing an efficient routing protocol in MANETs.

A number of routing protocols have been proposed in the literature [6][7][8]. These protocols generally fall into three categories namely table-driven (proactive), on-demand (reactive) and hybrid routing protocols. Table-driven routing protocols aim to maintain routes to all possible destinations in the network at all times. Examples of table-driven routing protocols include Optimized Link State Routing (OLSR) [9] and Destination-Sequenced Distance-Vector (DSDV) routing [10]. In contrast to table-driven approach, on-demand routing protocols, e.g., Ad-hoc On-demand Distance Vector (AODV) routing [11], Dynamic Source Routing (DSR) [6], and Associativity-Based Routing (ABR) [12], discover a route only when it is needed. Hybrid routing protocols, e.g., Zone Routing Protocol (ZRP) [13] and Core-Extraction Distributed Ad-hoc Routing (CEDAR) [14] combine the features of both proactive and reactive routing protocols.

In on-demand routing protocols, the routing process consists of two phases namely route-discovery and route-maintenance. These protocols rely on broadcasting for route discovery. For example, in the case of AODV, a source node that needs to send data to a destination node triggers the route discovery mechanism by broadcasting a special control packet called Route Request (RREQ) to its neighbours who then rebroadcast the RREQ packet to their neighbours. The process continues until the RREQ packet arrives at the destination node. The destination node sends a control packet called Route Reply (RREP) that follows the path of RREQ in reverse direction and informs the source node that a route has been established. Since every node on receiving the RREQ for the first

time rebroadcasts it, it requires  $N-2$  rebroadcasts in a network of  $N$  nodes assuming the destination is reachable. This kind of broadcasting is called pure flooding of which details can be found in Chapter 2.

Pure flooding often results in substantial redundant transmissions because a node may receive the same packet from multiple nodes. This phenomenon is commonly known as Broadcast Storm Problem (BSP) [15], and triggers frequent contention and packet collisions leading to increased communication overhead and serious performance complications in densely populated networks. The broadcast storm problem equally affects the route maintenance phase during which routes are refreshed by triggering new route discovery requests to replace the broken routes.

To elevate the damaging impact of pure flooding, a number of improved broadcasting techniques have been proposed in the literature [4],[10] [16]. These techniques generally fall into two categories namely deterministic and probabilistic broadcasting. Deterministic schemes (e.g., MPR [17] and Self Pruning Scheme [18]) exploit network information to make more informed decisions. However, these schemes carry extra overhead to exchange location and neighbourhood information among nodes. On the other hand, the probabilistic schemes (e.g., Fixed Probabilistic [1], distance-based [19], counter-based [20] and location-based [15]) take local decision to broadcast or not to broadcast a message according to a predetermined probability.

The communication is not error free. A number of channel impairments like thermal and environmental noise, co-channel interference, signal attenuation, fading and user mobility affect the transmission in MANETs. The Packet Error Rate (PER) is closely related to Signal to Interference plus thermal Noise Ratio (SINR) and packet size [21].

The IEEE 802.11 MAC standard uses the Distributed Coordination Function (DCF). The DCF relies on the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) protocol. The CSMA/CA suffers from exposed and hidden nodes, as a consequence of higher interference. Maximising concurrent transmissions can be achieved by balance between exposed and hidden nodes. Carrier sensing range is vital in achieving this balance [22]. so how to reduce interference by finding an optimal value of the sensing range is not a trivial problem and normally, it is left equal to the transmission range [23]. If the carrier sensing range is not chosen carefully, it may result in collision probability. Thermal noise is another important factor which has negative effect on the performance of on-demand routing protocols, because higher thermal noise leads to frequent packet losses (both data packets and control packets).

Previous studies have shown that routing protocols based on probabilistic broadcast schemes outperform the traditional pure flooding based routing protocols [24][25]. However, the results of those studies can be argued under noisy MANETs (where thermal noise and interference are taken into account). It is because those studies either ignored noise and interference altogether [20] [26] or they used the noise-level value drawn from a linear distribution rather than measuring it at lower layers [2].

The research goals are to investigate the effects of interference plus thermal noise on on-demand routing protocols such as AODV and analyse the existing solutions for broadcasting schemes in the route discovery process of on-demand routing protocols, and propose new broadcasting scheme which the interference plus thermal noise are taken into account. The network density is another important parameter must be taken into account as well. Because the network density leads to higher interference and

higher packet error rate which result in redundant retransmission of control packets. As a result of that the average routing overhead increases with increasing node density.

## **1.2. Research Questions**

Following are the research questions:

In the questions below, the term noisy will be used to refer to thermal noise and co-channel interference

- **What are the effects of carrier sensing ranges on the performance of on-demand routing protocols using pure flooding broadcast scheme in the route discovery phase in noisy MANETs?**
- **What is the impact of thermal noise on the performance of on-demand routing protocols with using pure flooding broadcast scheme in route discovery phase in MANETs?**
- **How does the probabilistic broadcasting scheme perform under noisy conditions?**
- **How can an efficient channel adaptive broadcasting scheme for the route discovery phase of routing protocols be developed by considering the effect of interference plus thermal noise and the network density?**

## **1.3. Contributions**

The main contributions of this research work can be summarised as follow:

1. Investigates the effects of physical and virtual carrier sensing ranges on the performance of on-demand routing protocol such as AODV, and highlights how

a suitable value of physical and virtual carrier sensing ranges would have an effect on the noisy MANET's performance.

2. Highlights the impact of thermal noise on the performance of on-demand routing protocol with using pure flooding broadcasting scheme in route discovery phase in the on-demand routing protocol.
3. Investigates the performance of probabilistic broadcasting schemes and pure flooding broadcasting scheme under noisy and noiseless conditions
4. Proposes a novel broadcasting scheme called Channel Adaptive Probabilistic Broadcast (CAPB) to address the Broadcast Storm Problem (BSP) in on-demand routing protocols. The CAPB scheme adjusts the probability of rebroadcasting packets dynamically by taking into account two factors. The first factor is the measured co-channel interference and thermal noise. The second factor is nodal density in the neighbourhood. The performance of the suggested approach (CAPB) has been compared with state of the art (SoA) schemes in terms of routing overhead, throughput, end-to-end delay and energy consumption.

## 1.4. Thesis Outline

The rest of the thesis is arranged as follows:

**Chapter 2:** This chapter provides the background information necessary for understanding the research work. It includes an overview of MANETs which describes the key characteristics as well as the applications of MANETs. Second it describes the related work, the route discovery and broadcasting in MANETs. Third, the chapter

presents an overview of cross layer solutions. Finally, presents a brief description of the network simulators, and defining the performance metrics used in this research work.

**Chapter 3:** This chapter presents the effects of physical and virtual carrier sensing ranges on the performance of on-demand routing protocols with using a pure flooding broadcasting scheme in noisy MANETs and highlights how a suitable value of physical and virtual carrier sensing ranges does have an effect on the noisy MANET's performance.

**Chapter 4:** This chapter presents the impact of thermal noise on on-demand routing protocols' performance with using pure flooding broadcasting scheme in the route discovery phase in MANETs.

**Chapter 5:** This chapter presents an extensive analysis of the impact of the interference plus thermal noise on the pure flooding and probabilistic broadcasting schemes. The performance of the mentioned schemes has been investigated for a wide range of forwarding probabilities.

**Chapter 6:** This chapter proposes a new broadcasting scheme called the Channel Adaptive Probabilistic Broadcast (CAPB). The proposed scheme is implemented in the network simulator ns-2 and its performance has been compared with SoA schemes in terms of routing overhead, throughput, end-to-end delay and energy consumption.

**Finally, Chapter 7** presents the conclusion of the dissertation by highlighting the main results revealed in this research and outlines future research work.

# **Chapter 2**

## **Background and Related Work**

This chapter provides the background information necessary for understanding the following chapters. It is organised as follows. Section 2.1 describes an overview of MANETs. Section 2.2 presents an overview of routing in MANETs. Section 2.3 discusses the broadcasting schemes in MANETs. Section 2.4 discusses cross-layer solutions. Section 2.5 outlines the common simulation assumptions which apply throughout this research study. It also outlines the simulation models, method of study and the performance metrics used in this research work. Finally, Section 2.6 provides a summary of the chapter.

### **2.1. Overview of MANETs**

#### **2.1.1. Characteristics of MANETs**

This subsection presents the challenges, which are briefly shown in Table 2.1, and it discusses the important characteristics that need to be considered when MANETs are designed and deployed [27][28].



Table 2.1: Challenges of MANETs

Layers	Challenges in Each Layer	All Layers
Application Layer	New/killer Applications:	Energy Conservation Quality of Service (QoS) Reliability Scalability Network Simulation Performance Optimisation Hardware, Software Tool Support
Presentation Layer	Networks Auto-configuration	
Session Layer	Location Services Security (Authentication, Encryption)	
Transport Layer	Transport Control Protocol(TCP) Adaptation Back-off Window	
Network Layer	Routing Protocols Addressing	
Data Link Layer	Media Access Control Error Correction	
Physical Layer	Spectrum usage/allocation	

The subsequent sections discuss important characteristics of MANETs.

***Autonomous and Infrastructure-less:*** The network is considered as an autonomous system comprised of interlinked nodes without any infrastructure or centralised administration. Serving as an independent router, every node in the system generates and forwards messages to other nodes outside of their transmission range [28][29][30].

**Limited Resources:** As opposed to their wired counterparts, MANET nodes such as laptops, sensors and Personal Digital Assistants (PDAs) often have limited or restricted resources, particularly in terms of energy, computational power, and memory [7][31].

**Mobility:** Devices in MANETs generally contain no physical boundaries, and their locations remain changeable depending on occurring movements. The varying movements of participating nodes mean that the network topology is highly dynamic. Thus, intercommunication patterns between nodes are unpredictable. As an unwelcome consequence, frequent path breaks are experienced by on-going communication sessions. Broadcasting and routing protocols for MANETs should thereby ensure high mobility management efficiency [32].

**Energy Consumption:** MANET mobile devices usually outsource energy from batteries. Batteries in turn have relatively constrained power, and are also highly prone to non-rechargeable batteries. Moreover, activities like wireless signal transmission, reception, retransmission, and beaconing operations all reduce battery power. Finally, MANET nodes consume extra energy whenever packets are forwarded to their neighbours; as such, nodes jointly function as an end system and a router [33].

**Computational Power:** Limited capacity and low processing power are the usual hurdles encountered by the computing components of mobile devices – mainly memory and internal processors. The most sought-after improvement in MANET protocols' design, therefore, is diminishing the utilisation of the aforementioned resources [34].

**Limited Bandwidth:** Similar to computational capacity, the available bandwidth of the wireless channel in MANETs is comparatively lower than their wired equivalents [35][33]. Nodes within the same transmission range are contingent on a single wireless

channel; thus the bandwidth available per wireless channel is dependent upon the total number of nodes and the traffic each element injects in the network. Thereby only a fraction of the total bandwidth is utilised by each node. This bandwidth limitation causes problems in the regular maintenance of topological information through routing and broadcast protocols.

***Wireless Channel:*** The wireless communication medium is generally prone to impaired transmissions. These communication difficulties include path loss, interference and fading [36]. Path loss is defined as the ratio of two signal powers: the power of the transmitted signal vs the received signal at the receiver on a given path [37]. The aforementioned ratio calculates the effects of the terrain and the carrier frequency used for signal propagation. Hence, accurate estimation of path loss is considered a key element in the design and deployment of MANETs. Multi-path fading is another leading transmission impediment associated with radio frequency networks. It is defined as the rapid fluctuation of signal strength received at the receiver. Propagation mechanisms play vital roles in this case, especially with procedures such as reflection, refraction, or diffraction performed on the transmitted signal [28][38]. Lastly, distortion generated from the receiver (thermal noise) and the environment is termed “noise”. Interference is caused by other frames being received by the receiver at the same time as the desired frames. [39]. Those sources create hurdles that limit the data rate, reliability and range of wireless transmissions. In response to these signal failures, all communication protocols designed for MANETs should provide efficient solutions to these issues.

***Heterogeneity:*** MANET applications are designed to cover large spaces. Therefore, the number of performing nodes in a system may range from a small group to tens of

thousands. Node mobility also varies according to need and/or environment, from static sensor nodes to mobility nodes. MANETs typically restrict the speeds considered (unlike Vehicular Ad hoc Networks (VANETs)). Moreover, as dissimilar nodes adapt to their respective functions, their sizes, memories, computational abilities and battery powers also differ. This heterogeneity in the network, node mobility and node features cause a variety of topology dynamics, which then influence the performance and design of MANET protocols [40][41].

***Network Security:*** MANETs are not as heavily equipped as their wired counterparts when it comes to security. They are susceptible to information attacks and physical threats; especially the physically unprotected nodes used for shared broadcast wireless channels. Moreover, the distributed and deconstructed nature of MANETs keeps the system reliant on individual security solutions. These solutions are outsourced from each mobile node, as centralised security control is difficult to operate [42].

***Low Connectivity and Reliability:*** MANETs achieve network connectivity through routing and forwarding processes executed among different mobile nodes. Adversely, disruptions in the system may occur when a node fails to forward the packet, usually because of unpredictable circumstances such as nodes acting selfishly, overloading, or broken links. Signal collision is also a greater possibility in wireless networks, in contrast to wired networks, because of shared channels. The high transmission error rate produced by the system makes the communication less reliable [38].

### **2.1.2. Applications of MANETs**

During the last two decades, there has been a tremendous growth in the use of MANETs, not only due to the development in the technology but also due to the many

advantages they have over infrastructure (access point) wireless networks and wired networks [27].

Here is a list of major applications of MANETs which multi-hop communication and/or dynamic routing is implementing:

**Applications:**

- Tactical Networks [43]
  - Military communication, operations
  - Automated battlefields
- Sensor Networks [44]
  - Home applications: smart sensor nodes and actuators can be buried in appliances to allow end user to manage home devices locally and remotely
  - Environmental applications include tracking the movements of animals (e.g. birds), chemical/biological detection, precision agriculture, etc.
  - Tracking data highly correlated in time and space, e.g. remote sensors for weather earth activities
- Emergency Services [45]
  - Search and rescue operations, as well as disaster recovery, e.g. early retrieval and transmission of patient data (record, status, diagnosis) from/to the hospital
  - Replacement of a fixed infrastructure in case of

earthquakes, hurricanes, fire, etc.

- Commercial Environments [46]
  - E-Commerce, e.g. electronic payments from anywhere (e.g. taxi)
  - Business
  - Dynamic access to customer files stored in a central location on the fly
  - Provide consistent database for all agents
  - Mobile office
  - Vehicular Services
  - Transmission of news, road condition, weather, music
  - Local ad-hoc network with nearby vehicles for road/accident guidance
- Home and Enterprise Networking
  - Home/Office Wireless Networking Wireless Local Area Network(WLAN), e.g. shared whiteboard application, use of Personal Digital Assistant (PDA) to print anywhere, trade shows
  - Personal Area Network(PAN)
- Educational applications
  - Setup virtual classrooms or conference rooms
  - Setup ad-hoc communication during conferences
- Entertainment
  - Multi-user games

- Robotic pets
- Outdoor internet access
- Location aware services
  - Follow-on services, e.g. automatic call-forwarding, transmission of the actual workspace to the current location
  - Information services
  - Push, e.g. advertise location-specific service, such as gas stations.
  - Pull, e.g. location-dependent travel guide, services (printer, fax, phone, server, gas stations) availability of information

## 2.2. Routing in MANETs

The responsibilities of a routing protocol include: exchanging the route information; finding a feasible path to a destination based on criteria such as hop length, minimum power required, and lifetime of the wireless link; gathering information about the path breaks; mending the broken paths, expanding minimum processing power and bandwidth. There are several challenges in designing routing protocols such as mobility, bandwidth constraint, error-prone and shared channel, and location-dependent contention. Other resource constraints, including constraints on resources such as computing power, battery power, and buffer storage, also limit the capability of a routing protocol.

Routing protocols are completely essential in ensuring the operation efficacy of a MANET [31][47]. Their central function is to build and regulate paths between nodes,

so packets can travel from source to destination. A MANET path is composed of an ordered intermediate node set, which enables the transport of a packet across a specified network. Each node receives and forwards a packet to other nodes in the system until said packet reaches its selected destination. Due to the singular characteristics of MANETs, such as those outlined in Section 2.1.1, routing in this type of network becomes a complicated undertaking. For instance, node mobility brings about highly dynamic networks with rapid topological changes, which in turn causes recurring route failures [11].

MANET environments, therefore, require dynamically-adaptable and bandwidth-efficient routing protocols. Such protocols must readily adjust to the changes in network topology, as well as reduce routing control overhead to make bandwidths available for actual data communication.

Extensive research is being done to further advance MANET routing protocols [9][48][49][11]. There are various methods for classifying MANETs routing protocols, as shown in Figure 2.1. A very common approach for MANETs routing protocols classification is according to route discovery and routing information update mechanisms. Under this classification, MANETs routing protocols are divided into three groups: proactive (or table-driven), reactive (or on-demand driven) and hybrid. Consistent, up-to-date information is processed and maintained in proactive routing protocols (as exhibited in [10][48]). Reactive routing protocols on the other hand, only establish routes in accordance with the requirements of a particular system. This is further illustrated in [11]. Lastly, hybrid approaches demonstrate an assimilation of proactive and reactive routing components. Reactive protocols are highly adjustable to



route changes; they also consume less bandwidth and battery power because they avoid the unnecessary periodic updates of routing information at each node, a process mostly undertaken by other categorical routing protocols. Distinctive protocols under the reactive category include ad-hoc on-demand distance vector (AODV)[11], and dynamic source routing (DSR) [48] are typical and well-known examples of routing protocols in this category. A general classification of MANETs routing protocols is given next, followed by a background of AODV protocol.

### **2.2.1. Classifications of Routing Protocols**

Several comparative analyses of MANET routing protocol works and surveys have been published in academic papers [6][7] [8]. They present a comprehensive overview of routing solutions for ad-hoc networks. Classification of routing protocols for MANETs can be presented based on different criteria, Here is a brief explanation of the groups (see Figure 2.1) [15][18] [51]. First, the routing information update mechanisms are classified based on proactive mechanism, reactive and hybrid. Second, they are classified based on path selection using path history and predication. Third, they are classified based on topology information (flat and hierarchical). Finally, they are classified based on utilisation of specific resources (power-aware or geographical).

Note that there are so many protocols, because an ad hoc routing protocol is often established for a specific purpose. Since the AODV performs well in more stress situations (more load, higher mobility). The author has used the AODV routing protocol in the performance evaluation in the next chapters. So this subsection also explains the well-known on-demand routing protocol (AODV).

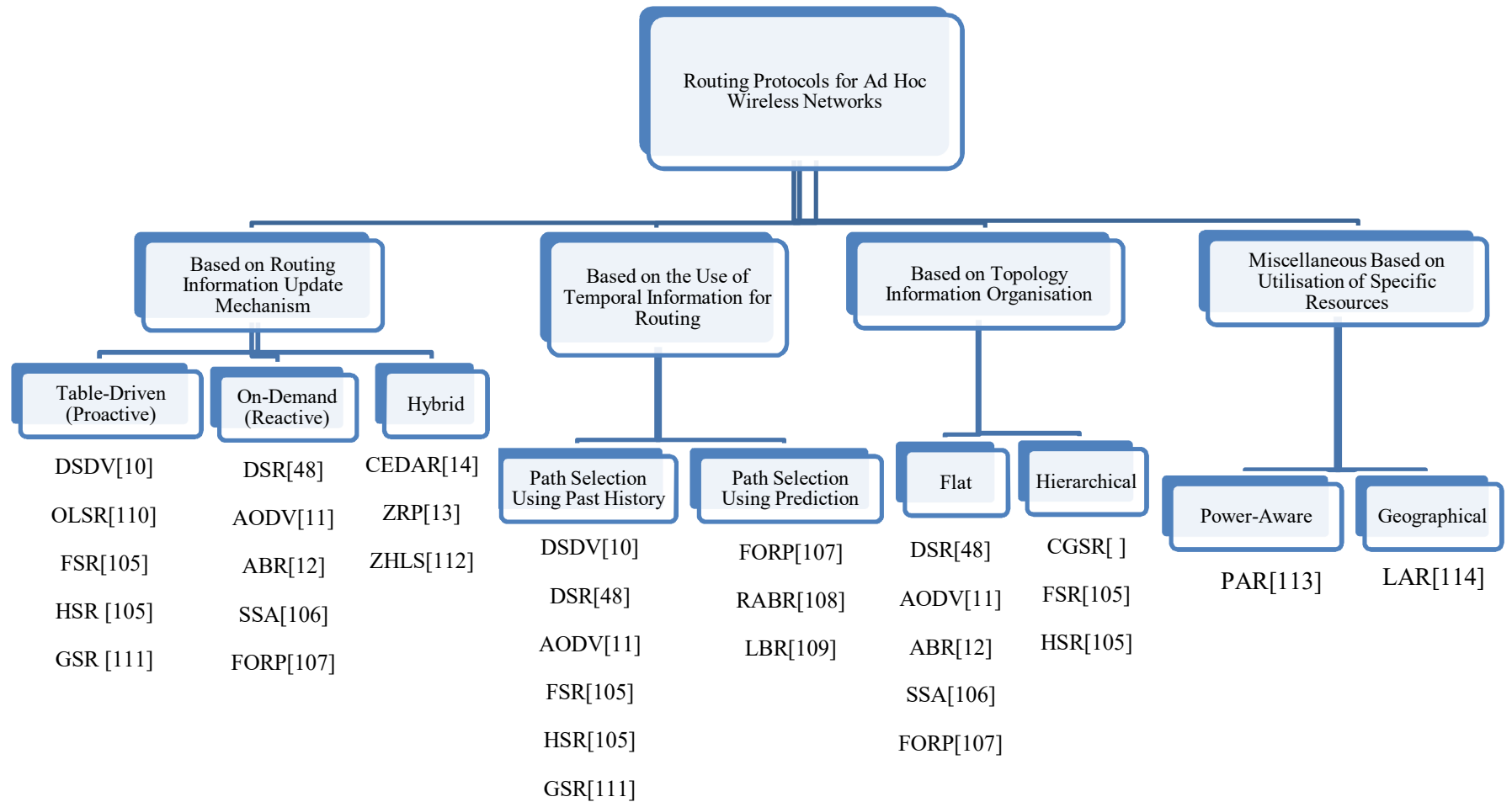


Figure 2.1: Classifications of Routing Protocols [51]

### **2.2.1.1. Ad-hoc On-Demand Distance Vector (AODV)**

In this subsection, the AODV routing protocol is briefly explained; because the performance analysis for the broadcasting schemes, as well as the suggested new scheme in Chapter 6 (The CAPB), are tested by being equipped with this well-known routing protocol.

Among the aforementioned reactive procedures, the AODV is the most popular and highly-researched MANET routing protocol [11]. The AODV routing protocol supports dynamic route conditions, it has a minimised memory overhead, it requires low processing and network utilisation, and the AODV is able to determine unicast routes to destinations within the mobile ad-hoc network.

In an on-demand algorithm, both route discovery and maintenance mechanisms are controlled by the sender nodes as they are needed or controlled “on-demand”. Additionally, sequence numbers are used to ensure that routes are updated. AODV is loop-free, self-starting, and is able to scale to large numbers of nodes [11].

AODV has the advantages of DSR, such as creating routes on demand and building the path between the sender and receiver through the route discovery mechanism. Additionally, AODV has the advantages of the Destination Sequenced Distance Vector (DSDV) protocol as it has sequence numbers for maintaining the latest information between nodes.

The AODV algorithm works by building the route on demand. This route is not updated until either the route breaks or times out, thus reducing the network overhead. In order to minimise the network overhead, each node is only responsible for ensuring connectivity to local nodes (perhaps one or two hops away) instead of the whole route.

Therefore, each node is responsible for maintaining any broken links to neighbouring nodes and thus only needs to update the route table once a connection has broken or timed-out. In this way, it is possible to control ad-hoc networks over a large area because the network overhead is minimised.

In AODV every node maintains a table containing information about which neighbour to send the packets in order to reach the destination. The sequence number, which is one of the key features of AODV, ensures the freshness of routes [52].

The AODV routing design is composed of two phases: route discovery and route maintenance [11].

### ***Route Discovery***

A source node that needs to send data to a destination node triggers route discovery mechanism by broadcasting a special control packet, called Route Request (RREQ), to its neighbours who then rebroadcast the RREQ packet to their neighbours. The process continues until the RREQ packet arrives at the destination node. The destination node sends a control packet called Route Reply (RREP) that follows the path of RREQ in the reverse direction and informs the source node that a route has been established.

Since every node on receiving the RREQ for the first time rebroadcasts it, it requires  $T-2$  rebroadcasts in a network of  $T$  nodes assuming the destination is reachable. This kind of broadcasting is called pure flooding [11] and is depicted in simplified form in Figure 2.2.

AODV uses an expanding ring technique when flooding RREQ. Each RREQ has a time to live (TTL) that states for how many hops this RREQ should be rebroadcasted. If TTL value exceeds a certain threshold, an error is detected and a unicast Route Error (RERR) packet is sent to the source. Also the RERR packet could be sent, if the destination node cannot be located, before the RREQ reaches its destination at a particular intermediate node

The RERR packet usually follows the same route as that discovered by the first RREQ up to the failure point, but in reverse order [7]. In both of the aforementioned error cases the source initiates a new route discovery process with a different sequence number, which is repeated until a successful route is found.

Once the route is broken due to the mobile nature of the network, the path can be rebuilt through additional route discovery mechanisms. However, when a link to an intermediate node is broken, the local nodes will attempt to repair the link by creating a new receiver sequence and flooding that sequence to all nodes within a specific area,

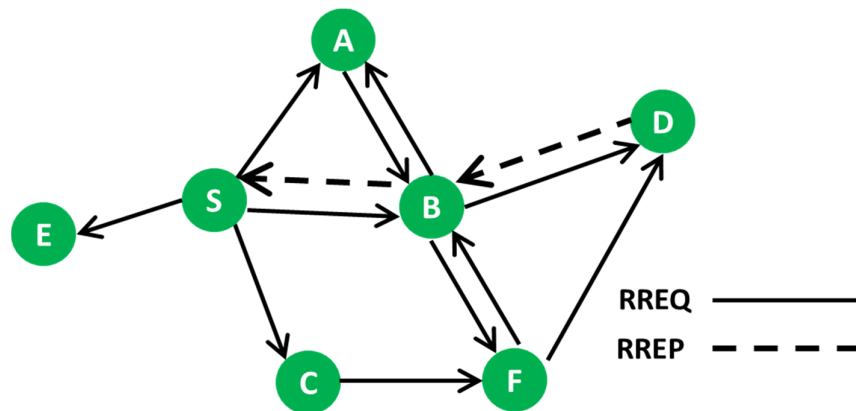


Figure 2.2: Route discovery process between nodes S and D

which is limited to hop counts of lower values than the original hop count used to discover the network. If the node that detects the broken route cannot find an alternative path to the destination, a RERR packet will be transmitted to the sender. In which case, the route discovery will be re-initiated over a larger area (a greater hop distance) than that of the local node, if, indeed, the route is still needed [11].

The length of the packets exchanged during route discovery is kept small compared to the data packets, but is still significant, especially when dealing with multiple route discovery phases [11]

### ***Route Maintenance***

Route maintenance is the second and final phase of the AODV routing protocol. This is the process of responding to changes in network topology which occurs after a route is primarily established. The routes are regularly maintained so long as they serve their purpose. During maintenance, intermediate nodes keep a consistent monitor of active links. Each node also carries an up-to-date list of its 1-hop neighbours, obtained through periodic exchange of hello packets. The routing table contains a pre-allocated destination, the next forward hop towards the destination, and a sequence number.

Route update is largely dependent on the sequence number of incoming messages. Updates are only performed when the incoming sequence number is larger than the existing number. A pre-determined route expiration time is also maintained by the routing table. This expiration time is updated to the current time plus the timer value, which is called ACTIVE\_ROUTE\_TIMEOUT and is attached to each route entry; this expiration time used whenever a particular route is utilised for data packet delivery to highlight whether the status of the route is out-dated or not by testing the usage or

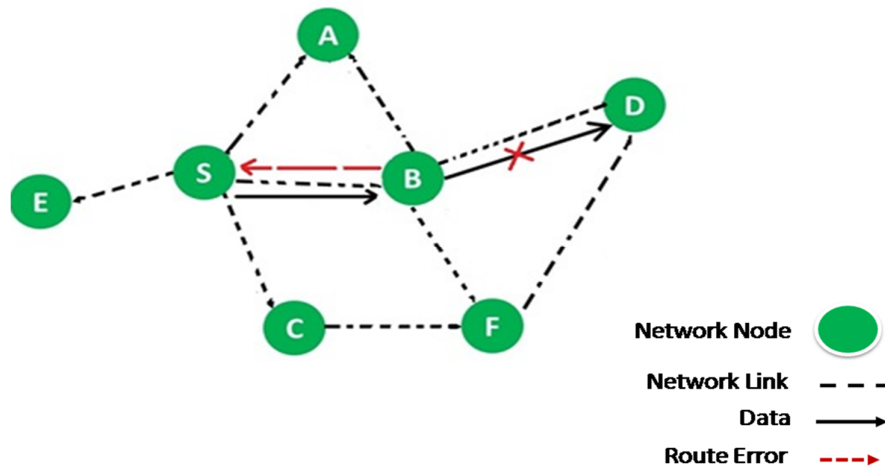


Figure 2.3: Route maintenance process in AODV

refreshment within this time. Once the specified period expires, the routing table is declared void. During instances of broken links, or when a node receives data packets with destinations absent from its forwarding route, a Route Error (RERR) message must be created by the node and sent as a form of immediate response [53].

Figure 2.3 demonstrates the maintenance process performed when node links are disrupted. In the illustration above, the link between node B and D is experiencing breakage. Node B generates a RERR message, which is then transmitted to node S. AODV applies two route repair approaches to deal with link breakage. Routes can either be rebuilding a new route by the source node (Source Repair), or they can be locally repaired by the intermediate node (Local Repair).

## 2.3. Broadcasting in MANETs

Broadcasting is generally defined as the process of transmitting a packet from a source node to all nodes in the network. Broadcasting is more frequently used in MANETs,

especially in the route discovery process in on-demand routing protocols, compared to wired networks. In MANETs, intermediate nodes are employed to assist in the broadcast operation. Intermediate nodes are tasked with forwarding the packet from the source node to other remote nodes in the network.

Broadcasting (the one-to-all model) contains nodes capable of transmitting packets to all nodes within its transmission radius. The one-to-all model is frequently studied in research. The broadcasting of routing control packets (e.g. route request) in some routing protocols is a prime example of this model [11] [48]. In addition, broadcasting is also regularly employed in the distribution of news (e.g. alarms and announcements), for resource detection and advertisement (e.g. topology allocation and maintenance [54]), and for sensor data distribution (e.g. data accumulation [31] and consistency update propagation [55]).

During traditional broadcast settings (i.e. flooding, in which all nodes in the network forward every distinctively received packet exactly once), packet dissemination regularly consumes prime network resources such as bandwidth and node power. This is largely caused by the redundant transmissions of broadcast packets. Consequently, this form of wasteful retransmission leads to high contention and collision in the network, which then causes more waste in restricted bandwidth, and the ultimate potential collapse of the network (especially density networks). This phenomenon is termed the *broadcast storm problem* [15].



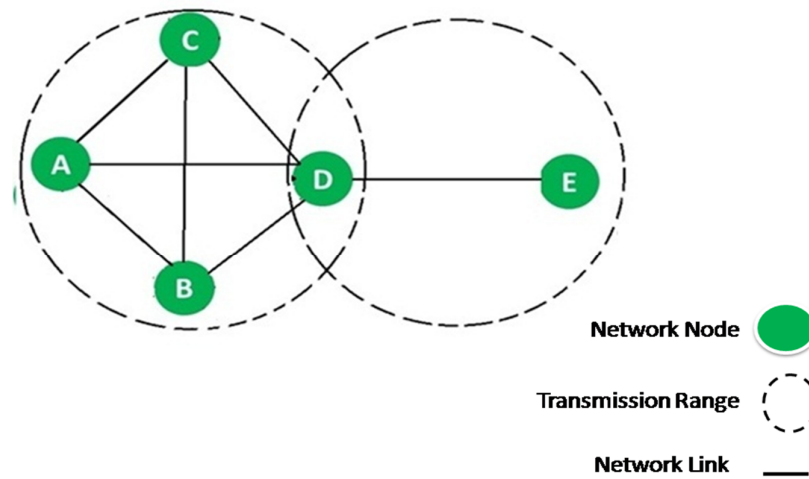


Figure 2.4: Illustration of a network comprised of five nodes

### 2.3.1. Broadcast Storm Problem

The broadcast storm problem is a consequence of the flooding phenomenon. As an example, Figure 2.4 illustrates a network comprised of five nodes. If node A broadcasts a packet, nodes B, C and D will receive the packet. These three nodes will then forward the packet, and E, as the final node, will broadcast the packet. This case proves the redundancy naturally-occurring in flooding. In actuality however, forwarding of the broadcast packet by A and D will be adequate enough to cover all five nodes of the whole broadcast operation.

However, as the size of the network increases and the network becomes denser, more transmission redundancy will likely occur, and this in turn may cause major dilemmas

(i.e. redundant rebroadcast, contention and collision). The broadcast storm problem is highly capable of causing a network meltdown [15][56].

All transmission drawbacks will be expounded in the following discussion:

**Redundant Rebroadcast:** This ensues when a node rebroadcasts packets that neighbouring nodes have already received. The phenomenon is depicted in Figure 2.4. When node A broadcasts a packet to nodes B, C and D, and node B rebroadcasts the same packet to A, C and D regardless of the nodes' previous reception and storage of the file, then the whole transmission is declared redundant and extremely wasteful.

**Channel Contention:** This phenomenon occurs during the consecutive transmission of packets from the source node to other nodes in the system. When a node broadcasts a packet to its neighbours, and all the receiving neighbour nodes attempt to retransmit the packet simultaneously, the transmissions are thus forced to rigorously struggle against each other within a shared physical channel. The ensuing battle for signal and successful retransmission causes delays in the otherwise efficient distribution of data packets.

**Collision:** In line with the competition for shared medium and concurrent retransmission, if more than one node transmits during a particular time on the channel, then the data packets will most likely collide.

### **2.3.2. Classification of Broadcasting Techniques**

Due to the increasing effects caused by the broadcast storm problem, numerous broadcast schemes have been suggested to solve the issue [56][57][58][59]. These schemes are largely grouped into two main approaches: deterministic and probabilistic. In the probabilistic, approach each node in the system rebroadcasts the packet to its

neighbours with a predetermined forwarding probability value, which can be affixed or computed by a node based on the node local density or counter value, or its distance/location to the sender. In deterministic approaches, however, predetermination and selection of neighbouring nodes are involved. A brief account of these approaches will be provided in the following discussion.

### **2.3.2.1. Deterministic Schemes**

Deterministic schemes basically require some topological information of the network, such as local, global, or partial-global information, in order to build a fixed backbone that cover all nodes of a network for a broadcast operation. The topological information can be obtained through the periodic exchange of “hello” packets, where information about node neighbourhood and topological comprehension of the network is gathered.

Deterministic schemes utilise a specific subset of nodes in the network to advance the broadcast packet[60]. The deterministic schemes are presented below.

#### ***Self-pruning Scheme***

Self-pruning is the simplest neighbour knowledge-based broadcasting method. This is indicated as the “flooding with self-pruning” scheme by Lim and Kim [18]. Each node in this system is required to contain information about its 1-hop neighbours; such data is acquired through the periodic exchange of “hello” packets. These nodes then include a list of their 1-hop neighbours in the header of each broadcast packet. The lists are compared to the sender’s neighbour list. If any additional nodes are unreachable to the receiving node, the packet is retained, or else the node will rebroadcast the packet [61].

### ***Scalable Broadcast Scheme (SBS)***

The Scalable Broadcast Scheme (***SBS***) contains nodes that have full knowledge of their neighbours within a 2-hop radius. The neighbour information is combined with the receiving node's identity, thus allowing the receiving node to calculate its possibilities of reaching additional nodes by rebroadcasting the broadcast packet. Through the periodic exchange of "hello" packets, which include the node's identifier and list of neighbours, 2-hop neighbour information is collected and processed. A node which obtains "hello" packets from all its neighbours then contains 2-hop topology information circulating on its identity [60].

### ***Dominant Pruning (DP)***

Dominant Pruning, similar to the (***SBS***), utilises nodes with knowledge of their 2-hop neighbours. This information is again obtained through "hello" packets. DP requires forwarding nodes to proactively choose rebroadcast nodes from its 1-hop neighbours. DP nodes may choose some, or all of their neighbouring nodes depending on need, and those chosen to proceed will be allowed to rebroadcast. Rebroadcasting instructions sent to neighbours include their source address as part of the list contained in each broadcast packet header. Every node receiving a broadcast packet will check if the packet's header address is part of their list. Once confirmed, it uses a Greedy Cover Set<sup>3</sup> algorithm, which recursively chooses 1-hop neighbours which cover the most 2-hop neighbours and recalculates the cover set until all 2-hop neighbours are covered, to shortlist a neighbour subset that will be tasked with rebroadcasting the packet [18][60].

### ***Multipoint Relaying Scheme***

The Multipoint Relaying Scheme also involves information from a node's 2-hop neighbours. This is gathered through "hello" packets used for routing decisions. Each node in the scheme chooses a 1-hop neighbouring subset, which is then assigned as multipoint relays (MPRs) for the 2-hop neighbourhood. When a node communicates a broadcast packet, the MPRs of the transmitting node will be the only elements of the system allowed to rebroadcast the packet. In turn, their MPRs shall be the only ones permitted to rebroadcast data. Thus the scheme runs through a system of permitted MPRs. A node can locally compute its own MPRs through heuristics. This computation depends on the availability of neighbourhood topology data [9] [17].

### ***Ad-Hoc Broadcast Protocol***

The system processes of the ad-hoc broadcast protocol (AHBP) are relatively similar to multipoint relaying. Forward nodes in AHBP are called Broadcast Relay Gateways (BRGs), and as such are the only nodes allowed to rebroadcast packets. BRGs are carefully evaluated and selected from every upstream sender also assigned as a BRG. Both BRG and MPR selection utilise the same algorithm, and the AHBP scheme can be extended to accommodate high mobility networks [62].

### ***Cluster-based Algorithms***

Cluster-based broadcast schemes divide a network into several groups of clusters. All clusters compose the backbone infrastructure. A cluster head is then assigned to each cluster. A cluster head is of the highest rank among all members, and its tasks include the forwarding of packets and selection of forwarding nodes for the whole cluster.

Gateway nodes link two or more overlapping clusters. All cluster heads and gateway nodes composing a MANET form a Connected Dominating Set (CDS) [63]. A CDS-based broadcast algorithm has been formulated and suggested by Peng and Lu [64]. The aforementioned algorithm evaluates the packet's sender and its selected forward nodes with lower node CDS. It then defines and selects the forward nodes' subsequent forward nodes set to keep the system running.

Wu and Li [65] have also devised a marking process that selects forward node sets (or gateways) which will compose a CDS. Each node with two neighbours that are not directly connected is assigned as a gateway and shall serve as the forward node of the broadcast process. Additional enhancements are also mentioned. Though clustering is a desirable scheme in MANETs, resulting from cluster formation and maintenance are usually non-trivial. The total number of forwarding nodes is thus utilised as the general cost criterion for broadcasting. The problem of determining the minimum number of forward nodes that compose the minimum connected dominating set is recognised as NP-complete [66].

### ***Hybrid Broadcast Algorithms***

A unique form of hybrid broadcast algorithm that combines self-pruning schemes with neighbour-designating schemes was formulated by Wu and Dai [67]. A node prepares for the transmission of a broadcast packet by assigning forward nodes that will partially include its 2-hop neighbour set. Specially-selected receiving forward nodes will rebroadcast a received packet, while regular forward nodes will use self-pruning algorithms to determine the forward/non-forward status of a received broadcast packet.

Deterministic schemes are declared generally non-scalable because they require excessive overheads that are mainly associated with the building and maintenance of network topological data, especially in high-mobility cases.

### **2.3.2.2. Probabilistic Schemes**

Probabilistic broadcast schemes [24][2][68][69][70][25] are categorised by packets that are broadcasted with a probability  $p$ . The general classification for probabilistic schemes is divided into four solid groups: fixed probabilistic, counter-based, location-based, and distance-based schemes.

#### ***Fixed Probabilistic Scheme***

All mobile nodes in this scheme are allowed to rebroadcast a packet based on a predetermined forwarding probability  $P$ , which is then used to measure the overall rate of the system's effectiveness [68] [69].

Probabilistic schemes propounded by Cartigny and Simplot [26] compute the forwarding probability  $P$  from the local density  $n$  (i.e. the number of neighbours of the node considering rebroadcast). The authors introduced a fixed value parameter  $k$  to achieve high reachability for a particular network topology. These broadcast schemes, however, are largely constant in nature, since all nodes of the network determine their forwarding probability from the fixed efficiency parameter.

#### ***Counter-based Scheme***

This scheme requires a node which, upon reception of a broadcast packet, immediately employs a random assessment delay (RAD), along with a timer that calculates the

number of received duplicate packets. Upon expiration of the timer, and if the counter exceeds the assigned threshold value, the consecutive node decides not to rebroadcast, as it supposes that its neighbours have all received the data packet. If the counter stays within the assigned threshold value however, the consecutive node will proceed with the rebroadcast. It is very important to select an appropriate threshold value, as this dictates the efficiency of the whole technique. It has been demonstrated in how choosing a threshold value between 2 and 4 can reduce transmission redundancy[20].

### ***Distance-based Scheme***

This particular scheme calls for a node to forward a packet based on an additional covering neighbouring nodes: a measurement calculated from the distance between itself and neighbouring nodes that have already forwarded the packet. In this scheme, a node that receives a broadcast packet for the first time checks the topology of the received packets' senders. If upon survey it encounters a sender located closer than the assigned threshold distance value ( $D$ ), the node shall discontinue the rebroadcast; otherwise, the node rebroadcasts the packet. Topological knowledge in the distance-based scheme can be gained through the use of a GPS receiver, where nodes can supply their information in each transmitted packet. As an alternative, factors such as signal strength can provide a distance estimate of the received packet's source [71].

### ***Location-based Scheme***

The location-based scheme requires each node to carry self-topology information relative to the sender's position. This kind of knowledge is calculated through geo-location techniques such as GPS. When a node receives a previously unknown packet, it first deploys a waiting timer, and then gathers data about the packet's coverage area. If



the accumulated coverage area is larger than the assigned threshold value, upon expiration of the timer, the node will refuse to rebroadcast. Otherwise, the rebroadcast process shall continue [56].

## **2.4. Cross-Layer Designs**

The layering design of the protocol has great success in wired networks. However, the mobility of the nodes together with wireless transmission effect such as thermal noise, interference and raise some inherent issues of mobile ad hoc networks make cross-layer designs the best solution to improve the performance operation of a MANET.

### **2.4.1. A Definition of Cross-Layer Design**

To illustrate: a layered structure divides an overall network into defined layers, by which services provided by individual layers are assigned by a hierarchy. This is best exemplified by the seven-layer open systems interconnect (OSI) model [72]. The services at the layers are decided upon by specially-designed protocols for the varying layers. This type of architecture blocks direct communication between nonadjacent layers, while limiting communication to calls and responses between adjacent ones [73].

Following the architecture model also provides protocols well-interfaced, such that a protocol will not require any additional interfaces that are absent from the reference structure. On the other hand, protocols may be designed to differ from the reference structure. For example, it may allow direct communication between nonadjacent layers, or distribution of variables among layers, regardless of location.

This special design is called a cross-layer with respect to a fixed layered architecture. Examples of cross-layered architecture include the generation of new interfaces between network layers, reassessment and reformation of layer boundaries, constructing layer protocols based on existing layer designs, combined modification and adjustment of parameters across layers, etc.

To explain further, a hypothetical three-layer model is used as an illustration. The layers are indicated as L1 (the lowest layer), L2, and L3 (the highest layer). Remember that in this design, no interface exists between L3 and L1. It is quite possible, nonetheless, to construct an L3 protocol that requires L1 to pass a parameter to L3 during runtime. As an alternative, L2 and L1 can be treated as a single layer, and thereby it is possible to construct a joint protocol for this “super layer”. Furthermore, in designing L3’s finalising protocol, the designer should be wary of L1’s existing processes before proceeding. In so doing, independent designing of different layer protocols is no longer a possibility. The aforementioned methods are samples of cross-layer design with respect to the specified three-layer architecture. As cross-layer solutions increase in propensity and occurrence, the original architecture completely loses its meaning with the passage of time [73].

## **2.4.2. Approaches Based on Cross-layer Design**

### **Optimisation**

Methods of implementing cross-layer interactions are being discussed in the literature [73]. These methods can be grouped into three classifications:

#### **2.4.2.1. Direct Communication between Layers**

Runtime information sharing is possible through interactive communication. A straightforward method of this is to allow layers to directly communicate with each other, so that information on dynamic vertical calibration. This is further illustrated in Figure 2.5a. Take into account that such a method is only applicable when runtime information sharing between layers (e.g. in cross-layer designs that rely on new interfaces or in dynamic vertical calibrations) is required. In other words, direct communication between layers allows the visibility of variables from one layer to another during runtime.

#### **2.4.2.2. A Shared Database across Layers**

Another set of proposals recommends the assembly of a common database that is open to all layers, as demonstrated in Figure 2.5b. The common database is akin to a new layer, acting both as a storage and retrieval unit for all layers in the system. Through the shared database, an optimisation program can interface with the different layers immediately. Likewise, new interfaces between layers are also recognised through the same database. In this approach however, a designer should be capable of conceptualising an organised pattern of interactions between the different layers and the shared database in order to achieve the maximum efficiency of such a method.

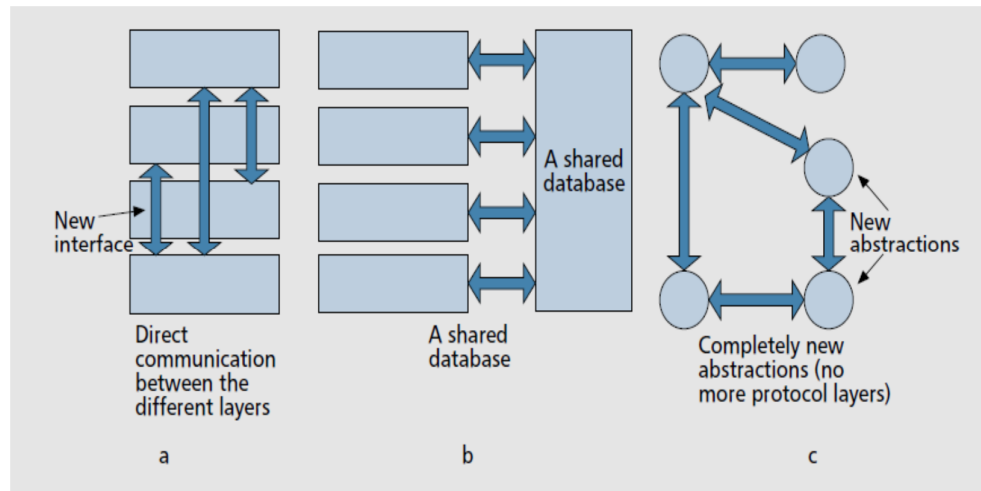


Figure 2.5: Proposals for architectural blueprints for wireless communications [73]

### 2.4.2.3. Completely New Abstractions

The third and final class of proposals suggests completely new abstractions, as illustrated schematically in Figure 2.5c. This particular schematic offers a new way of organising protocols through heaps, as opposed to the standard layering structure which uses stacks. Such innovation may provide greater flexibility during the design and runtime stages. It can however, alter the original organisation of the protocols, and may therefore call for completely new system-level operations/implementations [74].

## 2.5. Simulation Environment

MANETs face several challenges due to their lack of coordination or configuration prior to set up. These challenges include routing packets in an environment where the topology is changing frequently, facing wireless communications issues, and dealing with resource issues such as limited power and storage. These challenges make

simulation an extremely feasible, cost-effective, and useful tool for analysing the operation of these networks [30][75].

### 2.5.1. Network Simulators

In computer network and communication research, network simulation is defined as a technique where the behaviour of a network is modelled.

In a simulation, various services, applications and the behaviour of the network can then be observed during experiments in the lab, using different environment parameters that can also be adapted in a controlled manner to study the performance of a network under various conditions. In this subsection, the author has discussed both commercial simulators and open source simulators, such as NS-2, NS-3, OPNET, OMNeT++, J-Sim and QualNet. In Table 2.2, the author provides a brief overview of the network simulators in terms of its programming language and pros and cons.

Table 2.2: Comparisons between network simulators

Simulator	Language	Pros	Cons
NS-2	C++, TCL, Otcl	Easy to add new protocols. There are a large number of protocols available. There are visualisation tools. Open Source. Large number of user-groups.	Takes time to learn. Poorly documented.
NS-3	C++, Python	It is a new simulator; NS3 is not an extension of NS-2	Windows platform are lightly supported as Some ns-3 aspects depend on Unix / Linux support
OPNET	C, C++	Large number of customers Professional support. Well-documented.	Relatively it is costly – but there is a suitable price for universities. OPNET seems more

			suitable for network managers than for research into generic performance.
OMNeT++	C++	Easy to trace and bug. Simulates power consumption problems.	Limited routing protocols available. No compatibility (not portable).
QualNet	C++	Usability. Animation capabilities. There is support for distributed computing and multiprocessor systems.(GloMoSim is an open source of QualNet which is freely available and specialized for ad hoc networks. However, GloMoSim lacks some of the QualNet facilities)	Installation problems on Linux. Slow Java-based UI. It is costly.
J-Sim	Java, Tcl	Open source Reusability and interchange-ability models. Easy to trace and debug programs.	Efficiency of simulation is low. There is only one MAC protocol provided for wireless networks. Run-time overhead.

### 2.5.2. Method of Study

In this research work, simulation is considered as the method of study. The NS-2 simulation has been chosen as the simulation tool in this research. The NS-2 is based on three languages: C++ implements the schedulers, TCL writes the simulation script, and OTCL defines the simulation parameter. The outputs created by NS-2 can be NAM format trace files, personalised trace files, and general format trace files. NS-2 is free, difficult scenarios can be easily analysed and studied, and results can be quickly obtained.

The NS-2 also provides an environment with specific advantages over the other methods, including:

- Allowing repeatable scenario evaluation and exploration of a variety of metrics.
- Providing an aid to the development and refinement of networking protocols by allowing the protocol developer to make changes to the protocol and retest the protocol in the same scenario, which provides deeper understanding of how the changes affect the performance results.
- The control of parameters can be implemented during the run. This gives the effects of mobility, density, data traffic or transmission range, etc. and allows them to be analysed in detail while all other parameters are held constant.
- It also allows a wide variety of scenarios and network configurations to be evaluated in a reasonable scale, time frame and budget.
- It is a proven simulation tool utilised in several previous MANET studies and has been validated and verified [76].

#### **2.5.2.1. Assumption**

The assumptions of this research have also been largely adopted in the study's literature [77][2][78][79][20]. From the beginning until the end of the simulation time, the total number of nodes in a specific topology remains fixed and constant. A node will not be added or extracted from the simulation area during the simulation time. The behaviour of the proposed algorithms can be simultaneously studied at the same time and in the same environment. These conditions will also allow direct and fair comparisons between new and existing algorithms, without losing nodes in the process.

All mobile nodes during the broadcasting protocol of a network are homogeneous. In other words, every node is provided with IEEE 802.11g transceivers only in the scenario, and each node offers full participation through the forwarding of data packets from one node to the next.

MANET nodes contain limited power. Any source node carrying a transmission packet (i.e. control or data packet) may launch a broadcast operation or route discovery process. Further assumptions shall be expounded in the subsequent chapters.

### **2.5.3. Performance Metrics**

To judge the merit of a routing protocol, here are some important performance evaluation metrics of routing protocols[80][81]:

- ✓ End-to-end delay: includes all possible delays caused by buffering during route discovery latency, queuing at the interface queue, retransmission delays at the MAC, propagation delay, and transmission delay.
- ✓ Jitter: it is used as a variability measurement over time of the packet latency across a network. A network with constant latency has no variation.
- ✓ Packet Loss: It happens once one or more traveling packets across a network fail to reach their destination.
- ✓ Route Acquisition Time: it is the time required to establish route(s) when requested.
- ✓ Network life time: it is a time when a node finished its own battery for the first time. And system Life time: it is a time when 20% of nodes in a network finish their own battery.



- ✓ Routing Overhead: is defined as the ratio of the number of routing packets (control packets) transmitted per data packet received.
- ✓ Throughput: is defined as the amount of data received by a node per unit of time.
- ✓ Energy Consumption: accounts for the energy consumed in the transmitting, forwarding and receiving of application layer data and routing-related control data.
- ✓ Packet delivery ratio: it is the ratio of the number of packets successfully received by all destinations to the total number of packets lost into the network by all sources.

Out of these metrics, this thesis uses four metrics (**average throughput, routing overhead, average end-to-end delay and average energy consumption**). The justification of chosen those metrics as follow: since this thesis proposes a new scheme to reduce broadcast storm problem, so it is essential to evaluate the effect of this scheme on the network layer parameters, as well as the application layer parameters.

## 2.6. Summary

This chapter has presented the characteristics of MANETs. It has also discussed routing protocols which are developed for MANETs, with a particular emphasis on route discovery process in AODV as a common example of the use of broadcasting mechanisms, and then the fundamental phases of the AODV routing protocol, where both route discovery and maintenance operations have been briefly outlined. The background and related work on broadcasting in mobile ad-hoc networks has been highlighted. Broadcasting in MANETs has been discussed along with the performance

drawbacks of the broadcast storm problem. This has been extended by discussion of the different categories of existing broadcast schemes which have been proposed to reduce the effect of the broadcast storm problem. This chapter also provided a brief overview of the cross-layer approaches. This chapter discussed the network simulators in terms of their programming language and pros and cons, and a discussion on the choice of simulation as a tool of study in this research. Finally, it outlined the performance evaluation metrics used and some assumptions that applied throughout this research.

Several studies have been presented in the literature to address on-demand routing protocols performance in MANET s. However, these studies do not consider how the effects of interference, which exist in noisy MANETs, can be reduced by the effects of lower layer parameters such as physical and virtual carrier sensing ranges. So, the next chapter will examine the effect of different carrier sensing ranges on the performance of on-demand routing protocol and interference.

## Chapter 3

# Effects of Carrier Sensing Ranges on the Performance of On-demand Routing Protocols in Noisy MANETs

The IEEE 802.11 MAC standard defines two coordination functions as follow: Distributed Coordination Function (DCF) and Point Coordination Function (PCF) [82]. The PCF mechanism deploys a polling technique through the access points. That is why the PCF mechanism is not suitable for multi-hop networking. In the DCF mechanism, active nodes compete to use the channel in a distributed manner. So, the DCF mechanism is commonly used in ad-hoc networks.

The DCF mechanism uses a CSMA/CA scheme, the CSMA/CA utilise physical carrier sensing and it optionally uses virtual carrier sensing, which is the Request-To-Send/Clear-To-Send (RTS/CTS) dialogue to mitigate the so-called hidden terminal and exposed terminal problems for WLANs, those problems are usually formed in a multi-hop network [83].

The Physical Carrier Sense is used when a node, seeking to transmit, first assesses the channel. If the energy detected on the channel is above a certain threshold (the carrier sense threshold), the channel is deemed busy, and the node must wait. Otherwise, the channel is assumed idle, and the node is free to transmit. A Virtual Carrier Sense uses a special handshake approach to "reserve" the channel, called the RTS/CTS mechanism [35].

The transmission range and sensing range of a transceiver play a vital role in successful communications. The first parameter is more or less fixed by the vendor and hardware specifications while the second one is a tuneable parameter. IEEE 802.11 specification does not specify a particular value of sensing range. How to find an optimal value of the sensing range is not a trivial problem and normally, it is left equal to the transmission range [23].

An unsuitable carrier sensing range value directly affects the interference in mobile ad-hoc networks, as a result higher collision probability in the channel. The higher collision probabilities have direct impact on the routing overhead that affects the whole MANET performance [22]. This can be explained by a high demand of route discovery process is placed on the network layer to establish routes between nodes. So, a challenge for a designer is to reduce routing overhead by decreasing the collision probability (interference) in the channel by using a suitable carrier sensing range.

Motivated by the above observation, this chapter investigates the effects of physical and virtual carrier sensing ranges on the performance of on-demand routing protocols in noisy MANETs, and highlights how the carrier sensing ranges affect the collision probability (interference). **Parts of the results presented in this chapter have been published in [84] and [77].**

The rest of the chapter is arranged as follows: Section 3.1 presents an overview of the carrier sensing ranges. Section 3.2 analyses the effects of the physical and virtual carrier sensing ranges on an on-demand routing protocol (the AODV routing protocol, which uses a pure flooding broadcasting scheme) in noisy MANETs. Finally, section 3.3 summarises the chapter.

### 3.1. Carrier Sensing Ranges

The Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) is a protocol that uses physical and virtual carrier sensing (called RTS/CTS mechanisms in 802.11) for avoiding collisions. The RTS/CTS mechanism has three steps:

- (1) The sender initiates the process by sending an RTS message.
- (2) The destination replies with CTS.
- (3) The actual data/Acknowledgment (DATA/ACK) exchange will be achieved. As a result, it reserves the channel for the coming DATA/ACK transmission.

In regard to the physical carrier sensing range, when a node is ready to transmit, it must first determine whether the channel is busy. If so, then, in order to minimise the collision possibility, the retransmission is postponed for a random Back-off time. A channel is determined to be busy if the signal power on that channel exceeds a specific threshold known as Carrier Sense Threshold (CST). If the signal power is lower than this threshold, the channel is deemed to be idle [85][86]. The value of the CST can be used to tune the network sensing range, and reducing the collision probability in the channel. If the CST is low, the signal can be sensed over a long range and vice versa.

Figure 3.1 illustrates the relationship between the transmission range and the carrier sensing range. Typically, the transmission range is much smaller than the physical carrier sensing range.

If there is interference between A and B nodes see figure 3.1, a packet can be received but might not be decoded correctly within the physical carrier sensing range. However, the physical carrier sensing scheme is more efficient than the virtual carrier sensing

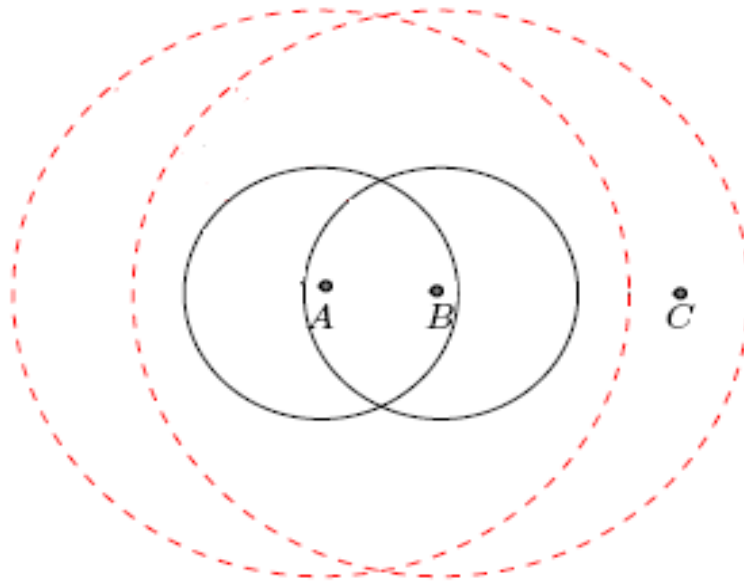


Figure 3.1: Transmission and Carrier sensing range (the small and large circle denote the transmission and sensing range respectively)

scheme for avoiding interference in MANETS, because the physical carrier sensing has a direct effect on the number of concurrent transmissions which leads to more interference [84][85].

The number of possible concurrent transmissions is reduced by a long carrier sensing range, and consequently the average throughput will be lowered. As this results in a higher level of detection of a busy channel, fewer transmissions will occur. Typically, interference will likely be present when there is a higher chance for concurrent transmissions. This is why normally it is left equal to the transmission range [23].

A concurrent transmission is the important key to enhance the MANETs performance. This requires a mechanism to determine a suitable carrier sensing range, and an unsuitable carrier sensing range directly affects the SINR value, because of a high interference level.

## 3.2. Performance Evaluation

This section highlights the causal effects of carrier sensing ranges on the performance of on-demand routing protocol (such as the AODV routing protocol) in noisy MANETs using simulations. The performance has been evaluated in terms of routing overhead, end-to-end delay and throughput by varying the carrier sensing range. The simulation environment takes into account the thermal noise and co-channel interference.

### 3.2.1. Simulation Setup

The author used the ns-2 simulator (2.35v) [75] to study the impact of physical and virtual carrier sensing ranges on on-demand routing protocols (the AODV routing protocol [87]).

#### 3.2.1.1. Simulation Models

Here are the descriptions of models used in the simulation setup:

##### *Mobility Model*

MANET Nodes are frequently mobile, so modelling their movement patterns is quite a challenge and it is essential to use a mobility model in analysing a new protocol's performance [88].

There are two basic types of mobility models used in the analysis of MANET algorithms: trace-driven models and synthetic models [89]. The mobility patterns for trace-driven models are gleaned from standard real-life system observations. Data collected from large groups of participants under long periods of observation, usually provide precise patterns. The collection, evaluation and dissemination of such statistics may be inhibited by certain privacy issues, with concerns to data confidentiality, time

and cost privileges. On a different note, synthetic models vie to represent mobile node behaviours in the absence of traces. They are not as accurate in data and results production as trace-driven models (i.e. in terms of real life system representation). However, this kind of model provides researchers a reliable estimate of nodes' behaviour patterns at lower costs and shorter time periods.

This research work utilised synthetic mobility models, due to limited availability and high scenario specificity of traces. The traces available for study prohibit sensitivity analysis of algorithm performance, as the value of parameters in the simulation scenario remains constant and affixed. Synthetic models are categorised into two models: entity models and group mobility models, with respect to how participating nodes were observed in the system. Numerous entity mobility models for the generation of synthetic traces have been postulated and promulgated for MANETs[90][91]. A classic example of this model is the Random Way-Point (RWP) mobility model [88].

In this model a collection of nodes scattered randomly within a restricted simulation area. Each node begins the simulation at a stationary position during pause time, and then selects a random destination inside the area. The nodes then move towards the chosen destination with a random speed determined from a uniform distribution (minimum speed, maximum speed). Upon reaching its destination, every node pauses for a time interval, upon which it chooses another random destination and speed. Thus the whole process is continued until the end of the simulation time. The RWP model credits its popularity to the simplicity of its procedures. So, the RWP model [88] was utilised in this research.



### ***Signal to Interference plus Thermal Noise Models***

Noise is defined as unwanted signal, normally caused by a random fluctuation in an electrical signal, undesired random disturbance of a useful information signal and a summation of unwanted or disturbing energy from nature. Noise can be generated by several different effects. For example, thermal noise is presented at non-zero temperature. Thermal noise is sometimes called Johnson or Nyquist noise which is unavoidable at non-zero temperature, and generated by the random thermal motion of charge carriers.

The Signal to Interference plus Thermal Noise Ratio (SINR) is considered as a common way to measure the quality of a wireless connection. The definition of the SINR model has been used as described by Chafekar, *et. al* [92] and Adarbah, *et. al* [52].

SINR attempts to create a representation of the channel while only considering thermal noise and interference.

SINR is defined as:

$$SINR = \frac{P}{I+N} \quad (1)$$

Where  $I$  is the amount of interference,  $N$  is the thermal noise power, and  $P$  is the received power.

The medium access control (MAC) protocol is simulated using the ns2 library dei80211mr [21]. This library calculates the Packet Error Rate (PER) using pre-determined curves (PER Vs. SINR) for different packet sizes. Figure 3.2 shows the PER Vs. SINR curve [21] used in the simulations.

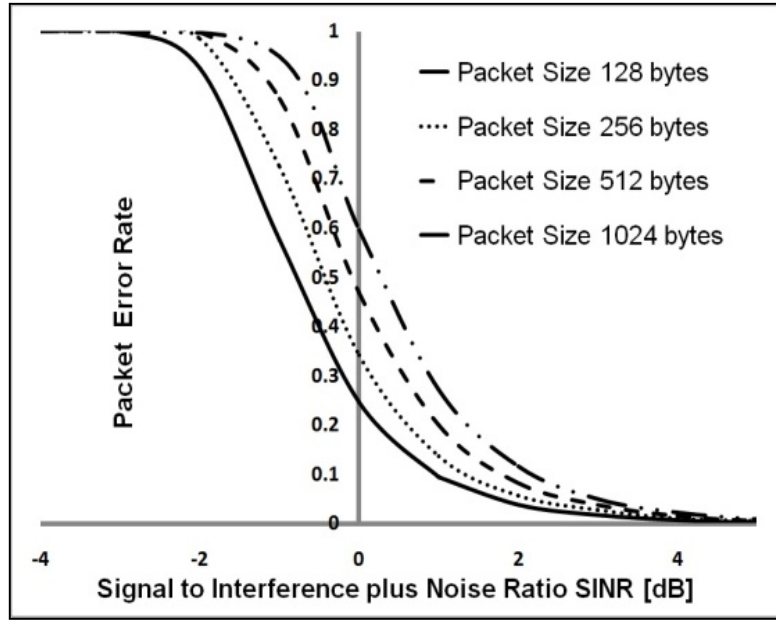


Figure 3.2: Relationship between PER and SINR for different packet sizes [21]

The value of thermal noise is set to -95dBm in the simulation following recommendations from [93].

### 3.2.1.2. System Parameters

The key components of the research simulation models in this research work, as mentioned in other related works [5][77] [68], are: simulation area, number of nodes, mobility model, and speeds. The simulation parameters generally follow [2][56].

The network bandwidth is set to 6 Mbps. Transmission power, path loss and receive power threshold are set such that the effective transmission range is 250m. Because of that the author wanted to have a scenario with higher interference, where the MANET nodes were placed randomly in an area of 1000x1000 square metres. The scenario consists of 16 nodes, because the virtual carrier sensing scheme is not recommended in MANETs with high nodal density, as it causes a lot of routing packets in the network

layer. The physical carrier sensing range starts from 250m, because it is not recommend being less than the transmission range [23]. The radio propagation is based on 2-ray Ground Reflected Model for clarity of results. The two-ray ground reflection model considers both the direct path and a ground reflection path. This model gives more accurate prediction at a long distance than others such as the free space model.

The nodes move according to the Random Waypoint mobility model [88] with a maximum speed of 5 m/s and pause time set to zero, because the author wanted a scenario with higher presence of mobility. To consider the effects on application layer, FTP (File Transfer Protocol) agents are attached to nodes such that node  $i$  is downloading a file of infinite size from node  $i+M/2$  for  $i=1,2,\dots,M/2$  where  $M$  is the total number of nodes.

### **3.2.2. Results and Analysis**

Simulation results are obtained by averaging the results of 30 runs to have the smooth plots of the figures, each using a different seed value and lasting for 800 seconds. The seed value is used to set the initial location of MANET nodes within the area. The aforementioned performance metrics (routing overhead, end-to-end delay and throughput) were shown by varying physical carrier sensing ranges with considering the thermal noise and co-channel interference.

#### **3.2.2.1. Routing Overhead**

The routing overhead is defined as the total number of routing packets transmitted for each data packet received. Examples of routing packets are Hello messages, RREQ, RREP, etc. Figure 3.3 shows routing overhead against the physical carrier sensing range for basic Access (i.e. without RTS/CTS mechanism), and RTS/CTS mechanism. As it

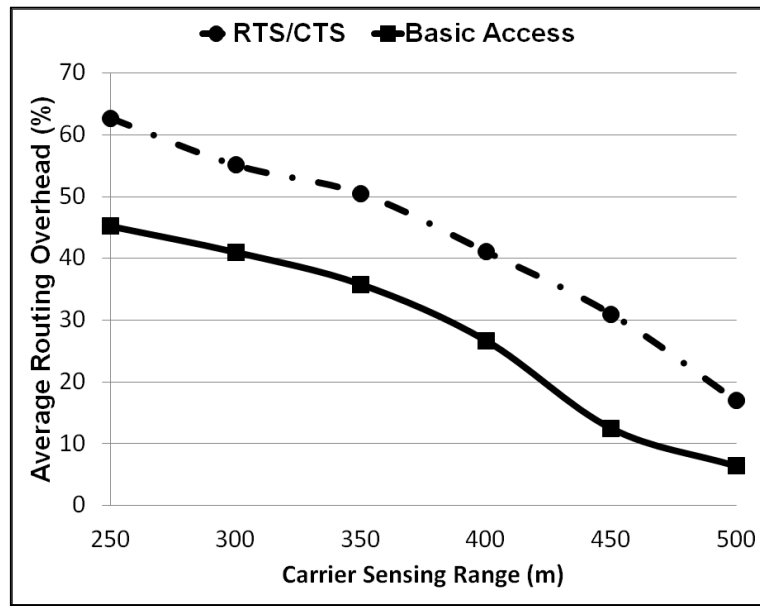


Figure 3.3: Routing overhead vs carrier sensing range

can be seen from figure 3.3, that average routing overhead for both basic access and RTS/CTS decreases significantly from around 61% to under 20% for RTS/CTS ,and from around 45% to under 10% for basic access, over increasing a carrier sensing range from 250m to 500m. It can be explained by increasing the carrier sensing range, the nodes, which are ready to transmit, go to a defer state, because of sensing the current node's data transmission. So, there will be less number of concurrent transmissions which decreases collisions probability. Note that there are some nodes which cause some collisions by starting their transmissions in the beginning of the same time slot.

It can also be observed from figure 3.3, that the average routing overhead of the basic scheme is generally less than the RTS/CTS scheme. Because of the RTS/CTS dialogue has been deployed, the RTS/CTS mechanism does not sense the carrier again. Some nodes may start a transmission and destroy the data packet reception at the receivers, because they are outside of the carrier sensing range of the sender

In conclusion, the average routing overhead decreases over increase carrier sensing ranges. Because of that, shorter carrier sensing ranges lead to more concurrent transmissions. The larger amount of concurrent transmissions explains why the routing overhead of a network is higher.

It is recommended that the average routing overhead must be low, because of being high means that the energy consumption will be high. However, it cannot be said that the larger carrier sensing range leads to better performance, because the larger carrier sensing range can negatively affect other MANET performance parameters as shown in the next sections (end to end delay as well as throughput).

### **3.2.2.2. End-to-End Delay**

The average end-to-end delay includes all possible delays caused by buffering during route discovery latency, queuing at the interface queue, retransmission delays at the MAC, and propagation and transfer times. Figure 3.4 shows the end to end delay against the carrier sensing ranges for basic Access, and RTS/CTS mechanism.

It can be observed from figure 3.4 that the average end to end delay for both basic access and RTS/CTS increase significantly from around 0.08 seconds to almost 0.12 seconds for basic access, and from around 0.11 seconds to under 0.16 seconds for RTS/CTS, over increasing a carrier sensing range from 250m to 500m, this increase in the end to end delay can be explained as follow: since the larger carrier sensing range leads to more nodes being able to sense the node's data transmission and go to a postpone state. As a result of that, there will be less number of concurrent transmissions causing more discovery latency and retransmission delays. It can also be observed from

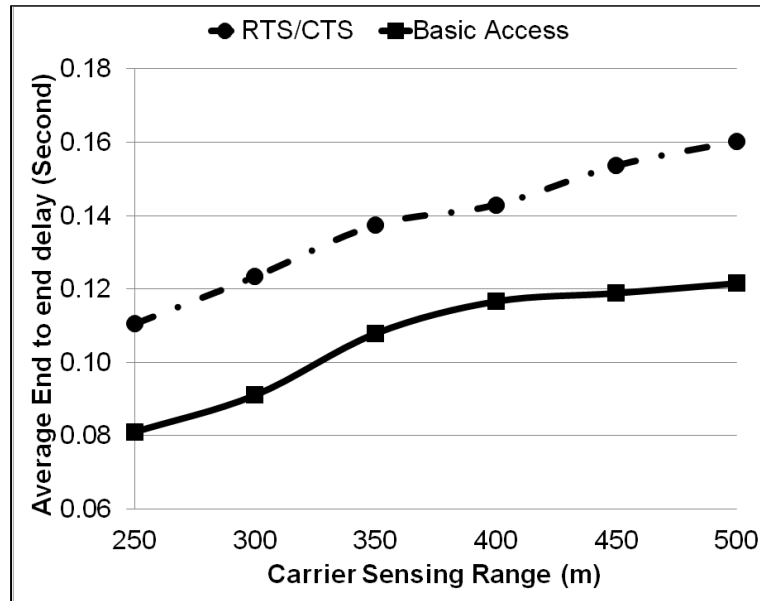


Figure 3.4: End to end delay vs carrier sensing range

figure 3. 4, that the basic scheme is generally better than the RTS/CTS scheme. This is because the RTS/CTS scheme needs more time for the RTS/CTS dialogue to be exchanged.

### 3.2.2.3. Throughput

Throughput is defined as the amount of data received by a node per unit of time. Figure 3.5 shows the throughput against the carrier sensing ranges for basic Access, and RTS/CTS mechanism. It can be seen from figure 3.5 that the average throughput for both basic access and RTS/CTS decreases significantly from around 3.5Mbps to under 2.5Mbps for basic access, and from around 2.9Mbps to almost 1.5Mbps for RTS/CTS, over increasing a carrier sensing range from 250m to 500m. The average throughput shows better level once the carrier sensing range is close or equal to the transmission range of 250m, because there will be higher end to end delay if the carrier sensing range is higher than the transmission range as shown in figure 3.4. However, once the carrier

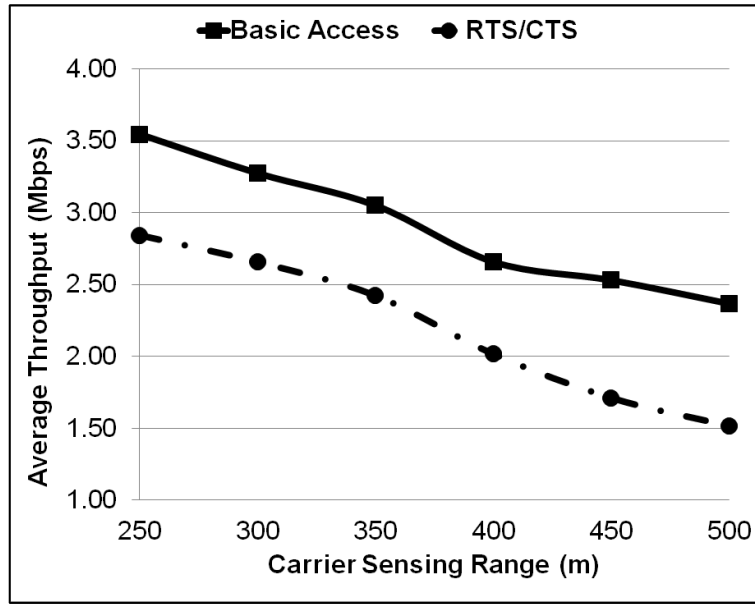


Figure 3.5: Throughput vs carrier sensing range

sensing range close or equal to the transmission range there will be more routing packets as shown in figure 3.3.

### 3.3. Summary

This chapter focused on the impact of varying physical carrier sensing range on on-demand routing protocol (the AODV routing protocol) in terms of these metrics (routing overhead, end-to-end delay and throughput), and highlighted the effects of carrier sensing range on interference by showing that an unsuitable physical and virtual carrier sensing ranges have negative effect on interference, because of that, the high amount of concurrent transmissions causes the high probability of collisions, and packet error rate (PER) is closely related to Signal to Interference plus thermal Noise Ratio (SINR).

Simulation results have shown that: 1) the average routing overhead (Figure 3.3) decreases about 40% for RTS/CTS, and around 30% for basic access over changing the physical carrier sensing ranges from 250m to 500. 2) The average end to end delay

(Figure 3.4) rises around 0.04 seconds for basic access, and around 0.05 seconds for RTS/CTS over changing the physical carrier sensing ranges, and 3) the average throughput (Figure 3.5) decreases about 1.2Mbps for basic access, and around 1.8Mbps for RTS/CTS over changing physical carrier sensing ranges from 250m to 500m.

Since, the more routing packets (controls packets) are generated, the more energy is consumed. Therefore, the average routing overhead should be balanced with the other MANET performance parameters. So, the routing overhead should be taken into account by selecting an appropriate carrier sensing range. Since the PER value closely related to SINR So, the next chapter will examine the impact of thermal noise on the performance of on-demand routing protocol.



## Chapter 4

### **Impact of Thermal Noise on the Performance of On-demand Routing Protocols in MANETs**

In communication systems, distortion generated from the receiver (thermal noise) and the environment is termed “noise”. Interference, however, is caused by other frames being received at the same time as the desired one. Thermal noise contributes to the vibration of charge carriers. As discussed earlier in Chapter 3 that Packet Error Rate (PER) depends on the signal to thermal noise plus interference ratio at the receiver side.

The following two possible events may take place at the receiver side because of the variations of the signal to thermal noise plus interference [94]: First, if a node initiates a route repair or route discovery, and a RREQ or RREP packet is lost during a route discovery process over a good link, the associated route will not be considered as part of the new route. So, good routes may be excluded.

Second, If RREQ and RREP packets are successfully transmitted over a poor link; the poor link will be included as the new route. As a consequence, there will be subsequent loss of packets on the poor link, and the necessary new route discovery or repair, will reduce throughput. This causes a very serious problem in MANET implementations and testing [95].

A number of studies have been carried out to study the effects of thermal noise in general wireless networks and have shown that thermal noise affects the reception quality. The performance evaluation and simulation of on-demand routing protocols is an active research topic in MANET s [96] [97]. Such routing algorithms tend to be affected by the presence of the thermal noise resulting in increased packet loss within the network. However, most of the existing studies in the literature just ignore the impact of thermal noise in the reported performance of on-demand routing protocols [24][98].

Motivated by the above observation, this chapter investigates the effects of thermal noise on the On-demand routing protocols (the AODV routing protocol in the author's case), which uses a pure flooding based broadcasting scheme, and highlights how the thermal noise affects the performance of routing protocol. **Parts of the results presented in this chapter have been published in [52] and [99].**

The rest of the chapter is organised as follows: Section 4.1 presents performance evaluation of on-demand routing protocol by varying thermal noise levels and Section 4.2 summarises the findings of the chapter.

## **4.1. Performance Evaluation**

This section highlights the impact of thermal noise on the performance of an on-demand routing protocol (the AODV routing protocol) in MANETs. The performance has been measured in terms of routing overhead, end-to-end delay and throughput by varying the thermal noise level.

#### **4.1.1. Simulation Setup**

The simulation parameters generally follow Chapter 3 to study the impact of thermal noise on the performance of on-demand routing protocols (the AODV routing protocol [87]).

Since the author wanted to show the effect of the thermal noise, so the range of the thermal noise in the simulation must be high. From the point of view of realism, the author assumed these nodes are in hot weather, which leads to heat the nodes. The range of thermal noise used in the simulation is from -51dBm to -59dBm, because of that from the simulation results of the author's scenario, it has been noted that if the noise level is greater than -51dBm, there will be no connection between the nodes because at this level the noise would have corrupted the signal and all packets are lost, and the simulation results are almost stable, if noise levels are less than -59dBm.

#### **4.1.2. Results and Analysis**

Simulation results are obtained by averaging the results of 30 runs to have the smooth plots of the figures, each run using a different seed value and lasting for 800 seconds. The seed value is used to set the initial location of MANET nodes within the area. The aforementioned performance metrics (routing overhead, end-to-end delay and throughput) were shown by varying the thermal noise level.

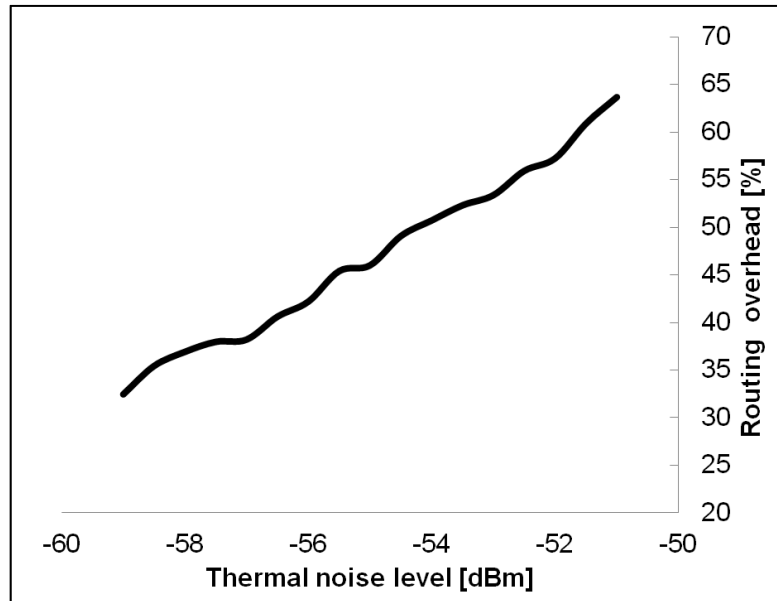


Figure 4.1: Routing overhead vs thermal noise level

#### 4.1.2.1. Routing Overhead

Routing overhead is defined as the ratio of the routing packets number (control packets) transmitted per data packet received. Figure 4.1 depicts the average routing overhead as a function of thermal noise level. It can be seen that the average routing overhead increases dramatically from around 31% to around 65% with increased thermal noise level between -59dBm and -51dBm, a rise about 34% routing overhead by changing thermal noise levels. This can be explained by increasing the thermal noise level, the probability of getting a packet corrupted due to thermal noise increases. This affects the route discovery process e.g., when RREQ (broadcasted or rebroadcasted) or RREP is lost; the route discovery process may have to be triggered again. Higher thermal noise may also affect receiving data packets. Frequent loss of data packets due to thermal noise may result in assuming that the route is broken and lead to triggering a new route discovery process. Both of these phenomena would lead to higher routing overhead.

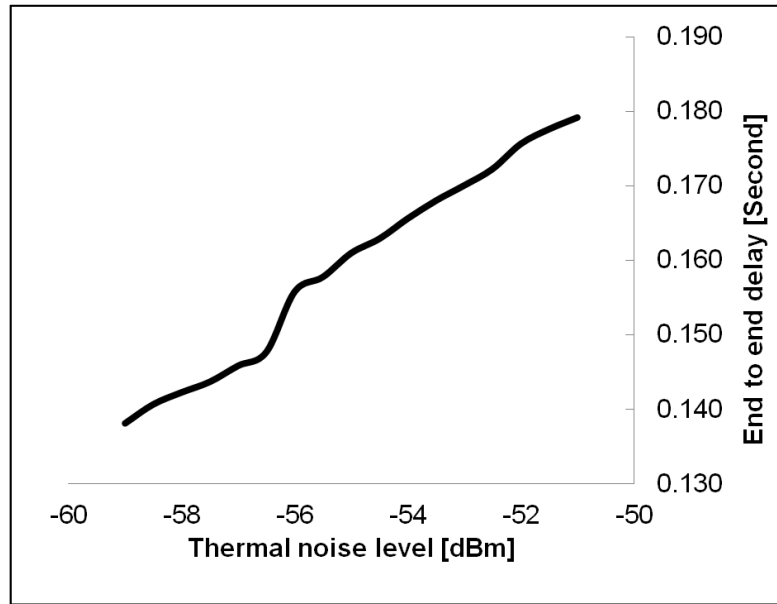


Figure 4.2: Average end to end delay vs thermal noise level

#### 4.1.2.2. End-to-End Delay

The average end-to-end delay shows the time a data packet takes to arrive from the source node to the destination node and includes all possible delays caused by route discovery latency, queuing at the interface queue, transmission and propagation, at all intermediate nodes. Figure 4.2 shows the average end-to-end delay for data packets for all nodes as a function of thermal noise level. The end-to-end delay rises dramatically from under 0.140 seconds to around 0.180 seconds by increasing the noise level from -59dBm to -51dBm.

This is because the receiving of data packets is affected by increased level of thermal noise. The frequent loss of data packets by a sender due to thermal noise may cause assuming that the routing path is broken, and would lead to triggering a new route discovery process. As a result, it is more likely the nodes would retransmit the data

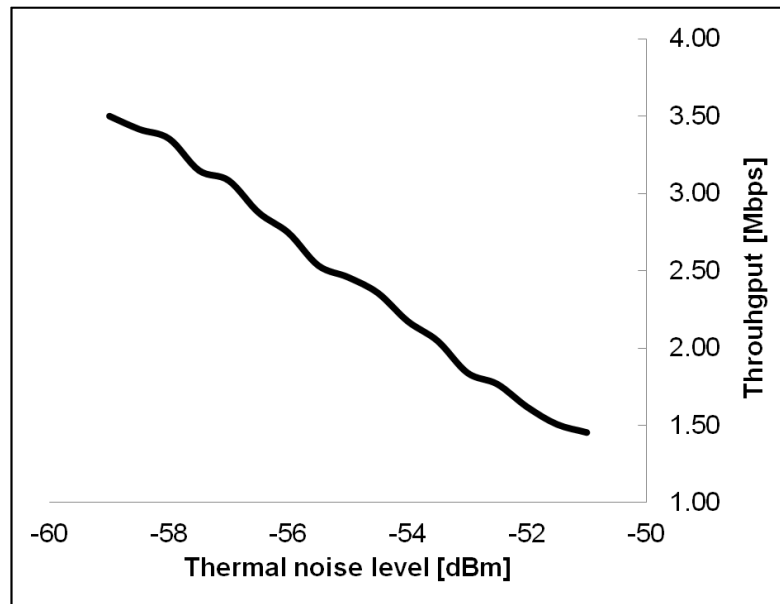


Figure 4.3: Throughput vs thermal noise level  
 packets or rebuild the routes more often. This phenomenon would clearly lead to a higher average end-to-end delay.

#### 4.1.2.3. Throughput

Throughput is defined as the amount of data received by a node per unit time. Figure 4-3 shows the average throughput of all nodes as a function of thermal noise level. It can be seen that the average throughput decreases dramatically from just around 3.5Mbps to around 1.5 Mbps by increasing the thermal noise level between -59dBm to -51dBm. This can be explained by that thermal noise leads to higher average end to end delay as shown in figure 4.3. The FTP application has to wait longer time before it could start sending data. Moreover, since higher thermal noise leads to lost data packets, this leads TCP retransmits messages depends on its congestion control mechanism after adjusting the transmission window.

## 4.2. Summary

This chapter focused on the impact of thermal noise on the performance of AODV routing protocol that uses pure flooding based broadcasting scheme. Simulation results have shown that the thermal noise has significantly affected the performance metrics (routing overhead, end-to-end delay and throughput). Higher thermal noise leads to frequent packet losses (both data packets and control packets). The simulation results have shown that the average routing overhead (Figure 4.1) increased about 34%, and the average end to end delay (Figure 4.2) increased around 0.04 second, and the average throughput (Figure 4.3) decreased about 2Mbps by changing thermal noise level from -59dBm to -51dBm. Therefore, thermal noise level should be carefully considered in designing new routing protocols. Thermal noise power is given by  $P(t) = 4kTB$  where  $k$  is Boltzmann's constant in joules per kelvin,  $T$  is the temperature in kelvin and  $B$  is the bandwidth.

The author has focused on on-demand routing protocol for MANETs with a particular emphasis on route discovery process in AODV as a common example of the use of broadcasting scheme. The next chapter will examine the effect of interference plus thermal noise on probabilistic broadcasting schemes.

## Chapter 5

### **Performance evaluation of probabilistic broadcasting schemes**

Broadcasting is a vital part of on-demand routing protocols to discover new routes in Mobile Ad-hoc Networks (MANET). Pure flooding is the earliest and still widely used mechanism of broadcasting for route discovery in on-demand routing protocol. In pure flooding, a source node broadcasts a route request to its neighbours. These neighbours then rebroadcast the received route request to their neighbours until the route request arrives at the destination node. Pure flooding may generate excessive redundant traffic leading to increased contention and collisions deteriorating the performance.

To elevate the damaging impact of pure flooding, a number of improved broadcasting schemes have been proposed in the literature [54] [25] [15]. These techniques generally fall in two categories namely deterministic and probabilistic broadcasting. Deterministic schemes (e.g., MPR [17] and Self Pruning Scheme [18]) exploit network information to make more informed decisions. However, these schemes carry extra overhead to exchange location and neighbourhood information among nodes. On the other hand, the probabilistic schemes, e.g., fixed-probabilistic [1], distance-based [19], counter-based [20] and location-based [15] schemes, take a local decision to broadcast or not to broadcast a message according to a predetermined probability. All these schemes try to minimise the number of rebroadcasted RREQ packets. In a fixed-probabilistic scheme, a node receiving the RREQ packet rebroadcasts it with a fixed probability. In the case of



distance-based scheme, a node receiving the RREQ packets decides to rebroadcast by considering its distance far away from the sending node, to cover large number of neighbouring nodes.

The communication is not error free. A number of channel impairments like noise, co-channel interference, signal attenuation, fading and user mobility affect the transmission. Previous studies have shown that routing protocols based on probabilistic broadcast schemes outperform the traditional pure flooding based routing protocols [15] [24]. However, the results of those studies can be challenged for noisy MANETs. It is because those studies either ignored the noise and the interference at all [100] [25] or they used a simplified model by translating the effects of noise and interference into a simple packet loss probability instead of using the packet error rates[2].

Zhang and Agrawal [24] suggested a probabilistic scheme that dynamically modifies the rebroadcasting probability based on the node distribution and the node movement by considering local information but without needing any distance measurements or exact location determination devices. Their results showed an improvement in performance when compared to both pure flooding and static probabilistic schemes. However, the effects of noise and interference were ignored. The same authors [70] suggested a levelled probabilistic routing scheme for MANETs. In this scheme, mobile hosts are divided into four groups and different rebroadcast probabilities are assigned to each group. The results showed gains in throughput.

Mohammed *et al.* [20] suggested a probabilistic counter-based scheme that reduces the retransmission of RREQ packets during the route discovery phase. The results revealed an enhancement in the performance of AODV in terms of routing overhead, MAC

collisions, and end-to-end delay while still achieving a good throughput. However, this approach did not consider thermal noise plus interference.

To the best of the author's knowledge, no previous work on probabilistic route discovery mechanisms has considered the effect of physical layer parameter such as thermal noise and co-channel interference. To remark conclusively about any probabilistic route discovery scheme if it is recommended approach or not for on-demand routing protocol in noisy MANETs, the effect of interference and thermal noise has to be taken into account.

Motivated by the above observation, this chapter studies the impact of thermal noise and co-channel interference on the performance of fixed- probabilistic [1] and distance-based [19] broadcasting schemes employed in the route discovery process of AODV routing protocol in MANETs. The performance has been evaluated using four metrics namely routing overhead, throughput, end-to-end delay and energy consumption. The performance evaluation has been carried out both with and without taking the thermal noise and co-channel interference into account. The reported results are supported by network layer measurements of the number of RREQs packets broadcasted, received and rebroadcasted by all nodes.

In this chapter, the signal strength, noise level and interference are measured at the physical and MAC layer and the resulting signal to interference plus noise ratio (SINR) is used to determine the successful reception of packets. SINR is a common way to represent a wireless channel and has been extensively used to measure the performance of wireless links [101]. Based on extensive ns-2 simulations, this chapter discovers that, contrary to the findings of previous studies, these schemes do not outperform pure

flooding scheme when thermal noise and co-channel interference are taken into account.

The results from this chapter have been **published as a journal paper in the international Computer Networks Journal – Elsevier.**

The rest of the chapter is organised as follows. Section 4.1 presents the simulation setup. In section 4.2 performance evaluation and discussion of results. Section 4.3 summarises the findings of the chapter.

## 5.1. Simulation Setup

The simulation parameters generally follow Chapter 3 to analyse the performance of fixed probabilistic and distance-based broadcasting schemes under realistic thermal noise and co-channel interference in noisy MANETs. AODV is the most widely used on-demand routing protocol [87][102] and it uses pure flooding as its broadcasting mechanism for route discovery. The author modified the standard AODV routing protocol to AODV-P and AODV-D by incorporating fixed-probabilistic and distance-based broadcasting schemes respectively. Here P in AODV-P denotes the rebroadcast probability while D in AODV-D denotes the distance threshold. A rebroadcasting node estimates its distance  $d$  from the sending node by using the signal strength of the received RREQ packet. The simulation parameters generally follow [2] [56]. Since the author wanted to study the effect of thermal noise plus interference on the probabilistic schemes and the number of node is 100, so the effect of interference in this scenario higher than thermal noise, so the suitable value of thermal noise is set to -95dBm following the recommendation in [93].

MANET nodes move according to the Random Waypoint mobility model [88] with a maximum speed of 10 m/s and the pause time set to zero, because the author wanted a

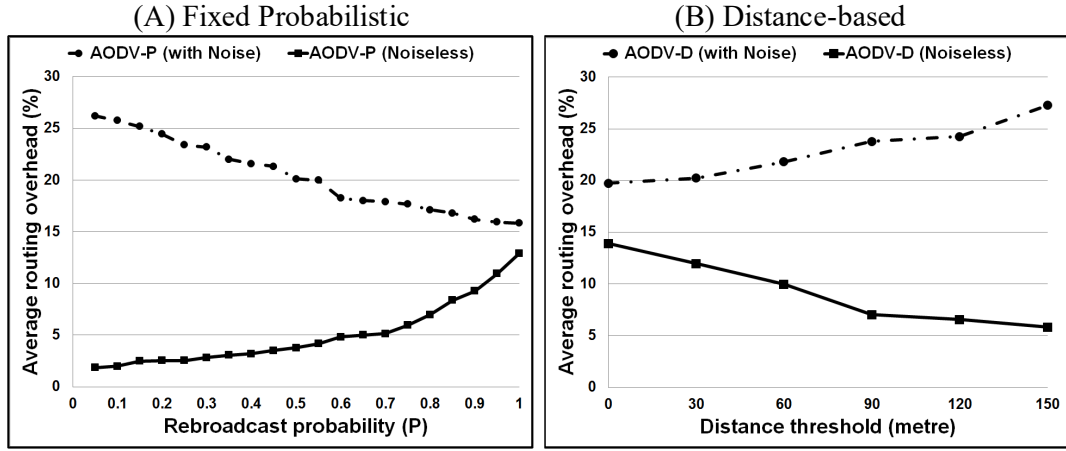


Figure 5.1: Average routing overhead versus (A) rebroadcast probabilities, (B) Distance threshold scenario with higher presence of mobility. For energy consumption analysis, each node has initial energy of 1000 joules.

## 5.2. Results and Analysis

Simulation results are obtained by averaging the results of 30 runs, each using a different seed value and lasting for 800 seconds. The seed value is used to set the initial location of MANET nodes within the area. The aforementioned performance metrics (routing overhead, throughput, end-to-end delay and energy consumption) were measured for different value of rebroadcast probability  $P$  for the AODV-P scheme and by varying the distance threshold  $D$  for AODV-D scheme with and without thermal noise and co-channel interference. In the discussion below, the term noisy will be used to refer to thermal noise and co-channel interference.

### 5.2.1. Routing Overhead

Routing overhead is defined as the number of routing packets (control packets) transmitted per data packet received. Figure 5.1 depicts the average routing overhead for both AODV-P and AODV-D schemes in noisy and noiseless MANETs. It can be seen

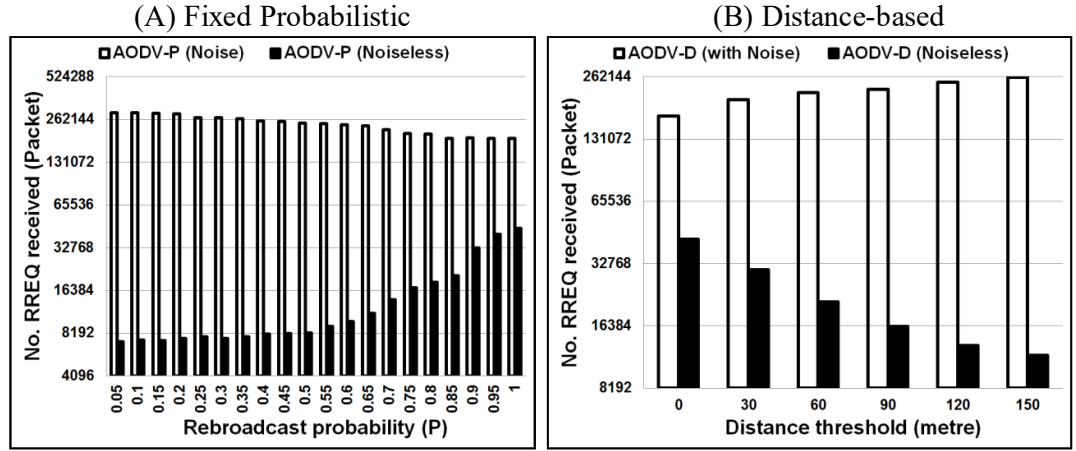


Figure 5.2: Number of RREQ received versus (A) rebroadcast probabilities, (B) Distance threshold

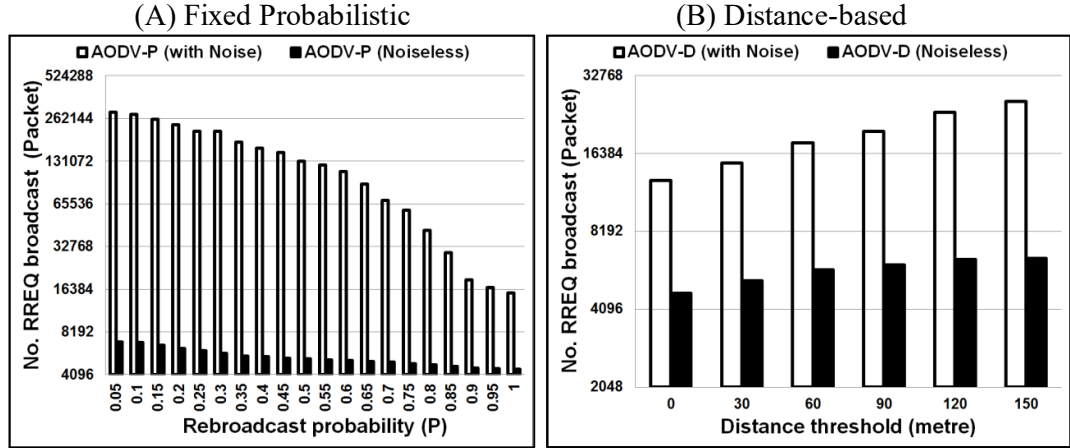


Figure 5.3: Number of RREQ broadcast versus (A) rebroadcast probabilities, (B) Distance threshold

that for the noiseless case, the average routing overhead increases with  $P$  (in case of AODV-P) and it decreases with  $D$  (in case of AODV-D).

This relationship is reversed when noise is taken into account for both AODV-P and AODV-D schemes. This can be explained by exploring the routing traffic. Let us consider the noiseless case first. By increasing the value of  $P$  or decreasing the value of  $D$ , the number of RREQs rebroadcasted and hence the number of RREQs received both increase (see Figures 5.2 and 5.4). This increases the reachability of RREQs maximizing

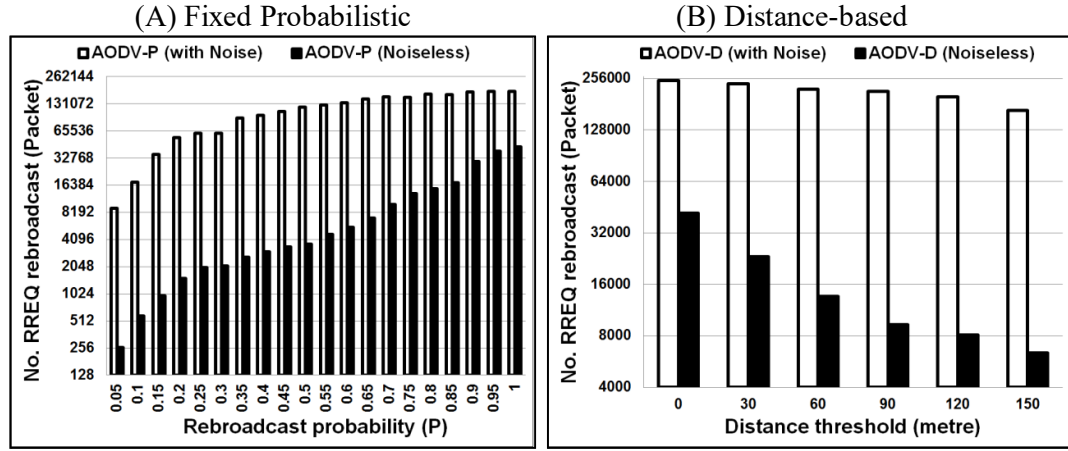


Figure 5.4: Number of RREQ rebroadcast versus (A) rebroadcast probabilities, (B) Distance threshold

the chances of finding a valid route in the first attempt. AODV checks its routing table and the impact if it did not find a suitable route that is why the total number of route requests, as denoted by the number of RREQ packets broadcasted, initiated by all nodes decreases by increasing the value of  $P$  or by decreasing value of  $D$  (see Figure 5.3). However, the downside is that many nodes receive multiple copies of the same RREQ from different neighbours. The redundant RREQ traffic increases with increasing the value of  $P$  or by decreasing the value of  $D$  leading to higher routing overhead.

Now let us consider the noisy case. Both thermal noise and co-channel interference cause bit errors leading to packet losses. Thermal noise is independent of the traffic while co-channel interference increases with traffic intensity, the traffic term here include overhead messages. Increasing the value of  $P$  or decreasing the value of  $D$  may increase the reachability of RREQs on one hand but it increases the co-channel interference, on other hand, leading to higher packet loss rate. This can be confirmed by observing that with increasing value of  $P$  or decreasing value of  $D$ , the number of rebroadcasted RREQs increases but the number of received RREQs decreases due to

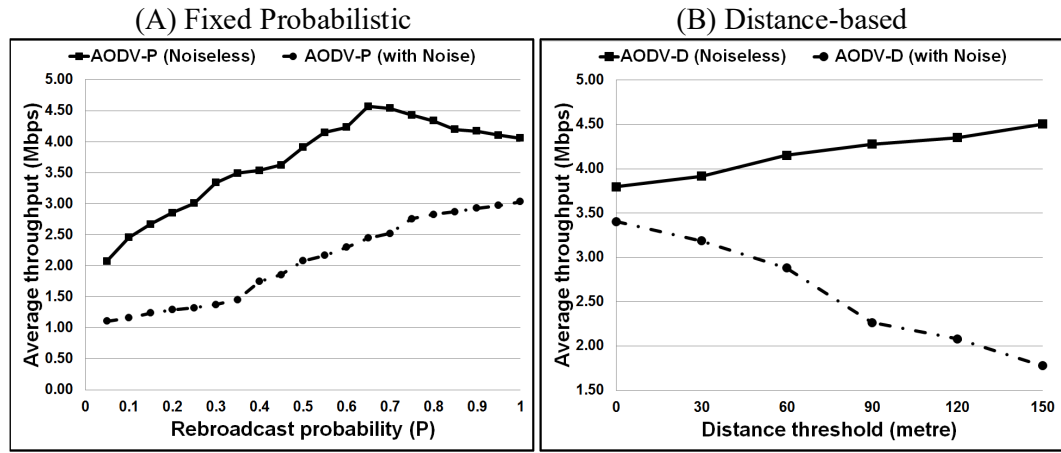


Figure 5.5: Average of throughput versus (A) rebroadcast probabilities, (B) Distance threshold  
 higher packet loss rate (see Figures 5.2 and 5.4). The fewer received RREQs limit the number of rebroadcasted RREQs as well. This explains why the number of rebroadcast packets increases with  $P$  at a lower rate for the noisy case compared to the noiseless case (see Figure 5.4). In fact, thermal noise and co-channel interference act as natural limiters for the traffic; the former is static while the latter is adaptive because it increases with traffic intensity. This reduces the chances of getting duplicate RREQs from the neighbouring nodes and adapts to the traffic intensity very well. In the presence of natural and adaptive limiters (thermal noise and co-channel interference), the artificial limiters (reducing the rebroadcast probability or rebroadcasting only from distant nodes) do not work well because they limit the reachability of RREQs independent of the traffic intensity and channel conditions. Nodes have to try several times before they get a valid route which increases the routing overhead.

### 5.2.2. Throughput

Throughput is defined as the amount of data received by a node per unit time. Figure 5.5 shows that for any given value of  $P$  (or  $D$ ), the throughput of noiseless AODV-P (or AODV-D) is much lower than the noisy AODV-P (or AODV-D) scheme. This is trivial

and can be explained by considering the packet losses caused by the noise. However, the important point here is the difference in how throughput changes with P (or D) for noisy and noiseless AODV-P (or AODV-D). For noiseless AODV-P, throughput increases with P, reaches a maximum value and then starts decreasing but the throughput of noisy AODV-P increases monotonically with P and is maximum at  $P=1$  which is pure AODV. Similarly, throughput increases monotonically with D for noiseless AODV-D while it decreases monotonically with D for noisy AODV-D. This shows that the throughput performance of AODV-P and AODV-D is almost reversed when noise is taken into account.

Lower values of P limit the reachability of RREQs. As a result, the route discovery mechanism may not be successful at first attempt and may have to be initiated repeatedly. This would increase the time to establish a route from the source node to the destination node. The FTP application has to wait longer before it could start sending data. Moreover, node mobility invalidates old routes more frequently and interrupts the data supply until an alternative route is established. The lower the rebroadcast probability will be, the longer it will take to find the alternative route. This results in prolonged interruption in data supply that decreases the throughput further. Increasing the rebroadcast probability increases the reachability of RREQs and hence the throughput improves. However, beyond certain value ( $P>0.65$ ), the nodes start getting significantly higher number of duplicate RREQs from neighbouring nodes that cost network bandwidth and the application layer throughput starts reducing from the peak value of 4.5Mbps. For AODV-D, by increasing the value of D the number of RREQ packets decreases significantly (see Figures 5.2, 5.3 and 5.4) that helps to improve the throughput.



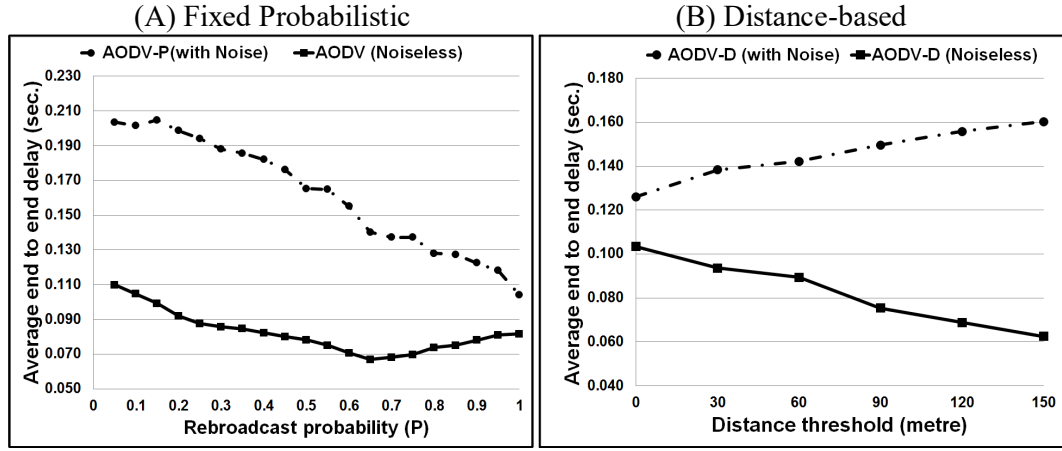


Figure 5.6: Average of end to end delay versus (A) rebroadcast probabilities, (B) Distance threshold

In presence of noise, the strategy of limiting RREQ rebroadcasting harms the performance rather than improving it. This is because the decision of rebroadcasting RREQ packets is taken without taking the channel conditions and current traffic into account. In presence of noise, the throughput increases by increasing the value of  $P$  for AODV-P, even beyond  $P=0.65$ , and by decreasing the value of  $D$  in AODV-D. In fact, the side effects of generating redundant RREQ packets by increasing the value of  $P$  or decreasing the value of  $D$  are diminished by noise itself because it acts as a natural limiters as explained in Section 5.2.1.

### 5.2.3. End to End Delay

Average end-to-end delay shows the time a data packet takes to arrive from the source node to the destination node and includes all possible delays caused by route discovery latency, queuing at the interface queue, retransmission delays at the MAC layer, propagation delay and transmission delay at all intermediate nodes. Figure 5.6 shows the average end-to-end delay for data packets for all nodes. It can be seen that for any given value of  $P$  (or  $D$ ), the end-to-end delay of noiseless AODV-P (or AODV-D) is much higher than the noisy AODV-P (or AODV-D) schemes. Similar to the throughput case,

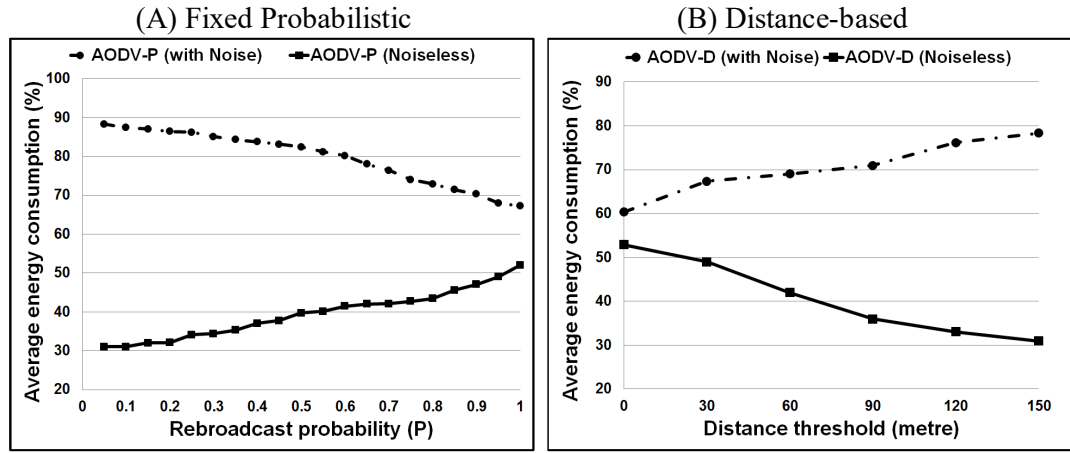


Figure 5.7: Average of energy consumption versus (A) rebroadcast probabilities, (B) Distance threshold  
it is trivial and can be explained by considering the packet losses caused by the noise. However, the effect of the increasing value of P and D on end-to-end delay using AODV-P and AODV-D respectively is almost reversed when noise is taken into account.

Lower values of P (or higher values of D) limit the reachability of RREQ packets and the route discovery may fail. Consequently, the route discovery may need to be tried several times to get a valid route which increases the end-to-end delay. Higher values of P (or lower values of D) generate excessively large number of RREQ packets which contest with the application layer traffic and consume bandwidth. As a result the end-to-end delay is increased. However, when noise is considered in the simulation, excessive RREQ packets are lost due to interference and do not reach to other parts of the network for rebroadcasting, avoiding the broadcast storm problem. That is why the end-to-end delay is not penalised by increasing the value of P (or decreasing the value of D).

#### 5.2.4. Energy Consumption

Energy consumption accounts for the energy consumed in transmitting, forwarding and receiving of application layer data and routing-related control data. Figure 5.7 depicts

the average energy consumption of all nodes as a function of rebroadcast probability  $P$  and distance threshold  $D$ . For any value of  $P$ , the energy consumption of noisy AODV- $P$  is higher than that of noiseless AODV- $P$ . Similarly, for any value of  $D$ , the energy consumption of noisy AODV- $D$  is higher than that of noiseless AODV- $D$ . This is because, first, extra energy is consumed to compensate losses, second, the routing overhead in presence of noise is much higher than that of the noiseless case (see Figure 5.1). This can also be verified by the total number of RREQ packets (broadcasted and rebroadcasted) which are much higher in the noisy case than that of the noiseless case (see Figure 5.2, 5.3 and 5.4).

In the noiseless case, by increasing the value of  $P$  or decreasing the value of  $D$ , the energy consumption increases but in noisy case it decreases. This is perfectly aligned with the routing overhead that increases in noiseless case but decreases in the noisy case by increasing the value of  $P$  or decreasing the value of  $D$ . In fact, for the noiseless case, by increasing the value of  $P$  (or decreasing the value of  $D$ ), even though the reachability of RREQ increases but the RREQ traffic shoots up exponentially which is more devastating in terms of energy consumption. When noise is taken into account, increasing the value of  $P$  (and decreasing the value of  $D$ ) does not cause RREQ traffic to shoot up because noise acts as a natural limiter, excessive RREQ traffic is dropped due to inference and does not propagate further which reduces the energy consumption.

### 5.3. Summary

Broadcasting is often used in on-demand routing protocols to discover new routes in MANETs. A number of probabilistic broadcasting schemes have been presented in the literature to limit the number of broadcast messages. However, these approaches were not evaluated under realistic conditions and have ignored the effects of thermal noise and co-channel interference which are inherent to noisy MANETs.

This chapter studied the effects of thermal noise and co-channel interference on the performance of two probabilistic schemes from the literature, namely fixed-probabilistic and distance-based broadcast schemes. the author adopted the dei80211mr library of ns-2 based on the standard 802.11g MAC layer protocol. This library uses SINR-based packet level error model by considering thermal noise and co-channel interference. The standard AODV routing protocol was modified to AODV-P and AODV-D by integrating fixed-probabilistic and distance-based broadcasting schemes respectively. The performance metrics include routing overhead, throughput, end-to-end delay and energy consumption.

The ns-2 simulation results revealed that, in contrast to the previous studies, fixed-probabilistic and distance-based broadcasting schemes performed worse than the standard AODV when thermal noise and co-channel interference were taken into account. The simulation results revealed the fundamental problem of fixed- probabilistic and distance-based broadcasting schemes that these schemes try to avoid the broadcast storm problem by limiting the rebroadcasting of RREQs statically and independent of the current traffic intensity. As a result, it may help in some cases while penalise in other cases. In fact co-channel interference acts as an adaptive limiter for traffic and

sheds the extra traffic only when the system is overloaded by bursts of RREQs. The performance of AODV deteriorates with fixed-probabilistic and distance-broadcasting schemes when thermal noise and co-channel interference are taken into account. The suggested channel adaptive broadcasting scheme that takes into account the deficiencies mentioned above will be discussed in the next chapter.

# Chapter 6

## Channel Adaptive Probabilistic Broadcast

As discussed in Chapter 5, broadcasting is the backbone of the route discovery process in on-demand routing protocols in Mobile Ad-hoc Networks (MANETs). Pure flooding is the simplest and most common broadcasting technique for route discovery in on-demand routing protocols. In pure flooding, the route request (RREQ) packet is broadcasted and each receiving node rebroadcasts it. This continues until the RREQ packet arrives at the destination node. The obvious drawback of pure flooding is excessive redundant traffic that degrades the system performance. This is commonly known as broadcast storm problem (BSP).

To address BSP, various probabilistic broadcast schemes have been proposed in the literature where a node broadcasts a RREQ packet with a certain probability[15][54][25]. Cartigny and Simplot [26] presented an improved probabilistic scheme combination where the rebroadcast probability is calculated from the number of neighbors which are considering retransmission. This scheme was shown to achieve significant reduction in the number of rebroadcasts. However, this scheme did not consider thermal noise and co-channel interference.

Al-Bahadili and Sabri [2] proposed a probabilistic algorithm for route discovery based on the noise-level called Dynamic Noise-Dependent Probabilistic (DNDDP) scheme. In this scheme the noise-level value is drawn from a distribution rather than measuring it at lower layers. The simulation results showed that the suggested algorithm presented

higher network reachability than simple flooding and the dynamic approach in which each node calculates its rebroadcasting probability according to the number of first-hop neighbor for the transmitting node with a reasonable increase in the number of retransmissions for a wide range of noise-levels.

To the best of the author's knowledge, no previous work on probabilistic broadcast in route discovery mechanism has considered the effects of thermal noise, co-channel interference, and node density in the neighbourhood simultaneously to address the BSP.

Motivated by the above observation, this chapter presents a novel Channel Adaptive Probabilistic Broadcasting (CAPB) scheme that adapts the probability of rebroadcasting RREQ packets dynamically according to the thermal noise, co-channel interference and node density in neighbourhood. **Parts of the results in this chapter have been published in 2015 International Symposium on Performance Evaluation of Computer and Telecommunication Systems, Chicago, IL, USA, IEEE COMSOC.**

The rest of the chapter is organised as follows: Section 6.1 introduces the proposed CAPB algorithm. Section 6.2 discusses the performance analysis of the CAPB scheme by implementing the proposed scheme and two related SoA schemes from the literature ([1] and [2]) in the standard AODV routing protocol to replace the pure flooding based broadcast. Finally, section 6.3 summarises the findings of the Chapter.

## **6.1. Proposed Broadcast Scheme**

The proposed CAPB scheme adjusts the probability of rebroadcasting RREQ packets dynamically by taking into account two factors. The first factor is the measured co-channel interference plus thermal noise, and the second factor is node density in the

neighbourhood. These two factors affect the efficacy of disseminating RREQ packets as discussed below.

### **6.1.1. Effect of Co-Channel Interference & Thermal Noise**

Consider Figure 6.1 where node A broadcasts a RREQ message in an effort to find the route to node G. In Figure 6.1 the circles are the transmission range of nodes (A, B, and C). In Figure 6.1 (a), using pure flooding in absence of co-channel interference and thermal noise, the destination node (G) receives the RREQ packet from node B as well as node C. The destination node (G) however, will only send one RREP packet to either node B or C whichever forwards the RREQ first. Using probabilistic broadcast, there are three possibilities (i) both B and C, (ii) either B or C and (iii) neither of the two nodes will rebroadcast the RREQ packet. As exemplified in Figure 6.1b, using probabilistic broadcast in absence of co-channel interference and thermal noise, only node B manages to rebroadcast the RREQ. By considering the effects of thermal noise and co-channel interference (Figure 6.1c), assuming that node A fails to deliver the RREQ packet to node B (because of thermal noise plus interference in the area), but is able to deliver the same packet to node C, the RREQ packet is therefore undelivered to node G. Node G will thus be declared unreachable.



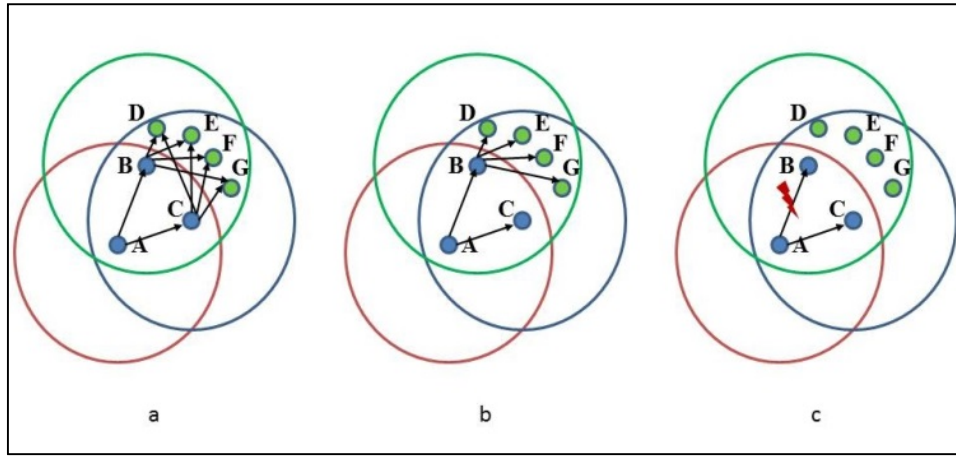


Figure 6.1: (a) Simple flooding in noiseless MANETs, (b) Fixed Probabilistic scheme in noiseless MANETs, and (c) Fixed Probabilistic scheme in noisy MANETs

Packet Error Rate (PER) is closely related to SINR (Signal to Interference plus Noise Ratio) and packet size as explained in Chapter 3. In the proposed CAPB scheme, when a node receives a RREQ packet, it obtains the SINR value, as measured at the physical layer and infers the PER using the previous relationship (see Figure 3.2 Chapter 3). If the PER is higher, then the probability of receiving the same RREQ packet by the neighbouring nodes is low. In this case, naturally the lucky node that has received the RREQ should rebroadcast the RREQ with high probability to increase the dissemination of this particular RREQ packet. On the other hand, a low PER implies that many nodes in the neighbourhood have also received this RREQ packet with high probability, therefore the rebroadcast probability should be relatively low to avoid the BSP.

### 6.1.2. Effect of Nodal Density in Neighbourhood

When a node receives a RREQ packet, the decision of rebroadcasting should take into account the number of nodes and their geographic distribution to make a wise decision. In a densely populated area, not all nodes need to rebroadcast to avoid redundancy and the risk of increased collision leading to packet loss and energy wastage. On the other

```

    Upon receiving a RREQ packet  $m$  at a node  $R$ 
Event: Node  $R$  receives RREQ packet  $m$ 
if Node  $R$  is the destination node for RREQ  $m$ 
    Send RREP
else
    Calculate  $N_b$ 
    Obtain SINR and infer PER
    Calculate  $N_{eff}$  using eq. 4
    Calculate  $P_{reb}$  from eq. 6
    Generate a random number  $\delta$  between 0 and 1.0
    if  $\delta \leq P_{reb}$  then
        Broadcast the RREQ message  $m$ 
    else
        Drop the RREQ message  $m$ 
    end if
end if
End if

```

Figure 6.2: Proposed CAPB scheme

hand, in a sparsely populated area relatively more nodes should rebroadcast the RREQ packet to ensure dissemination of the RREQ packet. Here the author considers only the number of nodes in the transmission range of the node receiving the RREQ packet to determine the rebroadcast probability.

### 6.1.3. The Proposed CAPB Algorithm

Figure 6.2 presents the outline of the proposed CAPB scheme. When node  $R$  receives a RREQ packet, for which  $R$  is not the destination node, it rebroadcasts the RREQ packet with probability  $P_{reb}$ . To determine the value of  $P_{reb}$ , node  $R$  determines the value of  $N_{eff}$  which is the number of effective nodes within its transmission range  $r$  which have

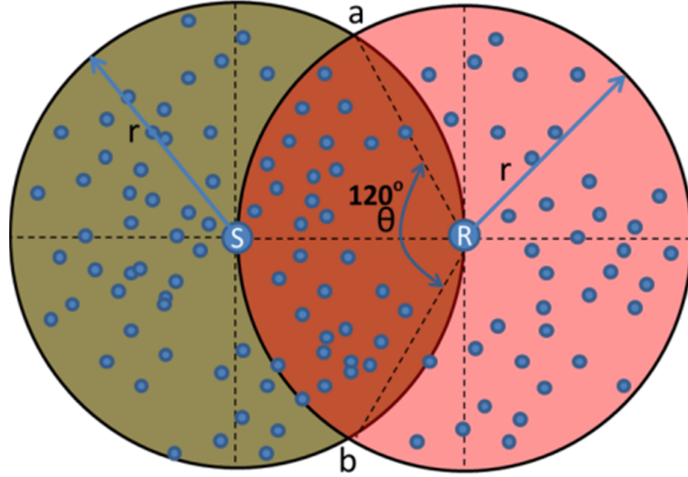


Figure 6.3: Node R receiving RREQ from node S.

received the same RREQ packet. This is done as follows. Assume  $N$  is the total number of nodes within the transmission range of node R. the author uses Hello Packets to infer the value of  $N$ . The number of nodes  $N_b$  which are located within the transmission range of both nodes R and node S can be calculated from the overlapped area  $A$  of the two circles as shown in Figure 6.3. Using geometry, the overlapped area  $A$  can be given by

$$A = (\theta \times \pi/180 - \sin\theta) \times r^2 \quad (1)$$

Here  $\theta$  is the angle of the circular segment in degrees. Note that  $\theta=120^\circ$  when node R is at the edge of the transmission range of node S, and  $\theta=180^\circ$  when node S is very close to node R. Node R estimates its distance from node S from the signal strength of the received RREQ packet and calculates the value of  $\theta$  using simple trigonometric relations. To keep the author's scheme simple, the author assumes that nodes are uniformly distributed. With this assumption, the value of  $N_b$  can be given by

$$N_b = N \times A/\pi r^2 \quad (2)$$

To take into account the effects of thermal noise and co-channel interference, node R obtains the SINR from the physical layer at the time of receiving the RREQ packet and infers the PER using the relationship explained in Chapter 3 (see Figure 3.2). The value of  $N_{eff}$  is given by

$$N_{eff} = N_b \times (1 - PER) \quad (3)$$

Equation (3) can simplified to

$$N_{eff} = N \times \left( \frac{\theta}{180} - \frac{\sin\theta}{\pi} \right) (1 - PER) \quad (4)$$

A higher value of  $N_{eff}$  implies that more nodes have received the RREQ and consequently the value of  $P_{reb}$  should be lower and vice versa. This suggests an inverse relationship between  $P_{reb}$  and  $N_{eff}$ .

$$P_{reb} = d \times \frac{1}{N_{eff}} \quad (5)$$

Here  $d$  is a constant value representing the dissemination factor. The value of  $d$  is greater than unity to compensate the PER. For very low ( $\leq N_l$ ) and very high ( $\geq N_u$ ) values of  $N_{eff}$  equation (2) may not hold true so fixed values of  $P_{reb}$  are used in those cases. In general  $P_{reb}$  can be given as follows:

$$P_{reb} = \begin{cases} P_{max}, & \text{for } N_{eff} \leq N_l \\ d \times \frac{1}{N_{eff}}, & \text{for } N_l < N_{eff} < N_u \\ P_{min}, & \text{for } N_{eff} \geq N_u \end{cases} \quad (6)$$

Appropriate values of  $N_l, N_u$  can be derived from an estimated maximum and minimum possible node density and the transmission range of nodes. The implementation of the proposed scheme and its performance evaluation is presented in the next section.

## **6.2. Performance evaluation of the CAPB algorithm**

This section presents the performance evaluation of the proposed CAPB scheme using four metrics namely routing overhead, throughput, end-to-end delay and energy consumption for different node densities, mobility profiles, and traffic load. Traffic load is varied by changing the number of source-destination connections. The proposed CAPB scheme has been compared with three related broadcasting schemes. The first one is pure flooding that is part of the standard AODV routing protocol, the second one is the fixed probabilistic scheme of [1] denoted by AODV-P where P shows the rebroadcast probability, and the third scheme is DNDP (Dynamic Noise-Dependent Probabilistic) scheme of [2].

### **6.2.1. Simulation Setup**

The simulation parameters generally follow previous chapters to implement and evaluate the proposed scheme in MANETs using AODV routing protocol. Standard AODV uses pure flooding. The proposed CAPB scheme and the two other schemes (AODV-P and AODV-DNDP) have been implemented in the route discovery process of AODV. In AODV-P scheme, the value of P is set to 0.6 after running simulation with a range of values for P and choosing the one giving the best performance. The parameters of AODV-DNDP scheme follow recommendations in [2]. For CAPB, the author

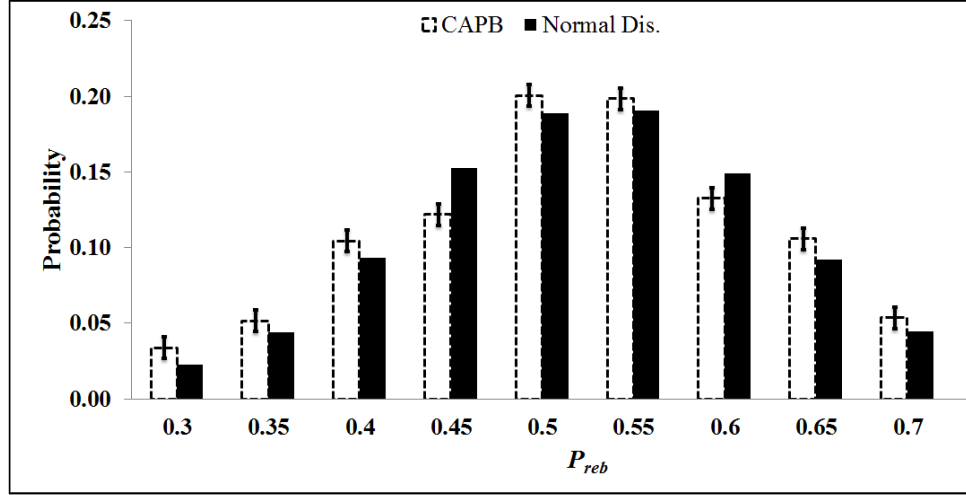


Figure 6.4: PDF of  $P_{reb}$   
 sets  $N_l = 7$ ,  $N_u = 16$ ,  $P_{max} = 0.7$ ,  $P_{min} = 0.3$  and  $d = 5$ . These values are partly heuristic and partly simulation guided.

Each node has a FTP (File Transfer Protocol) agent attached to it such that node  $i$  is downloading a file of infinite size from node  $i+M/2$  for  $i=1,2,...,M/2$  where  $M$  is the total number of nodes for density and mobility scenarios. For energy consumption analysis, each node has initial energy of 1000 joules.

### 6.2.2. Simulation Results and Analysis

The author used three sets of simulations, the density scenario, the mobility scenario, and traffic load scenario. The density and traffic load scenarios use a fixed node speed of 6km/hour for each node. In the density scenario the number of nodes is varied. In the traffic load scenario the number of source-destination connections is varied. The mobility and the traffic load scenarios use fixed number of nodes (set to 100) and in the mobility scenario node speed is varied i.e. in each simulation run of the mobility scenario the mobility speed is increased. Simulation results are obtained by averaging the results of 30 runs within the same confidence interval of 95%. Each run uses a

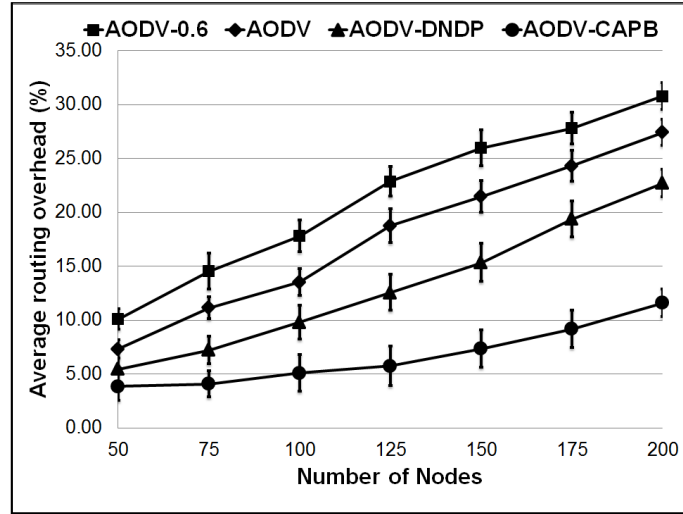


Figure 6.5: Routing Overhead vs Number of Nodes

different seed value and lasts for 800 seconds. The seed value is used in the mobility model to yield different mobility profiles and to set the initial location for each node. Since the direct outcome of the proposed CAPB algorithm is the probability  $P_{reb}$  of rebroadcasting RREQ, the author collected  $P_{reb}$  values over a number of runs from three scenarios. The mean and variance of  $P_{reb}$  is found to be 0.5 and 0.01 respectively. Figure 6.4 shows that the distribution of  $P_{reb}$  follows closely the normal distribution truncated at below 0.3 and above 0.7 with the same mean and deviation.

#### 6.2.2.1. Routing Overhead

Routing overhead is defined as the ratio of the number of routing packets (control packets) transmitted per data packet received. Figure 6.5, Figure 6.6 and Figure 6.7 show the average routing overhead as a function of node density, node speed and traffic load respectively.

In all cases, the average routing overhead increases with increasing node density, node speed and traffic load. A higher number of neighbouring nodes and traffic load both lead to higher contention and PER which result in redundant retransmission of control

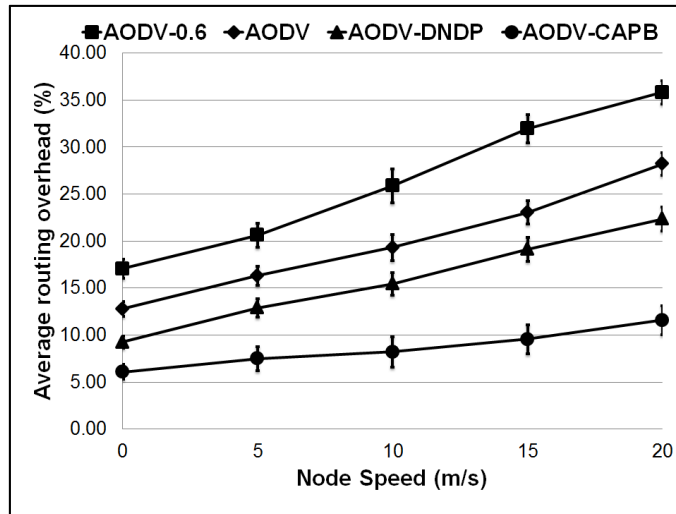


Figure 6.6: Routing Overhead vs Node Speed

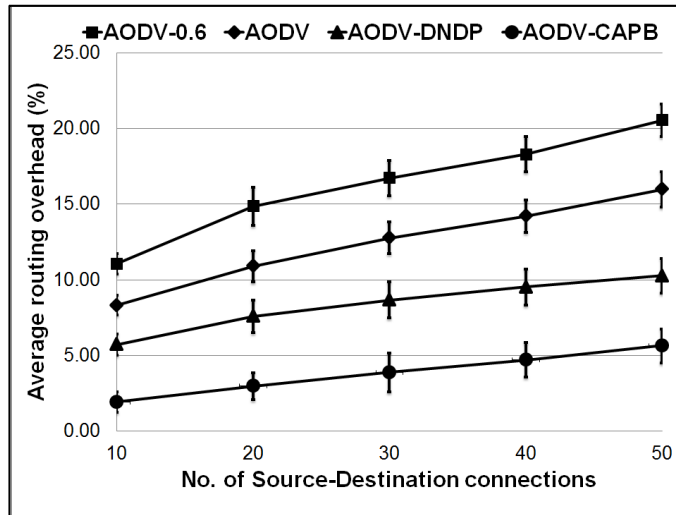


Figure 6.7: Routing Overhead vs traffic load

packets. Similarly, increasing node speed makes the network topology more dynamic. Routes get expired quickly and new route discovery mechanism is triggered more frequently to replace the expired routes. This can be verified by observing the total number of RREQ packets transmitted as shown in Figure 6.8, Figure 6.9 and Figure 6.10.



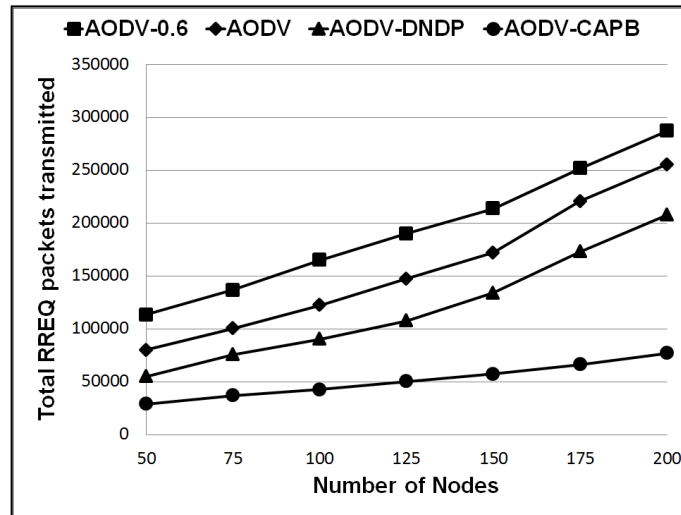


Figure 6.8: Total number of RREQ packets transmitted for different number of nodes

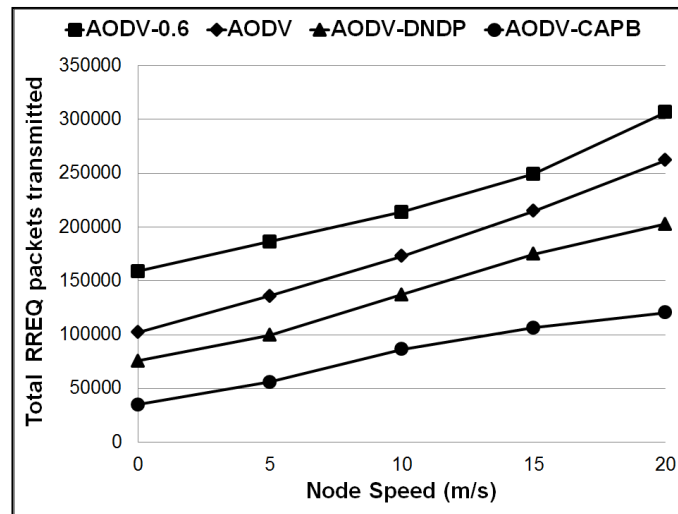


Figure 6.9: Total number of RREQ packets transmitted for different values of node speed

The proposed CAPB scheme uses the least number of RREQ packets. Increasing the number of RREQ broadcasts increases the reachability of nodes on one hand but on other hand, it may increase the co-channel interference leading to higher PER which may limit the reachability and require to restart the route discovery process.

This is the reason of higher overhead of pure AODV scheme. Fixed probabilistic scheme (AODV-0.6) limits the number of RREQ blindly which often limits the

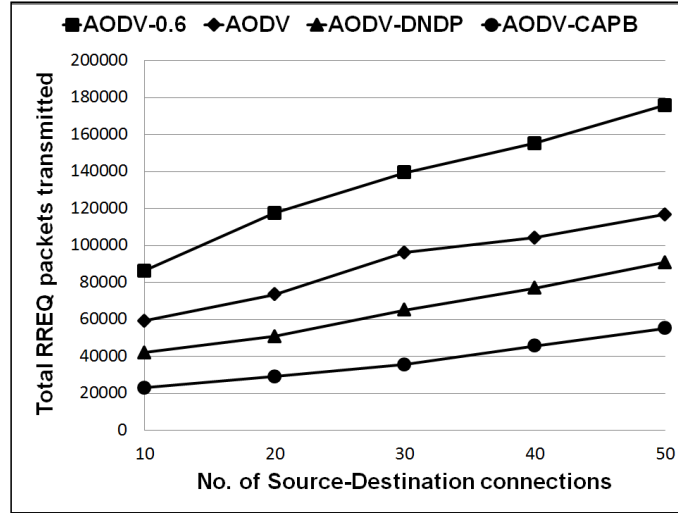


Figure 6.10: Total number of RREQ packets transmitted vs. traffic load reachability of RREQ packets to the destination node and route discovery mechanism has to be triggered more frequently leading to higher overhead. It is interesting to note that the routing overhead of pure AODV is better than AODV-0.6 scheme. In fact, thermal noise and co-channel interference act as natural limiters for the traffic; the former is static while the latter is adaptive because it increases with traffic intensity. This reduces the chances of getting duplicate RREQs from the neighbouring nodes and adapts to the traffic intensity very well.

In presence of natural and adaptive limiters (thermal noise and co-channel interference), the artificial limiter (reducing the rebroadcast probability without considering the effect of interference and thermal noise), does not work well because it limits the reachability of RREQs independent of the traffic intensity. Nodes have to try several times before they get a valid route which increases the routing overhead. In AODV-DNDP, the probability is not fixed and is drawn from a distribution without considering the current level of noise and interference. The proposed CAPB scheme is able to achieve significantly lower routing overhead as compared to other schemes. The savings in

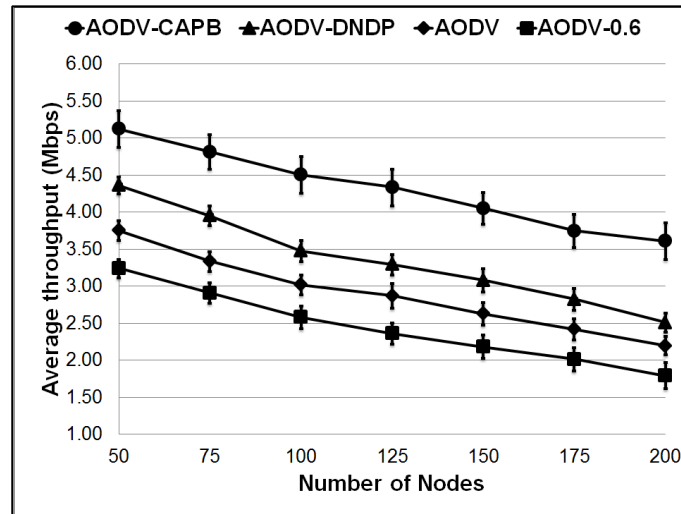


Figure 6.11: Average throughput vs. Number of Nodes  
routing overhead increases with the increase in node density, node speed and traffic load.

#### 6.2.2.2. Average Throughput

Throughput is defined as the amount of data received by a node per unit time. Figure 6.11, Figure 6.12 and Figure 6.13 show the average throughput, measured at the application layer, for all nodes as a function of number of nodes, node speed and traffic load respectively. In general, the average throughput decreases by increasing the number of nodes and traffic load due to increased contention ratio and higher collision rate. The average throughput also decreases with increasing node speed because routes are broken more frequently due to changing neighbourhood and network topology causing a temporary pause in data transmission till the new route is established. The time required to establish new routes to replace the broken ones and the routing overhead affect the throughput significantly.

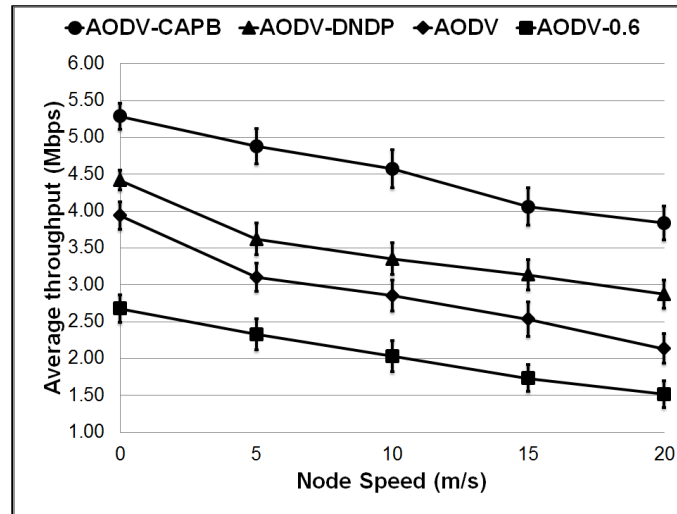


Figure 6.12: Average throughput vs. Node Speed

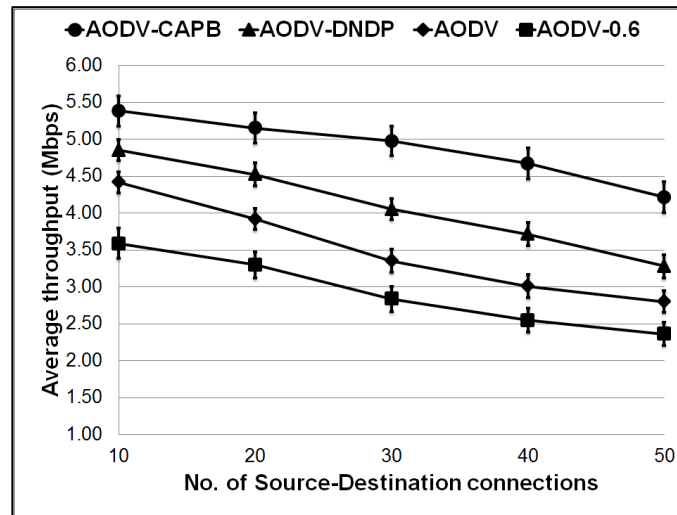


Figure 6.13: Average throughput vs. traffic load

Inefficient or blind decision of rebroadcasting the RREQ packets may not result in a successful route establishment at first attempt and the process may have to be initiated repeatedly. This would increase the time to establish a route from the source node to the destination node. The FTP application has to wait longer before it could start sending data. Moreover, node mobility invalidates old routes more frequently and interrupts the data supply until an alternative route is established. The proposed scheme is able to achieve significant throughput gain over the other schemes. This is because the

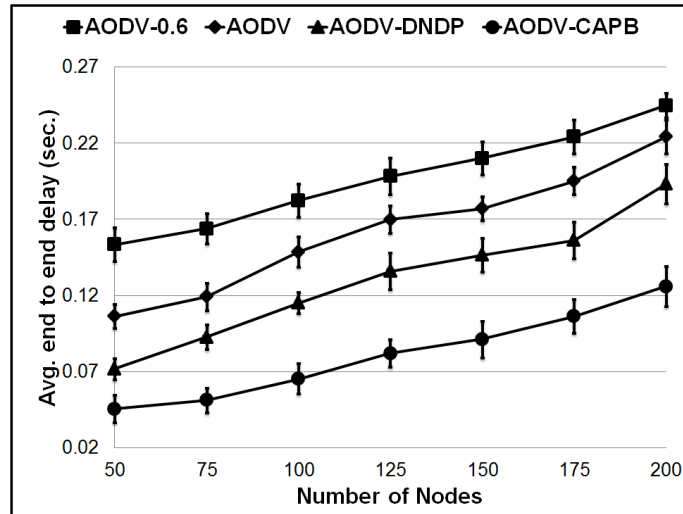


Figure 6.14: Average end to end delay vs. number of node rebroadcasting decision in CAPB takes into account SINR and nodal density in the neighbourhood which increases the reachability of RREQ to the destination node while keeping the routing overhead at minimum.

### 6.2.2.3. Average End-to-End Delay

The average end-to-end delay shows the time a packet takes to reach from the source node to the destination node. It includes all possible delays caused by buffering during route discovery, queuing at the interface queue, retransmission delays at the MAC, propagation delay and transmission delay. Figure 6.14, Figure 6.15 and Figure 6.16 show the average end-to-end delay for data packets for all nodes as a function of number of nodes, node speed and traffic load.

It can be seen that for all schemes, the average end-to-end delay increases with increasing number of nodes, node speed and traffic load. By increasing the number of node and traffic load, contention increases leading to higher queuing delay at the transmitter's buffer and higher packet loss rate due to increased collision. A data packet may need to be retransmitted multiple times for a successful delivery. With increased

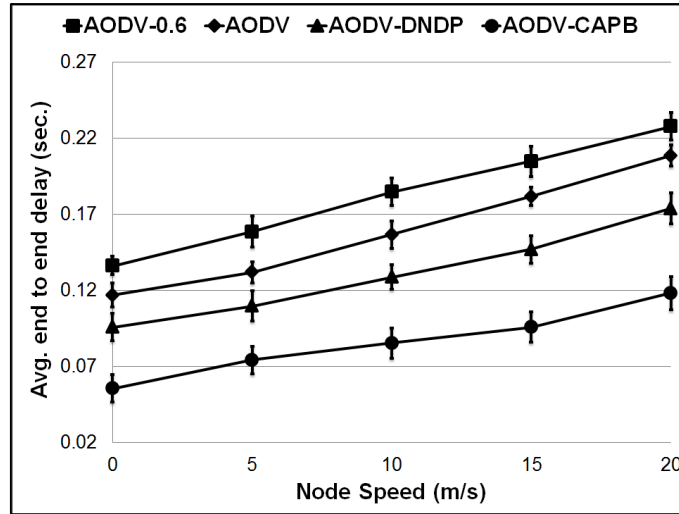


Figure 6.15 Average end to end delay vs. node speed

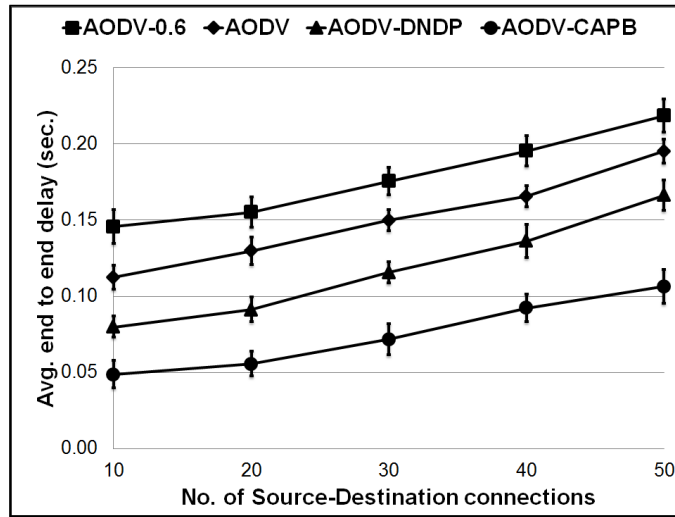


Figure 6.16 Average end to end delay vs. traffic load

mobility, route breaking and repairing takes places more frequently leading to higher average delay.

The proposed CAPB scheme achieves much lower end-to-end delay as compared to other schemes. It is possible because the proposed scheme produces fewer routing packets, which helps to decrease the contention and collision, and it increases the reachability of RREQ packets to the destination which helps to establish or repair broken routes faster.

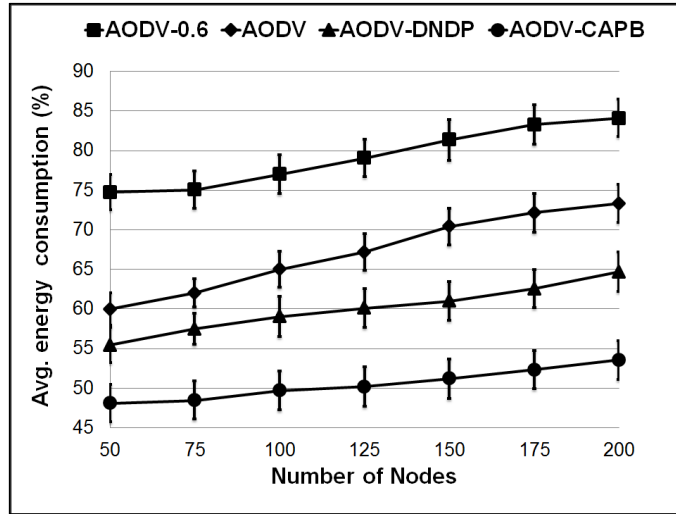


Figure 6.17 Energy Consumption vs. Number of Nodes

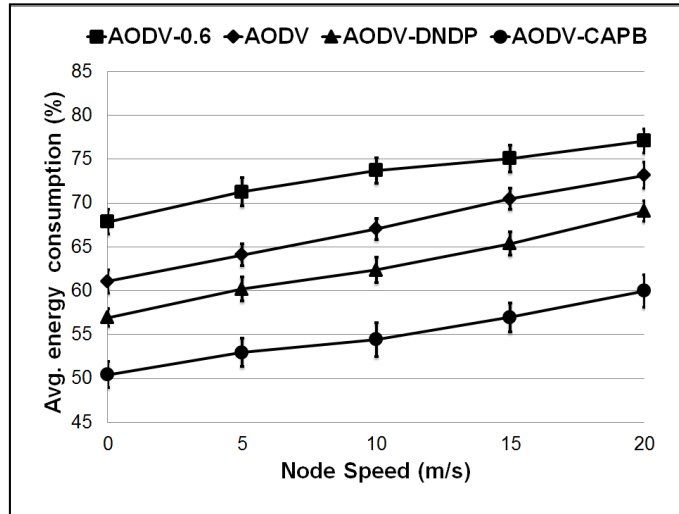


Figure 6.18: Energy Consumption vs. Node Speed

#### 6.2.2.4. Average Energy Consumption

Energy consumption accounts for the energy consumed in transmitting, forwarding and receiving packets (both data and routing packets). Figure 6.17, Figure 6.18 and Figure 6.19 depict the average energy consumption for all nodes for different number of nodes, node speed, and traffic load respectively. The proposed scheme CAPB achieves better

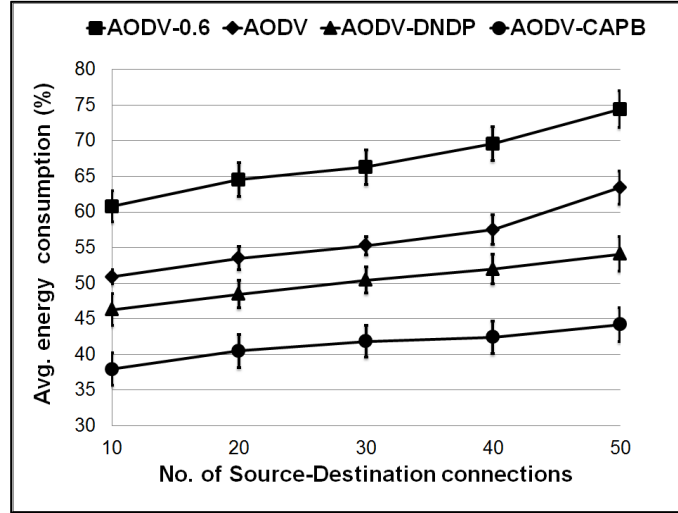


Figure 6.19: Energy Consumption vs. traffic load  
energy efficiency as compared to the other schemes. The energy saving of CAPB is achieved by adapting the rebroadcasting of RREQ packets to current channel conditions and number of neighbouring nodes which helps to reduce unnecessary transmissions of RREQ packet. However, the savings in energy is not in proportion to the saving in RREQ packets (see Figure 6.5, Figure 6.6 and Figure 6.7). It is because the CAPB achieves much higher throughput as well which consumes extra energy.

### 6.3. Summary

Broadcasting is a vital part of route discovery phase of on-demand routing protocols in MANETs. Many on-demand routing protocols (e.g., AODV) use pure flooding to broadcast the RREQ packet. However, pure flooding generates excessive control traffic which may lead to the broadcast storm problem. A number of probabilistic broadcasting schemes have been proposed to limit the broadcast traffic but these schemes do not consider the thermal noise and the co-channel interference and hence do not perform well in realistic noisy MANETs. Node density in the neighbourhood is another important factor to determine the rebroadcast probability. This chapter has presented a



novel Channel Adaptive Probabilistic Broadcast (CAPB) scheme that adapts the rebroadcast probability to the thermal noise, co-channel interference and node density in the neighbourhood dynamically. Extensive ns-2 simulations have shown that the proposed CAPB scheme outperforms the standard AODV and the two related schemes significantly in terms of routing overhead, throughput, end-to-end delay and energy consumption. Simulation results also revealed that the distribution of the rebroadcast probability follows normal distribution closely. The proposed scheme is simple and does not require any extra information to be exchanged among the neighbouring nodes.

# Chapter 7

## Conclusion and Future Work

The proliferation of handheld gadgets, laptops, and smartphone devices, that are developed based on the IEEE 802.11 standard of wireless protocol have made Mobile Ad-hoc Networks (MANETs) an active area of research over the past two decades. A MANET is a self-configuring, self-healing and infrastructure-less network of mobile nodes connected to each other over single-hop or multi-hop wireless links on ad-hoc basis [3] [4]. The MANET topology is dynamically changed by the movement of MANET nodes. MANET nodes adapt to the changing topology by discovering new neighbours and establishing new routes to destinations. There is a numbers of routing protocols have been suggested in the literature. These protocols generally categorised into three; table-driven (proactive), on-demand (reactive) and hybrid routing protocols.

The communication is not error free. The Packet Error Rate (PER) is closely related to Signal to Interference plus thermal Noise Ratio (SINR) and packet size. The IEEE 802.11 MAC standard defines Distributed Coordination Function (DCF). The DCF mechanism is commonly used in ad-hoc networks. The DCF mechanism uses carrier sensing. An unsuitable carrier sensing value directly affects the interference in mobile ad-hoc networks, as a result higher collision probability in the channel. **Chapter 3** emphasised on the impact of varying physical carrier sensing ranges on the performance of on-demand routing protocol (the AODV) in terms of these metrics: routing overhead, end-to-end delay and throughput with considering the thermal noise and co-channel interference. Simulation results have shown that the average routing overhead decreases with increasing in carrier sensing range, and average end to end delay and throughput

decreases with decreasing in carrier sensing range, because unsuitable physical and virtual carrier sensing do negatively affect the value of signal to interference plus thermal noise ratio (SINR). In conclude the routing overhead needs to be considered in the way that the physical and virtual carrier sensing range chosen in noisy MANETs.

**Chapter 4** analysed the effects of thermal noise on the MANET performance using on-demand routing protocol (the AODV) which uses pure flooding broadcasting scheme in the route discovery process. It has been shown that the thermal noise significantly affects the routing performance in MANETs by increasing the likelihood of packet collision. The simulation results have shown that thermal noise has a significant impact on three characteristics of MANET performance (routing overhead, end to end delay, and throughput).

Broadcasting is used in on-demand routing protocols to discover new routes in MANETs. A number of probabilistic broadcasting schemes have been presented in the literature to limit the number of broadcast messages. However, these approaches were not considered realistic conditions and have ignored the effects of thermal noise and co-channel interference which are inherent to noisy MANETs. **Chapter 5** investigated the effects of thermal noise and co-channel interference on the performance of probabilistic broadcast schemes employed in the route discovery mechanism in an on-demand routing protocol MANETs. Based on ns-2 simulations, this analysis discovers that, contrary to the findings of previous studies, probabilistic broadcast schemes do not outperform pure flooding scheme in terms of routing overhead, throughput, end-to-end delay and energy consumption significantly when thermal noise and co-channel interference are taken into account.

To takes into account the deficiencies mentioned above **Chapter 6** suggested a novel Channel Adaptive Probabilistic Broadcasting (CAPB) scheme that adapts the probability of rebroadcasting RREQ packets dynamically according to the thermal noise, co-channel interference and node density in neighbourhood. Simulations results have shown that the proposed CAPB scheme outperforms the standard AODV routing protocol and the two related schemes ([1]and [2]) significantly in terms of routing overhead, throughput, and end-to-end delay and energy consumption. The proposed scheme is light and does not require any extra information to be exchanged among the neighbours.

The proposed scheme depends on carefully chosen values of certain parameters ( $N_l$ ,  $N_u$ ,  $P_{max}$ ,  $P_{min}$  and  $d$ ). These parameters were chosen partly heuristically and partly simulation guided in this thesis. However, research on a systematic approach to find out the optimal values of the aforementioned parameters would be a potential extension of this work.

In addition to broadcasting form, a future work would be to examine the suggested scheme (CAPB) in the other forms of collective communication in MANETs, such as all-to-all (gossiping) [103],and all-to-one (reverse broadcasting) [104]. Moreover, the Simulation is a valuable tool for the performance evaluation of a MANET. However, the models in the simulation might not capture important factors that might affect system performance. So, more realists modelling of signal propagation, mobility models, and running the simulation with a continuous UDP stream.

It would be to examine the suggested scheme in resource discovery. Resource discovery is similar to route discovery process, has a challenging task in MANETs due to the

mobility of nodes. Because nodes have no prior knowledge of the resources in the network, Resource discovery is vital in MANETs designing. It would be beneficial to deploy real experimental measurements on one of testbeds, so that the simulation results reported in this research can be verified.

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