Al-Humoud, Sarah Omar (2011) *The dynamic counter-based broadcast for mobile ad hoc networks.* PhD thesis.

http://theses.gla.ac.uk/2673/

The Dynamic Counter-Based Broadcast for Mobile Ad hoc Networks

Sarah Omar Al-Humoud

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

School of Computing Science
The College of Science and Engineering
University of Glasgow

Abstract

Broadcasting is a fundamental operation in mobile ad hoc networks (MANETs) crucial to the successful deployment of MANETs in practice. Simple flooding is the most basic broadcasting technique where each node rebroadcasts any received packet exactly once. Although flooding is ideal for its simplicity and high reachability it has a critical disadvantage in that it tends to generate excessive collision and consumes the medium by unneeded and redundant packets.

A number of broadcasting schemes have been proposed in MANETs to alleviate the drawbacks of flooding while maintaining a reasonable level of reachability. These schemes mainly fall into two categories: stochastic and deterministic. While the former employs a simple yet effective probabilistic principle to reduce redundant rebroadcasts the latter typically requires sophisticated control mechanisms to reduce excessive broadcast. The key danger with schemes that aim to reduce redundant broadcasts retransmissions is that they often do so at the expense of a reachability threshold which can be required in many applications.

Among the proposed stochastic schemes, is counter-based broadcasting. In this scheme redundant broadcasts are inhibited by criteria related to the number of duplicate packets received. For this scheme to achieve optimal reachability, it requires fairly stable and known nodal distributions. However, in general, a MANETs' topology changes continuously and unpredictably over time.

Though the counter-based scheme was among the earliest suggestions to reduce the problems associated with broadcasting, there have been few attempts to analyse in depth the performance of such an approach in MANETs. Accordingly, the first part of this research, Chapter 3, sets a baseline study of the counter-based scheme analysing it under various network operating conditions.

The second part, Chapter 4, attempts to establish the claim that alleviating existing stochastic counter-based scheme by dynamically setting threshold values according to local neighbourhood density improves overall network efficiency. This is done through the implementation and analysis of the *Dynamic Counter-Based* (DCB) scheme, developed as part of this work. The study shows a clear benefit of the proposed scheme in terms of

average collision rate, saved rebroadcasts and end-to-end delay, while maintaining reachability.

The third part of this research, Chapter 5, evaluates dynamic counting and tests its performance in some approximately realistic scenarios. The examples chosen are from the rapidly developing field of Vehicular Ad hoc Networks (VANETs). The schemes are studied under metropolitan settings, involving nodes moving in streets and lanes with speed and direction constraints. Two models are considered and implemented: the first assuming an unobstructed open terrain; the other taking account of buildings and obstacles.

While broadcasting is a vital operation in most MANET routing protocols, investigation of stochastic broadcast schemes for MANETs has tended to focus on the broadcast schemes, with little examination on the impact of those schemes in specific applications, such as route discovery in routing protocols. The fourth part of this research, Chapter 6, evaluates the performance of the Ad hoc On-demand Distance Vector (AODV) routing protocol with a route discovery mechanism based on dynamic-counting. AODV was chosen as it is widely accepted by the research community and is standardised by the MANET IETF working group. That said, other routing protocols would be expected to interact in a similar manner. The performance of the AODV routing protocol is analysed under three broadcasting mechanisms, notably AODV with flooding, AODV with counting and AODV with dynamic counting. Results establish that a noticeable advantage, in most considered metrics can be achieved using dynamic counting with AODV compared to simple counting or traditional flooding.

In summary, this research analysis the Dynamic Counter-Based scheme under a range of network operating conditions and applications; and demonstrates a clear benefit of the scheme when compared to its predecessors under a wide range of considered conditions.

Table of Contents

List of Figures

List of Tables

Acknowledgments

I am heartily thankful to my supervisors Dr. Lewis M. Mackenzie and Dr. Wim Vanderbauwhede for their fruitful discussions, exceptional support and encouragement. My gratitude also goes to Dr. Mohamed Ould-Khaoua who was my supervisor for more than one year before he left the University of Glasgow, for his enlightening debates and guidance.

Deepest gratitude is also due to my colleagues, support personnel and staff members at the University of Glasgow, especially, the Embedded, Networked and Distributed Systems (ENDS) research group for their beneficial and insightful comments during my talks. Particularly, I thank Dr. Jamal-deen Abdulai with whom I have co-authored research papers, for his initial help on using the ns-2 simulator and for regular discussions on the research.

I would also like to thank Imam University, my employer, for providing me with the scholarship, and the Saudi Arabian Cultural Bureau in London for their support and facilitation.

Finally, I am eternally thankful to my family, especially my parents, for their continual love, support and absolute confidence in me. I would also like to thank my friends in the UK and back home for always being there.

Abbreviations

AODV	Ad-hoc On-Demand Distance Vectoring
CB-AODV	Counter-Based AODV
DCB	Dynamic Counter-Based
DCBRD	Dynamic Counter-Based Route Discovery
EAC	Expected Additional Coverage
GPS	Global Positioning System
IFQ	Interface Queue
IEEE	Institute of Electrical and Electronics Engineers
LAN	Local Area Network
MAC	Media Access Controller
MANET	Mobile Ad hoc NETwork
MBWA	Mobile Broadband Wireless Access
MM	Metropolitan Mobility
MPR	Multi Point Relay
OLSR	Optimised Link State Routing
OSI	Open Systems Interconnection
RAD	Random Assessment Delay
RWP	Random WayPoint
SRB	Saved Rebroadcast
WiMAX	Worldwide Interoperability for Microwave Access
WLAN	Wireless Local Area Network
WMAN	Wireless Metropolitan Area Network
WPAN	Wireless Personal Area Network
WWAN	Wireless Wide Area Network

Chapter 1

Introduction

Mobile wireless networks are an appealing and fast growing option to extend or provide means of communication where it is hard or impractical to use a fixed wired network. Mobility, reduced installation time and long-term cost savings are some of the wireless networks' benefits. Wireless mobile networks can be categorised as [1]: *Wireless Local Area Networks* (WLANs), *Wireless Metropolitan Area Networks* (WMANs) and *Wireless Wide Area Networks* (WWANs). This classification is based on network size and geographic span. To add to the classification completeness it is essential to add one more network type, which is the *Wireless Personal Area Network* (WPAN). wireless network types [1-4] could be summarised with the following table:

Table 1-1: Types of wireless networks

Network type	Technology standard	Commercial name	Size
WPAN	IEEE 802.15	ZigBee, Bluetooth	Room size
WLAN	IEEE 802.11	Wi-Fi	Building size
WMAN	IEEE 802.16	WiMAX	City size
WWAN	UMTS, GSM and IEEE 802.20	MBWA	Earth size

Wireless PAN (WPAN) targets short-range communication of a person or a device forming a *piconet*. This is a network of users connected in a master slave fashion, where each piconet has one master and several slaves.

Wireless LANs (WLANs) are further classified by the IEEE 802.11 standard into two operational modes [5]: infrastructure-based and ad hoc as depicted in Figure 1-1. The former type of networks incorporates access points that facilitate wireless connection from and to network users.

Mobile Ad hoc NETworks (MANETs) are autonomous systems consisting of a set of mobile stations, (called also nodes) that are free to move without the need for a wired backbone or a fixed base station [3, 6, 7]. A *node* is "any device that contains an IEEE 802.11-conformant medium access control (MAC) and physical layer (PHY) interface to the wireless medium" [8]. MANET's mobile nodes can be arbitrarily located and are free to roam at any given time. Moreover, node mobility can vary from almost stationary to constantly moving nodes. Consequently, network topology and interconnections between nodes can change rapidly and unpredictably. Additionally, there are no dedicated routers: each node in a MANET acts as a router and is responsible for discovering and maintaining routes to other nodes [9].

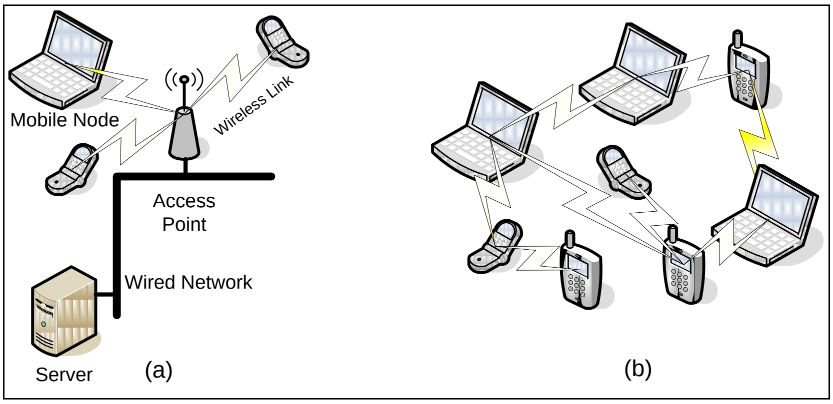


Figure 1-1: Wireless Local Area Networks. (a) Infrastructure-based wireless network (b) ad hoc wireless network

Wireless Sensor Networks (WSNs) are an example of MANETs. WSNs are MANETs with some of the following differences [10]: *mobility*; a sensor network's node is mostly stationary through its life time, whereas a mobile network node, as the name implies, is mostly mobile all the time. *Energy*, since mobile networks' nodes are expected to be devices held and operated by humans, it is likely for their batteries to be recharged or replaced; this is much less of an option with sensors' batteries. Knowing that energy is more of a concern with sensors than with mobile network nodes, caution is needed in designing and developing sensor applications. An aggregation of WSNs would form a *mesh network* that is more immune to single point failure and nodes' disabilities.

The IEEE 802.11 (1997) [9, 11] was one of the first standards devoted to facing the challenge of organizing a systematic standardised approach for WLANs [1]. This standard formalises the physical and MAC layers only as the upper layers (layer 3 and above) of the *Open Systems Interconnection* (OSI) model are independent of the network architecture. Further details on the MANET IEEE 802.11 architecture will be explained in Chapter 2.

Wireless MAN (WMAN) basic arrangement comprises one or more base stations, multiple subscriber stations and sometimes a repeater station or router to provide more network connectivity. Examples of WiMAX networks are *Mobily* in Saudi Arabia [12] and *Urban Wimax* in the United Kingdom [13].

Wireless WAN (WWAN) cellular systems use satellites and divide the network area into hexagonal cells that use multiple low-power transmitters and are served by its base station. Additionally IEEE 802.20 *Mobile Broadband Wireless Access* (MBWA) has some advantages over WiMAX: it provides full mobility up to 250 km/h which is vehicular speed [4].

1.1 Characteristics and Limitations of MANETs

MANETs have several key characteristics, owing to their lack of a centralized infrastructure.

The first characteristic of MANETs, Figure 1-1.(b), is decentralization, with all mobile nodes functioning as routers and all wireless devices being interconnected to one another.

The second characteristic of MANETs is that they possess a dynamic topology. Nodes are free to roam in or out of the geographical coverage area, causing rapid and unpredictable changes to the network topology over time. Alternative paths between a given pair of nodes are automatically found, after which data packets are forwarded across the multi-hop paths of the network [9]. To accommodate that, MANETs use different routing mechanisms which are further elaborated in the routing section 1.3, page 5.

Third, MANETs operate on bandwidth-constrained variable-capacity links. This is due particularly to the wireless communication medium. This type of communication is typically subject to frequent disconnections, low throughput, high response time and lack of security [1, 7, 14]. Additionally, low link capacity typically leads to network congestion [15-17].

Fourth, MANETs are often bound by energy constraints. This is because nodes in a MANET are often hand-held battery-powered wireless transmitters [16, 17].

Fifth, a problem that emerges with MANETs as a wireless dynamic topology environment is the hidden and exposed terminal issues [5]. Hidden-terminal may result in a situation where two nodes may send to a third node simultaneously without them sensing each other as they are out of each other’s range. Exposed-terminal may result in a delay of the transmission of a sender node because of irrelevant transmission accruing within its transmission range. This would imply the need for a more suitable MAC layer in oppose to static network environments [18].

Sixth, with wireless networks there is a lack of full reachability. That is to say, the assumption that each node can hear every other node is invalid [8].

Lastly, MANETs have a heterogeneous and fragmented network infrastructure that implies rapid and large fluctuations in network quality of service (QoS). This can result in poor end-to-end performance of different transport protocols across the network [9, 14]. This can also result in time-varying and asymmetric signal propagation properties [8].

1.2 Applications of MANETs

Mobile ad hoc networks, owing to their quick and economically less demanding deployment, find applications in many areas. Examples of MANET applications are ad hoc wireless networks between mobile laptop devices, military applications, collaborative and distributed computing, emergency operations, inter-vehicle communications and hybrid wireless network architectures. There follows a brief description of some MANET applications.

Military applications: mainly military environments need autonomous and adaptive communication with self-configuring ability. Thus, wireless ad hoc networks are excellent candidates for military networks [19, 20]. The military community is redefining the way wars will be fought in the future, evolving towards a *Network-Centric Warfare* (NCW) paradigm [21]. Moreover, future tactical networks such as the army modernization *Brigade Combat Team* (BCT) [22] will depend heavily on the use of MANETs [23].

Collaborative and distributed computing: the requirement of a temporary communication infrastructure with minimal configuration among a group of people, in a conference, for example, necessitates the formation of an ad hoc wireless network. However, the design, development and deployment of collaborative services in MANET environments raise complex group management issues [24]. Several research efforts are in progress to construct the kind of group management infrastructures required to support collaborative applications in MANETs [25-27]. All solutions share a common design principle to consider user location as the key grouping criterion: users can collaborate and are assumed to belong to the same group as long as they are co-located [24].

Emergency operations: ad hoc wireless networks are very useful in emergency operations of search and rescue, crowd control and in areas destroyed by war or natural disasters, such as earthquakes. An example of emergency application is the Smart project [28]; it aims to create a prototype of a mobile telemedicine system including hardware and software that can be rapidly deployed in rural areas or in disaster conditions. Smart project integrates MIPv6 and IEEE 802.11 MANET to provide telemedicine [28].

Inter-Vehicle Communications: aiming at improved driving comfort and safety, inter-vehicle communication is employed between vehicles in the same area [6, 29]. However, factors such as signal strength fluctuations, high mobility or channel load saturation [30] should be taken into consideration when designing an inter-vehicle protocol. The IEEE 802.11p standard, also referred to as Wireless Access for the Vehicular Environment (WAVE), enhances the original 802.11 standard by the support for *Intelligent Transportation Systems* (ITS) [2]. Additionally, it is based on the *Dedicated Short Range Communication* (DSRC) spectrum as it addresses the needs for high node mobility and rapid topological changes [31]. Several organizations are interested in the development and deployment of *Vehicular Ad hoc NETworks* (VANETs) with regards to both safety and traffic efficiency; Carlink [32], Car-to-car [29] and IntelliDrive [33] are some examples of currently running VANET projects.

Hybrid wireless networks: one of the major applications in ad hoc wireless networks is in hybrid wireless architecture such as *Multi-hop Cellular Networks* (MCN) and *integrated Cellular Ad hoc Relay* (iCAR) networks. MCN combine the reliability and support of fixed base stations of cellular networks with flexibility and multi-hop reliance of ad hoc wireless networks [9].

1.3 Routing

Routing in MANETs has the same principle as in its wired network counterpart: node *A* tries to send a message *m* to another node *B* using some type of routing mechanism. However, the design of a MANET routing protocol poses a challenging dilemma. Proposing a smart routing scheme should address limited resources and be adaptable to changing network topology in both size and traffic density [34, 35]. Packet switching networks typically use two classes of routing protocols: link state and distance vector routing. The former class of routing necessitates that each router holds an up-to-date version of the network connectivity graph along with each link state (up or down) stored in a link state database [36]. One of the main issues to be considered when designing a link state routing protocol is distributing link state reliably, that is ensuring consistency with link state information available to routers [37]. On the other hand in vector routing, each router maintains a routing table containing an entry for every other router in the network. This entry is composed of two parts: the best direction, vector, next hop leading to a destination and the distance cost of reaching that destination. The distance cost metric may be the number of hops, the time delay or the bandwidth [37, 38]. Moreover, routers periodically exchange routing tables until a network realisation state is reached where each router has copies of each neighbouring connection [36, 39]. In MANETs in particular, routing protocols are further classified into *table-driven (proactive);* and *source-initiated on-demand driven (reactive)*; and *hybrid* [34, 40]. Chapter 2 contains more explanation on MANETs routing protocols.

1.4 Broadcasting

Broadcasting is the process by which a given node sends a packet to all other nodes in the network. Broadcasting is a fundamental network element; it may be used for discovering neighbours, collecting global information, naming, addressing, route discovery and maintenance for many routing protocols; and sometimes helping in multicasting [41].

As broadcast operation may involve redundancy and medium contention, it is crucial to take that into account when trying to enhance this vital operation; that is, having some criteria to reduce unnecessary broadcasts in a way that does not affect the overall message reachability [41-44].

According to Brad and Tracy [42], broadcast techniques are categorized into four families utilizing the IEEE 802.11 MAC specifications [11], namely, blind flooding, probability-based methods, area based methods and neighbour knowledge methods.

Another way of categorizing of broadcast methods is to divide them into two groups: stochastic and deterministic. In *deterministic schemes*, a transmitting node predetermines its forwarding nodes before the broadcast. However, this incurs a large overhead in terms of time and message complexity for building and maintaining a fixed backbone, which is the set of forwarding nodes, especially in the presence of node failure or mobility. Examples include pruning [45, 46], multipoint relaying [47], node-forwarding [48], neighbour elimination [49] and clustering [50].

Stochastic schemes, in contrast, rebuild a backbone from scratch during each broadcast [51]. Nodes make instantaneous local decisions about whether to broadcast a message or not using information derived only from overheard broadcast messages. Consequently, these schemes incur a smaller overhead and demonstrate superior adjustment within changing environments when compared to deterministic schemes [52]. However, they typically sacrifice reachability as a trade-off against overhead.

Examples of stochastic broadcasting schemes are: probability-based, counter-based, and location-based broadcasting schemes. Before rebroadcasting a message in probability-based schemes a node waits for a period of time called jitter or *Random Assessment Delay* (RAD), to minimize the chance of collision and to assist a better broadcast decision. Probability-based scheme controls rebroadcasts with fixed probability *P*. Nodes using counter-based schemes rebroadcast a message when the number of received copies of that message is less than some predetermined threshold value and this test is done after RAD (the waiting period of time) expires. In location-based schemes, a node rebroadcasts a message if the area within the node's range that is yet to be covered by the broadcast is greater than a threshold *A*.

Both stochastic and deterministic schemes share the concept of suppressing excessive broadcast. The proposed scheme inherits the advantage of stochastic schemes through simple rebroadcast decision. However, it utilises neighbourhood information to further enhance the broadcast decision. That is, adjusting the counter threshold value to the current neighbourhood density per node. Thus, our proposed scheme is a hybrid broadcasting scheme. It combines the simplicity of stochastic schemes and adds the aptitude of neighborhood sensing.

1.5 Motivations

Broadcasting is an essential data dissemination mechanism that resolves many network issues such as route discovery in many well known routing protocols. Ad hoc On-Demand Distance Vector Routing is an example [53].

Several schemes, stochastic and deterministic have been proposed to alleviate problems related to flooding [42, 44, 46, 51, 54-58]. Unlike deterministic schemes, stochastic schemes are simple to implement with low overhead [42, 44]. However, this comes with the trade-off between reachability and saved rebroadcasts to inhibit excessive broadcasts.

However, some stochastic schemes rely on spatial information that is supported by the existence of a physical device, GPS (Global Positioning system) as in area-based scheme [42, 44]. In distance-based schemes, the estimated distance depends on parameters related to the physical environment, namely the carrier's wavelength and the antenna gains [44].

Moreover, among reviewed stochastic schemes is the counter-based scheme that uses a fixed-threshold value on a variable density network. For this available scheme to achieve the highest reachability, it should be applied on a network with a stable nodal distribution, a network distribution that is either sparse or dense. However, this is not the case of MANETs in reality, where network topology and node density in the network change instantly. Furthermore, Tseng *et al* [41] have proposed an adaptive counter-based scheme where they extended the fixed-threshold value into a function $C(n)$. Besides, they stated that ‘The function $C(n)$ is undefined yet’. Being among the stochastic schemes with negligible overhead, counter-based broadcast was an appropriate candidate for further research, enhancement and study.

Existing counter-based broadcasting schemes use a fixed-threshold value to reduce unnecessary broadcasts. However, this has several shortcomings.

- *First*, the topology of a MANET is often random and dynamic, with varying degrees of node density in the different regions of the network. Therefore, fixed counter threshold approach suffers from unfair distribution of the threshold value since every node is assigned the same value of *C*, regardless of its local topological characteristics as time passes by.

- *Second*, those schemes necessitate a trade-off between reachability and saved rebroadcast. Although the use of small threshold values provides significant broadcast savings, this also means that reachability decreases sharply in areas where the network is sparse. Increasing the value of *C* will improve reachability, but, once again, broadcast savings will be sacrificed as more rebroadcasts will happen [41].

- *Third*, we are unaware of any proposed method to dynamically and autonomously change the counter threshold value per node and per time.

1.6 Contributions

Motivated by the above observations, this research proposes a new dynamic counter-based broadcast scheme, where the counter threshold value and the RAD are dynamically set, utilizing local topological information. This research focus on enhancing the performance of broadcasting and routing in MANETs, specifically this is maintained by:

1. Minimise the number of redundant rebroadcasts.
2. Aid scalability by reducing collisions in dense regions.
3. Maintain an acceptable reachability level
4. Minimise end-to-end delay, allowing transmitted packets to be received in a timely manner

To achieve the mentioned objectives, a hybrid broadcasting scheme was developed that comprises the simplicity of stochastic schemes and adds the capability of sensing neighbourhood information, namely number of neighbours for each node. The number of neighbours per node is known through the exchange of ‘Hello’ packets within one-hop neighbourhood of that node.

Essentially, nodes in sparse networks would need a higher chance to rebroadcast than nodes in dense networks. This could be achieved by the following mechanism: altering the threshold value C to adapt to network density where a large threshold value C_2 is used for sparse networks and a small threshold value C_1 for dense networks.

This research contribution is the *Dynamic Counter-Based broadcast*, (DCB), where the threshold value is based solely on dynamic neighbourhood information. A more detailed discussion on DCB is found in Chapter 4.

1.7 Thesis Statement

Broadcasting is a vital operation in MANETs. For example, it is used in host paging, fault reporting and in many routing protocols to establish routes between source and destination. Broadcasting often relies on simple blind flooding. While this offers elevated reachability, it consumes high bandwidth and causes excessive redundancy and contention.

Several broadcasting techniques have been proposed to overcome problems related to blind-flooding, including stochastic and deterministic schemes [46, 50, 56, 59-61]. Among the stochastic schemes is the counter-based broadcasting where a node decides to rebroadcast a packet if the number of received duplicates is below a certain threshold value. The main advantage of counter-based broadcast is that it inherits the simplicity and autonomous quality of stochastic broadcasting schemes compared to deterministic schemes. Counter-based broadcast has been shown to greatly improve saved rebroadcasts over blind flooding [42, 44].

In this research I assert the following:

T1. While most previous studies have used a fixed counter threshold for rebroadcasting irrespective of the node status, this research proposes a Dynamic Counter-Based (DCB) algorithm that dynamically adjusts the counter threshold value as per the node's neighbourhood distribution and node movement using one-hop neighbourhood information. Employing neighbourhood information in forwarding decisions enhances the performance of existing fixed counter-based flooding in terms of reachability, saved rebroadcast and end-to-end delay.

T2. The performance properties of most proposed counter-based schemes, including our DCB above, have been evaluated in the context of random node movements according to the Random WayPoint mobility model. In this research the Metropolitan Model (MM) has been developed as an evolution of the existing Manhattan mobility model [62] to reflect scenarios where a node moves in straight lines, horizontal and vertical (i.e., streets) to avoid obstacles (e.g. buildings in a city) by the ability of each node to move right or left at each junction. When nodes move according to the Metropolitan Model the performance advantages of the suggested DCB become increasingly superior over the conventional fixed-counter scheme.

T3. Route discovery in reactive routing protocols could be enhanced using the DCB scheme stated in T1. Namely, performance results show that Ad-hoc On-Demand Distance Vectoring (AODV) routing would be further improved by reducing redundant transmissions of route request packets associated with conventional AODV. This is due to the fact that counting and using neighbourhood information per node to dynamically decide the counter threshold can significantly reduce routing overhead, packet collisions and end-to-end packet delay, while improving network throughput for most considered network scenarios.

1.8 Thesis Outline

The rest of the thesis is organised as follows:

Chapter 2 provides an overview of the related work and preliminary information necessary for accommodating subsequent chapters. It starts with a brief introduction on MANETs' routing protocols, proactive and reactive, getting into more details on the AODV reactive routing. This is followed by a section on broadcasting techniques in MANETs and several optimizations on the traditional flooding broadcast. Finally, there are the study methodology explanation, validation and justification.

Chapter 3 includes a baseline study of the fixed counter-based broadcasting scheme. Moreover, it presents the performance investigation of the scheme in a range of counter thresholds and RAD values over different network densities and traffic loads.

Chapter 4 introduces the *Dynamic Counter-Based* (DCB) broadcast scheme that combines the best features of stochastic and deterministic broadcast techniques, comparing the performance to the fixed counter-based broadcast.

Chapter 5 presents the study of the proposed DCB broadcast scheme in a metropolitan environment, reflecting two scenarios, referred to as the highway and the city-model.

Chapter 6 presents route discovery using the DCB broadcast scheme in the AODV routing protocol. The DCB route discovery controls excessive flooding, sensing the neighbourhood density and dynamically adjusting counter threshold value.

Chapter 7 concludes this thesis by summarising primary results and highlights possible future research work and directions.

Chapter 2
Related Work and Preliminaries

The key objective of this chapter is to provide the background information necessary for understanding subsequent chapters. Hence, this chapter is organised as follows. Section 2.1 sheds some light on MANET architecture. Section 2.2 is about routing techniques and broadcasting schemes in MANETs. Section 2.3 explains the study method adopted in the current thesis, including the simulation environment and validation approach; mobility models and system parameters and assumptions. Section 2.4 presents the considered performance metrics. Finally, Section 2.6 provides a summary of the chapter.

2.1 MANET Architecture

In Chapter 1 some light was shed on MANETs characteristics, limitations and applications. Additionally, a classification of wireless mobile networks was presented according to their geographic span. In this section necessary MANET technology and architecture is explained.

Most of the wireless LANs specifications were developed by the IEEE 802.11 working group [1]. Because the higher levels of the OSI reference model are independent of the network architecture the scope of the IEEE 802.11 covers the lower layers of the OSI model, the physical and data layers [1, 63] (Figure 2-1).

Data link layer in the IEEE 802.11 comprises two other layers: the *Medium Access Control* (MAC) layer and the *Logic Link Control* (LLC) layer [1]. As in any other link layer, LLC layer is concerned with the transmission of a link-level PDU (protocol data unit) between two stations. Where the MAC layer sets the rules to access the medium and send data, it provides the core framing operations. The Physical layer contains two sub-layers: the *Physical Layer Convergence Procedure* (PLCP) and the *Physical Medium Dependent* (PMD). The PLCP maps the MAC frames into a format suitable for radio transmission [63]. The PMD transmits any bits it receives from the PLCP into the radio medium using antennas [63, 64].

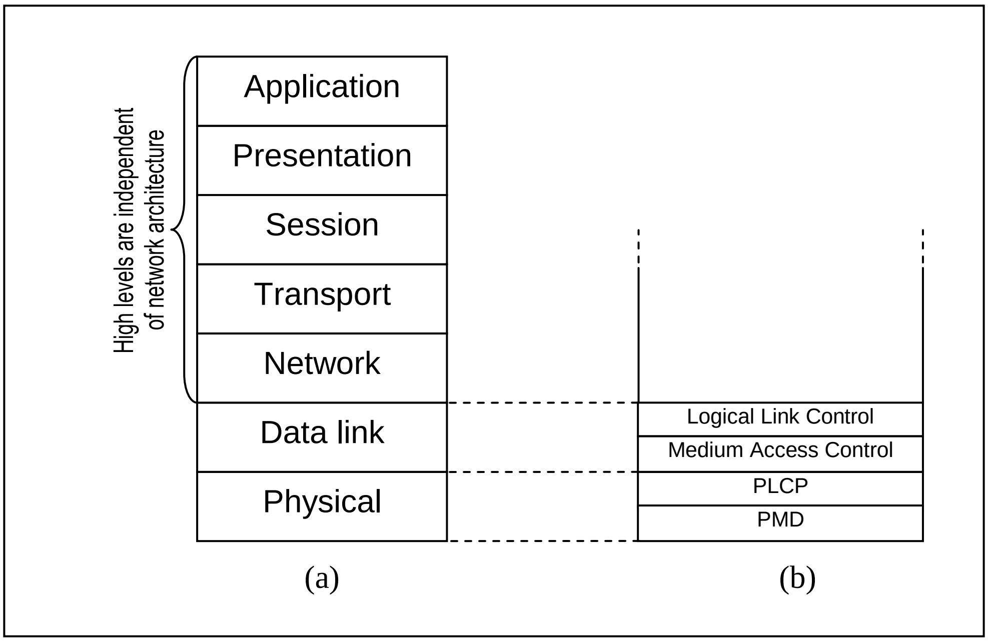


Figure 2-1: (a) OSI reference model, (b) IEEE 802 reference model

The IEEE 802.11 standard applies Ethernet-style networking into radio links with some differences stemming from WLAN characteristics such as mobility and the wireless communication medium. In MANETs, controlling access to the wireless medium is done through Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) with a distributed access scheme with no centralised controller [63]. Specifications of the IEEE 802.11 are shaped mainly by the MAC as it is responsible for handling network mobility seamlessly so it would appear for upper layers as if it is a wired LAN [8, 63]. Additionally, different physical layer standards may provide different transmission speeds and data rates using different radio frequency modulation techniques [1, 8, 63]. The most commonly used standards are 802.11b, 802.11a, 802.11g and 802.11n [65]. Radio modulation or spread-spectrum techniques fall into three main categories: *Frequency Hopping* (FH), *Direct Sequence* (DS) and *Orthogonal Frequency Division Multiplexing* (OFDM). In FH the system switches from one frequency channel to another in a random pattern that is known by both the transmitter and receiver. This makes it harder to eavesdrop the transmission [63]. The FH modulation supports 1 Mbps and 2 Mbps data rates [66]. The DS spread-spectrum spreads each bit into a multi-bit code, that is, it converts a 1 Mbps into an 11 MHz stream. Because the transmitter spreads a transmitted bit this minimizes the data loss [66]. The 802.11b and 802.11g standards use the DS modulation techniques. To be more specific 802.11b uses a high rate of DS spread spectrum (HR-DSSS) enabling the operation of 5.5 and 11 Mbps data rates [66]. The OFDM multiplexing provides data rates of 24 Mbps up to 54 Mbps. In OFDM the signal frequency is broken into *n* independent (orthogonal) channels. Following that the sub-channels are multiplexed [66]. This will aid the transmission against single fading failure [67]. The 802.11a, 802.11g and 802.11n standards use the OFDM modulation technique [66].

2.2 Routing and Broadcasting in MANETs

Routing in MANETs is classified into three types: reactive, proactive and hybrid. The following sections shed some light on the different routing classes in MANETs.

2.2.1 Table driven routing

In table driven, proactive routing protocols each node keeps one or more tables to store routing information. Basically the types and number of tables and how they are updated are the areas in which these protocols differ [40]. Examples of such routing protocols are: *Destination-Sequenced Distance-Vector Routing* (DSDV) [68], *Clusterhead Gateway Switch Routing* (CGSR) [69], *Global State Routing* (GSR) [70], *Fisheye State Routing* (FSR) [71], *Distance Routing Effect Algorithm for Mobility* (DREAM) [72], *Optimised Link State Routing* (OLSR) [73], *Topology Broadcast Reverse Path Forwarding* (TBRPF) [74] and *Wireless Routing Protocol* (WRP) [34, 40, 75]. Among the listed proactive routing protocols is OLSR which is one of the more marked and widely studied proactive routing protocols [19, 73, 76]. Moreover, OLSR is a link state routing protocol as opposed to distance vector routing. General features of both routing classes are depicted in Table 2-1.

Table 2-1: General features of two major routing classes Distance Vector and Link State Routing

Distance Vector Routing	Link State Routing
• Transmits a node's entire routing table • The router informs its neighbours of topology changes • Calculates paths using the Bellman-Ford algorithm • Easy to configure and administer • Well suited for small networks • Example: Destination-Sequenced Distance-Vector Routing (DSDV)	• Transmits only information about the node's immediate neighbours • The router informs all the nodes in a network of topology changes • Reacts more quickly, to connectivity changes • Requires more storage and more computing to run • Examples: Global State Routing (GSR), Optimised link state routing (OLSR)

The link state routing protocol maintains a partial map of the network. Additionally, when a network link changes state, a notification, called a *Link State Advertisement* (LSA) is *flooded* throughout the network. However, OLSR minimizes the flooding associated with a basic link state protocol by means of *Multi-Point Relays* (MPR). Additionally, the difference between flooding and MPR is depicted by Raffo [77] in Figure 2-2. The solid black nodes are relay points that are used to forward broadcast messages instead of indiscriminately forwarding messages by each node in the network which may lead to redundancy and collision.

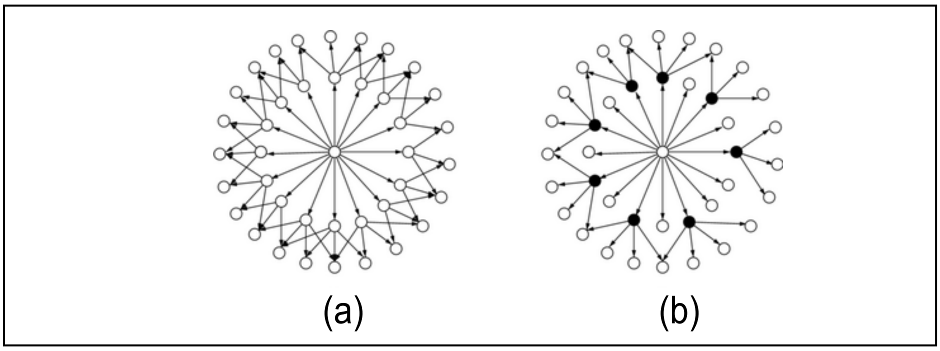


Figure 2-2: (a) Blind flooding and (b) MPR flooding, where solid nodes are MPRs

2.2.2 Source-initiated on-demand routing

In on-demand, reactive routing protocols the route is created only when desired by a source node. This feature enables these routing schemes to minimize the number of broadcasts to retrieve a valid path between source and destination. In [34] twelve on-demand routing protocols are investigated and compared, some of which are: A*d-hoc On-Demand Distance Vectoring* (AODV) [53, 78], *Dynamic Source Routing* (DSR) [79], *Associativity Based Routing* (ABR) [9], *Light-Weight Mobile routing* (LMR) [80], *Routing On-demand Acyclic Multi-path* (ROAM) [81], *Relative Distance Micro-Discovery Ad hoc Routing* (RDMAR) [82], *Location-Aided Routing* (LAR) [83], *Ant-colony-based Routing Algorithm* (ARA) [84], *Flow Oriented Routing Protocol* (FORP) [85] and *Signal Stability Routing* (SSR) [86]. Among the latest routing protocols is the *Dynamic MANET On-demand* (DYMO) routing protocol [87] which is still under development. Moreover, numerous routing protocols are proposed as an enhancement of the widely studied AODV. Examples are: DOA: DSR Over AODV Routing for Mobile Ad Hoc Networks [88], Dynamic Route Optimization Mechanism for AODV in MANETs [89] and *Optimized Ad-hoc On-demand Multipath Distance Vector* (AOMDV) [90]. The latter is included as a routing protocol within the latest version of the network simulator ns-2.34. Although referencing the existing reactive routing protocols provides a glimpse into their variety, it is worth showing in more details how one of the best known and studied routing protocols works; as depicted briefly in Section 2.2.4 and in more details in Chapter 6.

2.2.3 Hybrid routing protocols

Hybrid routing protocols are both proactive and reactive in nature [34]. Hybrid protocols aim to increase scalability by allowing nodes with close proximity to proactively maintain routes, where nodes far from each other follow a route discovery strategy [34]. Examples of such protocols are: *Zone Routing Protocol* (ZRP) [91], *Zone-based Hierarchical Link State* (ZHLS) [92], *Anchor Based Routing Protocol* [93], *Distributed Spanning Trees* based routing protocol (DST) [94] and *Distributed Dynamic Routing* (DDR) [95]. ZRP was first introduced in 1997 [91]. As the name implies, it divides the network into different zones. The size of a zone is given by a radius expressed by number of hops. Moreover, ZRP has the advantage of pro-active discovery within a node's local neighbourhood (Intrazone Routing Protocol (IARP)) [96] and using a reactive protocol for communication with nodes in other zones (Interzone Routing Protocol (IERP)) [91, 97].

While proactive routing employs large amounts of data for link maintenance, reactive routing may fall into network clogging by occasional excessive flooding. A reactive routing with controlled flooding is a more reasonable solution compared to the unnecessary link maintenance burden, especially in a mobile changeable topology network. Hence, only reactive routing has been considered in this research. The rest of this section describes the main functionality of a widely investigated and analysed reactive routing protocol, namely AODV [98].

2.2.4 Ad hoc On-Demand Distance Vector (AODV) Routing

The Ad hoc On-Demand Distance Vectoring (AODV) routing protocol was introduced in 1997 [53]. AODV, as a reactive routing protocol, reduces control traffic by originating path requests on-demand. This is valuable to mobile environments such as MANETs since maintaining a fully up-to-date route information from every node is unnecessary and would imply large communication overhead.

AODV uses a destination sequence number for each routing table entry. The sequence number is created by the destination node. The sequence number included in a route request or route reply is sent to requesting nodes. Sequence numbers are important as they ensure loop free routing which is a required quality in MANET routing [53]. Also, sequence numbers are used to determine the freshness of routing information. When selecting a route to a destination node, a source node will prefer routes with the greatest sequence number as they present the most recent path. Another feature in AODV is that link breakage and topological changes are localised to minimise control traffic as opposed to link state routing that necessitates a complete image of the network connectivity graph to be present at each node. More details on AODV routing mechanism is depicted in Chapter 6.

2.2.5 Broadcasting

Broadcasting in MANETs is an essential component for mobile routing protocols [79, 98]. Simple flooding is the conventional mechanism used to broadcast a message to mobile network nodes. Essentially, flooding happens when a source node disseminates a packet to all network nodes. Eventually, each of those receivers rebroadcasts the packet once it is received for the first time. If a duplicate packet is received it is simply dropped. This behaviour continues until all reachable nodes receive the packet. Though this approach offers simple implementation with high guaranteed reachability, it produces high transmission overhead and can cause, what is referred to as a broadcast storm [41, 43, 44, 99]

Two main schemes are discussed in the literature to alleviate the drawbacks of simple flooding: stochastic schemes and deterministic schemes. The stochastic approach inhibits some hosts from rebroadcasting to reduce redundancy, and hence, collision and contention. The decision whether or not to rebroadcast a particular received packet in these methods is taken individually by each node receiving that packet. The decision is simply direct: to rebroadcast or drop. On the other hand, in deterministic methods nodes utilize information gathered from neighbourhoods that may be up to three-hops' distance to determine which of these neighbours should have a copy of the broadcast packet forwarded to them. The decision here is somewhat more elaborate as opposed to the stochastic methods, since it involves the explicit selection of a subset of neighbouring nodes. In MANETs some of the stochastic and deterministic methods share the key element of localized decision making. That is, the decision is made independently at each node without relying on global network information or infrastructure. However, deterministic methods demand accurate neighbourhood information and up-to-date topology information to ensure coverage, and this can be a significant challenge in a high mobility network topology.

2.2.5.1 Deterministic Broadcasting Schemes

Deterministic approaches are classified according to the type of neighbourhood information used [100] as either location-information-based or neighbour-set-based broadcast protocols. The former approach needs special additional hardware to provide location information such as the existence of a GPS [100] whereas the latter approach uses neighbourhood information only to select a *forward node set*: a small set of nodes that forwards the broadcast packet [101]. In the following, some of the more common deterministic schemes are introduced.

Self-Pruning

This protocol requires that each node has knowledge of its one-hop neighbours which is obtained via the periodic exchange of ‘Hello’ packets. A node includes its list of known neighbours in the header of each broadcast packet. A node receiving a broadcast packet compares its neighbour’s list to the sender’s neighbour list. If the receiving node would not reach any additional nodes, rebroadcast is inhibited; otherwise the node rebroadcasts the packet [46, 54].

Scalable Broadcast

The Scalable Broadcast Algorithm (SBA) requires that all nodes have knowledge of their neighbours within two-hop distance. This neighbour knowledge, coupled with the identity of the node from which a packet is received, allows a receiving node to determine if it would reach additional nodes by rebroadcast. Two-hop neighbour knowledge is achievable via the periodic exchange of ‘Hello’ packets; each ‘Hello’ packet contains the node’s identifier (IP address) and the list of known neighbours. After a node receives a ‘Hello’ packet from all its neighbours, it has two-hop topology information centred in itself [99].

Dominant Pruning

In dominant pruning, the sending node selects adjacent nodes that should relay the packet to complete the broadcast. Nodes instruct neighbours to rebroadcast by including their addresses as part of a list in each broadcast packet header. When a node receives a broadcast packet it checks the header to see if its address is part of the list. If so, it uses a Greedy Set Cover algorithm to determine the largest set of neighbours that are not covered yet by the sender’s broadcast [55].

The Set Cover algorithm is a way to select a set of items that are packed in a fixed set of lots. The aim is to obtain all items with the minimal number of lots. The greedy heuristic begins by placing the largest subset in the set cover and marking all its elements as covered. Then, it repeatedly adds the subset containing the largest number of uncovered elements until all elements are completely covered [102]. An example of the Set cover problem is depicted in Figure 2-3.

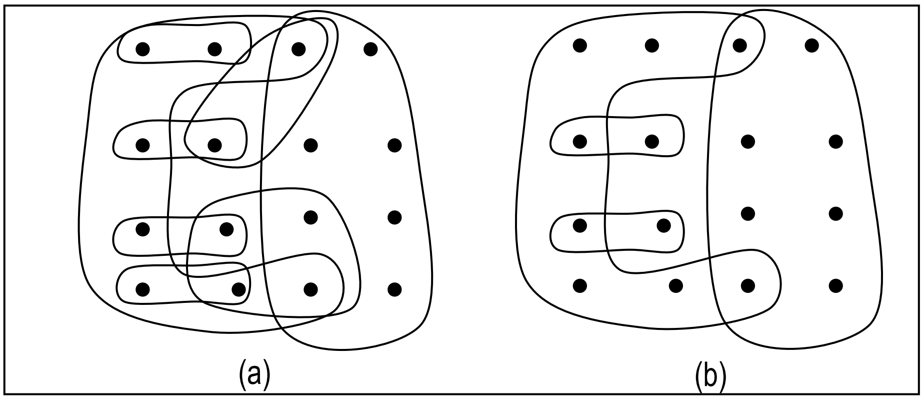


Figure 2-3: An example of the Set Cover algorithm: Input (a), output (b)

Cluster-Based

Previous methods were based on statistical and topological models which estimate the additional coverage of rebroadcast. However, clustering methods are based on graphic theoretical concepts. The idea of clustering is basically done by electing a cluster head; all surrounding nodes of a head are members of the cluster identified by the cluster head. Within a cluster, a member that can communicate with a node in another cluster is a gateway [50]. Using this formation, only cluster heads and gateways are allowed to rebroadcast messages. However, the overhead of cluster formation and maintenance; the required explicit control message exchange and the stationary assumption for cluster formation are costs that cannot be ignored [103].

2.2.5.2 Stochastic Broadcasting Schemes

Stochastic schemes aim to alleviate the flooding problem by reducing the possibility of redundant broadcasts. The decision to inhibit rebroadcast is made directly by a node and assisted either by information induced from the network topology, such as in counter-based, area-based, and distance-based schemes, or by a predefined probability threshold value as in probability-based scheme. There follows an outline of some of the stochastic schemes.

Probability-Based

The probability-based schemes alleviate problems associated with simple flooding, mainly by deciding whether to rebroadcast a message or not based on a fixed probability P. Clearly, when $P = 1$, the scheme is reduced to blind flooding [42, 44, 104]. These schemes operate as follows: when a node i receives a broadcast message, it starts a random delay timer. When the timer expires, the node rebroadcasts the message with probability P. This random delay ensures that the rebroadcast time is differentiated to minimize collision and contention [42].

Adjusted Probability-Based

Several improvements to the probability-based scheme are proposed [59, 60, 105]. The Dynamic Probabilistic Broadcast [59] enhances probabilistic broadcast by sensing or counting the number of received packets P_c and using this number as an indicator of network density. If P_c is high, this implies that the node is located in a dense area and should use a low probability P and vice versa. Nevertheless, adjusted probability-based broadcast [60, 105] improves the conventional probability-based algorithm by utilizing neighbourhood information. Moreover, it indicates the number of neighbours using 'Hello' packets to aid the selection of a probability that is density adapted.

Gossip-Based

Gossip-based broadcast, or so-called epidemic broadcast algorithm [56, 57] is similar to probability-based broadcast in that it attempts to control flooding by forwarding a broadcast message with a fixed probability. However, gossiping methods broadcast the message to only one randomly selected neighbour [106] rather than to all neighbours, as in probability-based broadcast. Additionally, gossip broadcast is aimed and developed mostly for Sensor Networks and gossiping was proposed to reduce the overhead of routing protocols that are typically dependent on flooding. Gossiping was combined with Ad-hoc On-Demand Distance Vectoring (AODV) to prove a significant improvement over the conventional AODV [61].

Adaptive Gossip

Several proposed variants of the gossip-based protocols are designed to be adaptive; that is, the transmission decision is based on local information gathered *passively*, through listening, or *actively*, through issuing query messages to neighbours [107]. Examples of the proposed adaptive Gossip-based protocols are Information via Negotiation (SPIN) [106, 107], Push&Pull [107], GOSSIP1(p, k), GOSSIP2(p_1, k, p_2, n) and GOSSIP3(p, k, m) [61]. The proposed protocols are dedicated for sensor settings; however, there is no obvious reason why they should not be employed in MANETs. Each of the proposed protocols makes use of local information in a different way. For example, GOSSIP1(p, k) starts gossiping with probability = *1* for the first k hops and with probability = p for the remaining hops. That would minimize the likelihood of the gossip to dying early.

Additionally, GOSSIP1(1, 1) is equivalent to flooding, since the probability of all nodes, including the one responsible for sending the first time is equal to 1.

The advantage of starting the gossip with $P = 1$ for the first hop is obvious when the sender node has few one-hop neighbours and more neighbours on the two-hop and so forth. However, when the situation is reversed, that is when a node is located in a dense one-hop neighbourhood and has few two-hop neighbours this would degrade the overall packet reachability. GOSSIP2 (p_1, k, p_2, n) performs better in randomly distributed networks where dense regions may exist. Moreover, GOSSIP2 works in a similar manner to GOSSIP1. However, it introduces two new features p_2 and n such that, if a node has fewer than n neighbours, it instructs its immediate neighbours to broadcast with probability p_2 rather than p_1 where $p_2 > p_1$.

Location-based

In location-based schemes, nodes are expected to have some means of identifying their exact location, in order to estimate the additional coverage more precisely and decide whether to rebroadcast the message. The detailed process of the scheme works as follows [44]. Let a host's location be $(0, 0)$. Suppose a host has received the same broadcast message from k hosts located at $(x_1, y_1), (x_2, y_2), . . . , (x_k, y_k)$. The additional area that can be covered can be calculated as follows, provided that the host rebroadcasts the message. Let $AC((x_1, y_1), (x_2, y_2), . . . , (x_k, y_k))$ denote the additional coverage divided by πr^2 which is the area of a circle that represents the transmission range of a node. Then this value is compared to a predefined coverage threshold A_{th} to determine whether the receiving host should rebroadcast or not.

Counter-based

The counter-based scheme is based on the idea of the inverse relation between the number of duplicate broadcast messages received and the *Expected Additional Coverage* (EAC) [42, 44]. EAC is defined as the number of additional nodes which would be reached if the current node is to forward the message. The idea of EAC is depicted by an example in Figure 2-4. The white nodes are source nodes that initiate the broadcast transmission, and the solid black nodes are nodes used to clarify the idea; referred to as (black-a, black-b). Apparently, black-a neighbourhood density is higher than that of black-b. Thus, the number of duplicate broadcast messages that would be received by black-a is higher as well. Moreover, it is likely that the nodes within the transmission range of black-a would already have been reached by other forwarding nodes. Therefore, the EAC of black-a is lower than the EAC of black-b.

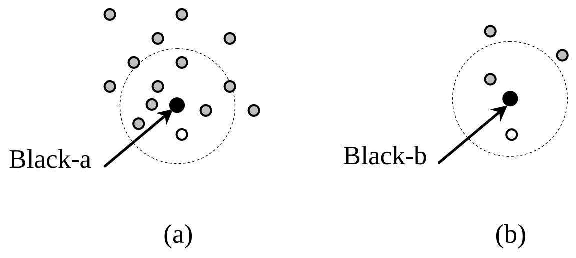


Figure 2-4: Example of Expected Additional Coverage

The counter-based broadcast works as follows when receiving a message for the first time: a counter *c* is set to keep track of the number of duplicate messages received. A *Random Assessment Delay* RAD timer is set. The RAD is simply a time delay randomly chosen between 0 and T_{max} seconds, where T_{max} is the highest possible delay interval. This delay is necessary for two reasons. First, it allows nodes adequate time to receive redundant packets and assess whether to rebroadcast or not. Second, the randomized scheduling minimises the likelihood of collisions to happen [42]. As soon as the RAD timer expires, the counter is tested against a fixed-threshold value *C*; broadcast is inhibited if $c > C$. The counter-based broadcast algorithm is proposed by Tseng *et al* [44]. Furthermore, Tseng *et al* [44] have proposed an adaptive counter-based scheme where they extended the fixed-threshold value into a function $C(n)$ where *n* is the number of neighbours of the host under consideration. Additionally, they stated that 'The function $C(n)$ is undefined yet'. The counter-based broadcast is further examined and explained in Chapter 3.

2.2.5.3 Counter-Based Related Schemes

Other variants of the counter-based broadcast scheme include *Color-based* [51] and *Distance-aware* [58] counter-based broadcast schemes. Both schemes are described briefly in the following sections.

Color-Based Broadcast

Keshavarz-Haddad *et al* [51] have proposed the *color-based* broadcast scheme. The main idea behind this scheme is appending colours to broadcast messages. Using η colours C1, C2, . . . , Cη each node transmitting a packet selects a colour which it writes to a colour field present in the broadcast packet. The algorithm executes in such a way that all nodes which hear the message rebroadcast it, unless they have heard all η colours by the time a random timer expires. Although, the *color-based* broadcast is a promising scheme, it has some shortcomings that are summarized in the following points:

The proposed scheme suffers from the same drawback as the fixed counter-based approach in that it scores high efficiency only when used with homogeneous density networks, e.g. when the network is sparse η =3, and when dense η =2.

Keshavarz-Haddad *et al* have stated that when increasing η, reachability increases. However, they also claim that there is no such threshold value that can provide full reachability for any arbitrary connected network.

This research aims to prove that the threshold value can be adapted autonomously and dynamically by nodes utilizing neighbourhood information.

Distance-Aware Counter-Based Broadcast

Chen *et al* [58] have proposed the ‘DIS RAD’ algorithm that is based on the counter-based algorithm proposed by Ni *et al* [44]. This algorithm introduces the concept of distance into the counter-based broadcast scheme by giving nodes closer to the node transmission range border a higher rebroadcast probability since they create better *Expected Additional Coverage* (EAC). The proposed algorithm runs as follows. First, the source node initiates a broadcast request. All of its neighbour nodes increase their counters as soon as they receive the broadcast message. The border nodes initiate an SRAD[*] and interior nodes initiate an LRAD. The remaining procedure is the same as in the counter-based scheme. Nodes increase their counters by 1 when hearing a duplicated message during RAD. When the RAD expires, if the nodes' counters exceed the threshold value, then the broadcast is blocked. Otherwise, the broadcast packets are sent out.

Adapting the concept of distance in the counter-based broadcast has improved reachability and saved rebroadcasts. This may be theoritically feasable assuming an open plane terrein with no obticales, as per the authors implementation. However, in realilty the presence of barriers and obstacles may affect the signal strength and hence degrade the potential of using distance as a dicision making foundation.

Adjusted-Counter-Based Broadcast

The Adjusted Counter-based algorithm [108] is based on the original counter-based algorithm [44]. This algorithm utilises two threshold values for dense and sparse

[*] SRAD stands for Short Random Assessment Delays, while LRAD stands for Long RAD

neighbourhood densities respectively. Moreover, this algorithm uses some spatial network parameters to calculate the average number of neighbours, such as network area or total number of nodes in the network. Effectively, the average and the current number of neighbours would determine the threshold value. Using spatial information to calculate the average number of neighbours may be synthetically feasible. However, in reality, to correctly implement this scheme one would need a central control mechanism to collect, measure and utilise spatial information.

2.3 Method of Study

After some consideration, simulation was chosen as the method of study in this research. Analytical models are of low cost with the ability to study much larger systems than simulation. Moreover, understanding of multi-hop wireless MANETs has increased in recent times [109]. However, that comes with the price of numerous simplifications and assumptions, especially with multi-hop wireless MANETs, and that may restrict their validity to a limited number of scenarios [110]. In contrast, analysis using simulation can incorporate more details to the level that mimics real-world scenarios.

The scope of this study includes networks of significant sizes. Deploying a suitable experimental test bed would incur excessive overhead in both management and cost certainly well beyond available resources. Therefore, simulation was chosen as it provides a reasonable balance between real-world accuracy and mathematical tractability [111]. Another advantage of simulation is that it facilitates the comparison between protocols implemented under the same settings.

2.3.1 Simulation Environment and Validation

Several network simulators are available both commercially and as an open source, for MANET performance analysis studies. Among the common simulators are ns-2 [112], GloMoSim [113], OPNET [114], QualNet [31, 115] and OMNeT++ [110]. Figure 2-5 shows the use of different simulators from 2001 to 2009 through IEEE conference and journal publications. A total of 313 publications considered on MANETs, more than half of which were using ns-2 as the benchmark simulator, as depicted in Figure 2-6. Unlike OPNET and QualNet, ns-2 is an open source tool that is open for rapid development and updated along with a well documented text.

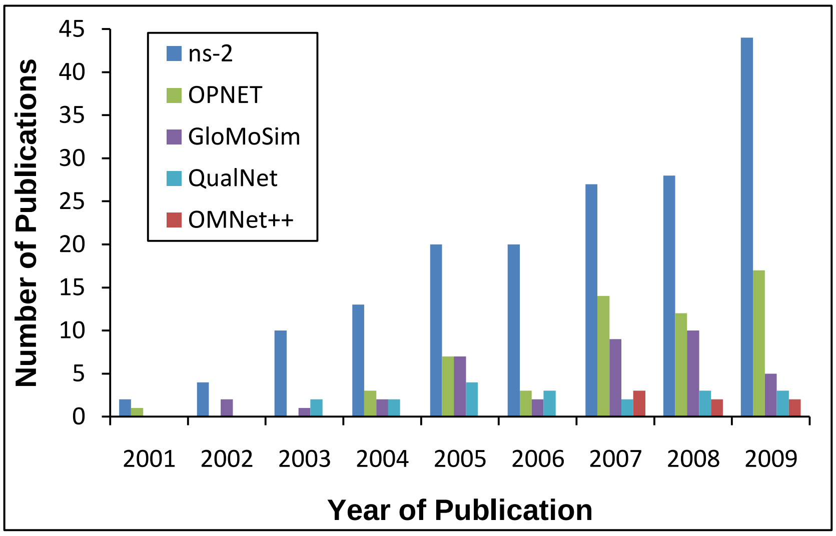


Figure 2-5: The use of different simulators for the MANET study

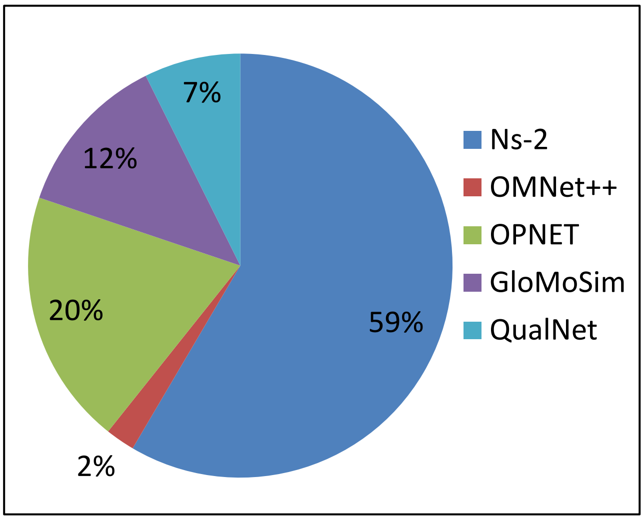


Figure 2-6: The proportion of using different simulators for the MANETs study from 2001 to 2009

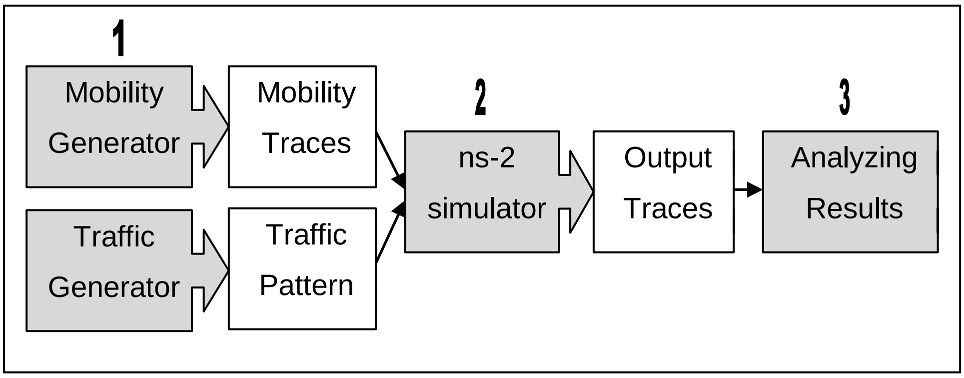


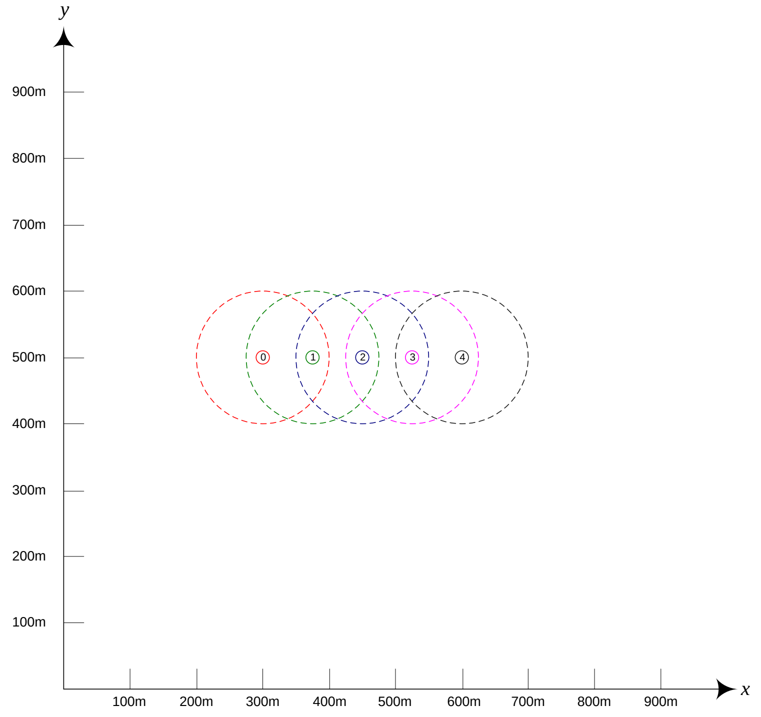
Figure 2-7: Simulation Environment

To evaluate the performance of the suggested broadcasting algorithm in MANETs, the ns-2 network simulator was selected. Ns-2 is widely used throughout the literature because of its detailed, comprehensive and up-to-date infrastructure library for the most important MANET protocols. The simulation process, Figure 2-7, starts with providing the simulator with the mobility traces and traffic patterns. Mobility traces contain spatial data describing network area, location and velocity of each node over time. A traffic pattern file specifies packet size, number of sending nodes and packet transmission rate.

Prior to running any simulation using ns-2, the simulator is validated using the 'validation test suite' [116]. This is a set of scripts provided by the developer [112] to test various parts of ns-2, compare results with known values and ensure that the current environment is executing properly.

To validate the extended part of ns-2, this research implements a 'fixed value' test [117]. This is a validation technique that involves selecting constant input parameters and checking output results against expected calculated values. The validation is to simulate the counter-based broadcast scheme, (see the Counter-based section page: 21), over a small network of five stationary nodes in an area of 1000m by 1000m as shown in Figure 2-8. The transmission range of each node is 100m and nodes were placed in a linear way starting from node (0) to node (4). The nodes' placement code is shown in the left-hand column in Figure 2-8.

Node positions are selected to ensure that a node can only communicate to its first-hop neighbour only. Moreover, node (0) is set to broadcast 2 packets per second for 100 seconds simulation time. The counter threshold for the nodes is once set to zero and another time set to one. The aim of this validation is to achieve 100% reachability when the threshold counter is one and 0% delivery success when the threshold is set to zero. Results from this validation matched expected aim.

Node Placement script	Network map
\$node_(0) set X_ 300.00 \$node_(0) set Y_ 500.00 \$node_(0) set Z_ 0.00 \$node_(1) set X_ 370.00 \$node_(1) set Y_ 500.00 \$node_(1) set Z_ 0.00 \$node_(2) set X_ 450.00 \$node_(2) set Y_ 500.00 \$node_(2) set Z_ 0.00 \$node_(3) set X_ 520.00 \$node_(3) set Y_ 500.00 \$node_(3) set Z_ 0.00 \$node_(4) set X_ 600.00 \$node_(4) set Y_ 500.00 \$node_(4) set Z_ 0.00	 Figure 2-8: Five nodes chain topology for the validation of the counter-based implementation in the ns-2 simulation

2.3.2 Mobility Models

MANET nodes are often considered mobile and a mobility model describes node moving patterns within a simulation by generating detailed movement specifications that are provided to the simulation core protocols. Using a proper mobility model is crucial to a successful simulation study. The credibility of mobility models emerges after considering a real network scenario, i.e. a vehicular network, a battlefield, a university campus or a conference hall, then designing a simulation environment and parameters that mimic that actual scenario.

Recently, mobility data fed into MANET simulations falls into two categories: real-world traces and synthetic traces. Real-world traces are detailed records of real-world movement; however, in many cases, communication data collected considers only users falling within the same hotspot or Wi-Fi Access Point (AP) range and not users in communication range of each other [118-120] . Moreover, most of the data collected from APs represent usage pattern, not mobility pattern, and those patterns correspond to devices mostly used while stationary only. That is, roaming was considered as users associating with different APs while remaining at their home location [118]. Therefore, although those traces are real-world records, they do not reflect the true communication pattern of users. Other problems include the time (up to years) to capture a significant amount of data [121] and privacy restrictions that may prohibit the collection and distribution of such data. Synthetic traces, on the other hand do not provide such accuracy in terms of real-life system representation as real-world traces; however, they enable researchers to estimate user movements in the absence of an appropriate real-world trace at low cost and in short-time scales. In this research, synthetic traces generated by coded mobility models are used. The reasons for this choice are the limited availability of real-world traces and the typically very high specificity of those that are public. A major reason for focusing on synthetic models is the ability to generate a variety of normal and extreme scenarios in which to test our developed system.

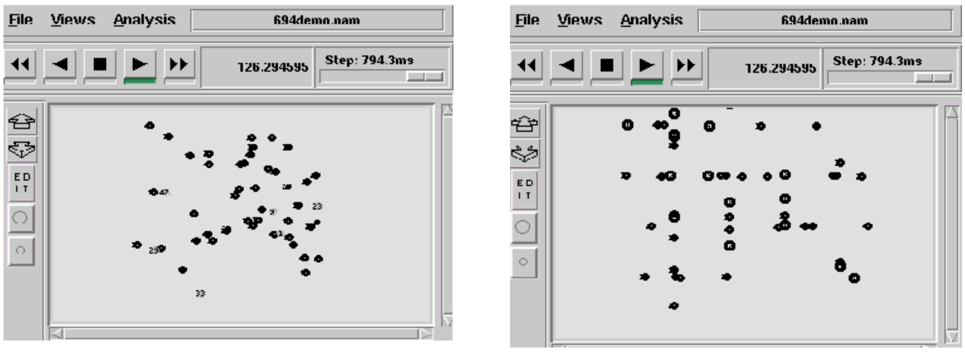
Synthetic mobility models have been classified into entity and dependent mobility models [122]. Entity mobility models represent mobility patterns of nodes moving independently of each other. Nevertheless, dependent mobility models represent node moving patterns that are spatial or temporally dependent.

In MANETs, many synthetic entity mobility models have been proposed that would involve random node movements with no restrictions such as the widely used Random WayPoint mobility model (RWP) discussed in Chapter 1. In Random WayPoint mobility model, each node selects a random location on the network as a destination, then travels towards it with a constant velocity that is selected randomly and uniformly from $[0,V_{max}]$, where the parameter V_{max} is the maximum allowable velocity for every mobile node [123]. Figure 2-9 (a) is a snapshot of the ns-2 network animator, *nam*, showing a simulation of 50 nodes moving randomly according to the RWP mobility model.

MANET mobility models considered in our research are: Random WayPoint mobility model and Metropolitan Model (MM). Metropolitan Model imitates the movement pattern of mobile nodes on streets defined by a map. This map is composed of a number of horizontal and vertical streets having one or two lanes of inverse direction. A node is allowed to move along a lane and to turn right or left at each intersection of a vertical and a horizontal street. Essentially, this model poses temporal and spatial dependency between nodes, and restricts node movements by geographical boundaries defined by the model map. Moreover, nodal movements are based on the Manhattan mobility model defined in

[62]. Figure 2-9 (b) shows a snapshot of 50 nodes moving according to a pre-defined map with 4 vertical and horizontal streets each having two lanes of opposite direction.

In this study a separate chapter is dedicated to study the proposed protocol under circumstances generated by a real-world setting. This examines MANET wireless transceivers-equipped vehicles in two scenarios, namely the highway scenario and the city scenario, with movement modeled by the MM.



(a) (b)

Figure 2-9: Ns-2 Network Animator screen plots of 50 nodes moving according to (a) Random Way Mobility model, (b) Metropolitan Model

2.3.3 System Parameters and Assumptions

The key parameters of our simulation study include network terrain area, mobility model, number of simulated nodes, minimum and maximum nodal speed, number of traffic flows and transmission rates. Our conducted simulation system settings include identical mobile nodes operating in a flat area of size 1000m x 1000m. For all simulated scenarios the simulation runs for 900 seconds to avoid immature simulation termination and to keep simulation time at a manageable level. Each node represents a communication device equipped with IEEE 802.11b wireless transceiver and has a transmission range of 250m. In reality, radio rays propagate in a non-linear fashion, as they are obstructed by environmental obstacles causing reflection or refraction [124]. Thus, this research considers a two-ray propagation model with the received signal consisting of two components: the line of sight ray and a reflected ray, which is the transmitted signal reflected off the ground. In this model, as the distance increases between the transmitter and the receiver, the resultant ray power would decay in an oscillatory fashion [125] which gives more accurate prediction at long distances than the free space model, which is another propagation model implemented and available within the network simulator, ns-2 [126].

To establish the results' statistical confidence several random topologies are run for each simulation. It was observed that the means of 30, 40 and 50 trials are within the same confidence interval of 95%. However, the mean values of 30 and 35 trials are almost the same. Consequently, our statistics were collected using a 95% confidence level over 30 randomly generated topologies. The error bars in the graphs represent upper and lower confidence limits from the means and in most cases they have been found to be fairly small so that they are obscured by the data series marker itself. For the sake of clarity and neatness, the error bars have not been included in some of the graphs. The *InterFace Queue* (IFQ) length used in this research is the default value selected by most MANET researchers enabling a reasonable balance between reachability and delay. Implementing a longer IFQ would aid in reachability, while resulting in more delays.

Other simulation parameters are shown in Table 2-2.

Additionally, some necessary assumptions, which have been commonly employed in the literature [41, 46, 54, 58, 59, 61], have been used in the context of this research:

- All network nodes are equipped with IEEE 802.11b transceivers that are active all time and have the same nominal transmission range.
- A broadcast request can be issued by any source node which has a packet to be distributed to the whole network.
- According to the broadcast algorithm considered in this research, a node has a chance of one or fewer times to rebroadcast a given packet.
- The total number of nodes in a given topology remains constant throughout the simulation time. However, network partitioning might occur during simulation so the network is not guaranteed to be fully connected all the time.
- Mobile nodes have sufficient power supply to function throughout the simulation time. At no time does a mobile node get turned off or malfunction because of lack of power.

It is worth noting that other assumptions will be acknowledged later in the following chapters when appropriate.

Table 2-2: Simulation parameter

Simulation parameter	Value
Simulator	ns-2 version (2.33)
Network Area	1000 x 1000 metre
Transmission range	100, 150, 250 metre
Data Packet Size	512 bytes
Node Max. IFQ Length	50
Simulation Time	900 sec
Number of Trials	30
MAC layer protocol	IEEE 802.11b
Mobility model	Random WayPoint model
Propagation model	Two Ray Ground
Traffic Type	CBR (Constant Bit Rate)
Channel Bandwidth	11Mb/sec
Confidence Interval	95%
Propagation model	Two Ray Ground

2.4 Performance Metrics

Performance metrics are used to measure the superiority and efficiency of the network performance. Performance metrics are indicators as to how effective are the proposed schemes (i.e.) pure broadcast and route discovery; also they are designated to enable comparing our algorithm to other related algorithms [41, 44]. Specifically, this research aims at minimising unwanted broadcast that would needlessly use up the available transmission medium. However, saving redundant packets is not enough as an indicator to scheme efficiency, as the purpose of the initial packet transmission is to reach its destination, the whole network, in broadcast transmissions. Consequently, it is crucial to measure successfully transmitted packets by measuring reachability or throughput metrics. Another aim of our proposed scheme is to minimise unwanted packet transmission delays by saving the medium from being occupied with redundant retransmissions, enabling a timely reception of the transmitted packets. Moreover, an important efficiency measure of a routing protocol or a broadcast scheme is the packet collision rate. Fewer collisions indicate better consumption of the available bandwidth, assuming that data packets are reaching their destinations safely (reachability) and in a timely manner (latency). The performance metrics are summarised as follows:

- *Saved Rebroadcast*: defined as $(r - t)/r$, where r is the number of hosts receiving a broadcast message, and t is the number of hosts that actually retransmitted that message.

- *Collision rate:* is the total number of packets dropped by the MAC layer as a result of collisions per unit time.
- *Routing overhead:* is the total number of *Route REQuest* (RREQ) packets generated and transmitted during the entire simulation time. For packets sent over multiple hops, each transmission over one hop is counted as one transmission.
- *Reachability*: is the percentage of nodes receiving the broadcast packet over the total number of mobile nodes that are reachable directly or indirectly.
- *Normalised throughput:* the ratio of the number of data packets successfully delivered to their destinations per unit simulation time over the theoretical throughput (i.e. the number of data packets generated per second).
- *Average latency*: which is the interval from the time the packet broadcast was initiated to the time the final destination receives this packet.

2.5 Summary

This chapter provided a summary of MANET architecture and standards. Following, is a general overview on the routing and broadcast methods in MANETs. Those include the stochastic, the deterministic and the counter-based related schemes that stem from the former class.

Different routing protocols are considered for MANETs research, including the proactive and reactive routing. Different broadcast techniques were discussed, as broadcasting is used heavily in MANET routing protocols and in many vital network operations. The two classes of broadcast schemes discussed are the stochastic and the deterministic.

Stochastic broadcasting schemes are one of the proposed solutions to reduce redundant rebroadcasts in a way that alleviate the broadcast storm. They are simpler to implement and to maintain compared to the deterministic schemes.

The chapter has also provided the study method and the main performance metrics including reachability, saved rebroadcast, collision rate and average latency.

Additionally, a validation study was carried out to successfully verify the correctness of the simulation model. The next chapter, Chapter 3, introduces a baseline study and analysis of the counter-based broadcasting scheme.

Subsequently Chapter 4 introduces the proposed scheme, Dynamic Counter-Based scheme (DCB) analysis and discussion. Chapter 5 is the study of the proposed scheme DCB in a metropolitan environment. Chapter 6 presents the test and analysis of the proposed scheme as a means of route discovery in the AODV routing protocol. Lastly, the conclusions and future directions are presented in Chapter 7.

Chapter 3

Analysis of Counter-Based Broadcast

3.1 Introduction

The fixed counter-based broadcast was suggested in [41, 44] to reduce the effect of excessive and redundant packet rebroadcasts. Those studies revealed that counter-based broadcast incurs lower overhead compared to blind flooding while maintaining a good degree of packet propagation through the network. Nevertheless, when studying the performance of counter-based broadcast these studies have not taken into consideration a number of important issues that could immensely impact the broadcast performance in MANETs. Such issues include network density, network traffic load, node transmission range and speed; and RAD length. This chapter investigates the effects of the different settings on the counter-based broadcast.

```
CBase_Broadcast_Algorithm

Pre: a broadcast packet p at node X was heard

Post: rebroadcast the packet or drop it, according to the algorithm

1.  Get the Broadcast ID
2.  Set RAD
3.  c = 1
4.  While (RAD) Do
        If (same packet heard)
              Increment c
5.  End while
6.  If (c > C)
        drop packet
        Exit algorithm
7.  End If
8.  Submit the packet for transmission
End CBase_Broadcast_Algorithm
```

Figure 3-1: Algorithm of the counter-based broadcast

The counter-based broadcast scheme is illustrated in Figure 3-1. In this scheme, when a node receives a broadcast packet *p* for the first time, a counter *c* is initiated to count every receipt of *p*. After a Random period of time called the Random Assessment Delay (RAD) *c* is compared against a predefined threshold value *C*. If $c > C$ the packet is dropped, otherwise it is rebroadcasted. When *C* is large this scheme reduces to blind flooding.

The remainder of this chapter is organized as follows: Section 3.2 presents the simulation environment and system parameters. Section 3.3 includes the analysis of the counter-based broadcast scheme under the effect of variable network nodal densities. The next section, 3.4 presents the study of the counter-based scheme under the effect network load. Following, Section 3.5 presents the RAD sensitivity analysis. Finally, Section 3.6 draws the chapter to a conclusion and state overall remarks.

3.2 Simulation Environment

The performance of the counter-based broadcast is evaluated using the ns-2 network simulator [112]. The counter-based broadcast was initially specified by [44]. Based on the specifications, an ns-2 implementation was carried out [42]. This implementation of the counter-based code [42] was modified mainly to encompass the realisation of different threshold values, supporting the IEEE 802.11b standard with a maximum data rate of 11Mbit/sec and configuring the Two-ray propagation model with a transmission range of 100m. These modifications were built upon the ns-2.33, the latest version at the time of writing this text.

The counter threshold values have been varied from 2 to 6. The analysis of the counter-based scheme is conducted using the simulation model and system parameters specified in Chapter 2 Section 2.3. The analysis is concerned with the effect of variable network densities and different traffic loads. The employed performance metrics include collision rate, saved rebroadcast and reachability as discussed in Chapter 2 Section 2.4.

3.3 Effects of Network Density

The study of network density is expressed by varying the numbers of nodes while maintaining other network parameters such as transmission range and network area fixed. The counter-based scheme is implemented with five different threshold values referred to as C2, C3, …, C6 meaning the counter-based schemes with threshold values 2, 3, …, 6 respectively. The simulation scenarios consist of numbers of nodes that range between 25 and 100 nodes with steps of 25 nodes. The network area is a terrain of 1000m wide by 1000m high with each node engaging in the communication with a transmission range of 100m. Each simulation trial runs for a 900 sec period of time. Each node moves according to the Random WayPoint mobility model with minimum and maximum speeds of 1m/sec and 8m/sec respectively. The packet injection rate is 10 packets per second initiated by 1 node randomly chosen from the whole node population creating a random traffic pattern. For all figures represented in this section the x-axis represents the variable network operational conditions under study, i.e. network density or traffic load, and the y-axis represents the actual resultant values scored over the network simulation.

3.3.1 Collision Rate

Figure 3-2 shows the effect of network density on the performance of the counter-based scheme with different threshold values and on flooding as well. The figure proves that for each counter-based implementation (with a different threshold value) there exists a relationship between the number of nodes and the collision rate; increasing the number of nodes while fixing all other network parameters results in an increase in collision rate. With the given simulation settings, a node covers 3% of the network area, calculated using Equation 3.1 where ***r*** is the node transmission range and ***w*** and ***h*** are the network width and height respectively. That is 25, 50, 75 and 100 nodes would ideally cover 75%, 150%, 225% and 300% of the network. However, the probability of overlapping radio transmissions increases when the number of nodes increases.

$$\frac{\pi \times r^2}{w \times h} \qquad \text{Equation 3.1}$$

Collision happens when two or more nodes within the same neighbourhood are sending at the same time. The probability of collision happening will increase when the number of nodes increases, as overlapping simultaneous transmissions are more likely to happen. For example, when the number of nodes increases from 25 to 100, the number of collisions increases by 460% and 1700% for C2 and C3 respectively. The increase of collision rate is not only related to the number of nodes but also to the threshold values. Figure 3-2 exposes this relationship between threshold values and the collision rate where increasing the threshold value increases the probability of a node retransmitting a packet, which in turn amplifies the collision rate. As the figure shows, increasing the threshold value from 2 to 6 increases the collision rate by 272% for a network with 50 nodes and by 366% packets/ sec for a network with 75 nodes. A final remark on Figure 3-2 is that imposing some kind of control over the broadcast mechanism, using the counter-threshold technique, decreases the collision rate. This is shown by higher collision rates with flooding broadcast compared to the counter-based broadcast at all network densities.

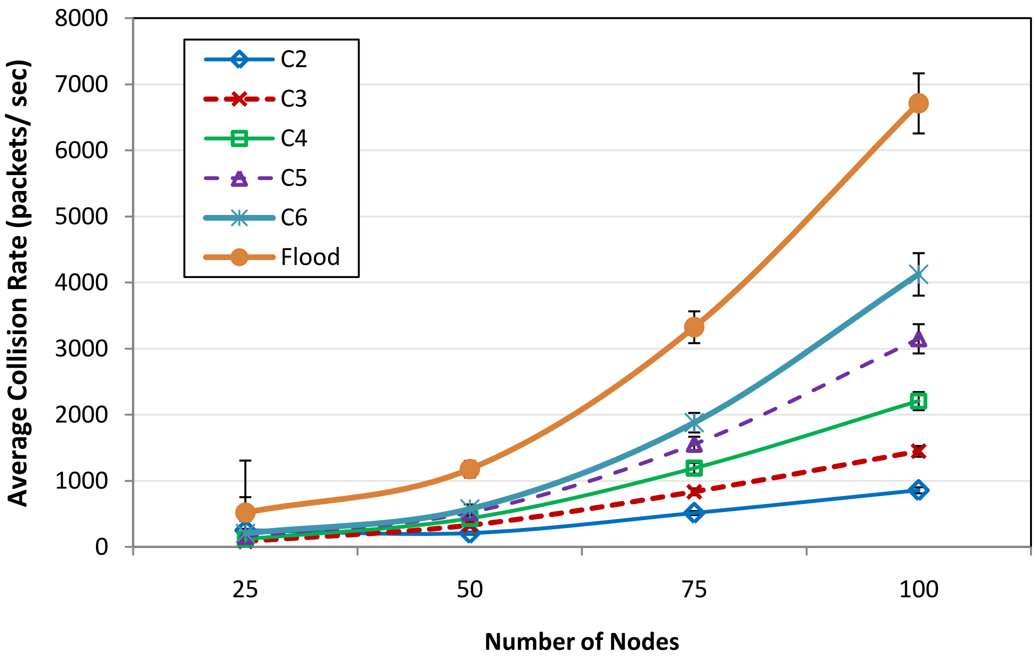


Figure 3-2: Average Collision rate (packets/sec) versus number of nodes placed over 1000mx1000m area with an injection rate of 10 packets/ sec studied with different threshold values and flooding

3.3.2 Saved Rebroadcast

Figure 3-3 shows the effects of variable network densities on the counter-based broadcast with different threshold values and on flooding in terms of the number of saved rebroadcasts. That is, how much a packet rebroadcast is saved, prohibited and not sent.

Figure 3-3 shows the relationship between number of nodes and broadcast savings. Increasing the number of nodes would increase the amount of savings and this may be explained by noticing that the number of nodes actually receiving a packet and not retransmitting it again would increase by increasing the number of nodes. For example: increasing the number of nodes from 25 to 100 would increase saved rebroadcast from 18% to 58% and from 10% to 46% for C2 and C3 respectively.

Another relationship derived from Figure 3-3 is that between the threshold values and saved rebroadcast. Increasing the threshold values decreases the amount of savings. That is because the increase in threshold values would allow more packets to be retransmitted, and not saved. From Figure 3-3 it is noted that the saved rebroadcast is decreased from 18% to 1% and from 58% to 14% when increasing the threshold value from 2 to 6 in a network with 25 and 100 nodes respectively. This assures the inverse relation between saved rebroadcast and threshold values. Broadcast by flooding, by definition, scores no savings through all nodal densities, as shown in Figure 3-3.

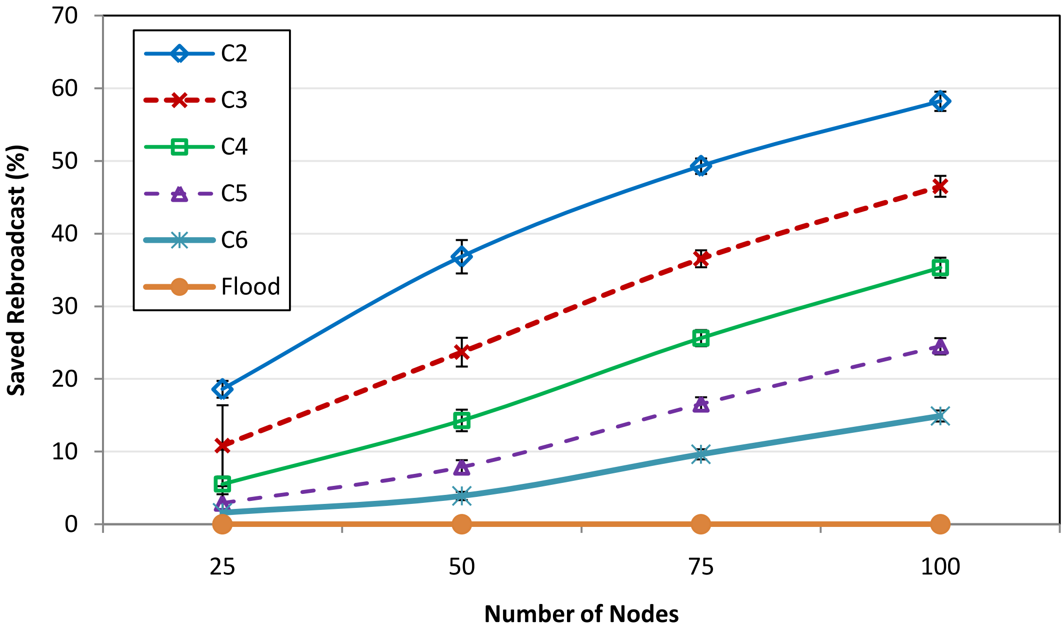


Figure 3-3: Saved Rebroadcast versus number of nodes placed over 1000mx1000m area with an injection rate of 10 packets/ sec studied with different threshold values and flooding

3.3.3 Reachability

Figure 3-4 shows the performance of the counter-based approach in terms of reachability, plotting the percentage of the network reached by a typical packet. The figure shows that increasing the number of nodes would increase reachability. This is a result of the increased network coverage with an increased number of nodes. Adding more nodes to the network would increase the available routes that the packet would possibly take to reach its destination (the whole network in the broadcast case). All broadcast schemes scored similar reachability, reaching almost 100% of reachability with 100 nodes. However, at networks of 25 nodes counter-based schemes with low threshold values experience a little loss in reachability. This is because of over-suppressing packet retransmissions in a low connectivity network. Flooding performed comparably better in terms of reachability at smaller networks, as it rebroadcast packets with no condition.

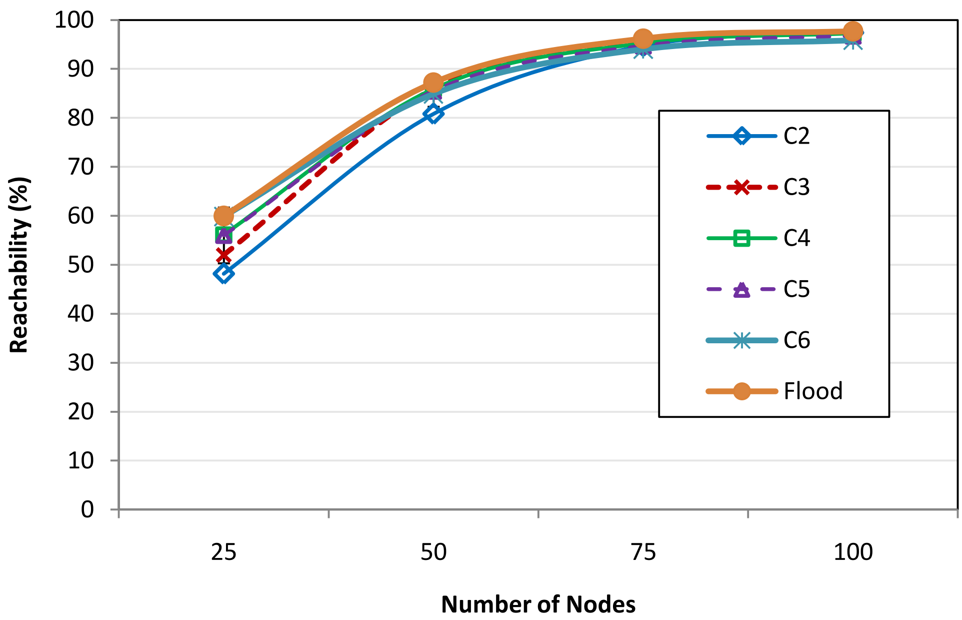


Figure 3-4: Reachability versus number of nodes placed over 1000mx1000m area with an injection rate of 10 packets/ sec studied with different threshold values and flooding

3.4 Effects of Traffic Load

The study of traffic load is carried out by varying the number of packets transmitted per second. This is done by deploying 100 nodes in a network area of 1000m wide by 1000m high with each node engaging in communication with a transmission range of 100m. Each node moves according to the Random WayPoint mobility model with minimum and maximum speeds of 1m/sec and 8m/sec respectively. The packet transmission patterns are 10, 20, 30, 40, and 50 packets/ sec sent by randomly chosen nodes each sending 1 packet/ sec.

3.4.1 Collision Rate

Figure 3-5 shows the effect of variable traffic load on the performance of the counter-based scheme in terms of collision rate. This figure depicts that when the traffic load in the network increases collision rate increases dramatically. This is because increasing number of transmitted packets, while maintaining other network parameters would increase the probability of two or more nodes within the same range sending packets simultaneously. This would result in more collisions in the network as a whole. Comparing counter-based schemes with different threshold values within the same injection rate, the scheme with threshold value 2 (C2) has comparably lower collision rates than schemes with higher threshold values or than flooding. For example, at an injection rate of 10 packets/ sec the collision rate increases as threshold values increase: 1162, 1448, 2208, 3151 and 4126 for

C2, C3, C4, C5 and C6 respectively. In other words, there is a noticeable increase in collision rate when increasing the threshold values, this is around: 25%, 50%, 40% and 30%, when increasing threshold values from 2 to 3, 3 to 4, 4 to 5 and 5 to 6. That is, higher threshold values result in higher number of retransmitting nodes and hence higher collision rate. With higher threshold values 5 and 6 the counter-based scheme behaviour converges to flooding. On the other hand, increasing the injection rate would increase the collision rate noticeably. For example, the collision rate increases by 1080% and by 926% for C2 and C3 respectively when the injection rate increases from 10 to 50 packets/ sec.

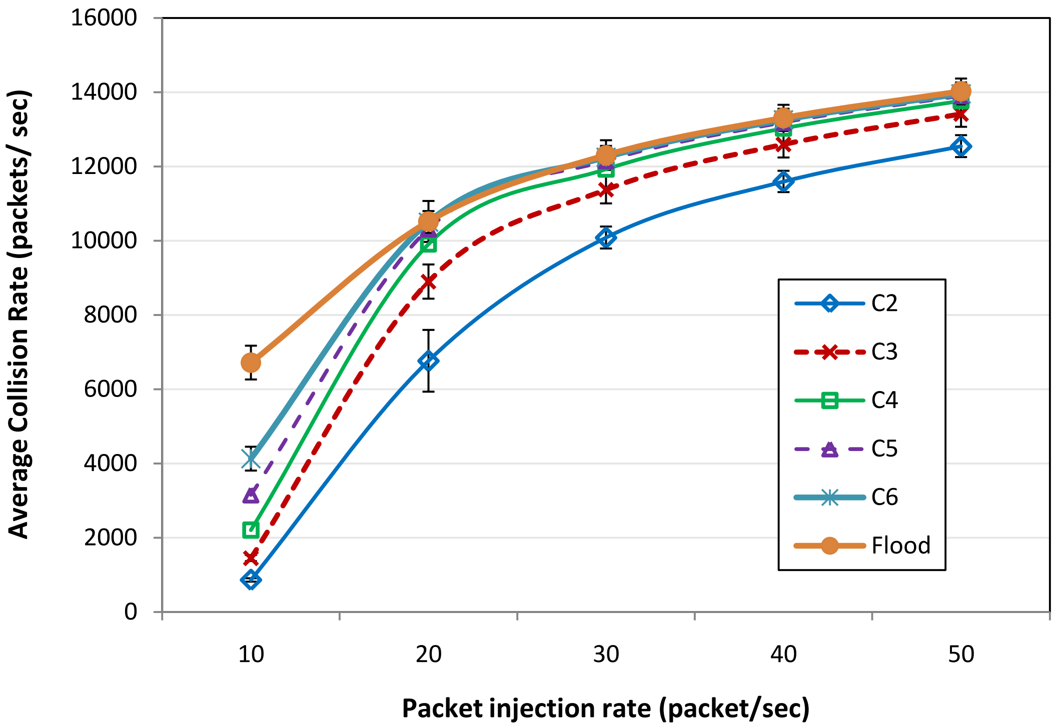


Figure 3-5: Average Collision rate (packets/ sec) versus broadcast injection rate of 100 nodes placed over1000mx1000m studied with different threshold values of the counter-based broadcast and flooding

3.4.2 Saved Rebroadcast

Results in Figure 3-6 show the effects of offered load on the performance of the counter-based broadcast with different threshold values and on flooding in terms of the number of saved rebroadcasts. The figure shows that increasing the injection rate decreases the number of saved rebroadcasts. Fixing all network parameters and increasing the number of packets generated per second leads to a higher demand on nodes to rebroadcast the increased traffic load, lowering the percentage of saved rebroadcast. For example, increasing the traffic load from 10 to 50 would decrease the saved rebroadcast from 58% to 20% and 46% to 10% for C2 and C3 respectively. Another relation is the link between threshold values and saved rebroadcast. That is, increasing threshold values would decrease saved rebroadcast. The reason behind this inverse relationship is that increasing threshold values increases the probability of a node rebroadcasting a packet rather than saving it. For example, increasing the threshold value from 2 to 6 under the same injection rate of 10 packets/ sec decreases the saved rebroadcast from 58% to 14%. Broadcasting using flooding, by definition, scored zero savings with no savings through all injection rates.

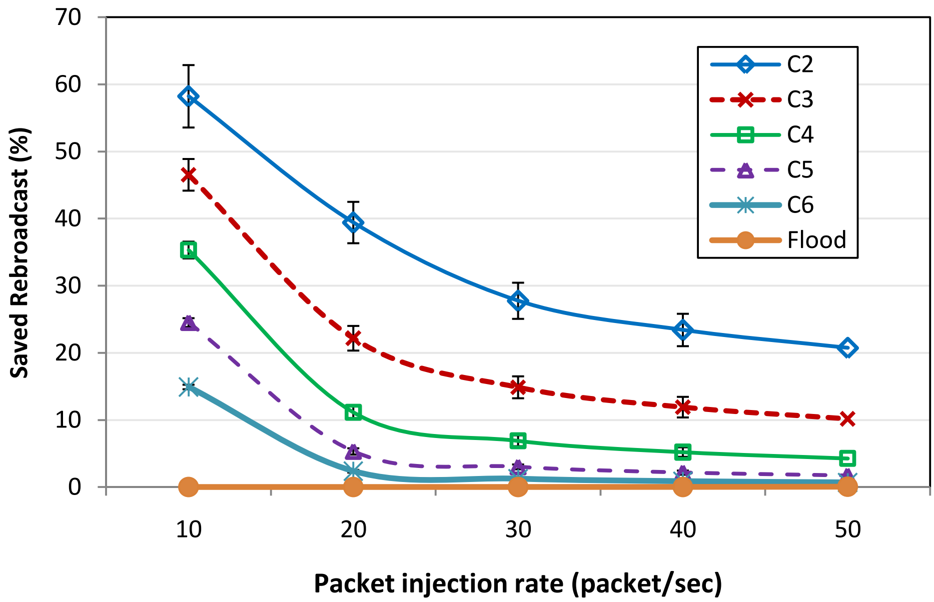


Figure 3-6: Saved Rebroadcast versus broadcast injection rate of 100 nodes placed over 1000mx1000m studied with different threshold values of the counter-based broadcast and flooding

3.4.3 Reachability

Figure 3-7 reveals the performance of the counter-based scheme in terms of reachability. Reachability indicates the percentage of the network reached by a packet. The figure shows that overall reachability decreases with increased traffic load. This is a result of the increased collisions with higher injection rates. For example, increasing injection rate from 10 to 50 decreases reachability from around 95% to 40%, C2, C3 and flooding.

However, the counter-based scheme with threshold 2 (C2) scored somewhat higher reachability at higher network loads. For example, at an injection rate of 20 packets /sec the reachability was: 85%, 78%, 73%, 70%, 68% and 67% for C2, C3, C4, C5, C6 and flooding respectively. The counter-based schemes with thresholds 5 and 6 (C5 and C6) behaviour were similar to that of flooding.

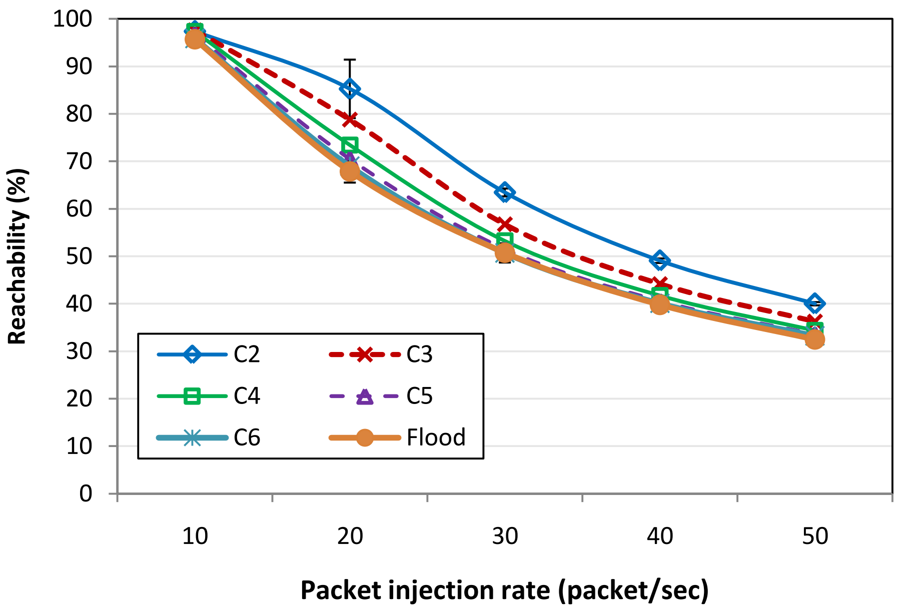


Figure 3-7: Reachability versus broadcast injection rate of 100 nodes placed over 1000mx1000m studied with different threshold values of the counter-based broadcast and flooding

3.5 RAD Analysis

The counter-based broadcast algorithm incorporates into the original flooding broadcast technique a small waiting time referenced as the Random Assessment Delay (RAD), discussed in Chapter 2. For a successful deployment of counter-based broadcast the RAD range must be selected carefully to serve as a waiting time to receive more packets and not to add to the overall packet end-to-end delay.

The results in this section show that using different RAD ranges affects the performance of the counter-based dramatically. RAD is calculated to be within the range from 0 to T_{max}. Original implementation of the counter-based scheme [42] employs the value of 0.01 seconds as T_{max} (the maximum possible interval of RAD). However, it was used within a network size of 350 x 350 meters and a transmission range of 100 m. To exhibit the effect of different values of T_{max} on the counter-based performance, four different implementations were simulated. All four implementations deployed 75 nodes in a network of 1000m by 1000m. Moreover, one node is elected to broadcast 4 packets/ sec through the whole simulation period. In the first and second sets of simulations, nodes are equipped with a wireless transmitter with 250m of transmission range and moving at a maximum speed of 20m/ sec and 8m/ sec for the first and second sets respectively. At the third and fourth set of simulations nodes are equipped with a wireless transmitter with 150m of transmission range with nodes moving at a maximum speed of 20m/ sec and 8m/ sec for the third and fourth sets respectively.

Table 3-1: RAD sensitivity analysis

R	Set ID	Speed	T_{max}	SRB	Avg Sending Nodes	Col Rate	RE
250m	1	20m	0.1	63%	27	73	99%
			0.01	1%	72	739	99%
			0.001	0	73	770	99%
	2	8m	0.1	50%	37	214	99%
			0.01	13%	73	612	99%
			0.001	0	73	765	99%
150m	3	20m	0.1	32%	39	41	81%
			0.01	1%	64	209	87%
			0.001	0	64	223	87%
	4	8m	0.1	33%	41	40	83%
			0.01	2%	65	197	89%
			0.001	0	66	221	89%

Table 3-1 shows the different network metrics used to explain the effects of different RAD intervals on counter-based performance. Where ***R*** is the transmission range, ***Speed*** is the maximum allowed nodal speed, $\boldsymbol{T_{max}}$ is the maximum waiting time, ***SRB*** is Saved Rebroadcast, ***Avg Sending Nodes*** is the average number of sending nodes, ***Col Rate*** is the collision rate and finally ***RE*** is reachability. In set 1 at T_{max} = 0.1 seconds the Saved rebroadcast shows the highest value among other T_{max} values and all other network parameters. High waiting time (0.1 second) maximises the probability of a node having the threshold value exceeded to discard the packet and not resend it. This implies a low collision rate, as shown in Table 3-1. Additionally, this high waiting time (0.1 seconds) implies that the number of nodes involved in the transmission is low (27 nodes). looking at Set 1, at T_{max} = 0.001 seconds the number of sending nodes is 73 nodes, which is almost the total number of available nodes in the network. This implies very low saving (zero) and a higher rate of collisions: an average of 770 packets/ sec. The same concept applies on simulation Sets 2, 3 and 4, with the difference of speed and transmission range. Lower nodal speed (8 m/sec) aids with more reachability, as seen in Set 4 compared to Set 3. Comparing Sets 1 and 2 to 3 and 4 shows that a higher transmission range also serve as a reachability booster. Both lower speeds and higher transmission range would minimise the probability of network partitions and hence would imply more reachability.

3.6 Conclusions

This chapter presented a performance analysis of flooding and the counter-based schemes as means of broadcasting and stochastically enhanced broadcasting respectively. The study examined the network performance under the variation of nodal density and offered load.

Results show that network density and traffic load both have a dramatic and direct effect on the scheme performance with regards to collision rate, saved rebroadcast and reachability.

Nodal density in the network has a proportional relationship to reachability, collision rate and saved rebroadcast. Increasing nodal density increases the latter three metrics. Moreover, threshold values have an inverse relation to saved rebroadcast and a direct relation to collision rate. That is, collision rate increases with higher threshold values. However, higher threshold values decreases saved rebroadcast.

Moreover, the study in this chapter acted as a validation indicator to our simulator as the trends and behaviour of the results shown in this chapter coincide with the result's trend presented in a previous study [127]. The differences in the exact result's figure may stem from some differences in the simulation environment employed. For example [127] used a different mobility model that is a restricted form of the Random WayPoint mobility model used in this research.

Original implementation of the counter-based broadcast employed a constant range of waiting time (RAD). It is proven that this range, bounded by the interval (0-Tmax] is extremely correlated to the network parameters selected such as network size, transmission range and nodal speed. Selecting an appropriate RAD range affects the network performance.

Considering MANET's aspect of dynamic changeable topology, the deployment of the counter-based scheme with a fixed-threshold value is not adequate. The subsequent chapter introduces a dynamic counter-based scheme where the threshold values are selected independently for each node according to its local specific neighbouring conditions. This produces a hybrid broadcast scheme having the quality of both stochastic and deterministic broadcasting schemes by implying counting and neighbour sensing respectively.

Chapter 4

Dynamic Counter-Based Broadcast

4.1 Introduction

In Chapter 3, it was shown that the counter-based broadcast scheme reduced the effect of the broadcast storm problem associated with flooding. However, the counter-based scheme uses a fixed-threshold value at all network densities. This chapter present the claim that adding a neighbourhood sensing capability to the fixed counter-based scheme, enabling it to dynamically adjust the threshold value, would further reduce levels of unnecessary broadcast transmission, leading to greater scalability and adaptability to changeable network topological conditions.

Assigning the same threshold value to all network nodes can results in poor distribution of the threshold values. Mainly, using small threshold values would aid in greater packet savings, but this may affect reachability especially in sparse networks. Alternatively, larger threshold values are beneficial in sparse networks, but can unnecessary swamp a denser network with unneeded redundant packets in a flooding-like manner. Consequently, the aim is to achieve some balance between saving and reachability to reduce the chance of a node located in a dense region rebroadcasting a received message, while increasing the chance of rebroadcasting for nodes within a sparse network area.

The scheme described here aims at significantly reducing communication overhead while still achieving reachability comparable to that of flooding. To achieve this, it utilises neighbourhood information, specifically by using the number of neighbours to select the most suitable counter threshold. The *number of surrounding neighbours* (n) that a node has at a given time is monitored by periodic exchange of 'Hello' packets among neighbouring nodes. This aids a sensible selection of the threshold value, enabling adaptability to the fluctuating network densities that occur in highly mobile networks.

Utilizing 'Hello' packets to collect one-hop neighbouring information will inevitably induce some extra communication overhead. However, 'Hello' packets are already in use with many important MANET broadcast [45, 47, 100] and routing operations [34, 40, 73, 78] to maintain local connectivity [128].

The performance of the suggested algorithm, the *Dynamic Counter-Based* (DCB), is evaluated by comparing it against the existing blind flooding as well as the fixed-counter-based in terms of the widely used metrics, namely average collision rate, saved rebroadcast, reachability and end-to-end delay. Simulation results confirm that new algorithm reveals superior performance in terms of the above metrics, leading to greater adaptability and scalability.

The remainder of this chapter is organised as follows. Section 4.2 describes in detail the Dynamic Counter-Based broadcasting algorithm. Section 4.3 discusses the study of DCB under the effect of variable nodal densities. Section 4.4 exhibits the performance of the proposed scheme DCB under variable network traffic load. Finally, Section 4.5 draws several conclusions from this study.

4.2 Dynamic Counter-Based Broadcast

Among the reviewed probabilistic broadcasting schemes [41, 44, 51] is the counter-based scheme that uses a fixed-threshold value on a variable density network, Chapter 3. For this available scheme to achieve the highest reachability, it should be applied within a pre-known nodal distribution in a network, which is a stable distribution that is either sparse or dense. This is due to the fixed-threshold value pre-selected and used in this scheme. To adapt the traditional counter-based scheme to suit MANETs with changeable and unpredictable network topology that continually varies in a disorderly manner with time, two questions must be answered:

- How to identify network density as either sparse or dense?
- Is there a decentralised mechanism enabling a node to realise its local network density?

To tackle the second question, a simple mechanism is implemented enabling a node to sense its neighbouring density. This is done through incorporating into the original counter-based scheme a simple technique to aid neighbour sensing. Specifically, this is done by the exchange of small ‘Hello’ packets between all one-hop neighbours where each packet holds the sender ID. Unlike other deterministic methods, this ‘Hello’ packet holds the sender IP only. This enables each node to have some knowledge about its neighbouring nodes.

The first question is tackled by carrying out the following reachability study. Results of this study are shown in Figure 4-1. This figure illustrates the reachability of traditional broadcast through flooding versus number of nodes *N* within two different scenarios. Both scenarios share some common parameters such as: network area *A* (1000m x 1000m), traffic generation pattern of 10 packets per second sent by one node through the whole simulation time and a maximum nodal speed of 8m per second. However, the transmission range *R* varies to be 250m and 150m for the first and second scenarios respectively, namely, *R250* and *R150*.

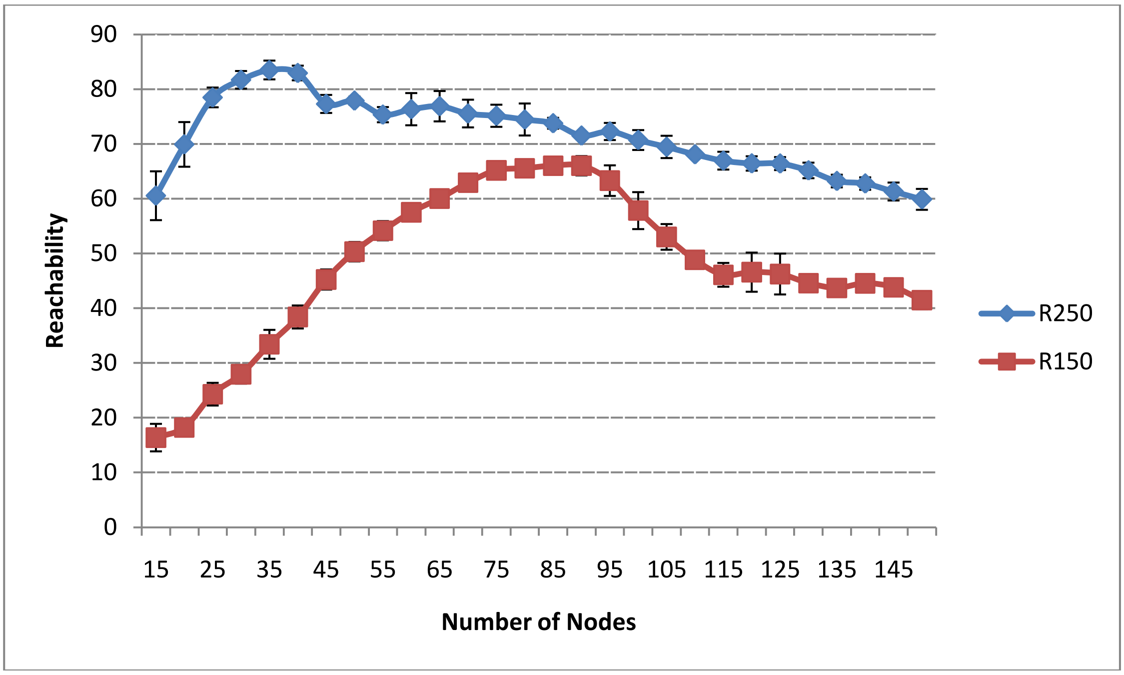


Figure 4-1: Reachability versus number of nodes within two different transmission ranges (R150, R250)

The number of nodes at which reachability is at its maximum is: 35 and 93 nodes for 250m and 150m of transmission ranges respectively. An estimation of the average number of nodes *n* at each of the maximum reachability scenarios is known, theoretically, by Equation 4.1, that addresses the relation between number of nodes, transmission range, network area and average number of nodes [129] .

$$n = (N-1)\frac{\pi R^2}{A} \qquad \text{Equation 4.1}$$

Table 4-1 show that the average number of neighbours of a node in a network with (93 nodes and a 150m transmission range) and (35 nodes and a 250m transmission range) has been found to be around 7 nodes. Therefore on average, a node is considered to be in a sparse network when its number of reachable neighbours is less than 7 and in a dense network otherwise.

Table 4-1: Average number of neighbors

A	N	R	$n = (N-1)\frac{\pi R^2}{A}$
1000m x 1000m	93	150	6.50 ≈ 7
1000m x 1000m	35	250	6.68 ≈ 7

Enhancing the counter-based broadcast algorithm enabling a node to sense and decide for its rebroadcast according to the surrounding environmental topology enhances the overall network efficiency in terms of saved rebroadcast and reachability.

Essentially, sparse networks require a higher chance to rebroadcast than dense networks. This can be achieved by utilising a sliding scale mechanism centred at the expected average number of neighbours, 7. This would slide the threshold value *C* by a scale *s* amount to adapt to network density. A broad sensitivity analysis of the scale size *s* was carried out to prove that 3 is the best candidate for the scale size *s*, providing a sliding mechanism centred at 7 as illustrated in Figure 4-2.

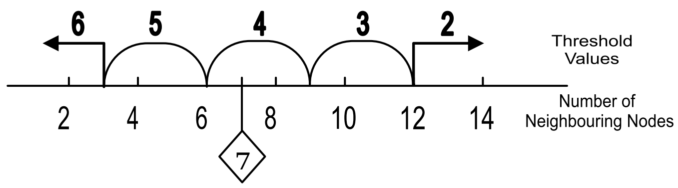


Figure 4-2: The DCB sliding scale concept

Additionally a smaller threshold value C_1 (2) is used for dense networks (high number of neighbours with low EAC*) and a large threshold value C_2 (6) for sparse networks (low number of neighbours and high EAC). The threshold slides from 6 to 2 according to the actual number of neighbours per each node in real-time.

The proposed scheme, Dynamic Counter-Based (DCB) works as follows: when receiving a broadcast packet for the first time a node sets the RAD, which is randomly chosen between 0 and T_{max} second and initiates the counter to one. During RAD, the counter is incremented by one for each redundant packet received. Following, the appropriate threshold value is

* Explained at the Stochastic Broadcasting Schemes (2.2.5.2) within the Counter-based Section

selected according to the node local neighbourhood information. That is, the node checks the number of neighbours n against the scale size s. If $n \leq s$, (Figure 4-3, line 7) then the neighbourhood is considered very sparse and C_2 is selected as the threshold value, otherwise the *sliding scale* loop shown in Figure 4-3, line 8 is executed, where n and s are the current number of neighbours and the scale size respectively.

Additionally, the values C_1 and C_2 are selected in a way that considers the expected additional coverage EAC. That is, C_2 (sparse network threshold) should be in a way larger than C_1 (dense network threshold) in order for the node to have a higher chance to rebroadcast in a sparse area, given that the EAC of a sparse network is higher than that of a dense network.

Lastly, (line 10, Figure 4-3) the counter is checked against the threshold value; if the counter is less than or equal to the threshold, the packet is rebroadcast. Otherwise, it is simply dropped.

```
DCB_Broadcast_Algorithm

Pre: a broadcast packet p at node X is heard.

Post: rebroadcast the packet or drop it, according to the algorithm

1.  Get degree n of node X
2.  c = 1
3.  i = 1
4.  Set RAD
5.  While (RAD) Do
         If (same packet heard) Increment c
6.  End while (RAD)
7.  If (n <= s) C = C2
8.  While (i > 0) Do
        if ((n > s*i) AND(n <= s*(i+1))
                C = C2-1
                If (C < C1)
                        C = C1
                Goto End while (i)
        End If
        i = i + 1
9.  End while (i)
10. If (c > C)
        drop packet
        Exit ACB_Broadcast_Algorithm
11. End If
12. Submit the packet for transmission
End DCB_Broadcast_Algorithm
```

Figure 4-3: The Dynamic Counter-Based broadcast Algorithm

4.2.1 DCB Analysis Settings

This section presents the performance evaluation of the three broadcast algorithms, namely Dynamic Counter-Based (DCB), fixed counter-based (CB) and flooding (Flood) within variable MANET topologies.

To develop the simulation models, the network simulator ns-2 (v2.33) [112] is used. The simulation process starts with traffic and mobility pattern generation, as discussed in Section 2.3.1 and shown in Figure 2-7. After that, core algorithm operations are run and results are extracted from output traces, ready for final analysis.

4.3 Effects of Network Density

The study of network density is expressed by varying the number of nodes available in each network while maintaining other network parameters such as transmission range and network area fixed. The counter-based scheme is implemented with two threshold values 2 and 3 referred to as C2 and C3. The simulation scenarios consist of a wide range of considered network sizes, number of nodes in each network range between 25, and 300 nodes with steps of 25 nodes. Most of the network parameters are mentioned and discussed earlier in Section 2.3.3. Among the marked parameters is the network area which is a terrain of 1000m wide by 1000m high with each node engaging in communication with a transmission range of 250m. Each node moves according to the Random WayPoint mobility model, with minimum and maximum speeds of 1m/ sec and 8m/sec respectively, that is a maximum speed of approximately 29 km/ hour. The packet injection rate for this density study is 4 packets/ sec, initiated by 1 node randomly chosen from the whole node population, creating a random traffic pattern. For all figures represented in this section, the *x*-axis represents the variable network operational condition under study (i.e. network density, or traffic load) and the *y*-axis represents the actual resultant values scored over the network simulation.

4.3.1 Collision Rate

Figure 4-4 shows the effect of variable network densities on the performance of the DCB scheme in terms of the average collision rate. The figure proves that there exists a relationship between the number of nodes and the collision rate; increasing the number of nodes while fixing all other network parameters results in an increase in collision rate.

Collision happens when two or more nodes within the same proximity are sending packets at the same time. Therefore, the probability of a collision increases when the number of nodes increases, as overlapping simultaneous transmissions are more likely to happen with more nodes. The amount of the increase is higher in C2, C3 and flooding than in the DCB, which suggests that DCB is more scalable than other schemes. The percentage reduction in collisions experienced by DCB relative to each of the other schemes in a network of 200 nodes is around 150%, 900% and 7400% for C2, C3 and flooding respectively. The amount of DCB's collision reduction is even greater in networks with higher densities. For example, this reduction in a network of 300 nodes would be around 800%, 3000% and 8000% for C2, C3 and flooding respectively.

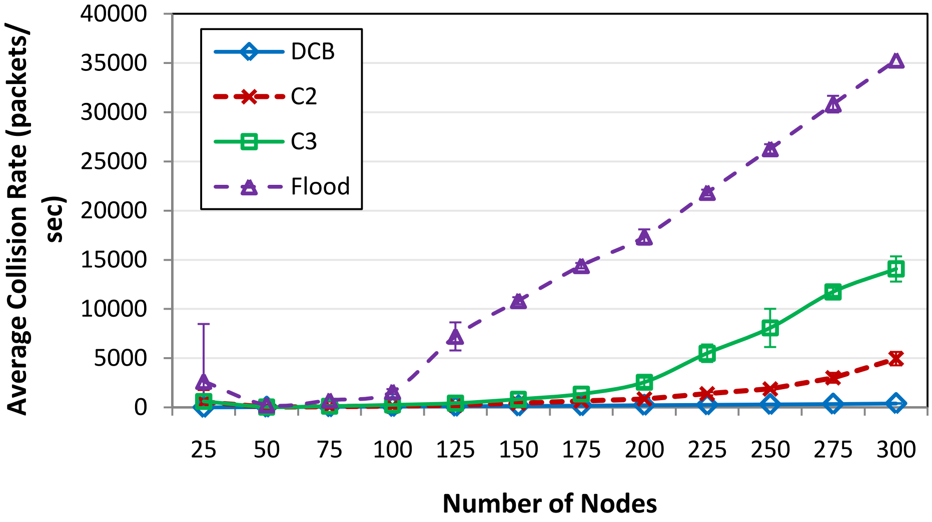


Figure 4-4: Average collision rate versus number of nodes placed over 1000m x 1000m area using 4 packets/ sec broadcast injection rate

Figure 4-5 is a sub-graph of Figure 4-4 plotting only DCB along with the best of its competitors in terms of collision rates, namely C2. This figure shows clearly the adaptability of the DCB to higher network densities, well-controlling the rebroadcast of redundant packets through the network and hence reducing collision rate.

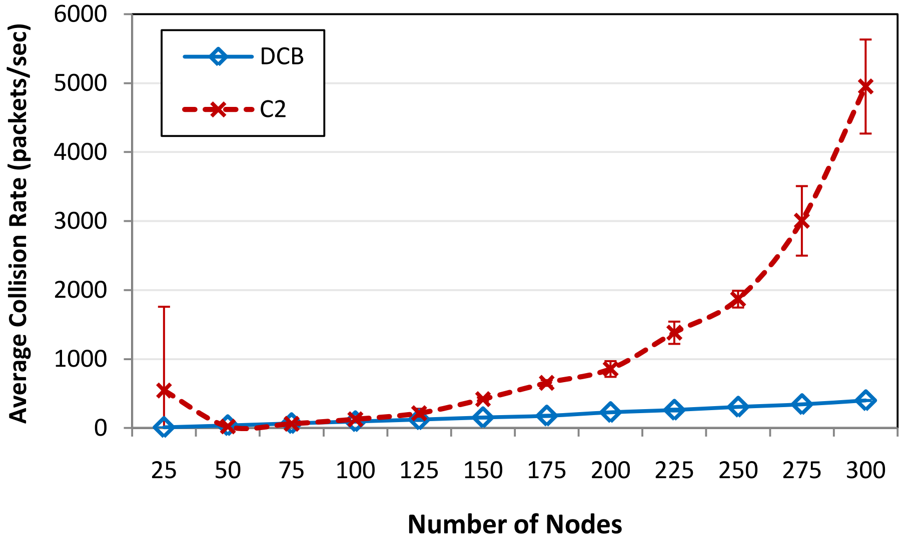


Figure 4-5: sub graph of previous figure: Average collision rate versus number of nodes placed over 1000m x 1000m area using 4 packets/ sec broadcast injection rate

4.3.2 Saved Rebroadcast

Figure 4-6 shows the effects of variable network densities on DCB, fixed counter-based (C2, C3) and on flooding in terms of the number of saved rebroadcasts. This measures the extent to which possible packet rebroadcasts are saved. This figure clearly show the advantage of DCB over conventional counter-based (C2, C3) and flooding by the increase of savings. For DCB, this saving is also increased with higher nodal densities, again promising better scalability. Other schemes, C2 for example, exhibit a noticeable decrease in saved rebroadcast behaviour with higher numbers of nodes (above 250 nodes). This decrease in savings is more apparent in C3 as the amount of saving decreases with networks of more than 200 nodes. With networks of 300 nodes, DCB scored around 25% and 60% more savings than C2 and C3 respectively. This proves that DCB has greater scalability than other schemes. Saved rebroadcast measures the amount of savings compared to that of flooding where flooding, by definition, does not save any packets.

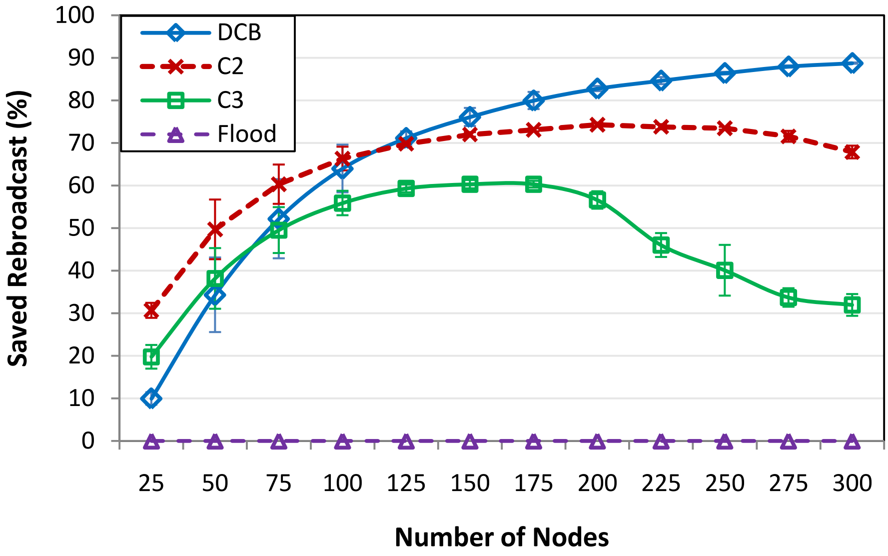


Figure 4-6: Saved rebroadcast versus number of nodes placed over 1000m x 1000m area using 4 packets/ sec broadcast injection rate

4.3.3 Reachability

After proving the advantage of DCB in decreasing the collision rate and maximizing packet savings, it is important to investigate the reachability criterion as a key measure of scheme efficiency. Reachability is the percentage of the network reached by each broadcast packet. Figure 4-7 shows that all schemes suffer a relatively poor reachability at networks with 25-50 nodes. This stems from the connectivity problem. When the network size is 1000m by 1000m and the total number of nodes in the network is 25 or 50, disconnects are likely to happen, causing some packets not to reach their destinations. With networks of 100-200 nodes most schemes score 100% reachability with the exception of pure flooding, as its reachability decreases with more than 100 nodes, reaching about 40% of reachability with 300 nodes. This is expected, as flooding generates redundant rebroadcast packets, which leads to more collisions and packet loss. With networks of 200-300 nodes C3's reachability drops considerably, and a noticeable drop in reachability starts to happen with C2 at networks of more than 275 nodes. DCB preserves around 100% reachability for all networks of more than 100 nodes up to 300 nodes.

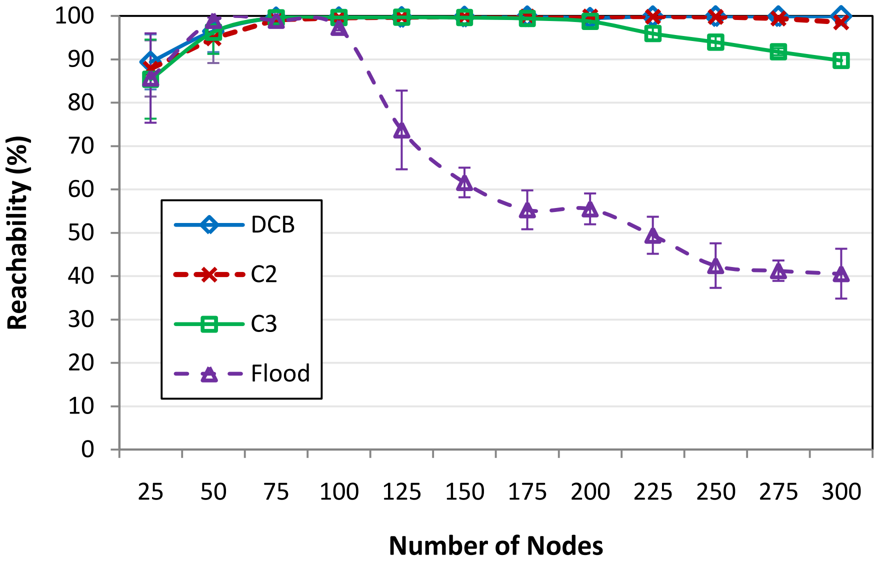


Figure 4-7: Reachability versus number of nodes placed over 1000m x 1000m area using 4 packets/ sec broadcast injection rate

4.3.4 End-to-end Delay

This section examines latency, the time each packet takes to reach its final destination. As Figure 4-8 shows, latency is initially low for all schemes but worsens noticeably as the network size increases; however, the point at which the degradation begins varies from one scheme to another. In DCB scheme, there is no significant worsening of latency at any network size up to the simulated maximum, 300. C3 begins to suffer a loss of performance at networks of 225 nodes while latency in flooding increases steeply at sizes over 100 nodes. The behaviour of increased latency could be understood better when studying the collision behaviour of all schemes. The increase in collisions would affect the time a packet takes to reach its final destination. Looking at Figure 4-4, a dramatic increase in flooding collision rate starts to happen in networks of more than 100 nodes. This is exactly the same network size that generated the sharp increase in the end-to-end delay for flooding, Figure 4-8. This same principle applies for the other schemes.

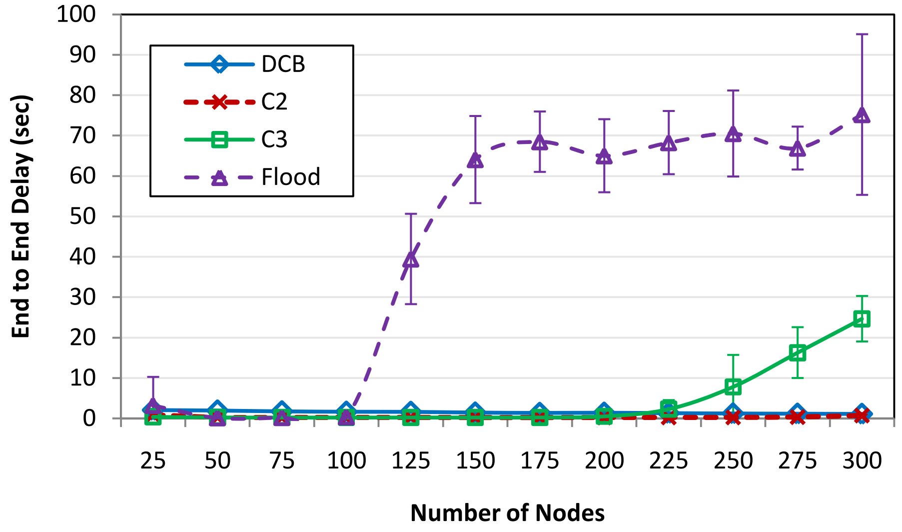


Figure 4-8: End-to-end delay versus number of nodes placed over 1000m x 1000m area using 4 packets/ sec broadcast injection rate

4.4 Effects of Traffic Load

The study of traffic load is carried out by varying the number of packets transmitted per second. This is done by deploying 100 nodes in a network area of 1000m wide by 1000m high with each node engaging in communication with a transmission range of 250m. Each node moves according to the Random WayPoint mobility model with a minimum and maximum speed of 1m/sec and 8m/sec respectively. The packet transmission patterns consist of 1, 5, 10, 15, 20, 25 and 30 randomly chosen nodes transmitting 1 broadcast packet per second. A different broadcast transmission pattern such as unicast transmissions are considered and studied in Chapter 6.

4.4.1 Collision Rate

This section studies the effects of variable traffic load on the performance of the different schemes in terms of collision rate. Figure 4-9 illustrates a relation between traffic load and collision rate, such that with the increase in traffic load there exists an increase in collision rate. This is because increasing the number of transmitted packets per second would increase the probability of two or more nodes within the same range sending packets simultaneously. This would result in more collisions in the network as a whole. When the number of packets sent per second increases from 5-10 packets per second, all schemes, except DCB, experience a sharp increase in collision rate. At an injection rate of 10 packets /sec DCB's collision rate is less by around 400% than other schemes.

At traffic loads of 20-30 packets /sec, all schemes have a flat collision rate, but DCB still experiences fewer collisions than all other schemes by 30%. This is because of the dynamic control imposed within the DCB rebroadcasts minimising redundant packets from consuming the transmission medium, hence, lower collision rates.

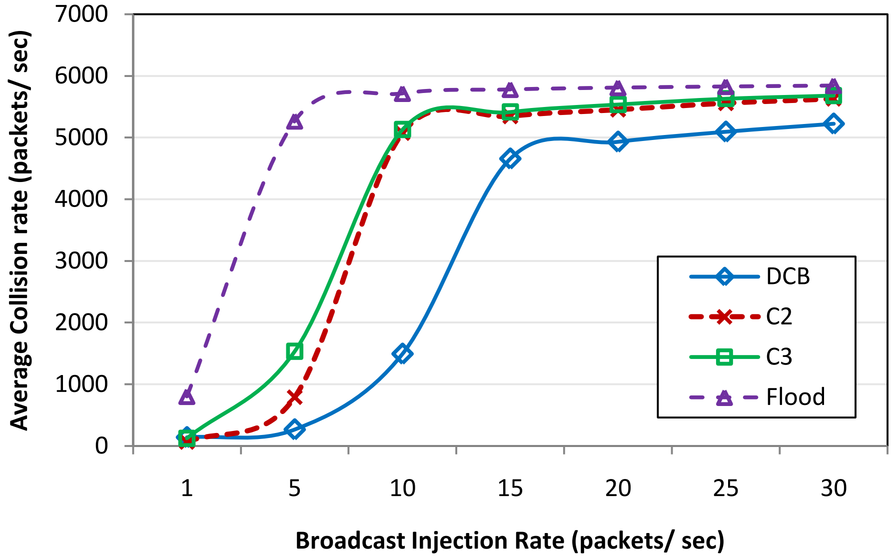


Figure 4-9: Average collision rate versus packet injection rate for a network of 100 nodes in 1000m x 1000m area

4.4.2 Saved Rebroadcast

Results in Figure 4-10 show the effects of offered load on the performance of the different schemes in terms of saved rebroadcasts. The figure illustrates that the amount of savings decreases as offered load increases. At 20 packets/ sec all schemes start to have a flat behaviour where DCB is scoring around 12% and 20% higher saving than C2 and C3 respectively. The slight dip in C2 and C3 saving behaviour could be explained by realising that as the load increases from 1 to 10 packets/ sec the schemes' savings decrease as more packets are generated and need to be transmitted to their destinations. With loads higher than 10 packets/ sec the schemes become swamped by the number of transmissions, resulting in collision and packet drop. As this happens, the number of packets to be delivered drops and saving becomes slightly higher, leading to stabilisation with loads more than 15 packets/ sec.

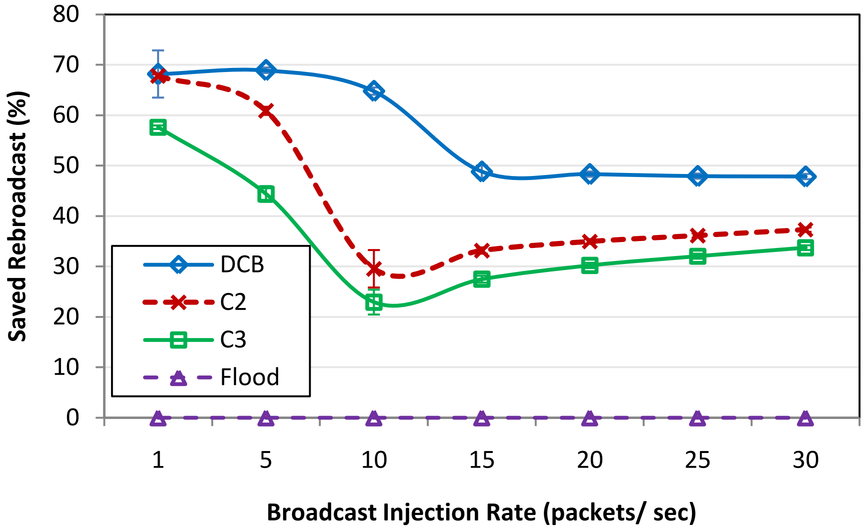


Figure 4-10: Saved rebroadcast versus packet injection rate for a network of 100 nodes in 1000m x 1000m area

4.4.3 Reachability

Figure 4-11 shows that the performance of all schemes with regards to reachability is degraded sharply with the increase in traffic load. Increasing traffic load increases the number of packets generated and should be delivered to every other node in the network.

For example, at the 400 seconds' point of the simulation time there should be a total of 400, 4000, 8000, 12000 successfully delivered packets for traffic loads 1, 10, 20 and 30 respectively. And the number of packets will double at around the end of the simulation time resulting in network congestion, enforcing lots of packets drops and not be delivered. At loads of 1 packet/ sec all schemes score full reachability; however, this behaviour starts to degrade with higher loads. The scheme most affected by higher loads is the flooding scheme. Flooding reachability starts to degrade with loads more than 1 packet/ sec. The fixed counter-based schemes, C2 and C3 are more immune to increased loads than flooding, showing degradation at loads higher than 5 packets/ sec. This is due to imposing some control over the packet rebroadcasts, yielding less collisions and hence better reachability. The maximum reachability achieved at higher traffic loads is DCB's; it shows greater immunity to the effect of higher traffic loads than the fixed counter-based schemes. That is, adapting the threshold value to the current nodal density, imposing more intelligent control over the packet retransmissions, leading to a better consumption of the available transmission medium and hence, higher packet delivery success rate, reachability.

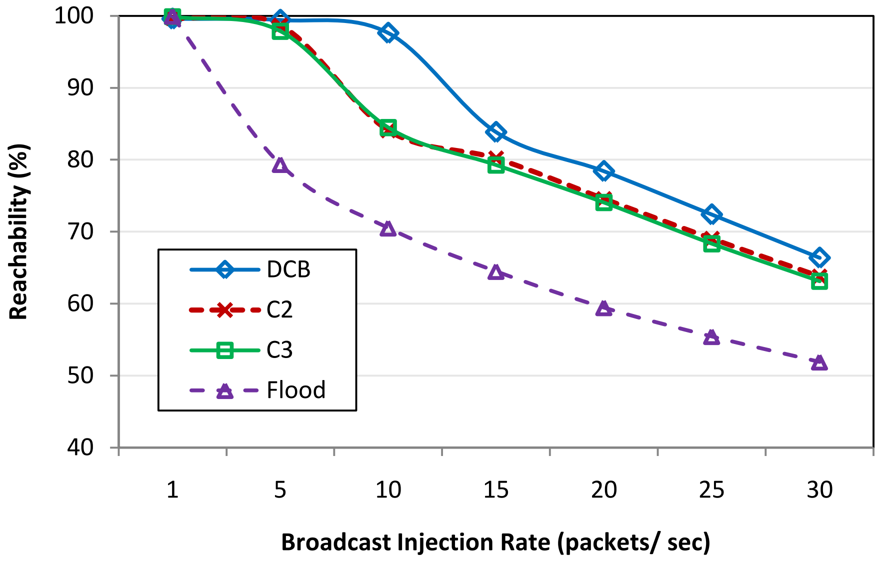


Figure 4-11: Reachability versus packet injection rate for a network of 100 nodes in 1000m x 1000m area

There exists a relation between reachability and collision rate where increased collisions would degrade reachability. This is illustrated in Figure 4-12 where the average collision rate (bar chart) and reachability (line chart) are plotted in one graph. Results show that schemes with lower collision rates score greater reachability.

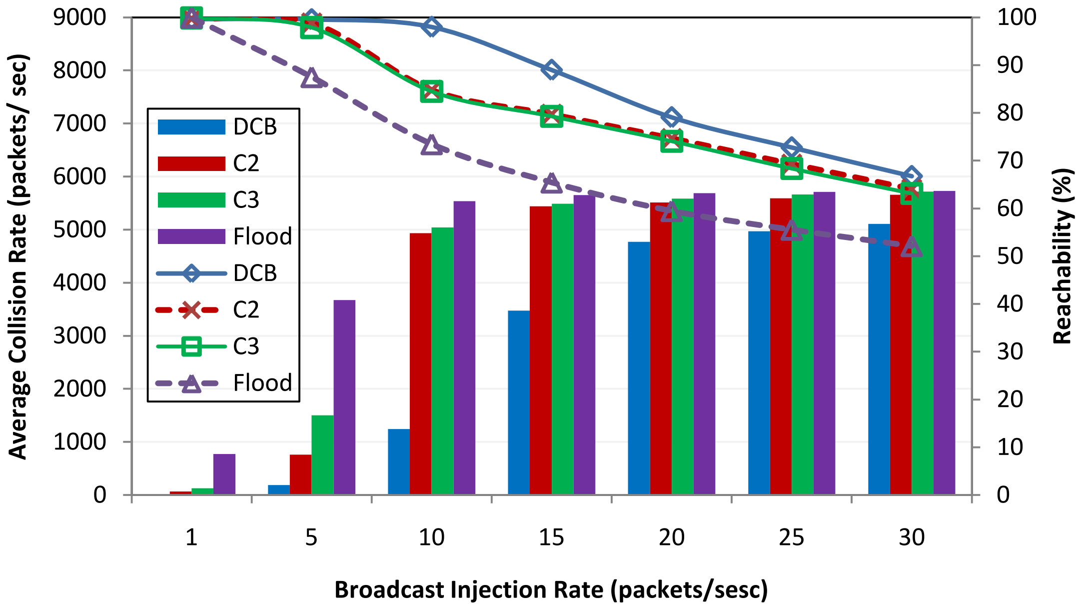


Figure 4-12: Average collision rate and Reachability versus packet injection rate for a network of 100 nodes in 1000m x 1000m area

4.4.4 Average Latency

Figure 4-13 shows packet delivery time with increasing traffic load. The figure shows that all schemes go through what this research refer to as a break point. That is, nodes consume a lot of time (more than 5 sec) trying to deliver a packet to its destination. This would be understandable if considering the amount of lost and dropped packets (low reachability) at loads of 5-10 packets/ sec for C2 and C3. The most robust scheme is DCB, which breaks at loads of 10-15 packets per second. Flooding break-point occurred even at fewer traffic loads of 1-5 packets per second. The end-to-end delay criteria measures the time each packet takes to successfully reach its final destination and increasing the injection rate increases the possibility of packet loss and collisions. Therefore, at higher loads the schemes tend to have a slight advantage with regards to the delay. This is clearly apparent with the flooding scheme as the delay increases at injection rates of 5 packets/ sec, and when injection increases even more, the number of packets that the flooding is capable of delivering is decreased, because of packet drop, resulting in the decrease in delay.

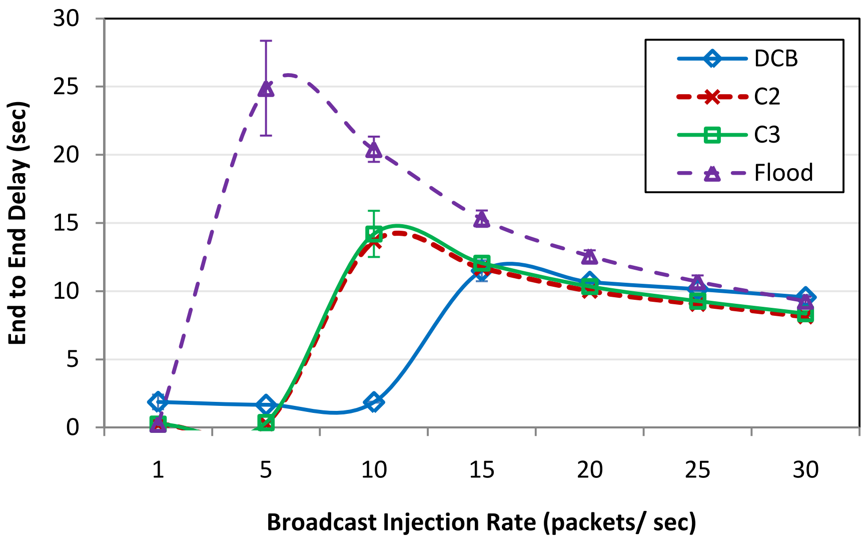


Figure 4-13: End-to-end delay versus packet injection rate for a network of 100 nodes in 1000m x 1000m area

4.5 Conclusions

This chapter presented a new broadcast scheme, the Dynamic Counter-Based broadcast scheme (DCB). This scheme is a hybrid scheme that combines packet counting, taken from probabilistic methods and local neighbour knowledge taken from deterministic methods.

Experimental study using simulations was carried out to compare the performance of DCB to its fixed counter-based candidate with threshold values 2 and 3 (C2 and C3), and to flooding. The performance analysis proves that DCB outperforms the other schemes (C2, C3 and flooding) in terms of average collision rate, saved rebroadcast, reachability and end-to-end delay, suggesting scope for greater scalability. Although the performance of all schemes degrades with higher traffic loads, the DCB responds more effectively, as it manages to reduce packet collision and channel contention by minimising unneeded broadcasts. The next chapter comprises a study of the different schemes under two different metropolitan models, exploring their behaviour under altered node movement patterns, speeds and transmission ranges.

Chapter 5

Scheme Performance in Metropolitan Vehicular Network

5.1 Introduction

An interesting application of wireless MANETs that is emerging with a high potential for research and development [130], is the inter-vehicle communication where nodes collect and distribute traffic information while moving in urban areas. This chapter presents the study of the proposed Dynamic Counter-Based scheme in metropolitan environment. The next section, 5.2 is a brief introduction to Vehicular Ad hoc Networks which is a special kind of wireless MANETs. Following, Section 5.3 introduces the metropolitan study's environment settings and system parameters. The section after, 5.4, presents the first part of the study under the highway model. Next, Section 5.5 introduces the second part of the study under the city model.

5.2 Vehicular Ad hoc Networks

Vehicular Ad hoc NETworks (VANETs) emerged from ideas explored in initiatives such as the Intelligent Vehicle/Highway Systems (IVHS) [131] and is a vital part of what is referred to nowadays as the Intelligent Transportation System (ITS) [130] with initiatives from Japan [132], America[133] and Europe[134]. VANETs are a special kind of MANETs primarily deployed with ideas of transport efficiency and traffic safety in mind [132]. Safety applications have real-time constraints, low delay being the first objective [130]. Examples of safety related applications include, accidents minimisation and avoidance, collision notice and traffic violation warning [135]. Transport efficiency applications include enhancing vehicle flows, route navigation, auto-traffic light scheduling and electronic toll collection [130]. Another interesting application of vehicular networks is infotainment [136], which focuses mainly on the convenience of driving and driver comfort [135]. Some examples include, SPARK, a real-time parking navigation system [137] and location-aware digital billboards proposed for vehicular networks advertisement [138].

VANET wireless connectivity patterns include: vehicle to vehicle (ad hoc), vehicle to infrastructure (cellular network and WLAN) and among vehicles (hybrid) [33, 130]. The distinctive characteristic of VANETs is the highly changeable topology, where network nodes move at potentially high speeds in constrained paths within a built-up area potentially resulting in frequent network partitions leading to immense connectivity issues [130]. With the aim to standardise wireless access in vehicular environments, IEEE amended a specification extension (IEEE 802.11p) to the IEEE 802.11 standard for wireless local area networks (WLANs) providing wireless communications while in a vehicular environment [18]. The IEEE 802.11p standard, also called Wireless Access for Vehicle Environment (WAVE), focuses on possible enhancements to the IEEE 802.11 standard, enabling wireless short-range communications for ITS. The IEEE 802.11p amendment released Physical PHY and MAC layer specifications enabling the VANETs communications in the 5.9 GHz spectrum [135].

VANETs communicate with the existing wireless LAN physical layers utilising the IEEE 802.11p standard and exchange data using the multi-hop decentralized network medium avoiding additional costs for communicating via the extension to the 3G cellular networks technology [130]. The first approach supports distributed coordination in ad hoc mode encompassing the Carrier Sense Multiple Access, CSMA technique enabling nodes to sense the carrier before sending. The second, extending 3G, has the possibility of flexible assignment of radio resources due to the Code Division Multiple Access, CDMA method, but suffers from the complexity of designing coordination function in ad hoc mode [139]. Utilizing the CSMA control mechanism in a vehicular environment has its downside. When a node senses the carrier and it happens to be busy, the node postpones the retransmission until the carrier is free again. This may lead to undesirable delays, especially in time-critical applications [140]. Another initiative to set wireless communication protocols in the vehicular environment is the Communications Access for Land Mobiles (CALM) architecture [141]. CALM covers and enables several methods of transmission, short-range (Bluetooth), medium-range (Wi-Fi) and long-range (WiMAX) [141]. CALM is still under study and research; however, the Cooperative Vehicle-Infrastructure Systems (CVIS) project [142] is aimed to implement vehicle communication technology based on the CALM architecture.

5.3 Metropolitan Network Mobility Study

The study of the DCB algorithm is carried out within two models which will be referred to as the highway model and the city model. The highway model exhibits the study of nodes commuting in highways with a maximum speed of 70km/ hour along streets in an open plane terrain. Additionally, nodes are able to communicate freely along the line of sight with no obstacles or buildings. This model may seem artificial, in the sense that it is unlikely that cars would move in a one km square area at a speed of 70km/ hour. However, this simplification of selecting a smaller network size is because of time and processing limitations. Additionally, this study is needed to illustrate the effect of buildings in the city model. In the city model, streets are often separated by buildings and other obstacles; therefore, there is not always a direct line of communications between nodes. That is, nodes can only communicate with nodes on the same street and with reachable relays at the corner of each street, Figure 5-1. The incorporation of relays facilitates vehicle-to-roadside communication as well as vehicle-to-vehicle communication patching the network partitioning problem. Figure 5-1, represents an illustration of the city model where the solid gray blocks represent buildings, the dots at the cross points represent the relays and circles around each dot represent the transmission range. The streets, the white areas between buildings, are the paths that nodes move on and it is the only way that the transmission can travel along. This restriction presents a great communication challenge for nodes employed in this model. Nodes implemented by the city model would commute at a maximum speed of 30km per hour, applying practical city centre speed limits.

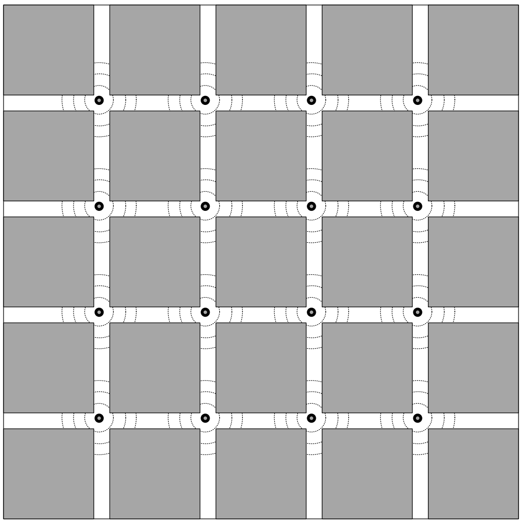


Figure 5-1: Illustration of the city model

5.3.1 Mobility Model Implementation

The mobility pattern specifications, for both mentioned models are based on the Manhattan mobility model [62] where the authors provided a C++ mobility generation script implementing core node movement within streets and lanes. This was tailored to incorporate the existence of gateways at the cross points within the city model. Mobility generation process is shown in Figure 5-2. The process starts with the map generation. A map specifies the number, direction and coordinates of each street. The resultant map is then fed to the C++ mobility generator. Utilising the Perl batch processor, mobility traces are created for variable number of nodes and different topological scenarios.

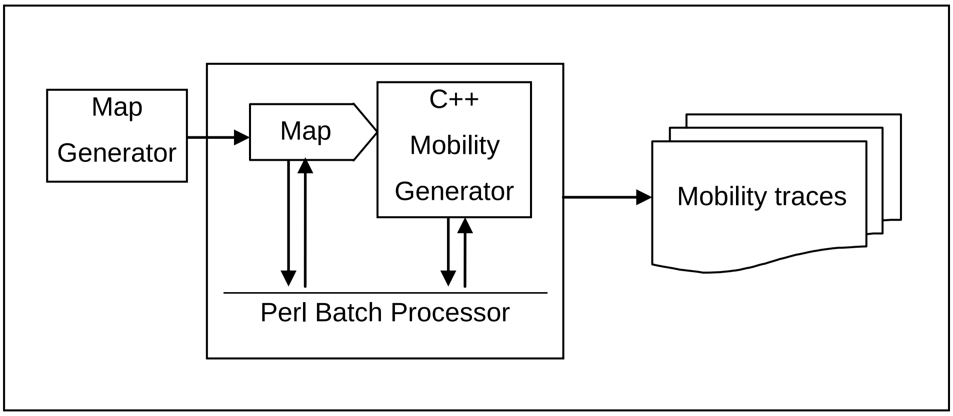


Figure 5-2: Mobility model generation

The considered number of nodes in each network are 25, 50, …, 300 nodes each having 30 different unique mobility trace. Mobility traces are then fed to the ns-2 simulator along with the traffic model, Figure 2-7. The map under study consists of 4 vertical and 4 horizontal streets each having 2 lanes of opposite directions as depicted in Figure 5-3. The considered map is a simplification of the Glasgow city centre map, Figure 5-4 which is composed of 10 vertical and 9 horizontal streets as shown in Figure 5-4.

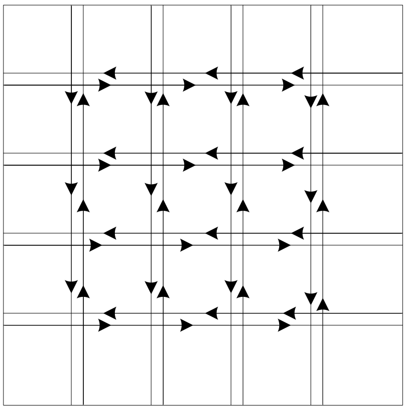


Figure 5-3: Metropolitan mobility model

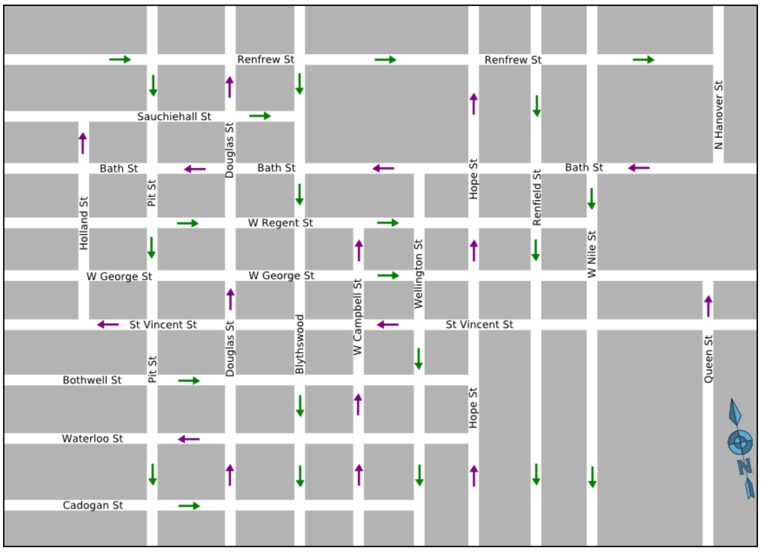


Figure 5-4: Glasgow city center

5.4 The Highway model

This part carries out the study and analysis of nodes commuting within a highway scenario. Nodes commute within streets using a transmission range of 250m. Schemes under study are the Dynamic Counter-Based (DCB), the Counter-Based (CB) and flooding broadcast schemes. Those schemes are studied under two kinds of variability: nodal density and traffic load. Metrics tested in each study are: collision rate, reachability and saved rebroadcast.

5.4.1 Effects of Network Density

The study of network density is carried out by varying the number of nodes while maintaining other network parameters fixed. Among the fixed network parameters are the traffic load having an injection rate of 4 packets/ sec and the transmission range of 250m. The number of nodes considered are 25, 50, ..., 300 with a step of 25 nodes.

5.4.1.1 Collision Rate

The average collision rate serves as an indication to scheme efficiency. Lower collision rates indicate a higher success at delivering a packet to its destination. Figure 5-5 shows a clear relation between the number of nodes and collision rate, where increasing the former increases the latter. This relation is apparent with flooding in a network with more than 100 nodes as collision rate increases dramatically with the increase in the number of nodes. This increase is less sharp with CB and DCB. A closer look at the behaviour of CB and DCB is depicted in Figure 5-6. This figure shows that the CB scheme scores a sharp increase in collision rates at networks of more than 200 nodes compared to a slight increase in DCB collision rate. This is because nodes implementing the DCB scheme incorporate a dynamic threshold assignment adaptable to the actual number of surrounding neighbouring nodes, inhibiting excess broadcasts of redundant packets resulting in fewer collisions.

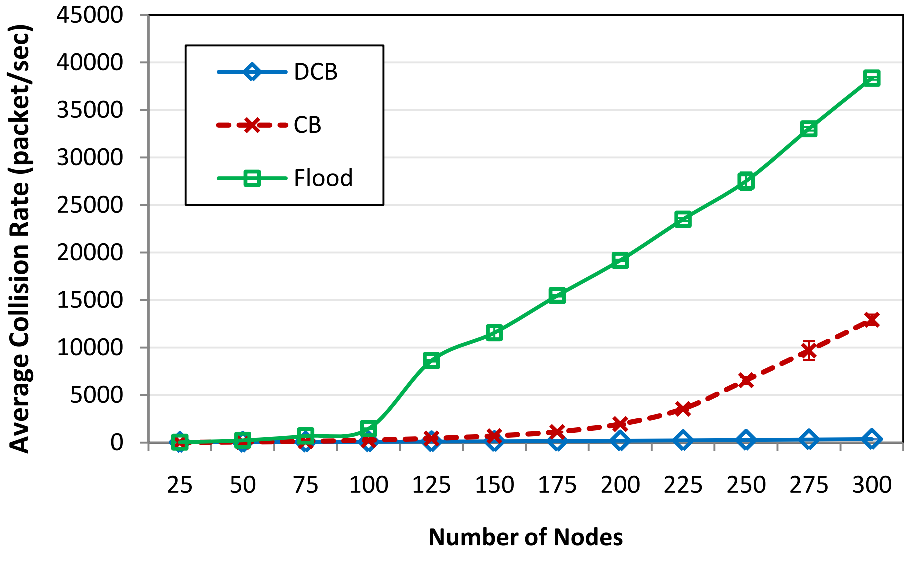


Figure 5-5: Average collision rate versus number of nodes in a highway model over network of 1000m x 1000m under a traffic load of 4 packets/ sec

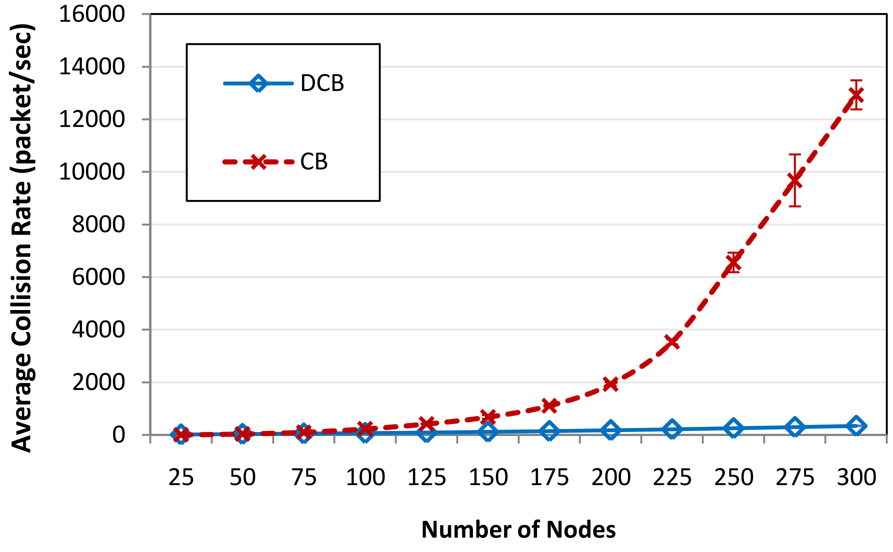


Figure 5-6: Average collision rate for schemes (DCB and CB) vs. number of nodes in a highway model over a network of 1000m x 1000m under a traffic load of 4 packets/ sec

5.4.1.2 Saved Rebroadcast

The number of saved rebroadcast packets is among the most important metrics signifying the efficiency of a scheme. Figure 5-7 shows the saving behaviour of the three considered schemes, with flooding (by definition) having no saving at all. The figure also shows that the amount of saving with low number of nodes (25 nodes) is around 18% for DCB and CB. The amount of saved rebroadcast increases for both schemes with the increase of DCB slightly higher than that of CB. The benefit in saving becomes more apparent at networks of 100 nodes, scoring a saving of 60% and 70% for CB and DCB respectively. With networks of a higher density (200 nodes) CB savings start to collapse, decreasing from 60% to 30% when network size increases from 200 to 300 nodes respectively. As the nodal density becomes higher, the number of received packets becomes even more. Nodes implementing the CB scheme would suffer from static criteria that result in rebroadcasting this high amount of received packets resulting in fewer savings. However, this is not the case with the Dynamic CB (DCB) as it scores even more savings with larger networks, increasing savings from 80% to 90% as the network size increases from 200 to 300 nodes. This suggests significant scalability advantage of DCB.

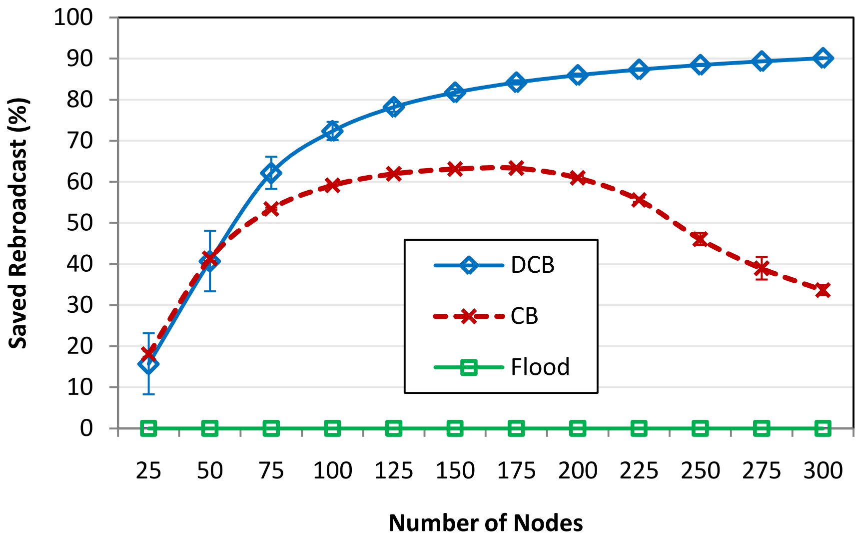


Figure 5-7: Saved rebroadcast versus number of nodes in a highway model over a network of 1000m x 1000m under a traffic load of 4 packets/ sec

5.4.1.3 Reachability

As Figure 5-8 shows, reachability of all schemes is affected at networks of 25 to 50 nodes as the network connectivity suffers with such a very low nodal density. In networks with 50 to 100 nodes, all schemes scored a reachability of around 100%. With networks of more than 100 nodes flooding reachability starts degrading until it reaches 40% in networks of 300 nodes. This is due to the higher collision rate resulting from the flooding behaviour of retransmitting every received packet with no conditions or sensitivity to nodal density. On the other hand, the performances of DCB and CB continue at its optimum until at network densities of 225 nodes when the CB reachability starts degrading. This reduction in CB's reachability is expected as the CB's collision rate, Figure 5-6, increases sharply within networks of 225 nodes and above, resulting in more packet loss. However, the DCB reachability continues to be around 100% even in dense networks having more than 225 nodes. This is related to the robust rebroadcasting decision making based on current local neighbouring density.

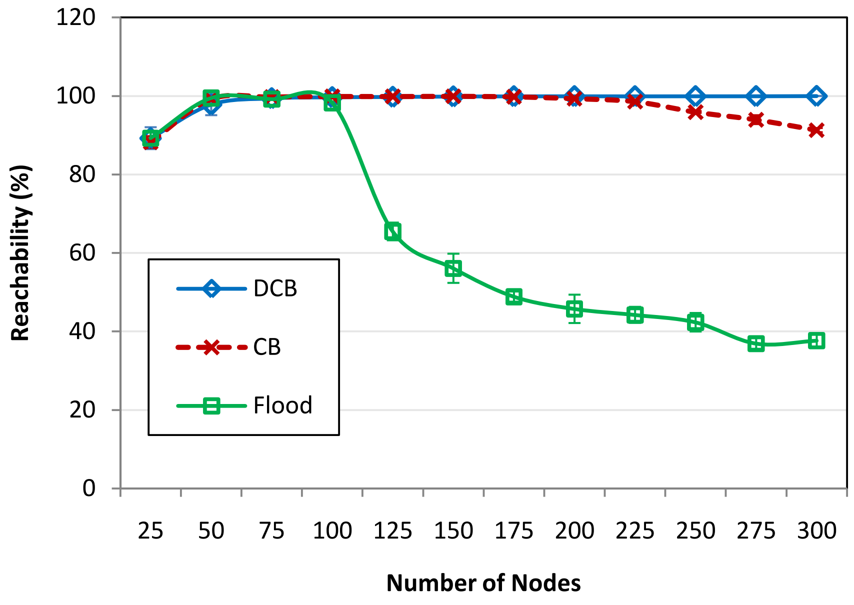


Figure 5-8: Reachability versus number of nodes in a highway model over a network of 1000m x 1000m under a traffic load of 4 packets/ sec

5.4.2 Effects of Traffic Load

This section and the following three sub-sections investigate the effects of variable traffic load on the proposed scheme employing a highway model. Traffic injection rate is 1 packet/ sec sent by 1, 5, 10, 15, 20, 25 and 30 different elected nodes in the network. A network of 100 nodes is considered in this study where nodes are moving with a maximum nodal speed of 70km/ hour along four horizontal and four vertical streets. Each street comprises two lanes of opposite directions as depicted in Figure 5-3. Moreover, nodes communicate with a transmission range of 250m. Three different metrics are considered in this study: average collision rate, saved rebroadcast and reachability.

5.4.2.1 Collision Rate

As Figure 5-9 shows, there exists a relation between packet injection rate and collision rate, where increasing the former results in an increase in the latter. Sharp increase in flooding collision rate is apparent at the increase from 1 to 5 packets/ sec. This dramatic increase repeats with counter-based (CB) scheme at higher traffic loads 5 to10 packets/ sec as this scheme incorporates the counting technique resulting in more resistance to the effect of the increase in packet injection rate. This resistance to traffic load increase is at its best with the dynamic counter-based (DCB) as it dynamically alters the threshold value prohibiting excess and unwanted packets to be sent through the medium. At the traffic load of injecting 10 packets/ sec, the average collision rates are approximately: 1000, 4500, 6000 packets/ sec for the schemes DCB, CB and flooding respectively. This is a benefit of 350% and 500% for DCB over CB and flooding respectively.

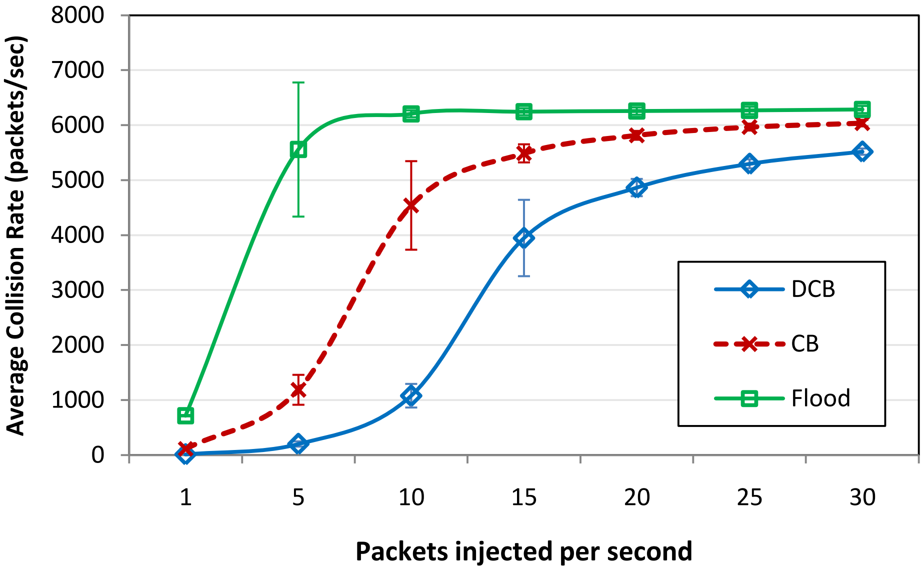


Figure 5-9: Average collision rate versus packet injection rate in a highway model over a network of a 1000m x 1000m network having 100 nodes

5.4.2.2 Saved Rebroadcast

The number of packets saved gives an indication as to how much of the medium is saved and not occupied with redundant packets, hence imposing fewer collisions. As Figure 5-10 shows, at low injection rates (1 packet/ sec) the amount of saving is 60% and 75% for the counter-based (CB) and the dynamic counter-based (DCB) respectively. When the injection rate increases from 1 to 10 packets/ sec the amount of saving of CB reduces dramatically, reaching its minimum 25% at 10 packets/ sec. However, when increasing the injection rate from 1-10 packets/ sec DCB's level of saved rebroadcast remains stable at around 70%; this is due to the dynamic threshold adjustment that inhibits excess packets from being sent across the medium and saving them instead. At injection rates higher than

20 packets /sec the amount of savings is stabilised at around 48% and 30% for DCB and CB respectively. Flooding, by definition, scored no savings at all considered loads as it retransmits the received packet unconditionally. Nodes refraining from sending redundant packets aid with fewer collisions, Figure 5-9, and more reachability, Figure 5-11. That is, more savings lead to fewer collisions and vice versa. The slight dip in CB may be explained by recalling the definition of savings that is defined as the percentage of the nodes receiving a packet and not retransmitting it. The increase in traffic load from 1 to 10 increases the number of received packets dramatically; at the same time nodes' saving is degraded with this increase. At an injection rate of 10 packets/ sec the CB's collision rate, increases sharply, Figure 5-9, then it is stabilised at a high level, leading to an immense decrease in savings, resulting from higher loads. With loads higher than 10 packets/ sec a slightly higher level of savings results from losing packets that are dropped, as a result of collision, resulting in fewer packets received and ready to be saved or sent. At loads of lower than 10 packets/ sec, most of the packets are still received and retransmitted (low saving) as opposed to savings at loads higher than 10 packets/ sec.

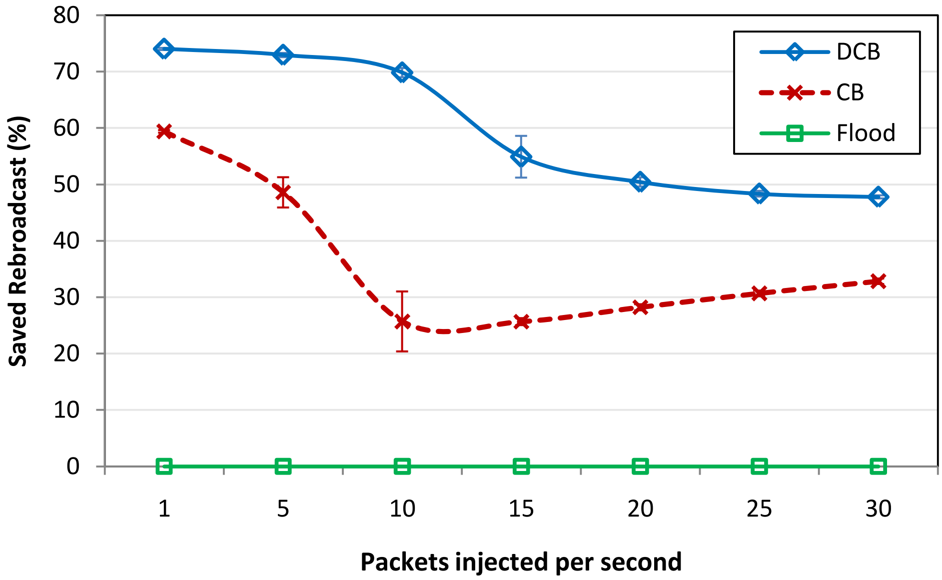


Figure 5-10: Saved rebroadcast versus packet injection rate in a highway model over a network of a 1000m x 1000m network having 100 nodes

5.4.2.3 Reachability

Reachability is linked to the number of collisions in the network, where more collisions lead to less reachability as collisions lead to packet loss and drops. As Figure 5-11 shows, reachability decreases with the increase in traffic load. Reachability for all schemes reaches 100% at 1 packet/ sec. However, flooding reachability falls when the injection rate increases from 1 to 10 and it continues to fall until it reaches around 50% at 30 packets/ sec. However, CB's reachability starts to fall at injection rates of 5 packets/ sec. This is better than that of flooding because of the condition imposed over resending packets inhibiting excess packets from congesting the transmission medium, decreasing the number of collisions and packets lost, hence improving reachability. This control imposed over packet retransmission in CB is even more refined with the DCB enabling for the dynamic threshold control that is suitable to the current nodal density. As shown in Figure 5-11, DCB scores 100% of reachability for injection rates of 1-10 packets/ sec; it decreases with higher injection rates until it reaches 70% at 30 packets/ sec.

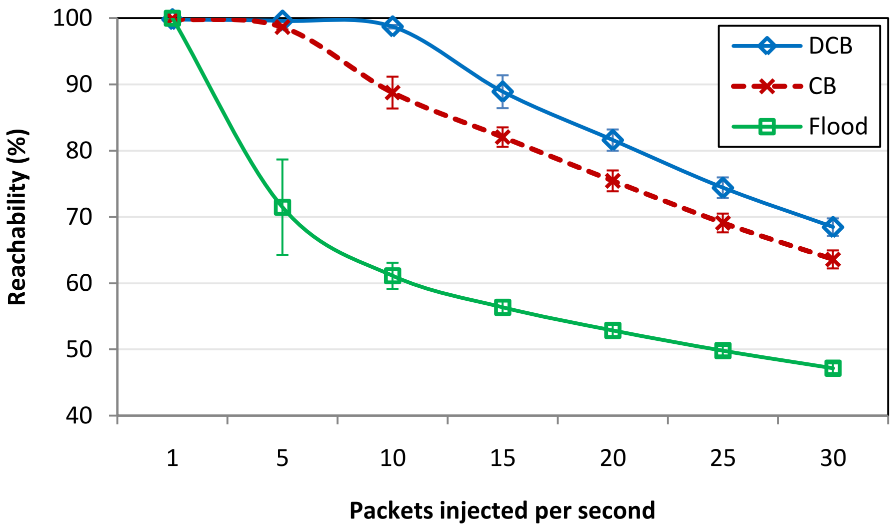


Figure 5-11: Reachability versus packet injection rate in a highway model over a network of a 1000m x 1000m network having 100 nodes

5.5 The City Model

This section studies the proposed scheme in a city-like scenario. In this model, nodes move in streets and lanes which are separated by buildings and other obstacles that result in obscuring the transmission of a node from reaching nodes on other streets, Figure 5-1. To mimic this situation, a transmission range of 150m is implemented for nodes moving along streets separated by a space of 200m in a 1000m x 1000m of network area, as illustrated in Figure 5-1. Moreover, nodes are implemented to move within a maximum speed of 30 km/ hour, applying the city speed limitations.

5.5.1 Effects of Network Density

This section carries out the study of network density by varying the number of nodes while maintaining other network parameters fixed. Among the fixed network parameters is the traffic load having an injection rate of 4 packets/ sec. The numbers of nodes considered are 25, 50, ..., 300 with steps of 25 nodes. Metrics considered are average collision rate, saved rebroadcast and reachability measured against the number of nodes in the network.

5.5.1.1 Collision Rate

Figure 5-12 illustrates the relation between collision rate and number of nodes. Increasing the number of nodes while maintaining other network parameters, results in an increased collision rate. This increase in collision rate is more apparent with flooding as the collision increases sharply in networks of more than 175 nodes. However, the same behaviour of sharp increase in collision rate started at smaller networks of 100 nodes for flooding in the highway scenario, Figure 5-5. This is because the highway model is implemented in an open space with no obstacles, enabling for even more collisions than that of the city scenario. CB’s collision rate is increasing slightly with the increase in the number of nodes in the network. This is not the situation with the highway scenario where the CB’s average collision rate increases sharply with networks of more than 200 nodes. The DCB’s increase in collision rate is more subtle than that of CB, implying better scalability in both highway and city scenarios.

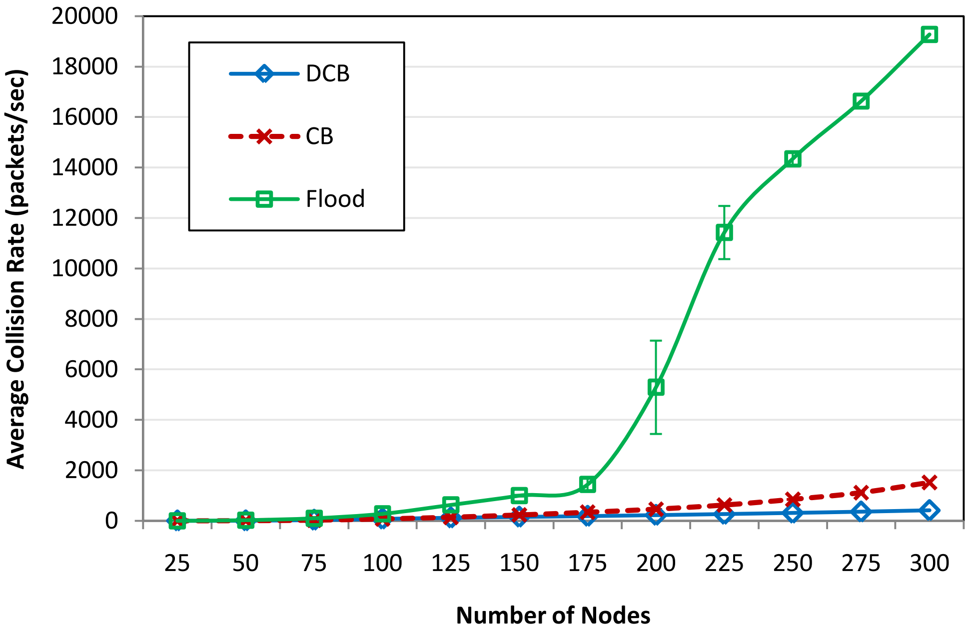


Figure 5-12: Average collision rate versus number of nodes in a city model over a network of 1000m x 1000m under a traffic load of 4 packets/ sec

5.5.1.2 Saved Rebroadcast

The level of saved rebroadcast, illustrated in Figure 5-13, generally increases with the increase in the number of nodes. As the figure shows, CB and DCB savings are affected by the network partitions for networks having 25 nodes. All schemes saving at 25 nodes is around 2% as opposed to all schemes savings at the highway model scoring around 20% at the same network size. In networks of 25-100 nodes the level of CB's saved rebroadcast is slightly better than that of the DCB; this is because DCB threshold assignment is dynamic, assigning high threshold values when the number of reachable neighbouring nodes is relatively low, allowing for more rebroadcasts (less saving). This is opposed to the fixed-threshold value (3) used by the CB scheme, inhibiting more packet rebroadcasts at networks of 25 to 100 nodes. Within networks of more than 100 nodes the DCB saving starts to overcome that of CB. This is due to the dynamic technique accommodating and sensing network density to decide for an appropriate threshold value inhibiting unwanted packets from being rebroadcast to the communication medium. The saving continues to increment until it reaches around 70% and 50% for DCB and CB respectively at networks of 300 nodes. Generally, comparing the amount of saving under this model to that of the highway model, Figure 5-7, reveals that schemes implemented under the city model score fewer savings. This is associated with the network partitions in the city model that result in fewer reachable neighbours and fewer received packets, which increases the likelihood of the threshold value not to be exceeded by the number of received packets, hence, rebroadcasting a received packet instead of saving it.

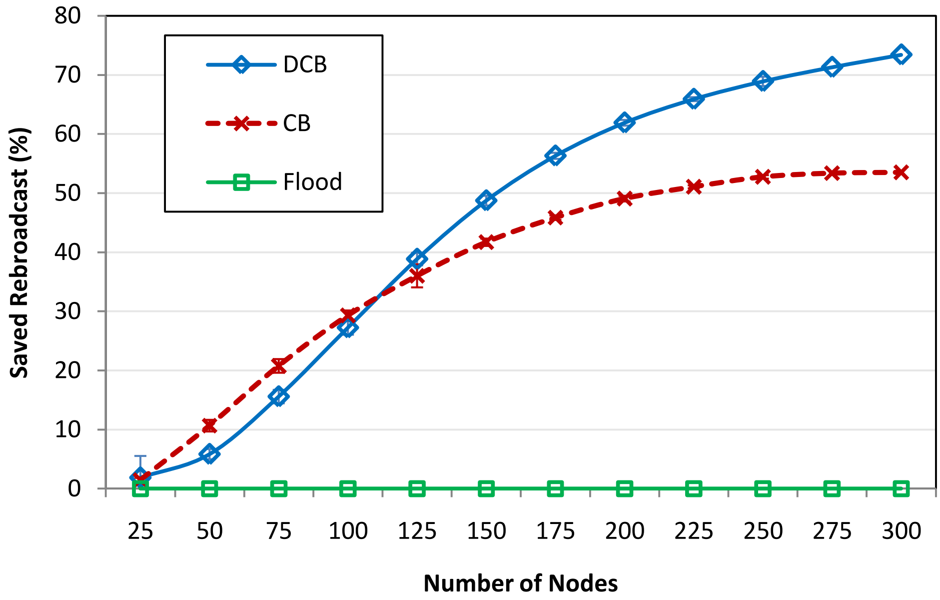


Figure 5-13: Saved rebroadcast versus number of nodes in a city model over a network of 1000m x 1000m under a traffic load of 4 packets/ sec

5.5.1.3 Reachability

Studying the different schemes under the city model, Figure 5-14, reveals how hard it is to reach maximum reachability with network partitions and node separation. While in the highway model, Figure 5-8, networks reach maximum reachability 100% though having 50 nodes only. Reachability in the city model barely reaches its maximum with 300 nodes in the network, proving that network partition is the worst hindrance to full network reachability. Network partitions and low nodal speeds in the city model make it hard for packets to reach some parts of the network, leading to poor reachability. Nevertheless, it is worth mentioning that flooding shows a slightly better performance of around 5% at densities of 75-125 nodes. This is linked to the fact that the other schemes impose some restrictions on the rebroadcast of a received packet resulting in a little loss of reachability in this specific density of 75 to 125 nodes, at this partitioned city model. The sharp decrease in flooding reachability at networks of 175 nodes may be understood by considering the sharp increase in collision rate at networks of the same size, Figure 5-12.

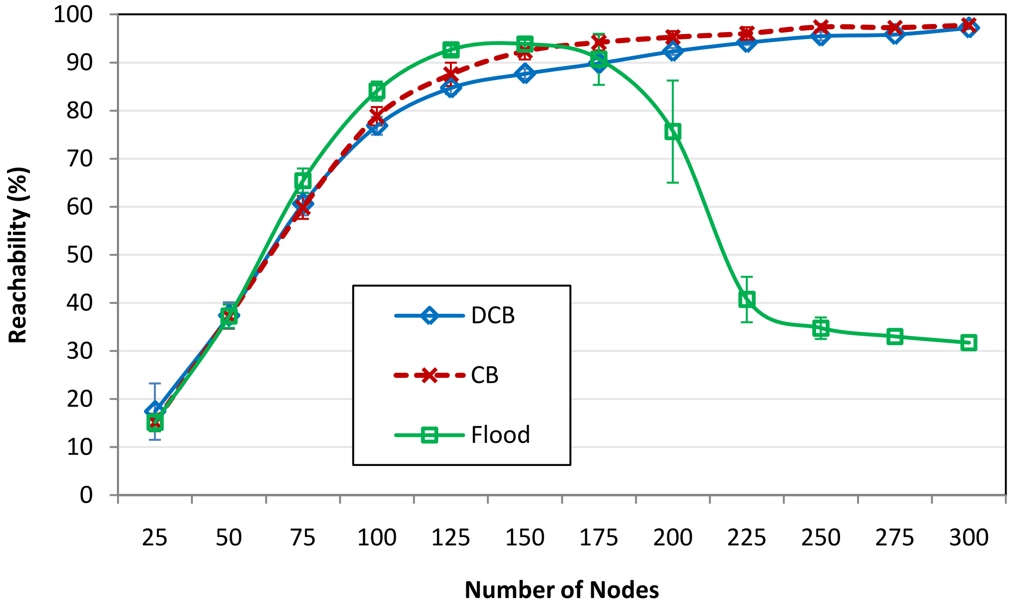


Figure 5-14: Reachability versus number of nodes in a city model over a network of 1000m x 1000m under a traffic load of 4 packets/ sec

5.5.2 Effects of Traffic Load

This section incorporates the study of the effects of variable traffic load on the proposed scheme, the dynamic counter-based DCB, the counter-based and flooding broadcast schemes. The study investigates the considered schemes behaviour in a city scenario. The number of nodes commuting through the network is 100 nodes, each communicating with a transmission range of 150m. Nodes move along four horizontal and four vertical streets where each street consists of two lanes of opposite directions, as depicted in Figure 5-3, with a maximum nodal speed of 30km/ hour. Traffic injection rate is 1 packet/ sec sent by 1, 5, 10, 15, 20, 25 and 30 different elected nodes in the network. Three different metrics are considered in the traffic load study: average collision rate, saved rebroadcast and reachability.

5.5.2.1 Collision Rate

Figure 5-15 shows the effect of variable traffic loads on the different schemes in terms of collision rate. As the figure illustrates, the average collision rate increases with the increase in traffic load. However, this increase at its maximum never reaches 3000 packets/ sec at highest traffic load, 30 packets/ sec, where in the highway model, Figure 5-9, collision rates reach around 6000 packets/ sec under the same traffic load. This is related to the network partitions in the city model that decrease the chance for nodes to be in the same vicinity of each other, consuming extensively the shared medium resulting in more collisions. The way the collision rate increases also reflects the sparseness of the city model, resulting in gradual and steady increase. By contrast, in the highway model, Figure 5-9, the increase in collisions is dramatic and sharp, reaching maximum collisions with only 5, 10, 15 packets/ sec for flooding, CB, and DCB respectively.

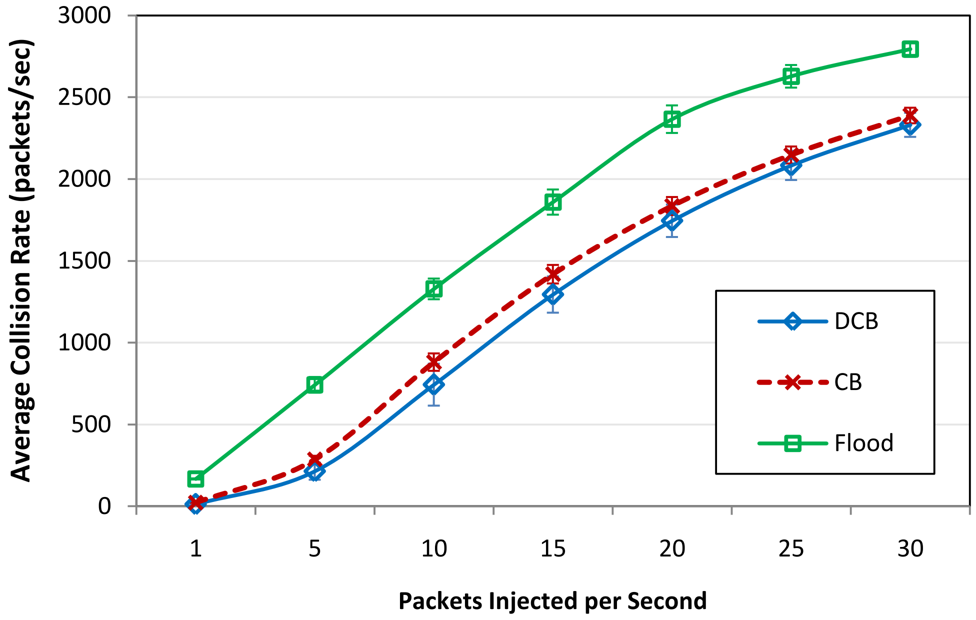


Figure 5-15: Average collision rate versus packet injection rate per second in a city model over a network of a 1000m x 1000m network having 100 nodes

5.5.2.2 Saved Rebroadcast

As illustrated in Figure 5-16, the amount of saving decreases with the increase in traffic load. At an injection rate of 1 packet/ sec, the savings of both DCB and CB are almost the same, 30%; however, the difference between their savings becomes more apparent with loads more than 5 packets/ sec. Both schemes' savings decrease until they reach 8% and 12% for CB and DCB respectively at an injection rate of 30 packets/ sec. DCB saving levels are even higher at extreme network conditions of high traffic loads as it deploys a dynamic environment-sensitive rebroadcasting decision. Comparing the amount of savings in the city model to that of the highway model, Figure 5-10, it is noticed that networks deployed as per the former model suffer partitions that generate more rebroadcasts as the threshold value is seldom exceeded by the number of received packets, the counter value. This in turn decreases the amount of savings for city networks as opposed to the highway model. For example, at injection rates of 1, 15 and 30 packets/ sec the DCB's saving under the highway model is around 70%, 60% and 50%, as opposed to 30%, 15% and 10% under the city model using the same settings.

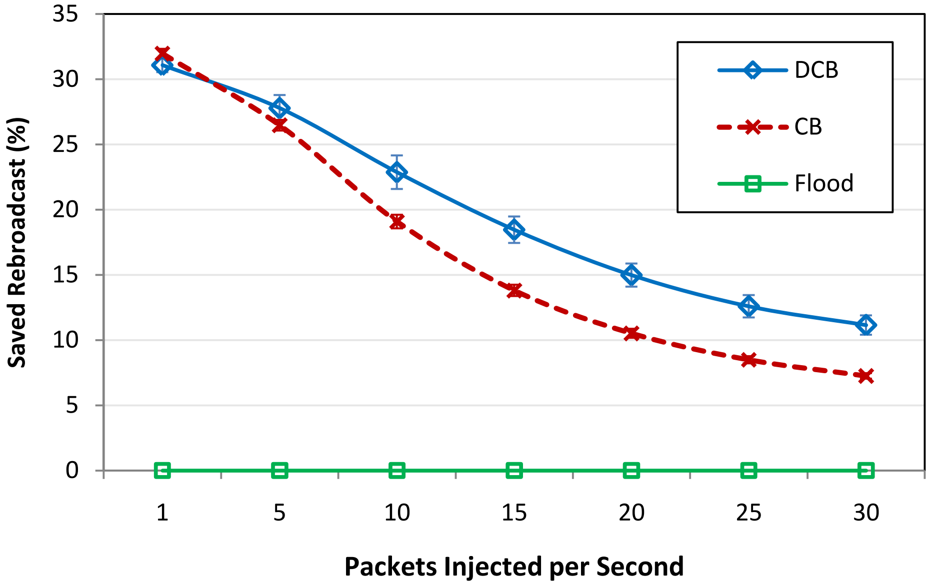


Figure 5-16: Saved rebroadcast versus packet injection rate per second in a city model over a network of a 1000m x 1000m network having 100 nodes

5.5.2.3 Reachability

As Figure 5-17 shows, at 1 packet/ sec all schemes suffer a deteriorated reachability of around 80% as opposed to 100% reachability for all schemes implemented by the highway model under the same injection rate, Figure 5-11. This is due to the high network partitions imposed by the city obstacles represented by the separation between streets (200m) and employing a transmission range of 150m per each node in the network. Reachability is degraded even more with higher traffic loads until it reaches around 30% at networks with an injection rate of 30 packet/ sec. This is compared to a reachability of 50% to 70% for all schemes implemented under the highway model Figure 5-11.

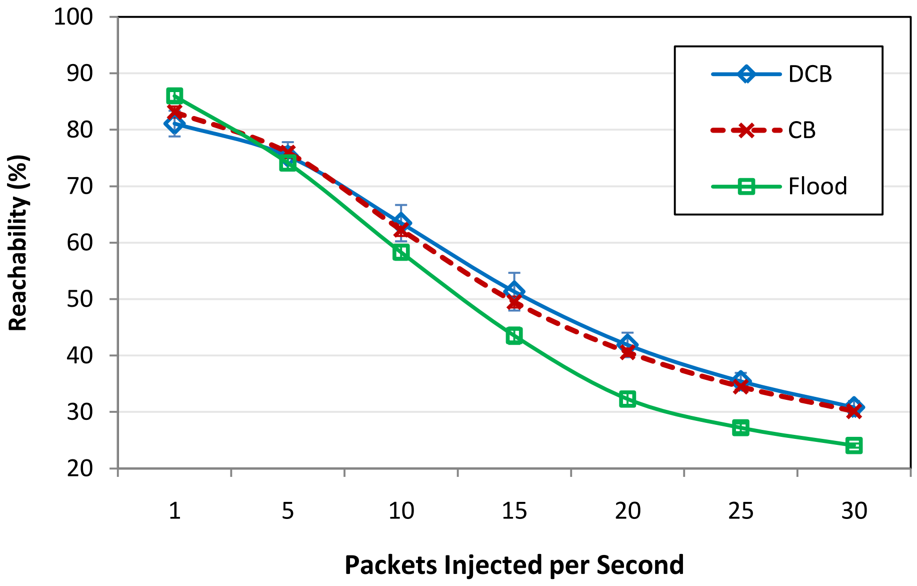


Figure 5-17: Reachability versus packet injection rate per second in a city model over a network of a 1000m x 1000m network having 100 nodes

5.6 Conclusions

This chapter described the performance of the new dynamic counter-based broadcast scheme under two models, the highway and the city centre. Both models impose some restrictions on the node movement, restricting them to move in specified streets and lanes. While the highway model employs an open plan terrain with no obstacles, the city model incorporates the existence of buildings that separate each street from the other, resulting in higher fragmentation and network partitions. Compared to the flooding and the fixed counter-based broadcast schemes, simulation results using the highway model presented earlier have revealed that the new scheme, DCB, can improve saved rebroadcast up to 60% compared to the counter-based and 90% compared to flooding even under high density, and high mobility conditions. A comparable enhancement can also be obtained with variable traffic loads applied to the network. Employing the city model, the amount of improvement in the DCB saved rebroadcast was 20% over CB and 70% over flooding. The results also show that all schemes implemented under the city model achieve lower savings than those under the highway model. That said, schemes implemented under the city model scored less collision as a whole showing a less sharp increase even at high nodal densities. With regards to reachability, all schemes implemented under the city model barely reach full reachability at networks of 175 nodes. Comparing this to the schemes under the highway model, the latter reaches a full reachability state at networks of 50 nodes only.

The next chapter will introduce and evaluate the AODV routing protocol incorporating both the counter-based and the dynamic counter-based, within the route discovery process. The performance of the two implemented protocols is compared against that of the conventional AODV routing.

Chapter 6

Performance Analysis of Dynamic Counter-Based Route Discovery

6.1 Introduction

The performance evaluation of most existing counter-based broadcast schemes suggested for MANETs [44, 51, 58, 143] , including the ones that have been discussed in the previous chapters, have employed “pure” broadcast scenarios lacking the study of their performance impact on real applications such as route discovery within routing protocols. A number of MANET routing protocols [53, 73, 78, 79, 87] employ flooding for the propagation of routing control packets, such as the *Route REQuest* (RREQ) *Packet Data Units* (PDUs) used during the route discovery process in for example, *On-Demand Distance Vector* (AODV) routing protocol.

Routing overhead associated with traditional AODV can be significantly reduced by imposing some control mechanism on the rebroadcasting by each node of every received RREQ control packet, resulting in less routing overhead. Motivated by this observation, this chapter evaluates the performance of the Dynamic Counter-Based Broadcast (DCB) scheme introduced in Chapter 4, as a means of route discovery in the well-known AODV routing protocol.

The performance of the route discovery based on DCB, referred to here as *Dynamic Counter-Based Route Discovery* (DCBRD) will be compared against two other protocols. The first is the original AODV with route discovery based on flooding [53] (AODV), and the second is AODV with route request utilizing *counter-based* (CB-AODV). Consequently, two different route discovery algorithms were implemented, namely, the DCBRD and the CB-AODV, the Dynamic counter-based route discovery and the counter-based route discovery respectively.

The rest of the chapter is organised as follows: Section 6.2 introduces an overview of route discovery process in AODV. Section 6.3 presents the proposed DCBRD and presents its algorithm. Section 6.4 explains the simulation environment and settings. Section 6.5

analyses the effects of different network operating conditions on the performance of the considered protocols. Finally, section 6.6 draws the chapter summary, findings and conclusions.

6.2 Ad hoc On-Demand Distance Vector (AODV) Routing Protocol

Efficient routing protocols are an essential part of the operation of a MANET [144]. Routing packets can be used to support a single destination, (unicast) or multiple destinations, (multicast). This research is concerned only with unicast routing protocols. Conventional routing protocols are based on routing tables, which store paths to all possible destinations in the network. A path consists of an ordered set of intermediate nodes that are possible candidates for passing a packet from the source node to the destination by forwarding it from one node to the other. The distinctive character of a MANET, as discussed in Section 1.1, makes routing in such a network a challenging task [145]. Notably, the constant mobility of nodes continually changes the network topology and affects nodal connectivity. Moreover, the limitations of the wireless transmission medium results in comparatively low bandwidth that is prone to channel contention. Consequently, routing protocols designed for a MANET environment require qualities such as dynamic adaptation to frequent network topological changes; and should also comprise a mechanism for inhibiting excess control overhead over the available channel bandwidth reserving it for actual data communication.

Over 30 diverse MANET routing protocols have been designed and proposed so far [145]. As was outlined briefly in Section 1.3, MANET routing protocols could be classified according to the protocol’s mechanism of route discovery and route update into three categories: proactive (table-driven), reactive (on-demand) and hybrid. Proactive routing protocols attempt to maintain up-to-date route information from each node in the network to every other node. Contrary to proactive routing protocols, reactive routing, as the name may imply, establish and discover a route to a node only when there is a demand for routing to that node. Hybrid approaches comprise characteristics of both reactive and proactive routing protocols. Reactive routing protocols adjust to network connectivity changes using minimal routing overhead by avoiding unnecessary periodic route information update at each node. Examples of well studied reactive routing protocols are:

Ad-hoc On-Demand Distance Vectoring (AODV) [53, 98], Dynamic Source Routing (DSR) [79] and Associativity Based Routing (ABR) [9].

Among the most discussed and studied routing protocols is AODV. It has been standardised by the MANET IETF working group in RFC 3561 [98]. Being reactive, AODV discovers and establishes routes only when needed and maintains only those that remain active. The protocol consists of two essential procedures: route discovery and route maintenance.

6.2.1 AODV Route Discovery

The discovery procedure is founded upon the flooding of queries and query-replies in cyclic fashion. When source node *S* wants to send a packet to a destination node *D*, it checks its route table for a route to *D*. If it has a route to *D* in its routing table, *S* forwards the packet to the next-hop node toward *D*. If S has no routing information to *D*, a route discovery is triggered by node S. Specifically, node S floods the network with a broadcast Route Request (RREQ) control packet containing the following fields: source address, destination address, source sequence number, destination sequence number, hop count and a broadcast ID.

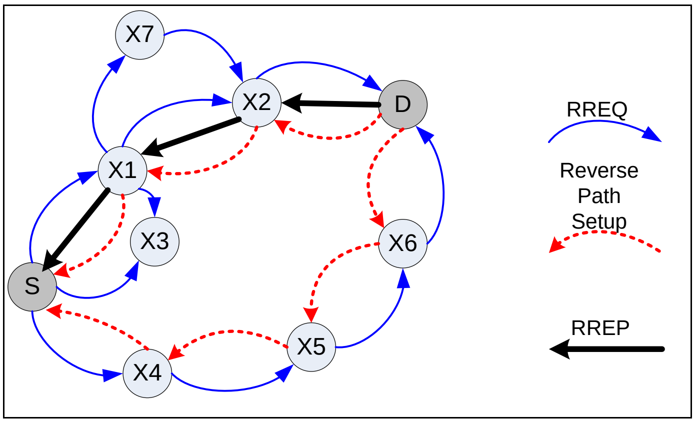


Figure 6-1: Route discovery illustration

Upon the reception of the RREQ packet by an intermediate node *X*, the latter acts as follows: If *X* has not received this RREQ before (noting broadcast ID and source address); and *X* is not the destination, nor has a current route to the destination, it rebroadcasts the RREQ. If *X* was the destination (*X* = *D*) or has a current route to *D*, it generates a Route Reply (RREP).

The RREP is unicast in a hop-by-hop fashion to the source *S*. As the RREP propagates, each intermediate node creates a route to the destination *D*. When *S* receives the RREP, it records the route to the destination *D* and can begin sending data. If *S* received multiple RREPs, the route with the shortest hop count is chosen [53]. Taking Figure 6-1 as an example, node *S* floods the network with a RREQ packets then each intermediate node *X* sets up a reverse path to the source *S*. When *D* receives the RREQ, it answers with a RREP packet using the shortest reverse path.

6.2.2 AODV Route Maintenance

The second main procedure besides route discovery is route maintenance and it is done primarily using *Route ERRor* (RERR) packets [146]. Route maintenance is the nodes' reaction to changes in the already discovered paths. When a node is not reachable any more, a RERR is sent back in a hop-by-hop fashion starting from nodes that are immediately prior to the unreachable node connecting it to other sources. 'Hello' messages may be used to detect and monitor the node's link state [147]. By the periodic exchange of 'Hello' messages between nodes, if a node fails to receive 'Hello' messages from a neighbour, it considers that neighbour unreachable. When a node moves from one location to another it triggers a route discovery process and it sends a RERR packet to all sources connected to it. Additionally, any node receiving a RERR, updates its routing table by setting the distance to the destination to infinity [148]. Moreover, a node caches a route between two endpoints and keeps this route for a length of time given by the *Active Route Time-Out* (ART). ART defines how long a route is kept in the routing table after the last transmission of a packet using this route [149].

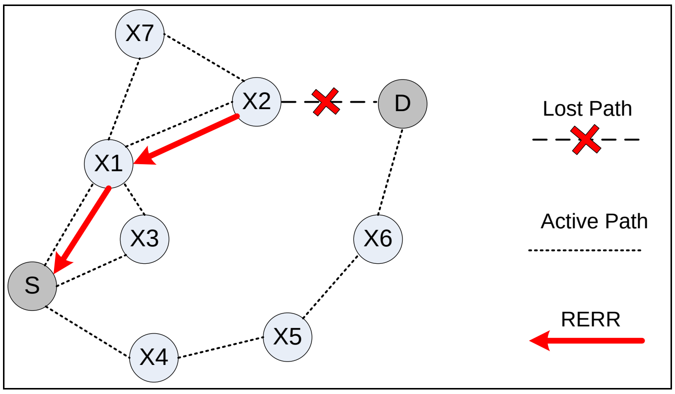


Figure 6-2: Route maintenance illustration

6.3 Dynamic Counter-Based Route Discovery (DCBRD)

In conventional AODV, a route discovery operation is initiated when a source node *S* wants to send data to another node *D*, where *S* does not currently hold a valid route to *D*. Consequently, node *S* sends a Route Request RREQ to all its one-hop neighbours. Intermediate nodes receiving the RREQ will flood it to the network by broadcast.

```
DCBRD_Algorithm

Pre: a RREQ packet at node X was heard for the first time, n
is number of neighbours, node's degree. S is the scale.

Post: rebroadcast the RREQ or drop it, according to the
algorithm

    1.  Add the RREQ packet ID to the received packet list
    2.  Set RAD
    3.  c = 1, i = 1
    4.  While (RAD) Do
             If (same RREQ heard) Increment c
    5.  End while
    6.  While (i > 0) Do
                 if ((n > w*i) AND(n <= w*(i+1))
                        C = C2-1
                        If (C < C1)
                               C = C1
                        Goto End while (i)
                 End If
                 i = i + 1
    7.  End while (i)
    8.  If (c > C)
             drop packet
             exit algorithm
    9.  End If
    10. Submit the RREQ packet for transmission
End DCBRD__Algorithm
```

Figure 6-3: Dynamic Counter-based Route Discovery, DCBRD Algorithm

However, nodes implementing DCBRD when receiving a RREQ packet initiate a counter, c, that counts the number of duplicate RREQ received, (see line 4, Figure 6-3). Counting continues until a waiting period (RAD) is finished. After that, the loop in (see line 6, Figure 6-3) is executed; this loop is explained in Chapter 4, Section 2 (4.2). Next, the counter *c* is checked against the threshold value *C* and RREQ broadcast is inhibited if $c > C$. The waiting period is called Random Assessment Delay (RAD), as before, and is randomly chosen from a uniform distribution between 0 and T_{max} seconds, where T_{max} is the maximum possible delay interval. The selection of the threshold *C* is based on neighbourhood information gathered using 'Hello' packets. When a node is located in a sparse area it selects C_2 as the threshold value and C_1 when located in a dense area of the network. C_2 is larger than C_1 to maximize the likelihood of a node located in a sparse region to forward the RREQ as opposed to a node employing C_1. C_1 is the minimal threshold value implemented to maximize the chance of nodes in a dense region suppressing the RREQ. It is desirable not to waste bandwidth in a busy region, if a node has low expected additional coverage. The values of C_1 and C_2 are calculated dynamically according to the local node neighbourhood, this was explained in more details in Chapter 4, the DCB algorithm. RREQ dissemination is continued until it is received by the destination D or by a node X having a valid route to the destination. After that, a Route Reply RREP packet is unicasted back to the source node along the reverse path made at the route discovery process. The DCBRD algorithm is depicted in Figure 6-3.

6.4 Simulation Environment

To evaluate the performance of the DCBRD scheme, the implementation of the AODV routing protocol included in the ns-2 simulator [112] has been modified to incorporate the functionality of the DCBRD and the CB-AODV schemes.

Table 6-1: Simulation Parametrs

Simulation parameter	Value
Simulator	ns-2 version (2.34)
Network area	1000 x 1000 meter
Transmission range	250 meter
Data Packet Size	512 bytes
IFQ length	50
Simulation time	900 sec
Pause time	0
Number of trials	30
MAC layer protocol	IEEE 802.11b
Mobility model	Random WayPoint model
Traffic type	CBR (Constant Bit Rate)
Channel bandwidth	11Mb/sec
Confidence Interval	95%
Maximum velocity	20 m/sec
Propagation model	Two Ray Ground
Sending rate	10 packets/ sec

The aim of this simulation is to evaluate and compare the DCBRD to *Flooding Based* AODV (AODV), and the *counter-based* AODV (CB-AODV) under different network conditions. Each node in this simulation scenario moves according to the Random WayPoint mobility model in a network area of 1000m x 1000m. To exercise the protocols' performance under extreme conditions of link breakage, a maximum nodal speed is selected to be 20m/ sec i.e. approximately 70 km/ hour. Data flows in a constant bit rate of

10 packets/ sec with a packet size of 512 bytes. The number of data connections established between a source and a destination is 20, if not stated otherwise. Simulation parameters used in this study are shown in Table 6.1.

6.5 Performance Evaluation

To evaluate the performance of the proposed protocol, three different scenario settings were implemented to enable testing the scheme under different network operating conditions. First, a study of network density is carried out by implementing different networks with variable numbers of nodes, while maintaining other network parameters. Second, a study of offered network load and its impact on the considered routing protocols, providing different numbers of source-destination connections (flows) within a fixed number of nodes. Finally, a study of the network is conducted employing different maximum nodal speeds. The performance metrics considered here are defined and discussed in Chapter 2 Section 4 (2.4). These are: the average collision rate, normalised network throughput, routing overhead and end-to-end delay.

6.5.1 Impact of Network Density

The study of network density has been carried out by varying the number of nodes over a fixed topology area of 1000m x 1000m. The number of nodes considered is 25, 50, ..., 200 and 250 nodes. The study of networks of 250 nodes has been added to explore the protocols' behaviour under extreme densities. Each point on the graph represents the average of 30 different scenarios of a group of nodes moving according to the random waypoint mobility model, with a random maximum velocity between 1 and 20 m/ sec. The offered network load is 20 randomly selected source-destination connections per simulation scenario, each sending 10 packets/ sec. The series naming in all graphs represents the protocol under test for example: DCBRD is Dynamic Counter-Based Route Discovery (DCBRD), (AODV) is traditional Flooding Based AODV; and CB-AODV is AODV with route request utilizing the fixed counter-based scheme.

6.5.1.1 Average Routing Overhead

Average routing overhead measures the average overhead caused by the transmitted RREQ packets per second. Lower overhead would imply a better protocol. As Figure 6-4 shows, the routing overhead increases with the increase in the number of nodes in a network. This increase in overhead is quite dramatic in AODV increasing by as much as 1500%, as the number of nodes in the network increases from 100 to 250. This dramatic increase in

AODV's overhead corresponds to a comparably lower increase in the overhead for DCBRD 100% and CB-AODV 160%, Figure 6-5, considering the same network size. This is because of the control imposed on the RREQ packets retransmissions in both of the schemes, DCBRD and CB-AODV.

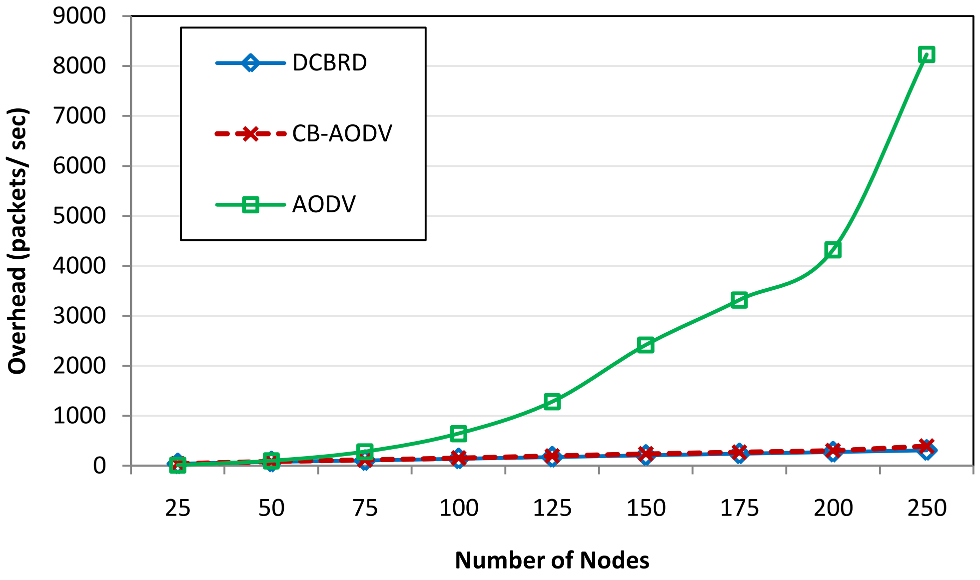


Figure 6-4: Routing overhead versus number of nodes placed over a 1000mx1000m area with an injection rate of 10 packets/ sec

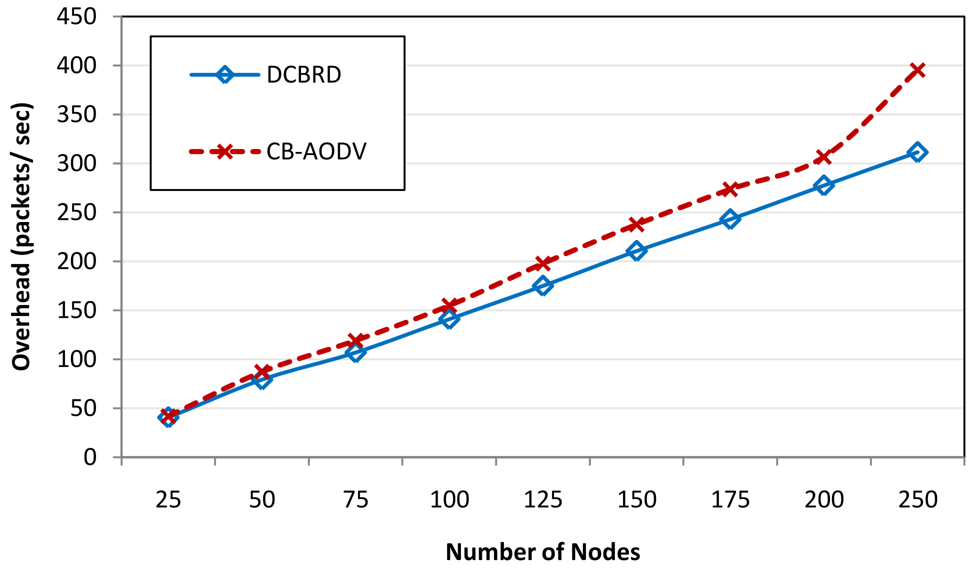


Figure 6-5: Routing overhead for DCBRD and CB-AODV versus number of nodes placed over a 1000mx1000m area with an injection rate of 10 packets/ sec

6.5.1.2 Average Collision Rate

Average collision rate measures the average RREQ packets' collision rate. As Figure 6-6 shows the AODV RREQ collision rate increases dramatically with the increase in the number of nodes in the network. Though the number of connections or flows is constant through all network sizes, increasing the number of nodes in the network would increase the number of RREQ packets transmitted through the network, which is obvious in AODV. However, in the other two protocols, some control over the RREQ packets retransmission is imposed; resulting in more resistance to the strain imposed by higher number of nodes and hence, higher loads. However, with a greater number of nodes and increased loads DCBRD shows more resilience compared to CB-AODV. When the number of nodes is increased from 200 to 250 the increase in DCBRD's collision is around 20% compared to the CB-AODV collision increase of around 80%. This implies DCBRD has improved scalability compared to CB-AODV.

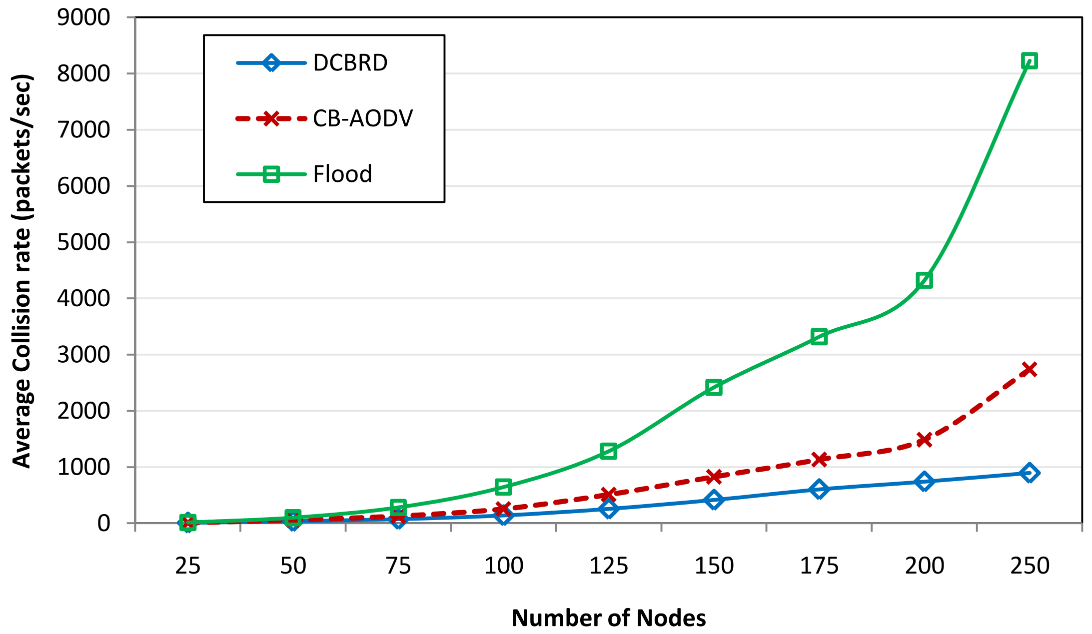


Figure 6-6: Average collision rate versus number of nodes placed over a 1000mx1000m area with an injection rate of 10 packets/ sec

6.5.1.3 Normalised Network Throughput

Normalised network throughput measures the ratio of successfully delivered data packets (to final destinations) to the number of generated data packets. Figure 6-7 shows the normalised throughput of the three protocols. The ratio of successfully delivered packets at networks of 25 nodes is below 65% for all protocols. This is due to the network partitions caused by the small number of nodes occupying a large network area of 1000m x 1000m.

This ratio increases sharply as the number of nodes in the network increases. Adding more nodes to the network would serve as a connectivity booster protecting data packets from being dropped. This increase in throughput continues until it reaches around 75% for all three protocols in networks of around 75 nodes. In networks of more than 100 nodes the throughput of all protocols starts to decrease. This is because of the higher loads caused by more control packets retransmitted in the network. However, DCBRD is again shown to be the most resilient to the increase in number of nodes, CV-AODV comes second and AODV is the worst. This is because DCBRD and CB-AODV both inhibit the retransmission of excess control packets (RREQ), lowering contention and collision and enabling the carrier to be occupied with the data packets that need to be sent. At higher loads of 200 nodes in the network, the DCBRD benefit over CB-AODV is more apparent as the former employs a dynamic threshold assignment dependent on the number of the surrounding neighbours. The stabilised throughput behaviour (not degrading) in dense networks again signifies DCBRD's scalability.

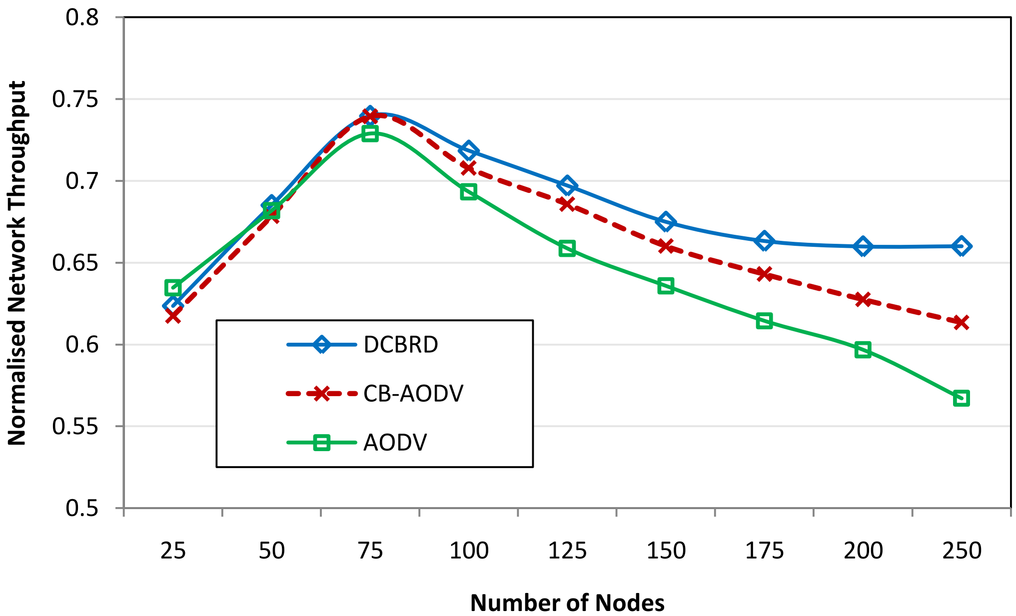


Figure 6-7: Normalised Network Throughput versus number of nodes placed over a 1000mx1000m area with an injection rate of 10 packets/ sec

6.5.1.4 End-to-End Delay

Figure 6-8 shows that the end-to-end delay is high for both sparse and dense networks. Sparse networks lack the connectivity; therefore RREQ packets take more time to be delivered to their destinations. With dense networks RREQ packets experience high packet contention and collision that result in them failing to reach their destinations. This in turn, increases the time required for a data packet to be delivered from a source to destination. DCBRD achieved lowest delay with more dense networks as it inhibits congesting the network with unnecessary RREQ packets. After DCBRD, comes CB-AODV with slightly higher delays at dense networks and AODV shows the highest delay with a greater number of nodes.

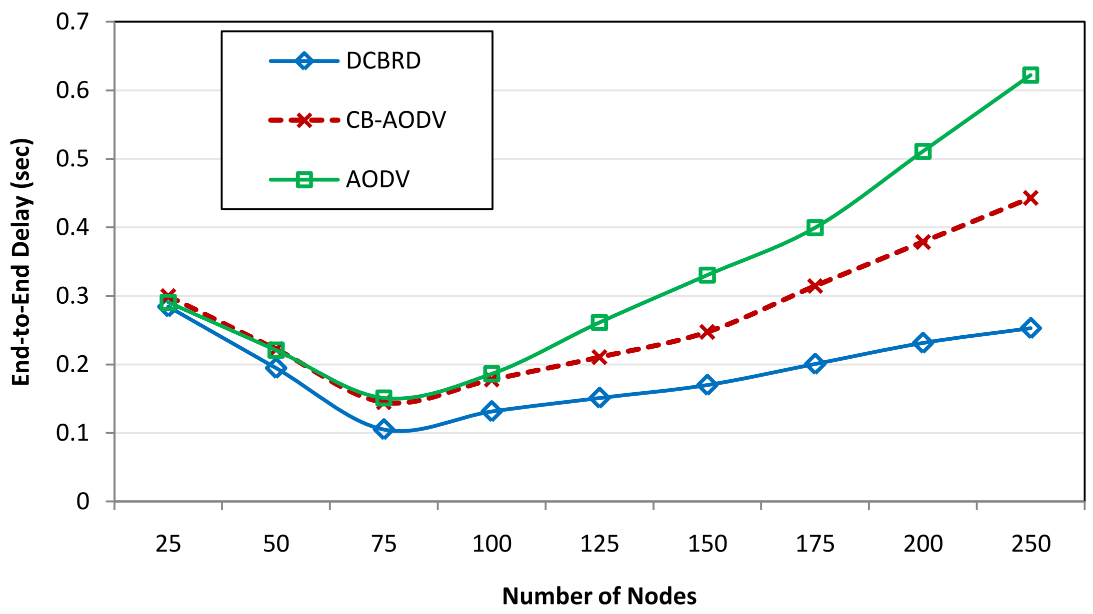


Figure 6-8: End-to-end delay versus number of nodes placed over a 1000mx1000m area with an injection rate of 10 packets/ sec

6.5.2 Impact of Offered Load

This section considers the study and analysis of the impact of offered load on the network. That is, the number of source-destination connections (flows) offered in a network of 1000m x 1000m containing 100 nodes. The number of data flows considered is varied over the range 10, 20, 30 and 40 flows while the maximum nodal velocity was 20m/sec for all simulation scenarios with a packet injection rate of 10 packets /sec.

6.5.2.1 Average Routing Overhead

Figure 6-9 shows that routing overhead increases with the increase in the number of data flows. As the number of flows increases, the number of generated RREQ packets also grows. This increase is more apparent with the AODV and CB-AODV protocols. They impose no control over the RREQ retransmission (AODV), or a weak control (CB-AODV) with threshold 4. The DCBRD overhead increase is small compared to the other two protocols, as it implements a dynamic route discovery that involves fewer participating nodes in dense areas, hence causing less RREQ packet overhead. When number of data flows increases from 10 to 40, the overhead increases by 25%, 40% and 66% for protocols DCBRD, CB-AODV and AODV respectively. Moreover, at network loads of 40 data connections DCBRD scored less overhead by 30% and 40% compared to the CB-AODV and AODV respectively.

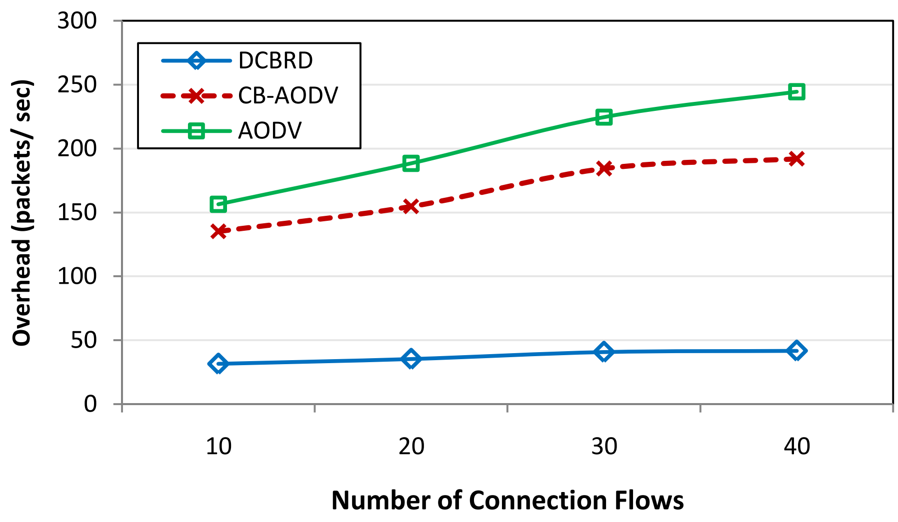


Figure 6-9: Routing overhead versus number of data flows of 100 nodes placed over a 1000mx1000m area

6.5.2.2 Average Collision Rate

Figure 6-10 shows that the increase in the number of flows results in an increase in the average RREQ packets' collision. At 10 data flows per network, AODV experiences more collisions by a factor up to 1900% than the other two protocols. This increase in the AODV collision rate continues to grow by a ratio of 150% as the number of flows increases from 10 to 40. The collision increase in CB-AODV and DCBRD is more under control as both schemes impose some condition on rebroadcasting a RREQ. It can also be observed that the DCBRD outperforms the CB-AODV for all considered data flows. This is because of the sensitivity to surrounding neighbourhood density inhibiting excess RREQ from being sent across the medium hence, fewer collisions.

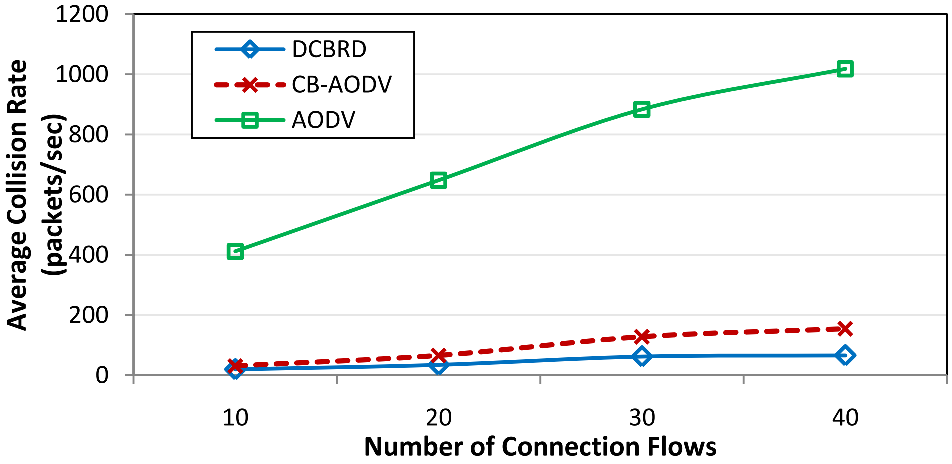


Figure 6-10: Average collision rate versus number of data flows of 100 nodes placed over a 1000mx1000m area

6.5.2.3 Normalised Network Throughput

Figure 6-11 shows that the network throughput is degraded with high loads, as the number of sent data packets that require successful reception would be also high. AODV throughput was lower than that of the other two protocols, as it is affected by the collisions happening with higher loads resulting from the unconditional transmission of all received RREQs. This concern is tackled with the other two protocols, the counter and the dynamic counter AODV. However, the DCBRD protocol shows better network throughput with higher loads than the other two protocols.

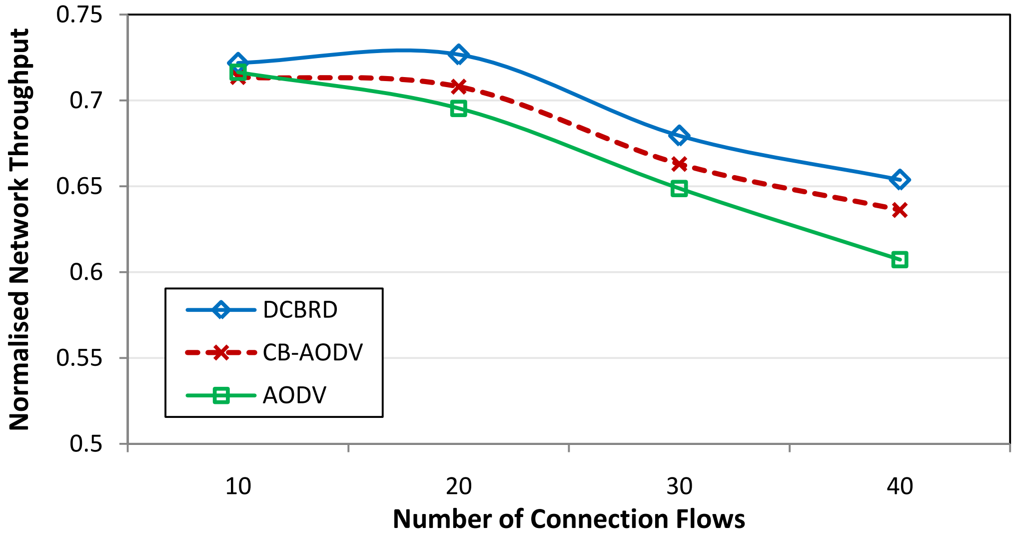


Figure 6-11: Normalized network throughput versus number of data flows of 100 nodes placed over a 1000mx1000m area

6.5.2.4 End-to-End Delay

Figure 6-12 shows that the time needed to deliver a data packet to its destination becomes higher with higher loads. Increasing the number of data flows implies a higher demand to deliver a larger amount of data packets resulting in the generation of more control packets, RREQ. This in turn, causes higher contention and collision leading to a significant increase in the end-to-end delay. This figure also illustrates that the average delay incurred by DCBRD is the lowest among the protocols. Dynamically controlling excess RREQ transmissions, results in some saving to the medium bandwidth, allowing data packets to be delivered in a timely manner.

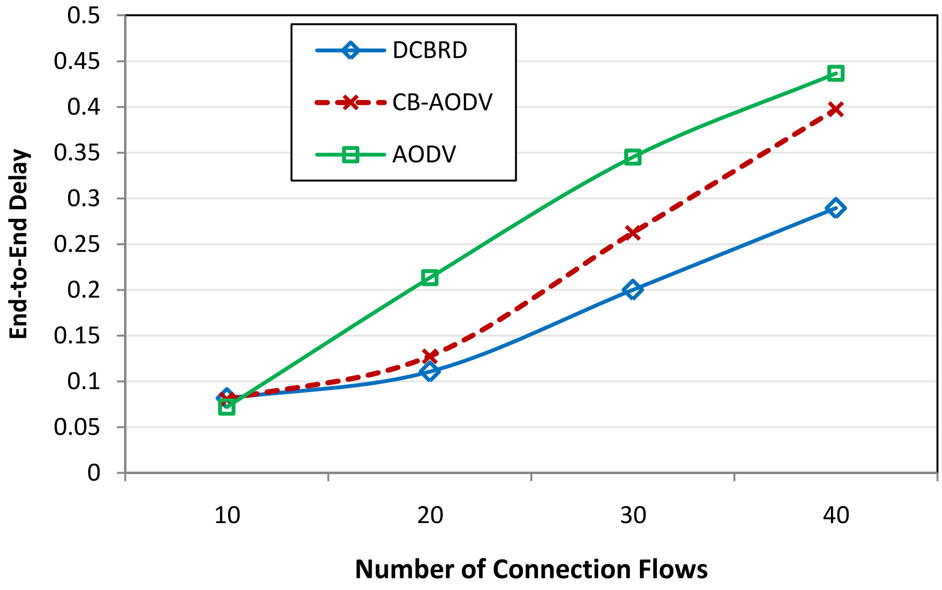


Figure 6-12: End-to-End delay versus number of data flows of 100 nodes placed over a 1000mx1000m area

6.5.3 Impact of Nodal Speed

This section studies the effect of nodal speed on the performance of the three considered protocols in a network of area 1000m x 1000m containing 100 nodes. Nodes move with a speed randomly chosen from 1 to S_{max} where S_{max} is equal to 5, 10, 15 and 20 m/ sec. The number of data flows considered in each scenario is 20 flows, with a sending rate of 10 packets/ sec.

6.5.3.1 Average Routing Overhead

Figure 6-13 shows that nodal speed has an effect on the routing overhead; increasing the former increases the latter. Higher speeds imply faster changes in the network topology requiring more maintenance packets to be generated to monitor this change, leading to higher overhead. AODV was the protocol most affected with nodal speed increase, as it retransmits control packets spontaneously and unconditionally, adding more to the overhead. This is not the case in the other two protocols. DCBRD scored the least overhead at all speeds with an increase rate of 12% compared to 23% and 26% for CB-AODV and AODV respectively when the nodal speed increases from 5 m/ sec to 20 m /sec. Moreover, the DCBRD scored a benefit of around 10% and 35% over the CB-AODV and the AODV respectively, under a maximum nodal speed of 20m/ sec.

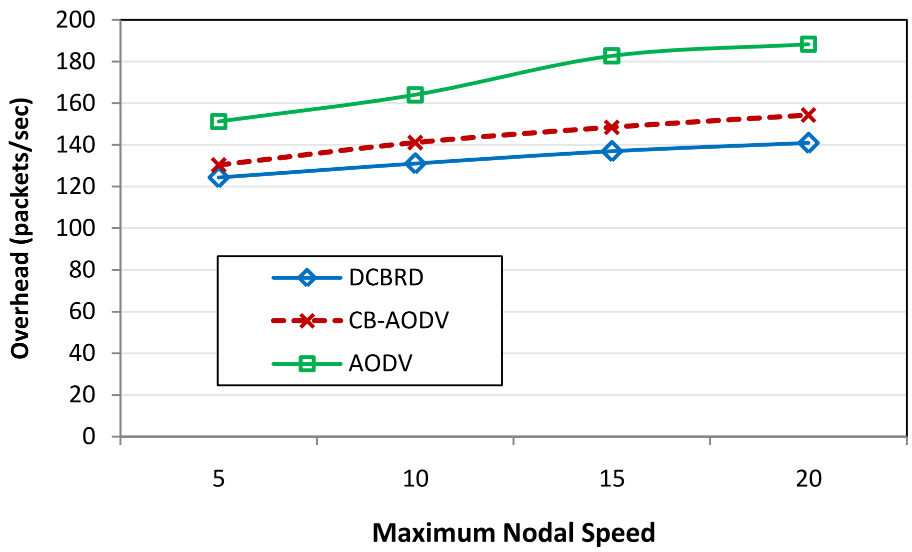


Figure 6-13: Routing overhead versus maximum nodal speed of 100 nodes placed over a 1000mx1000m area

6.5.3.2 Average Collision Rate

Figure 6-14 shows that the increase in nodal speed results in an increase in the average RREQ packets' collision rate. Increasing the speed changes the network topology, raising the probability of link breakage. This leads to more RREQ packets being transmitted in an attempt to repair these breakages. At all nodal speeds, AODV displayed the highest collision rate of all the schemes. With regards to collision rate, DCBRD is the least vulnerable to the increase in nodal speed, demonstrating an increase of 70% compared to 90% and 90% for CB-AODV and AODV respectively when nodal speed increases from 5 m/ sec to 20 m/ sec. Moreover, at the highest considered nodal speed, DCBRD scored a benefit of 60% and 370% over the CB-AODV and AODV respectively.

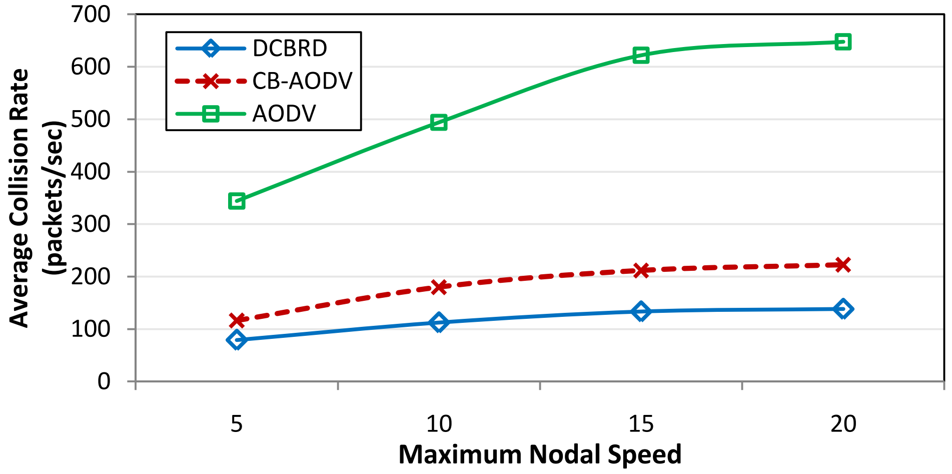


Figure 6-14: Average collision rate versus maximum nodal speed of 100 nodes placed over a 1000mx1000m area

6.5.3.3 Normalised Network Throughput

Figure 6-15 shows that the throughput is degraded at networks of higher speeds. At the lowest considered speed 5 m/ sec, the figure shows that almost 90% of the transmitted data packets are delivered successfully. This success rate drops as the nodal speed becomes higher. The DCBED benefit over other protocols becomes more evident at higher nodal speeds. Higher speeds lead to connection breakage that needs to be maintained by nodes sending control packets to discover new routes to their destinations. With DCBRD, the route maintenance uses the smallest number of control packets compared to the other two protocols.

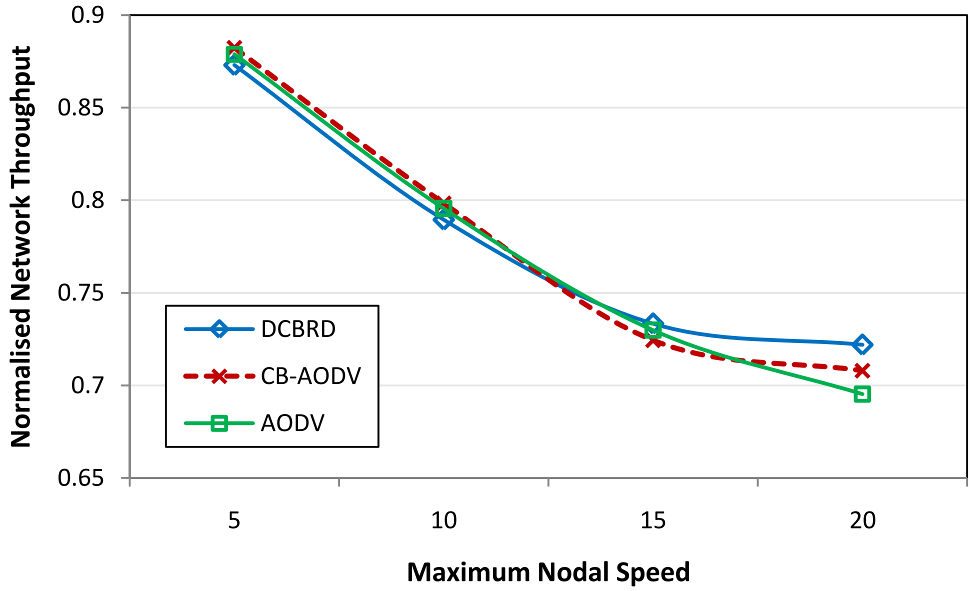


Figure 6-15: Normalized network throughput versus maximum nodal speed of 100 nodes placed over a 1000mx1000m area

6.5.3.4 End-to-End Delay

End-to-end delay measures the time required to successfully deliver a data packet to its destination. Figure 6-16 shows that as the nodal speed becomes higher, the time needed to deliver a data packet becomes higher as well. The concept behind that is that higher speeds instigate the need for more control packets to be sent over the medium compensating the connection breakage that results from higher nodal speeds. This leads to a higher consumption of the communication medium making it more difficult for data packet to reach their final destinations in a timely manner. The DCBRD benefit is apparent with higher nodal speeds that involve transmitting higher capacities of control packets. This is well controlled by the DCBRD dynamic retransmission technique. This is, DCB scored a benefit of 15% and 60% over CB-AODV and AODV respectively at the highest considered nodal speed.

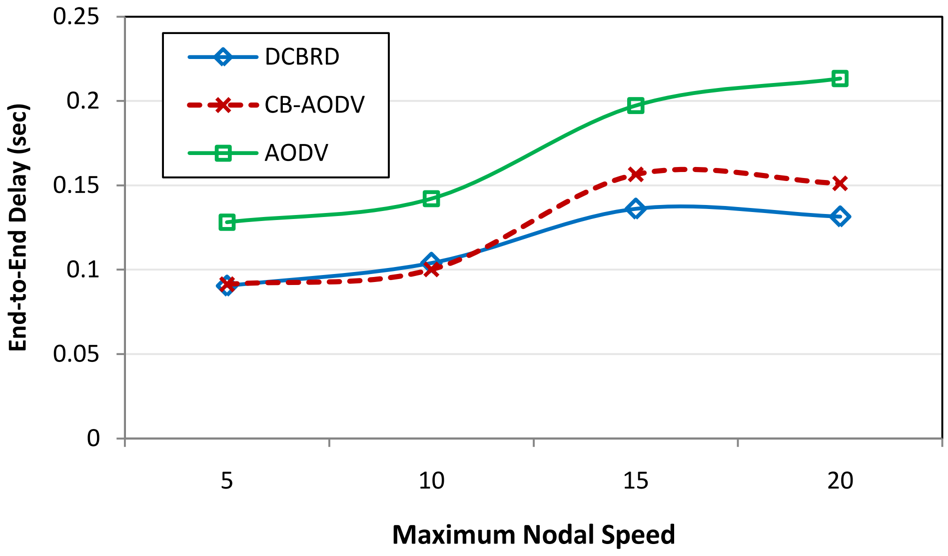


Figure 6-16: End-to-End delay versus maximum nodal speed of 100 nodes placed over a 1000mx1000m area

6.6 Conclusions

The new broadcast scheme, DCB proposed earlier in Chapter 4 was utilised as a route discovery mechanism in the AODV routing protocol, referred to as *Dynamic Counter-Based Route Discovery* (DCBRD). In DCBRD, the rebroadcast decision of a node is dynamically computed based on its neighbourhood density that would influence the selected threshold value. The performance of the resulting DCBRD routing protocol has been compared to the traditional AODV routing protocol that uses flooding as a route discovery mechanism and to the AODV routing that employs counter-based route discovery technique. These protocols are referred to here as AODV and CB-AODV respectively. Simulation results show that for all considered network densities DCBRD outperforms the other two routing protocols in terms of routing overhead, collision rate and end-to-end delay. For the network throughput, again DCBRD outperforms the other two routing protocols, especially in dense networks where the behaviour of DCBRD stabilises and does not degrade as sharply as the other two. In terms of collision rate at high densities, the increase of collisions in CB-AODV is around 80%, compared to a DCBRD collision increase of only 20%, implying better scalability for the latter.

Under variable traffic loads considering different numbers of data connections, DCRBD performed better at all considered metrics. In terms of overhead at the maximum considered network load of 40 data connections, DCBRD has a lower overhead by 30% and 40% compared to CB-AODV and AODV respectively. Finally, for all considered nodal speeds DCBRD outperformed CB-AODV and AODV in terms of routing overhead, end-to-end delay and average collision rate, placing a significantly smaller load on the available communication medium. Moreover, under the highest nodal speed of 20m /sec, DCBRD scored less end-to-end delay of around 60% and 15% compared to AODV and CB-AODV. Regarding the average collision rate, the DCBRD benefit is apparently higher at the maximum considered speed, 20m/ sec scoring a benefit of 60% and 370% over CB-AODV and AODV. Concerning the overall routing overhead, with regards to the RREQ control packets in specific, the DCBRD achieved a benefit of 10% and 35% over CB-AODV and AODV at the maximum nodal speed of 20m/ sec. Incorporating dynamic counting into the traditional AODV shows no disadvantages, rather it proves to enhance the protocol performance under broad network conditions and thus it is recommended as an potential candidate to the AODV routing protocol.

Chapter 7

Conclusions and Future Work

7.1 Introduction

Recent developments in telecommunication systems have led to the widespread deployment of wireless technology as a means of communication where it is not feasible to lay cables or where there is a requirement for user mobility. Mobile Ad hoc Networks (MANETs) are a natural solution in situations where a fixed infrastructure cannot be established such as battlefield, vehicle networks, emergency or disaster [14]. Each user in this type of network acts as a router that relays messages to other users in the network, hence the name ‘multi-hop network’ [3]. However, the nature of MANETs present major communication challenges, such as frequent topological changes due to node mobility and packet collision and contention due to using a shared or limited transmission medium [5].

Broadcast is a core operation in wireless communication. It is used for addressing and for neighbour and route discovery in many well-known routing protocols [36, 145]. The key problem associated with broadcasting in the wireless medium is the contention that results due to over-zealous retransmission, of which the most extreme example is flooding [44]. More efficient broadcast schemes that address key MANET network challenges while maintaining network coverage could significantly enhance overall network performance.

Researchers tend to explore and find ways to enhance the broadcast scheme by imposing some control over retransmission [41, 45-47, 49-51, 54, 56, 59, 60, 100, 101, 104]. Those efforts fall into two categories: deterministic and stochastic. Deterministic schemes [46, 47, 49, 50, 54] control excess flooding by building a knowledge-base of the network, which is used to send the broadcast message to the right candidate. This may work well in small networks with few nodes but would not scale well as networks grow in size. Stochastic schemes, [41, 51, 58, 104, 105] in the other hand, maintain a simple decision making scheme, depending generally on criteria derived from the received broadcast message. This would aid network scalability and keep computational overhead to a minimum. While maintaining minimal overhead and reducing excess broadcast, simple stochastic schemes are still insufficient. To achieve maximum reachability, they need a stable nodal distribution, and that is impossible in real-world MANETs, as the topology changes dynamically all the time. Additionally, some schemes may need additional hardware, such as a GPS device [44] to establish broadcast criteria. The aim of this research is to propose and analyse a hybrid broadcast scheme that combines the simplicity of stochastic schemes with neighbourhood analysis to reduce the number of redundant retransmissions, while maintaining the network coverage without the need of added hardware capabilities.

7.2 Summary of Results

This research has focused on the development and analysis of the dynamic counter-based algorithm as a broadcasting mechanism specifically designed to alleviate the problems related to broadcasting contention and collision discussed above. The main contributions made by this research are summarised below.

7.2.1 Fixed counter-based

- Fixed counter-based broadcasting [44] was one of the earliest suggestions aimed at minimising the problems related to flooding in the wireless medium. That said, there has been barely any attempt to analyse the scheme performance under the effect of different operating conditions of variable traffic loads, transmission ranges, RAD waiting time and nodal densities. Motivated by this observation, the first part of this research carried out the basic study and analysis of the fixed counter-based scheme performance under variable network operational conditions of traffic load and density.

- The study of the counter-based broadcast was conducted based on the initial specifications of the scheme [44]. Based on those, an ns-2 implementation was carried out [42]. This implementation of the counter-based code [42] was primarily modified to encompass the realisation of different threshold values, supporting the IEEE 802.11b standard with a maximum data rate of 11Mbit/sec and configuring the *Two-ray* propagation model with a transmission range of 100m, 150m and 250m. These modifications were built mostly upon the ns-2.33. The extensive simulation analysis conducted shows that under the network settings implemented using different traffic loads and network nodal densities, a considerable amount of packet saving is achievable by the fixed-counter-based scheme, provided that the appropriate threshold value is selected. Correspondingly, the results show that with higher threshold values, the amount of saving is degraded (inverse relation). For example, in networks with varying traffic load, the increase of the threshold value from 2 to 6 decreases the saving by an average of 30%, while the scheme reachability remains the same with different threshold values.

- Initial implementation of the counter-based broadcast employed a specific waiting time range that is bounded by the interval (0-Tmax]. However, this research has proved that this range is strongly correlated to the network parameters selected, such as network size, transmission range and nodal speed. Selecting an appropriate RAD range would affect the network performance.

- Implementing the fixed counter-based broadcast, a node would rebroadcast a packet according to a pre-selected static threshold value. This approach may show some benefit with small networks, with a predictable number of nodes. However, node distribution in MANETs is in constant flux as the topology changes, with nodes moving in or out of others reach. The behaviour of the counter-based scheme with larger networks is also considered in the second part of this research, comparing it to the proposed scheme outlined below.

7.2.2 Dynamic counter-based

- Motivated by the previous points, the second part of the research has proposed a new broadcast scheme, Dynamic Counter-Based (DCB) broadcasting. In this approach, when a node receives a new broadcast message it initiates a counter and dynamically selects a threshold value according to the local neighbourhood information at that position and time. The node then counts duplicate received messages until a random assessment delay expires. When this happens, the counter is checked: if it exceeded the threshold value the rebroadcast is inhibited, otherwise the message is forwarded.

- Extensive simulation studies have been conducted to compare the performance of the DCB scheme to that of the counter-based (CB) and flooding, with two fundamental factors determining network conditions: node density and traffic load. Results show that the performance of DCB outperformed the other schemes in terms of saved rebroadcast, collision rate, reachability and end-to-end delay in most of the cases considered. For example, the collision rate reduction in a dense network of 300 nodes would be around 1000% and 8000% compared to CB and flooding respectively, and under the highest considered packet injection rate, 30 packet/ sec, DCB was scoring an advantage of 20% lower collision rate compared to CB and flooding.

7.2.3 The Metropolitan mobility model study

- The third part of this research carried a study of DCB, CB and flooding under a Metropolitan Model (MM). This compares the schemes in a network given the space, movement and speed constraints likely to be experienced in an urban vehicular application. Two main scenarios are simulated, called the highway and city models. The highway model implements an open plan terrain with no obstacles or buildings, having the nodes move at a high speed of up to 70 km/ hour, as might be experienced in an outer-city environment. The second model implements a built-up area with the existence of buildings and other obstacles, as might be expected in a built-up city centre. Moreover, this model implements relay points at cross roads to repair the network partitions that result from the existence of densely packed buildings.

- The implementation of the schemes under the two considered metropolitan environments, highway and city, show significant advantage for the DCB over the other two schemes. Under the highway model, DCB improved saved rebroadcast up to 60% compared to the counter-based, and 90% compared to flooding, even under high density and high mobility conditions. Employing the city model, the amount of improvement in the DCB’s saved rebroadcast was 20% over CB and 70% over flooding. Moreover, DCB’s reachability is greater than or equal to the other two schemes implemented under both models.

7.2.4 The Dynamic counting route discovery

- The performance study of most of the existing broadcast schemes, including the new proposed scheme, DCB, has been carried out using only broadcast traffic. That is, each packet sent is targeted at all network nodes. There are no significant studies that implement those broadcasting schemes in an actual application such as routing. In an effort to bridge this gap, the fourth part of this research has examined the operation of these broadcasting schemes implemented as a route discovery technique within the AODV routing protocol. The variants of AODV thus implemented are referred to as Dynamic Counter-Based Route Discovery (DCBRD), Counter-Based AODV (CB-AODV) and conventional flooding AODV (AODV).

- The performance of the DCBRD has been compared against that of AODV employing counter-based route discovery, and against conventional flooding (AODV) under different network conditions of variable density, traffic load and nodal speed. Simulation results show that for all considered network densities, DCBRD outperforms the other two routing protocols in terms of routing overhead, collision rate and end-to-end delay. As to the network throughput, the DCBRD again outperforms the other two routing protocols, especially in dense networks. In terms of collision rate at high densities the increase of collisions in CB-AODV is around 80%, compared to the DCBRD collision increase of only 20%, implying better scalability for the DCBRD protocol. Under variable traffic loads considering a different number of data connections, DCRBD performed better. In terms of overhead, at the maximum considered network load of 40 data connections, DCBRD scored smaller overhead by 30% and 40% compared to the CB-AODV and AODV respectively. Moreover, for most considered nodal speeds, the DCBRD outperformed CB-AODV and AODV. Specifically, under the highest nodal speed of 20m /sec, DCBRD scored less end-to-end delay of around 15% and 61%; and fewer collisions of around 60% and 370% compared to the CB-AODV and AODV.

7.3 Directions for Future Work

Through this research several interesting issues have surfaced that require further study and investigation:

- While most of the existing schemes were studied under a random nodal movement using the Random WayPoint mobility model, this research proposed and analysed the study of the considered schemes in a metropolitan mobility scenario, where the velocity and node direction is constrained by streets, cross points and lanes. A possible line of research would extend the investigation and study of the schemes' performance under other mobility models, such as group and free walk models.

- This research explored the dynamic threshold analysis based on the local neighbourhood density. However, some preliminary studies done through the course of this research suggest that the incorporation of a dynamic RAD into the DCB scheme would show some benefit with regards to the minimisation of unnecessary delay. Specifically, a short RAD would be used for extremely dense or extremely sparse neighbourhoods and a medium to long RAD would be used with medium neighbourhood densities.

- This research presented an extensive performance analysis of the considered schemes in pure broadcast approach and as a technique of route discovery in one of the well-known reactive routing protocols, AODV. It would be interesting to study and analyse those schemes as a means of route discovery in the new reactive routing Ad hoc On-demand Multipath Distance Vector (AOMDV) [90] that is proposed and approved to be a part of the ns-2 (2.34) as an extension to the conventional AODV routing.

- Most of the surveyed studies, including the ones proposed in this thesis, have carried out the broadcasting study using the ns-2 network simulator. The ns-2 network simulator provides an excellent facility to develop the different broadcast or routing protocols. However, it would be interesting to do a comparative study between the broadcasting schemes implemented under ns-2 and OMNeT++[110], for example.

- Most existing studies, including the ones described in this thesis, have relied on simulation as a means of calibration and analysis. However, simulation studies may require the assumption of many simplifications to keep the complexity of the different network aspects implemented under control. Until now, there have been some limited initiatives in the direction of MANETs systems deployment, real experiments and emulation [150-152]. Those are mainly simple exploratory testbeds that are implemented to study a routing protocol in a specific setting. Provided the availability of adequate computational resources and infrastructure, it would be useful to carry out real experimental measurements and verify simulation results obtained in this research.

- In this research, the performance analysis of the proposed broadcasting scheme is studied under the Constant Bit Rate (CBR) broadcasting pattern, where the packets are sent constantly with a pre-determined rate relying on a UDP connection. Although this tests the schemes under an intense traffic condition, it would be interesting to explore the scheme behaviour under different patterns such as those generated by dominant TCP traffic.

References

[1] W. Stallings, *Wireless Communications and Networks*: Prentice Hall, 2002.

[2] H. Labiod, A. Hossam, and C. D. Santis, *WI-Fi, Bluetooth, Zigbee and Wimax*: Springer, 2007.

[3] P. Nicopolitidis, M. S. Obaidat, G. I. Papadimitriou, and A. S. Pomportsis, *Wireless Networks*: Wiley, 2003.

[4] K. R. Rao, Z. S. Bojkovic, and D. A. Milovanovic, *Wireless Multimedia Communications: Convergence, DSP, QoS, and Security*: CRC Press, 2009.

[5] S. Basagni, M. Conti, S. Giordano, and I. Stojmenovic, *Mobile Ad Hoc Networking* Wiley-Blackwell, 2004.

[6] J. Schiller, *Mobile Communications*, 2 ed: Addison Wesley, 2003.

[7] C. E. Perkins, *Ad Hoc Networking*: Addison Wesley, 2001.

[8] "IEEE Standard for Information technology telecommunications and information exchange between systems local and metropolitan area networks specific requirements," IEEE Computer Society, New York2007.

[9] C. S. R. Murthy and B. S. Manoj, *Ad Hoc Wireless Networks: Architectures and Protocols*: Prentice Hall PTR, 2004.

[10] H. Karl and A. Willig, *Protocols and Architectures for Wireless Sensor Networks*: Wiley, 2007.

[11] "Wireless LAN medium access control (MAC) and physical layer (PHY) specifications." Accessed: 26 June 2009. Retrieved from: www.standards.ieee.org

[12] "mobily." Accessed: 27 April 2010. Retrieved from: www.mobily.com.sa

[13] "Urban Wimax." Accessed: 27 April 2010. Retrieved from: www.urbanwimax.co.uk

[14] J. Geier, *Wireless LANs*, 2 ed: SAMS, 2002.

[15] D. Katsaros, A. Napoulos, and Y. Manolopous, *Wireless Information Highways*, 2005.

[16] C. Y. Chong, R. S. K. Wee, S. S. Lian, and T. J. Hui, "Mobile Ad Hoc Networking." Accessed: 30 June 2009 Retrieved from: www.dsta.gov.sg/index.php/572-Mobile-Ad-Hoc-Networking

[17] S. Corson and J. Macker,"Mobile Ad Hoc Networking (MANET): Routing Protocol Performance Issues and Evaluation Considerations", RFC 2501,

[18] B. A. Fette, *Cognitive Radio Technology*, Second ed: Academic Press, 2009.

[19] T. Plesse, J. Lecomte, C. Adjih, M. Badel, and P. Jacquet, "OLSR Performance Measurement in a Military Mobile Ad-hoc Network," presented at The 24th International Conference on Distributed Computing Systems Workshops, Hachioji, Tokyo, Japan, 2004.

[20] H. Wang, B. Crilly, W. Zhao, C. Autry, and S. Swank, "Implementing Mobile Ad Hoc Networking (MANET) over Legacy Tactical Radio Links," presented at The IEEE Military Communications Conference (MILCOM '07), Clarksburg, MD, USA, 2007.

[21] J. L. Burbank, P. F. Chimento, B. K. Haberman, and W. T. Kasch, "Key Challenges of Military Tactical Networking and the Elusive Promise of MANET Technology," *IEEE Communications Magazine*, vol. 44, pp. 39-45, 2006.

[22] "The Brigade Combat Team." Accessed: 28 March 2011. Retrieved from: www.bctmod.army.mil

[23] C.-Y. J. Chiang, R. Chadha, S. Newman, and R. Lo, "Towards Automation of Management and Planning for Future Military Tactical Networks," presented at The IEEE Military Communications Conference (MILCOM'06), Washington, D.C., 2006.

[24] D. Bottazzi, A. Corradi, and R. Montanari, "Enabling Context-Aware Group Collaboration in MANETs," presented at The Autonomous Decentralized Systems, (ISADS'05), Chengdu, Jiuzhaigou, China, 2005.

[25] R. Prakash and R. Baldoni, "Architecture for Group Communication in Mobile Systems," presented at The Seventeenth IEEE Symposium on Reliable Distributed Systems, West Lafayette, IN, USA, 1998.

[26] R. Friedman, "Fuzzy Group Membership," in *Future Directions in Distributed Computing*, vol. 2584, *Lecture Notes in Computer Science*: Springer Berlin / Heidelberg, 2003, pp. 114-118.

[27] M.-o. Killijian, R. Cunningham, R. Meier, L. Mazare, and V. Cahill, "Towards Group Communication for Mobile Participants," presented at The Principles of Mobile Computing (POMC'01), Newport, Rhode Island, U.S.A., 2001.

[28] E. M. Husni, Y. Heryadi, and M. S. Arifianto, "The Smart Tele-emergency Project: a mobile telemedicine unit based on Mobile IPv6 and mobile ad-hoc network for Sabah areas," presented at The RF and Microwave Conference (RFM'04), Subang, Selangor, Malaysia, 2004.

[29] "CAR 2 CAR Communication Consortium Manifesto." Accessed: 29 April 2010. Retrieved from: www.car-to-car.org

[30] M. Torrent-Moreno, M. Killat, and H. Hartenstein, "The Challenges of Robust Inter-Vehicle Communications," presented at IEEE 62nd Vehicular Technology Conference (VTC'05), 2005.

[31] S. Yanamandram and H. Shahnasser, "Analysis of DSRC based MAC protocols for VANETs," presented at The International Conference on Ultra Modern Telecommunications & Workshops (ICUMT '09), St.Petersburg, Russia, 2009.

[32] "CARLINK: Wireless Traffic Service Platform for Linking Cars." Accessed: 29 April 2010. Retrieved from: www.carlink.lcc.uma.es

[33] L. Fan and W. Yu, "Routing in vehicular ad hoc networks: A survey," *IEEE Vehicular Technology Magazine*, vol. 2, pp. 12-22, 2007.

[34] M. Abolhasan, T. Wysocki, and E. Dutkiewicz, "A Review of Routing Protocols for Mobile Ad hoc Networks," *Ad Hoc Networks*, vol. 2, pp. 1-22, 2004.

[35] H. Labiod, *Wireless Ad Hoc and Sensor Networks*: John Wiley & Sons Inc, 2008.

[36] D. Medhi and K. Ramasamy, *Network Routing: Algorithms, Protocols, and Architectures*: Morgan Kaufmann, 2007.

[37] A. S. Tanenbaum, *Computer networks*: Prentice Hall, 2003.

[38] P. Oppenheimer, *Top-down network design*: Cisco, 2004.

[39] J. L. Antonakos and K. C. Mansfield, *Computer Networking for LANs to WANs: Hardware, Software and Security*: Delmar Cengage Learning, 2009.

[40] E. M. Royer and C.-K. Toh, "A Review of Current Routing Protocols for Ad Hoc Mobile Wireless Networks," *IEEE Personal Communications*, vol. 6, pp. 46-55, 1999.

[41] T. Yu-Chee, N. Sze-Yao, and S. En-Yu, "Adaptive Approaches to Relieving Broadcast Storms in a Wireless Multihop Mobile Ad hoc Network," *IEEE Transactions on Computers*, vol. 52, pp. 545-557, 2003.

[42] W. Brad and C. Tracy, "Comparison of Broadcasting Techniques for Mobile Ad hoc Networks," presented at Proceedings of the 3rd ACM international symposium

on Mobile ad hoc networking and computing (MOBIHOC '02), Lausanne, Switzerland, 2002.

[43] Z. Hao and J. Zhong-Ping, "Performance Analysis of Broadcasting Schemes in Mobile Ad hoc Networks," *IEEE Communications Letters*, vol. 8, pp. 718-720, 2004.

[44] T. Yu-Chee, N. Sze-Yao, C. Yuh-Shyan, and S. Jang-Ping, "The Broadcast Storm Problem in a Mobile Ad hoc Network," *Wireless Networks*, vol. 8, pp. 153-167, 2002.

[45] L. Wei and W. Jie, "On Reducing Broadcast Redundancy in Ad hoc Wireless Networks," presented at the 36th Annual Hawaii International Conference on System Sciences, Big Island, Hawaii, 2003.

[46] J. Wu and F. Dai, "Broadcasting in Ad hoc Networks Based on Self-Pruning," presented at The Twenty-Second Annual Joint Conference of the IEEE Computer and Communications Societies (INFOCOM'03) 2003.

[47] A. Qayyum, L. Viennot, and A. Laouiti, "Multipoint Relaying for Flooding Broadcast Messages in Mobile Wireless Networks," presented at The 35th Annual Hawaii International Conference on System Sciences (HICSS'02), Big Island, Hawaii, 2002.

[48] C. Gruia, linescu, I. M. Ion, W. Peng-Jun, and Z. Z. Alexander, "Selecting Forwarding Neighbors in Wireless Ad hoc Networks," *Mobile Networks and Applications*, vol. 9, pp. 101-111, 2004.

[49] I. Stojmenovic, M. Seddigh, and J. Zunic, "Dominating Sets and Neighbor Elimination-Based Broadcasting Algorithms in Wireless Networks," *IEEE Transactions on Parallel and Distributed Systems*, vol. 13, pp. 14-25, 2002.

[50] L. Wei and W. Jie, "A Cluster-Based Backbone Infrastructure for Broadcasting in MANETs," presented at The International Parallel and Distributed Processing Symposium, Nice, France, 2003.

[51] A. Keshavarz-Haddad, V. Ribeiro, and R. Riedi, "Color-Based Broadcasting for Ad Hoc Networks," presented at 4th International Symposium on Modeling and Optimization in Mobile Ad Hoc and Wireless Networks, Boston, MA USA, 2006.

[52] P. Rogers and N. Abu-Ghazaleh, "Towards Reliable Network Wide Broadcast in Mobile Ad hoc Networks," 2004.

[53] C. E. Perkins and E. M. Royer, "Ad-hoc On-Demand Distance Vector Routing," presented at The Second IEEE Workshop on Mobile Computing Systems and Applications (WMCSA'99), New Orleans, LA USA, 1999.

[54] J. Wu and F. Dai, "Performance Analysis of Broadcast Protocols in Ad Hoc Networks Based on Self-Pruning," *IEEE Transactions on Parallel and Distributed Systems*, vol. 15, pp. 1027-1040, 2004.

[55] L. Hyojun and K. Chongkwon, "Multicast Tree Construction and Flooding in Wireless Ad hoc Networks," presented at The 3rd ACM international workshop on Modeling, analysis and simulation of wireless and mobile systems, Boston, MA USA, 2000.

[56] R. Karp, C. Schindelhauer, S. Shenker, and B. Vocking, "Randomized Rumor Spreading," presented at The 41st Annual Symposium on Foundations of Computer Science (FOCS'00), Redondo Beach, CA USA, 2000.

[57] D. Alan, G. Dan, H. Carl, I. Wes, L. John, S. Scott, S. Howard, S. Dan, and T. Doug, "Epidemic Algorithms for Replicated Database Maintenance," presented at The sixth annual ACM Symposium on Principles of distributed computing, Vancouver, British Columbia, Canada, 1987.

[58] C. Chien, H. Chin-Kai, and W. Hsien-Kang, "A Distance-Aware Counter-Based Broadcast Scheme for Wireless Ad hoc Networks," presented at IEEE Military Communications Conference (MILCOM'05), Atlantic City, NJ USA, 2005.

[59] Z. Qi and D. P. Agrawal, "Dynamic Probabilistic Broadcasting in Mobile Ad hoc Networks," presented at The IEEE 58th Vehicular Technology Conference (VTC'03), Orlando, FL USA, 2003.

[60] C. Julien and S. David, "Border Node Retransmission Based Probabilistic Broadcast Protocols in Ad-Hoc Networks," presented at The 36th Annual Hawaii International Conference on System Sciences (HICSS'03), Big Island, Hawaii, 2003.

[61] Z. J. Haas, J. Y. Halpern, and L. Li, "Gossip-Based Ad hoc Routing," presented at The Twenty-First Annual Joint Conference of the IEEE Computer and Communications Societies (INFOCOM'02), New York, New York USA, 2002.

[62] F. Bai, N. Sadagopan, and A. Helmy, "IMPORTANT: An evaluation framework to study the Impact of Mobility Patterns On RouTing in Ad-hoc NeTworks," *University of Southern California* 2005.

[63] M. S. Gast, *802.11 Wireless Networks: The Definitive Guide*: O'Reilly, 2002.

[64] D. D. Chowdhury, *High Speed LAN Technology Handbook*: Springer, 2000.

[65] T. Dean, *Network+ Guide to Networks*, 5 ed: Course Technology, 2009.

[66] P. Roshan and J. Leary, *802.11 Wireless LAN fundamentals* Cisco Press, 2004.

[67] R. Prasad, *OFDM for wireless communications systems*: Artech House Publishers, 2004.

[68] E. P. Charles and B. Pravin, "Highly Dynamic Destination-Sequenced Distance-Vector routing (DSDV) for mobile computers," *ACM SIGCOMM Computer Communication Review*, vol. 24, pp. 234-244, 1994.

[69] C.-c. Chiang, H.-k. Wu, W. Liu, and M. Gerla, "Routing in Clustered Multihop, Mobile Wireless Networks with Fading Channel," *IEEE Singapore International Conference on Networks*, pp. 197-211, 1997.

[70] T.-W. Chen and M. Gerla, "Global State Routing: A New Routing Scheme for Ad-hoc Wireless Networks," presented at IEEE International Conference on Communications (ICC'98), Atlanta, Georgia, USA, 1998.

[71] P. Guangyu, M. Gerla, and C. Tsu-Wei, "Fisheye State Routing: a Routing Scheme for Ad hoc Wireless Networks," presented at IEEE International Conference on Communications (ICC'00), 2000.

[72] B. Stefano, C. Imrich, R. S. Violet, and A. W. Barry, "A Distance Routing Effect Algorithm for Mobility (DREAM)," in *The Fourth annual ACM/IEEE international conference on Mobile computing and networking*. Dallas, Texas, United States: ACM, 1998.

[73] T. Clausen and P. Jacquet,"Optimized Link State Routing Protocol (OLSR)", RFC 3626,

[74] R. Ogier, F. Templin, and M. Lewis,"Topology Dissemination Based on Reverse-Path Forwarding (TBRPF)", RFC 3684, 17 Feb 2004.

[75] M. Shree and J. J. Garcia-Luna-Aceves, "An Efficient Routing Protocol for Wireless Networks," *Special issue: routing in mobile communications networks*, vol. 1, pp. 183-197, 1996.

[76] P. Jacquet, P. Muhlethaler, T. Clausen, A. Laouiti, A. Qayyum, and L. Viennot, "Optimized Link State Routing Protocol for Ad hoc Networks," presented at The IEEE International Multi Topic Conference (INMIC'01), Lahore University of Management Sciences, Pakistan, 2001.

[77] D. Raffo, *Security Schemes for the OLSR Protocol for Ad Hoc Networks*, PhD thesis, University of Paris 6: Paris 2005.

[78] C. Perkins, E. Belding-Royer, and S. Das,"Ad hoc On-Demand Distance Vector (AODV) Routing", RFC 3561,

[79] D. B. Johnson and D. A. Maltz, "Dynamic Source Routing in Ad Hoc Wireless Networks," *Mobile Computing*, vol. 353, pp. 153--181, 1996.

[80] M. S. Corson and E. Anthony, "A Distributed Routing Algorithm for Mobile Wireless Networks," *Wireless Networks*, vol. 1, pp. 61-81, 1995.

[81] J. Raju and J. J. Garcia-Luna-Aceves, "A New Approach to On-Demand Loop-Free Multipath Routing," presented at The Eight International Conference on Computer Communications and Networks, Boston, USA, 1999.

[82] A. George and T. Rahim, "RDMAR: A Bandwidth-Efficient Routing Protocol for Mobile Ad hoc Networks," in *The 2nd ACM international workshop on Wireless mobile multimedia*. Seattle, Washington, USA, 1999.

[83] K. Young-Bae and H. V. Nitin, "Location-Aided Routing (LAR) in Mobile Ad hoc Networks," *Wireless Networks*, vol. 6, pp. 307-321, 2000.

[84] M. Gunes, U. Sorges, and I. Bouazizi, "ARA-The Ant-Colony Based Routing Algorithm for MANETs," presented at The International Conference on Parallel Processing Workshops, 2002.

[85] S. William and M. Gerla, "IPv6 Flow Handoff in Ad hoc Wireless Networks Using Mobility Prediction," presented at Global Telecommunications Conference (GLOBECOM'99), 1999.

[86] R. Dube, C. D. Rais, W. Kuang-Yeh, and S. K. Tripathi, "Signal Stability-Based Adaptive Routing (SSA) for Ad hoc Mobile Networks," *The IEEE Personal Communications*, vol. 4, pp. 36-45, 1997.

[87] I. Chakeres and C. Perkins, "Dynamic MANET On-demand (DYMO) Routing." Accessed: 27 June 2009. Retrieved from: http://www.ietf.org/internet-drafts/draft-ietf-manet-dymo-17.txt

[88] R. Bai and M. Singhal, "DOA: DSR over AODV Routing for Mobile Ad Hoc Networks," *IEEE Transactions on Mobile Computing*, vol. 5, pp. 1403-1416, 2006.

[89] Z. Bilgin and B. Khan, "A Dynamic Route Optimization Mechanism for AODV in MANETs," presented at The IEEE International Conference on Communications (ICC), Cape Town, 2010.

[90] M. K. Marina and a. S. R. Das, "Ad hoc on-demand multipath distance vector routing," *ACM SIGMOBILE Mobile Computing and Communications Review*, vol. 6, 2002.

[91] Z. J. Haas, "A New Routing Protocol for the Reconfigurable Wireless Networks," presented at The IEEE 6th International Conference on Universal Personal Communications Record, San Diego, CA, USA, 1997.

[92] M. Joa-Ng and I. T. Lu, "A Peer-to-Peer Zone-Based Two-Level Link State Routing for Mobile Ad hoc Networks," *IEEE Journal on Selected Areas in Communications*, vol. 17, pp. 1415-1425, 1999.

[93] L. Huaizhi and M. Singhal, "A Scalable Routing Protocol for Ad hoc Networks," presented at The IEEE 61st Vehicular Technology Conference (VTC'05), Stockholm, Sweden, 2005.

[94] S. Radhakrishnan, G. Racherla, C. N. Sekharan, N. S. V. Rao, and S. G. Batsell, "DST-A Routing Protocol for Ad hoc Networks Using Distributed Spanning Trees," presented at The IEEE Wireless Communications and Networking Conference (WCNC'99), New Orleans, LA, USA, 1999.

[95] N. Nikaein, H. Labiod, and C. Bonnet, "DDR-Distributed Dynamic Routing Algorithm for Mobile Ad hoc Networks," presented at First Annual Workshop on Mobile and Ad Hoc Networking and Computing (MobiHOC'00), Boston, MA, USA, 2000.

[96] Z. J. Haas, M. R. Pearlman, and P. Samar, "The Intrazone Routing Protocol (IARP) for Ad Hoc Networks." Accessed: 27 June 2009. Retrieved from: www.ietf.org/proceedings/02nov/I-D/draft-ietf-manet-zone-iarp-02.txt

[97] Z. J. Haas, M. R. Pearlman, and P. Samar, "The Interzone Routing Protocol (IERP) for Ad Hoc Networks." Accessed: 27 June 2009. Retrieved from: http://www.ietf.org/proceedings/02nov/I-D/draft-ietf-manet-zone-ierp-02.txt

[98] C. Perkins, E. Belding-Royer, and S. Das,"Ad hoc On-Demand Distance Vector (AODV) Routing", RFC 3561, 2 July 2003.

[99] P. Wei and L. Xi-Cheng, "On The Reduction of Broadcast Redundancy in Mobile Ad hoc Networks," presented at The First Annual Workshop on Mobile and Ad Hoc Networking and Computing (MobiHOC'00) Boston, MA USA, 2000.

[100] J. Wu and F. Dai, "Efficient Broadcasting with Guaranteed Coverage in Mobile Ad Hoc Networks," *IEEE Transactions on Mobile Computing*, vol. 4, pp. 259-270, 2005.

[101] J. Wu and F. Dai, "A Generic Distributed Broadcast Scheme in Ad Hoc Wireless Networks," *IEEE Transactions on Computers*, vol. 53, pp. 1343-1354, 2004.

[102] S. S. Skiena, *The Algorithm Design Manual*: Springer, 1998.

[103] J. Y. Yu and P. H. J. Chong, "A Survey of Clustering Schemes for Mobile Ad hoc Networks," *IEEE Communications Surveys & Tutorials*, vol. 7, pp. 32-48, 2005.

[104] Y. Sasson, D. Cavin, and A. Schiper, "Probabilistic Broadcast for Flooding in Wireless Mobile Ad hoc Networks," presented at The IEEE Wireless Communications and Networking (WCNC'03), New Orleans, LA USA, 2003.

[105] M. Bani-Yassein, M. Ould-Khaoua, L. M. Mackenzie, and S. Papanastasiou, "Performance Analysis of Adjusted Probabilistic Broadcasting in Mobile Ad Hoc Networks," *International Journal of Wireless Information Networks*, vol. 13, pp. 127-140, 2006.

[106] H. Wendi Rabiner, K. Joanna, and B. Hari, "Adaptive Protocols for Information Dissemination in Wireless Sensor Networks," presented at The 5th annual ACM/IEEE international conference on Mobile computing and networking, Seattle, Washington, USA, 1999.

[107] A. V. Kini, V. Veeraraghavan, N. Singhal, and S. Weber, "SmartGossip: An Improved Randomized Broadcast Protocol for Sensor Networks," presented at The Fifth International Conference on Information Processing in Sensor Networks (IPSN'06) Nashville, Tennessee, USA, 2006.

[108] S. O. al-Humoud, L. M. Mackenzie, and J. Abdulai, "Neighbourhood-Aware Counter-Based Broadcast Scheme for Wireless Ad Hoc Networks," presented at 2008 IEEE GLOBECOM Workshops, New Orleans, LA USA, 2008.

[109] X. Hui, W. Xianren, H. R. Sadjadpour, and J. J. Garcia-Luna-Aceves, "A Unified Analysis of Routing Protocols in MANETs," *IEEE Transactions on Communications*, vol. 58, pp. 911-922, 2010.

[110] Y. Pan-long, T. Chang, and Y. Yong, "Analysis on Optimizing Model for Proactive Ad hoc Routing Protocol," presented at The IEEE Military Communications Conference, MILCOM'05, 2005.

[111] W. Chris, D. Arta, and C. Tracy, "A call to arms: it's time for REAL mobility models," *ACM SIGMOBILE Mobile Computing and Communications Review*, vol. 12, pp. 34-36, 2008.

[112] "The Network Simulator ns-2." Accessed: 11 May 2010. Retrieved from: www.isi.edu/nsnam/ns

[113] Z. Xiang, B. Rajive, and G. Mario, "GloMoSim: a library for parallel simulation of large-scale wireless networks," *SIGSIM Simul. Dig.*, vol. 28, pp. 154-161, 1998.

[114] OPNET, "OPNET Modeler® Wireless Suite." Accessed: 9 August 2009. Retrieved from: http://www.opnet.com
[115] "QualNet." Accessed: 24 Jan 2011. Retrieved from: www.scalable-networks.com/products/qualnet
[116] "The Network Simulator ns-2: Validation Tests." Accessed: 11 May 2010. Retrieved from: www.isi.edu/nsnam/ns/ns-tests.html
[117] G. S. Robert, "Verification and validation of simulation models," in *Proceedings of the 30th conference on Winter simulation*. Washington, D.C., United States: IEEE Computer Society Press, 1998.
[118] H. Tristan, K. David, and A. Ilya, "The changing usage of a mature campus-wide wireless network," in *Proceedings of the 10th annual international conference on Mobile computing and networking*. Philadelphia, PA, USA: ACM, 2004.
[119] K. David and E. Kobby, "Analysis of a campus-wide wireless network," *Wirel. Netw.*, vol. 11, pp. 115-133, 2005.
[120] M. Marvin and M. V. Geoffrey, "Access and mobility of wireless PDA users," *SIGMOBILE Mob. Comput. Commun. Rev.*, vol. 9, pp. 40-55, 2005.
[121] "The Community Resource for Archiving Wireless Data At Dartmouth." Accessed: 24 May 2010. Retrieved from: crawdad.cs.dartmouth.edu
[122] T. Camp, J. Boleng, and V. Davies, "A Survey of Mobility Models for Ad Hoc Network Research," *Wireless Communication & Mobile Computing (WCMC): Special issue on Mobile Ad Hoc Networking: Research, Trends and Applications,*, vol. 2, no. 5, pp. 483-502 2002.
[123] F. Bai and A. Helmy, "A Survey of Mobility Models in Wireless Adhoc Networks," in *Wireless Ad Hoc and Sensor Networks*: Kluwer Academic Publishers, 2004.
[124] A. Goldsmith, *Wireless Communications*: Cambridge University Press, 2005.
[125] T. S. Rappaport, *Wireless Communications Principles and Practice*, Second ed: Prentice Hall, 2001.
[126] "ns Notes and Documentation." Accessed: 11 March 2011. Retrieved from: www.isi.edu/nsnam/ns/doc
[127] A. Mohammed, *Hybrid Probabilistic Broadcast Schemes for Mobile Ad hoc Networks*, PhD thesis, University of Glasgow: Glasgow, 2009.
[128] I. D. Chakeres and E. M. BeldingRoyer, "The Utility of Hello Messages for Determining Link Connectivity," presented at The 5th International Symposium on Wireless Personal Multimedia Communications (WPMC), Honolulu, Hawaii, 2002.
[129] Z. Qi and D. P. Agrawal, "Analysis of Leveled Probabilistic Routing in Mobile Ad hoc Networks," presented at The IEEE International Conference on Communications (ICC'04), Paris, France, 2004.
[130] H. Hartenstein and K. Laberteaux, *VANET Vehicular Applications and Inter-Networking Technologies*: Wiley, 2010.
[131] T. A. Lasky and B. Ravani, "A Review of Research Related to Automated Highway Systems," Federal Highway Administration, Davis, CA1993.
[132] "ITS Japan." Accessed: 2 March 2011. Retrieved from: www.its-jp.org/english
[133] "ITS America." Accessed: 2 March 2011. Retrieved from: www.itsa.org
[134] "ERTICO, ITS Europe." Accessed: 2 March 2011. Retrieved from: www.ertico.com
[135] M. Amadeo, C. Campolo, and A. Molinaro, "Enhancing IEEE 802.11p/WAVE to provide infotainment applications in VANETs," *Ad Hoc Networks*, 2010.
[136] H. T. Cheng, H. Shan, and W. Zhuang, "Infotainment and road safety service support in vehicular networking: From a communication perspective " *Mechanical Systems and Signal Processing*, 2010.

[137] L. Rongxing, L. Xiaodong, Z. Haojin, and S. Xuemin, "SPARK: A New VANET-Based Smart Parking Scheme for Large Parking Lots," presented at IEEE INFOCOM, 2009.

[138] A. Nandan, S. Das, B. Zhou, G. Pau, and M. Gerla, "AdTorrent: Digital Billboards for Vehicular Networks," presented at The International Workshop on Vehicle-to-Vehicle Communications (V2VCOM), California, USA, 2005.

[139] J. Luo and J.-P. Hubaux, "A Survey of Inter-Vehicle Communication," 2004.

[140] K. Bilstrup, E. Uhlemann, E. G. Strom, and U. Bilstrup, "Evaluation of the IEEE 802.11p MAC Method for Vehicle-to-Vehicle Communication," presented at The IEEE 68th Vehicular Technology Conference, 2008.

[141] "Communications Access for Land Mobiles." Accessed: 8 March 2011. Retrieved from: www.calm.hu

[142] "Cooperative Vehicle-Infrastructure Systems." Accessed: 8 March 2011. Retrieved from: www.cvisproject.org

[143] S. O. Al-Humoud, L. M. Mackenzie, and J. M. Abdulai, "Neighbourhood-Aware Counter-Based Broadcast Scheme for Wireless Ad Hoc Networks," presented at The IEEE GLOBECOM Workshops, New Orleans, LA USA, 2008.

[144] M. Ilyas, *The Handbook of Ad hoc Wireless Networks*. London CRC Press, 2003.

[145] D. Lang, *Routing protocols for mobile ad hoc networks: classification, evaluation and challenges*. Saarbrücken: VDM Verlag Dr. Müller, 2008.

[146] S. K. Sarkar, T. G. Basavaraju, and C. Puttamadappa, *Ad hoc Mobile Wireless Networks: Principles, Protocols, and Applications*: Auerbach Publications, 2008.

[147] D. C. Ian and M. B.-R. Elizabeth, "AODV Routing Protocol Implementation Design," in *Proceedings of the 24th International Conference on Distributed Computing Systems Workshops (ICDCSW'04)*: IEEE Computer Society, 2004.

[148] V. V. Das, R. Vijayakumar, N. C. Debnath, J. Stephen, N. Meghanathan, S. Sankaranarayanan, P. M. Thankachan, F. L. Gaol, and N. Thankachan, "Information Processing and Management," presented at International Conference on Recent Trends in Business Administration and Information Processing, BAIP 2010, , Trivandrum, Kerala, India, 2010.

[149] C. Richard, C. E. Perkins, and C. Westphal, "Defining an Optimal Active Route Timeout for the AODV Routing Protocol," presented at Second Annual IEEE Communications Society Conference on Sensor and Ad Hoc Communications and Networks, 2005.

[150] N. Trung, N. Hoai-Nam, and Y. Shinoda, "eBATMAN: An Emulator-BAsed Testbed for Studying Mobile Ad-Hoc Network Security," presented at IEEE RIVF International Conference on Computing and Communication Technologies, Research, Innovation, and Vision for the Future (RIVF), Hanoi, 2010.

[151] L. Barolli, M. Ikeda, F. Xhafa, and A. Duresi, "A Testbed for MANETs: Implementation, Experiences and Learned Lessons," *IEEE Systems Journal*, vol. 4, pp. 243-252, 2010.

[152] M. Hiyama, M. Ikeda, L. Barolli, E. Kulla, F. Xhafa, and A. Durresi, "Experimental Evaluation of a MANET Testbed in Indoor Stairs Scenarios," presented at International Conference on Broadband, Wireless Computing, Communication and Applications (BWCCA), Fukuoka, 2010.

Publications during the course of this research

- S. O. Al-Humoud, L. M. Mackenzie, and W. Vanderbauwhede, "Dynamic Counter-Based Broadcast in MANETs," presented at The 5th ACM International Workshop on Wireless Multimedia Networking and computing, WMuNeP'09, Tenerife, Spain, 2009.
- S. O. Al-Humoud, L. M. Mackenzie, M. Ould-Khaoua, and J. M. Abdulai, "Threshold Analysis of Adjusted Counter-Based Broadcast in MANETs," presented at The Second UKSIM European Symposium on Computer Modelling and Simulation (EMS'08), Liverpool Hope University, Liverpool, UK, 2008.
- S. O. Al-Humoud, L. M. Mackenzie, M. Ould-Khaoua, and J. M. Abdulai, "RAD Analysis of Adjusted Counter-Based Broadcast in MANETs," presented at The 24th UK Performance Engineering Workshop, (UKPEW'08), Imperial College London, UK, 2008.
- S. O. Al-Humoud, L. M. Mackenzie, and J. M. Abdulai, "Neighbourhood-Aware Counter-Based Broadcast Scheme for Wireless Ad Hoc Networks," presented at The IEEE GLOBECOM Workshops, New Orleans, LA USA, 2008.
- S. O. Al-Humoud, L. M. Mackenzie, M. Ould-Khaoua, and J. M. Abdulai, "A Mobility Analysis of Adjusted Counter-Based Broadcast in MANETs," presented at The 9th Annual Post Graduate Symposium on the Convergence of Telecommunications, Networking and Broadcasting, (PGNET'08), Liverpool John Moores University, UK, 2008.