Hybrid Probabilistic Broadcast Schemes for Mobile Ad hoc Networks

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Abstract

Broadcasting is one of the fundamental data dissemination mechanisms in mobile ad hoc network (MANET), which is, for instance, extensively used in many routing protocols for route discovery process. The dynamic topology and limited communication bandwidth of such networks pose a number of challenges in designing an efficient broadcasting scheme for MANETs. The simplest approach is *flooding*, where each node retransmit every unique received packet exactly once on each outgoing link. Although flooding ensures that broadcast packet is received by all network nodes, it generates many redundant transmissions which can trigger high transmission collision and contention in the network, a phenomenon referred to as the *broadcast storm*.

Several probabilistic broadcast algorithms have been proposed that incur low communication overhead to mitigate the broadcast storm problem and tend to show superior adaptability in changing environments when compared to deterministic (i.e., non-probabilistic) schemes. However, most of these schemes reduce redundant broadcasts at the expense of reachability, a requirement for near-global network topological information or support from additional hardware.

This research argues that broadcast schemes that combine the important features of fixed probabilistic and counter-based schemes can reduce the broadcast storm problem without sacrificing reachability while still achieving better end-to-end delay. To this end, the first part of this research investigate the effects of forwarding probabilities and counter threshold values on the performance of fixed probabilistic and counter-based schemes. The findings of this investigation are exploited to suggest a new hybrid approach, the Probabilistic Counter-Based Scheme (PCBS) that uses the number of duplicate packets received to estimate neighbourhood density and assign a forwarding probability value to restrict the generation of so many redundant broadcast packets. The simulation results reveal that under various network conditions PCBS reduces the number of redundant transmissions, collision rate and end-to-

delay significantly without sacrificing reachability when compared against counter-based, fixed probabilistic and flood broadcasting.

Often in MANETs, there are regions of different node density due to node mobility. As such, PCBS can suffer from a degree of inflexibility in terms of rebroadcast probability, since each node is assigned the same forwarding probability regardless of its local neighbourhood conditions. To address this shortcoming, the second part of this dissertation proposes an Adjusted Probabilistic Counter-Based Scheme (APCBS) that dynamically assigns the forwarding probability to a node based on its local node density using a mathematical function. Thus, a node located in a sparse region of the network is assigned a high forwarding probability while a node located in denser region is assigned a relatively lower forwarding probability. These combined effects enhance end-to-end delay, collision rate and reachability compared to PCBS variant.

The performance of most broadcasting schemes that have been suggested for MANETs including those presented here, have been analysed in the context of “pure” broadcast scenarios with relatively little investigation towards their performance impact on specific applications such as route discovery process. The final part of this thesis evaluates the performance of the well-known AODV routing protocol when augmented with APCBS route discovery. Results indicate that the resulting route discovery approach reduces the routing overhead, collision rate and end-to-end delay without degrading the overall network throughput compared to the existing approaches based on flooding, counter-based and fixed probabilistic route discovery.

To all late in the three families

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Abbreviations

ACK	Acknowledgement
AP	Access Point
AODV	Ad hoc On-demand Distance Vector
BGR	Broadcast Relay Gateway
BSS	Basic Service Set
CBR	Constant Bit Rate
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
CTS	Clear To Send
DARPA	Defence Advanced Research Projects Agency
DCF	Distributed Coordination Function
DSDV	Destination-Sequenced Distance Vector
DSR	Dynamic Source Routing
DYMO	Dynamic MANET On-demand
ESS	Extended Service Set
FTP	File Transfer Protocol
IEEE	Institute of Electrical and Electronics Engineers
MAC	Medium Access Control
MANET	Mobile Ad hoc Network
NSF	National Science Foundation
OLSR	Optimized Link State Routing
OSI	Open Systems Interconnection
PCMCIA	Personal Computer Memory Card International Association
PDA	Personal Data Assistance
RFC	Request For Comments
RTS	Request To Send
SHARP	Sharp Hybrid Adaptive Routing Protocol
UDP	User Datagram Protocol
VANET	Vehicular Ad-hoc Network
VBR	Variable Bit Rate
Wi-Fi	Wireless-Fidelity

WLANs	Wireless Local Area Networks
WiMAX	Worldwide Interoperability for Microwave Access

Chapter 1

Introduction

The present proliferation of mobile devices (e.g., cell phones, laptops, handheld digital devices, personal digital assistants, wearable computers, etc) and the advances in wireless communication technology have stimulated the development in wireless networks and systems [1, 2]. With these advances, mobile devices with wireless interfaces have the capability of communicating with each other even when they are mobile. This type of communication paradigm has fuelled the desire for sharing information among mobile devices even in areas with no pre-existing communication infrastructure [3-7]. In many scenarios such as emergency rescue sites, battlefields, temporary conference meetings, etc, applications typically do not have central administration or an available fixed infrastructure. In such domain that lacks communication infrastructure or the existing infrastructure is inconvenient to use, mobile users can communicate through the formation of a temporary wireless Mobile Ad hoc Network (MANETs)[2].

A MANET [8] is a collection of wireless mobile devices (often referred to as nodes) forming a temporary network without the aid of any fixed infrastructure or centralized administration [9, 10]. The communication between the nodes takes place over a wireless medium, where each node communication capability within the network is restricted by its wireless transmission range, i.e., two devices can communicate directly with each other only if they are within the same transmission range. Nodes that are not within the transmission ranges of each other need the support of some intermediate nodes for their communication. As such, mobile node in MANET operates not only as a host (that generates and consumes data) but also as a router that can send and receive messages as well as forward messages for other nodes. For example, in the network depicted in Figure 1-1, Node *A* cannot communicate directly with Nodes *C* and *D* as they are both outside the range of Node A's transmission range and vice versa. In the same vein, Node *B* cannot communicate directly with Node *D* as the node is outside the range of Node B's transmission range. If Node *A* and *C* wish to exchange a packet, they need Node B to forward the packet for them, since B is inside both A's and C's transmission ranges. Likewise, exchange of packet between A and D need the support of B and C.

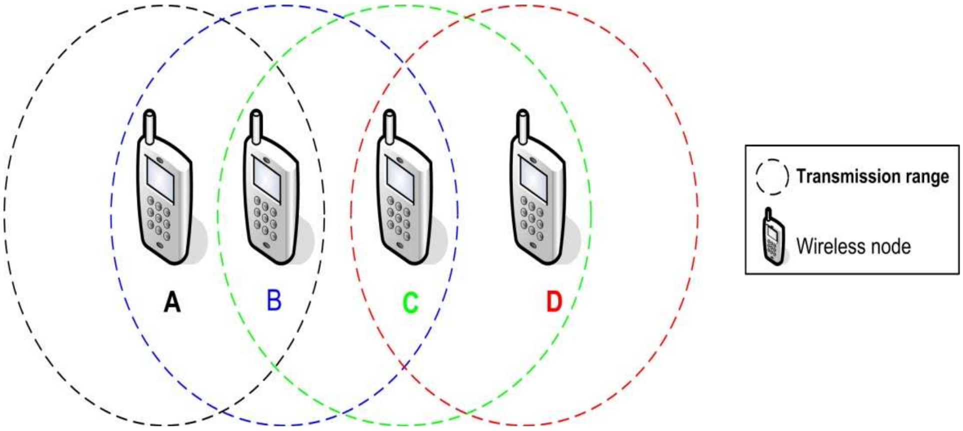

Figure 1.1: A Mobile Ad hoc Network

Due to the dynamic nature and frequent topology change of MANETs combined with the nature of wireless medium (i.e. shared physical channels and radio power limitation), mobile nodes need to exchange several messages to communicate with each other. As such, broadcast operations are frequently used in these networks. A wide-ranging MANETs applications, such as dissemination of aid information to coordinate relief activities in disaster region, resource discovery or advertisement in several routing protocols [11, 12], or sending an error message to erase invalid routes [13] employ broadcasting as a building block providing important control and route establishment functionality. Therefore, any enhancement to the process of broadcasting would have a direct benefit for important MANET applications.

1.1 Motivations

Broadcasting is the process of disseminating packets from a given source node to all other nodes in the network [14-16]. The simplest mechanism for broadcasting is *flooding*, where each node in the network forwards every unique received packet exactly once. Although flooding ensures a given packet reach every node in the network, it generates many redundant transmissions in the network [17-19]. In a dense network, more transmission redundancy would be introduced that is likely to generate significant transmission contention and collision. Such a phenomenon is referred to as *broadcast storm problem*[1] [18] and can lead to a total collapse in the operation of the entire network.

There has been considerable research efforts on mitigating the transmission redundancy associated with flooding [18, 20-23]. However, most of the proposed probabilistic schemes are inadequate in reducing the number of redundant broadcast while still guarantee that most nodes receive the packet. In some cases, the schemes require near-global network topological information [24-27] or used additional hardware devices for distance measurement or location identification [18] in order to reduce the redundant transmissions. Therefore, a broadcast scheme that can reduce the *broadcast storm problem* while still guaranteeing that all nodes receive the packet would be highly desirable.

Among the earliest proposed solutions to *broadcast storm problem* are the fixed probabilistic [18] and counter-based scheme [18]. In fixed probabilistic scheme, a mobile node rebroadcasts a packet according to a certain fixed forwarding probability value while in counter-based scheme packets are rebroadcast only when the number of copies of the packets received at a node is less than a threshold value. Although fixed probabilistic and counter-based schemes were the earliest suggested solutions to broadcast storm problem, neither of the two schemes separately is adequate in reducing redundant retransmissions and still guarantees most of the nodes receive the broadcast packet. Similarly, there has been so far hardly any attempt to analyse the effect of different forwarding probability values and threshold values on the performance of the two schemes taking into account important operating conditions in MANETs, such as node mobility, traffic load and network density.

The aim of this research is to suggest efficient probabilistic schemes for MANETs that combine the features of fixed probability and counter-based scheme in

[1] More detail on the broadcast storm problem is provided in Chapter 2.

order to mitigate the broadcast storm problem deleterious effects without sacrificing reachability (i.e. the ratio of nodes that can receive a broadcast packet).

1.2 Thesis Statement

An inefficient broadcasting method potentially leads to the broadcast storm problem which can drastically degrade network performance. This research argues that it is possible to develop efficient probabilistic broadcast schemes that can significantly reduce the degrading effect of broadcast storms without sacrificing reachability or requiring additional hardware while at the same time achieving good performance levels in terms of collision rate (i.e. the total number of packets dropped as a result of collisions per simulation time) and end-to-end delay (i.e. the delay a broadcast packet experiences to reach the node in the network).

In this thesis, I assert that:

> **T1:** A Probabilistic Counter-based Broadcast scheme (PCBS) can reduce the performance-degrading effects of the broadcast storm problem by exploiting the advantages of both fixed probabilistic and counter-based schemes. This is achieved by allowing each node to rebroadcast a received packet with a fixed forwarding probability if the number of duplicate packets received is less than a pre-defined threshold. This approach reduces the broadcast storm problem leading to improvement in end-to-end delay, reachability and number of retransmitting nodes compared to flooding, counter-based and fixed probability broadcast schemes.
>
> **T2:** The performance of PCBS can be significantly improved if the appropriate measures are taken to exploit the varying node density in MANETs. To do so, a mathematical function is used which dynamically compute the rebroadcast probability at a given node based on the node neighbourhood information (i.e. packet counter value). Nodes situated in dense area are assigned a low rebroadcast probability (as opposed to dropping the packet in PCBS) than those located in sparse area. This

scheme referred to as Adjusted Probabilistic Counter-based Broadcast Scheme (APCBS). We demonstrate that APCBS further improves reachability, collision rate and end-to-end delay compared to its PCBS variant especially in dense networks.

T3. Using the APCBS stated T2, an efficient route discovery algorithm can be developed for some reactive routing protocols (specifically Ad hoc On-demand Distance Vector routing protocol (AODV) [12]) which can further reduce the redundant transmission of Route Request (RREQ) packets associated with the conventional AODV protocol. This is achieved by making use of the number of duplicate packet received at a forwarding node to distinguish between regions of the networks that require high or low rebroadcast probabilities during the route discovery process. The simulation results reveal that the new scheme improves the route discovery process by further reducing the routing overhead, collision rate and end-to-end delay compared to counter-based, fixed probabilistic and conventional AODV route discovery methods.

1.3 Contributions

To address the research concerns listed in the motivations section, this research presents hybrid probabilistic broadcast schemes that overcome the limitations of the existing probabilistic schemes suggested previously for MANETs.

Several existing studies [17-19] have revealed that probabilistic schemes (in particular fixed probability-based and counter-based scheme) incur a lower communication overhead compared to flooding. However, the selection of an appropriate rebroadcast probability and counter threshold values are crucial to the performance of both schemes. Further, most of these studies have not taken into consideration the impact of important network operating conditions in a MANETs, such as node mobility, network density, and offered load to assess the performance of the fixed probabilistic and counter-based broadcast schemes over a wide range of forwarding probabilities and counter threshold values. As part of a preliminary investigation in this research, the first part of this dissertation investigates the impact of counter threshold and forwarding probability values on the performance of the fixed probabilistic and counter-based scheme under various network conditions characterised by node mobility, network density, and offered load. Simulation results show that an appropriate use of forwarding probability and counter threshold value can significantly reduce the redundant transmission of broadcast packets.

In the second part of this research, a new probabilistic scheme, referred to as Probabilistic Counter-based Broadcast Scheme (or PCBS), is described. The PCBS approach combines the desirable features of both fixed probabilistic and counter-based broadcast schemes. For instance one of the desirable features of the fixed probabilistic is the low number of retransmissions during broadcast operation performed in the network while that of counter-based scheme is the high achieved levels in throughput and reachability. However, given that few hybrid-based broadcasting strategies have been suggested for MANETs, the performance of the new approach will be compared against the existing schemes including flooding, fixed probabilistic and counter-based schemes.

In MANETs there are regions of various node densities and it is crucial to identify these regions so that appropriate forwarding probabilities can be assigned to each node in each region. To avoid unnecessary retransmission of broadcast packets in dense regions of the network it is appropriate to assign a low rebroadcast probability to nodes located in these regions. On the other hand, a high rebroadcast probability should be assigned to nodes located in sparse regions of the network in order to improve network connectivity. To this end, the third part of this research proposes a new probabilistic scheme, referred to as the Adjusted Probabilistic Counter-based Broadcast Scheme (or APCBS). APCBS is a further refinement of PCBS and uses a mathematical function that dynamically computes the forwarding probability value at a node based on its local neighbourhood density. Simulation results reveal that APCBS achieves superior performance in terms collision rate, number of retransmitting nodes, reachability and end-to-end delay compared to PCBS.

There has been so far comparatively little work reported investigating the performance merits of pure broadcasting algorithms in real applications, such as the route discovery process. In an effort towards filling this gap, the final part of this research evaluates the performance of APCBS as a route discovery mechanism in the AODV routing protocol. APCBS as well as fixed probabilistic and counter-based are incorporated into the AODV route discovery procedure and compared against the traditional AODV that employs simple flooding. Extensive simulation results reveal that APCBS-based route discovery achieves lower routing overhead, collision rate and end-to-end delay than the route discovery methods based on fixed probabilistic, counter-based and flooding.

1.4 Outline of the Thesis

The rest of the dissertation is organised as follows:

Chapter 2 provides the foundation necessary for the understanding of the subsequent chapters. It starts with an overview of the broadcast storm problem and describes well-known broadcasting and routing algorithms that have been proposed for MANETs. The chapter also describes the related work, method of study used and justification for the use of simulation as means of evaluating the proposed schemes. Finally, the chapter outlines the list of assumptions and performance metrics used in this research.

Chapter 3 conduct an extensive analysis of fixed probabilistic and counter-based broadcast schemes. It also investigates the performance of the two schemes for a wide range of forwarding probabilities and counter threshold values over varying network densities and traffic load.

Chapter 4 introduces the new Probabilistic Counter-based Broadcast Scheme (PCBS) for MANETs and compares its performance characteristics by means of extensive simulation experiments against those of the existing probabilistic schemes.

Chapter 5 presents the new Adjusted Probabilistic Counter-based Broadcast Scheme (APCBS) as a further refinement to PCBS. It uses a mathematical function which dynamically computes the forwarding probability value at a given node based on its neighbourhood information.

Chapter 6 presents the performance analysis of APCBS as route discovery mechanism for AODV routing protocol and compares its performance against that of existing route discovery methods.

Finally, chapter 7 concludes the dissertation by summarising the main results obtained in this research and outlines some potential directions for further research work.

Chapter 2

Background and Related Work

The main objective of this chapter is to provide the background information necessary for the understanding of the subsequent chapters. As such, the chapter is organised as follows. Section 2.1 describes the key characteristics and applications of MANETs. Section 2.2 present an overview of broadcasting protocols in MANETs. Section 2.3 presents a brief description of the network simulator (Ns-2). Section 2.4 outlines the common simulation assumptions which apply throughout this research study. Section 2.5 provides justification of the method used while simulation model and system parameters are presented in Section 2.6. Section 2.7 outlines the performance metrics employed for the evaluation of the proposed algorithms. Finally, Section 2.8 provides a summary of the chapter.

2.1 Preliminaries

The wireless communication arena has experienced an explosive growth in the past decade worldwide due to recent advances in mobile computing devices and wireless technology [16]. This arena has several segments ranging from satellite-based communication, cellular telephony, wireless local area networks (WLANs) and worldwide interoperability for microwave access (WiMAX) [16, 28].

The de facto adoption of the IEEE 802.11 standard [29] has fuelled the development of WLANs by ensuring interoperability of wireless transmission technologies among various vendors thereby aiding the technology's market penetration. This standard defines two major categories of WLANs depending on the underlying configurations, infrastructure-based and infrastructureless (or ad hoc) networks. Infrastructure-based WLANs require a special node called access point (AP), which hosts or terminals connect via existing wired LANs and act as a router and arbiter between mobile devices and the rest of the networks. This approach is used in Wi-Fi hotspots [30] to provide wireless internet access at coffee shops, airports, conferences and other public places. The set of mobile nodes that are associated with a particular AP is called the Basic Service Set (BSS) [16]. A number of BSSs can be connected together by means of a backbone network to form an Extended Service Set (ESS) [16], in order to extend the Wi-Fi coverage area. In ESS, every AP is given the same service set identifier, which serves as a network “name” for the network users.

In many dynamic environments such as disaster sites, battlefields and temporary conference meetings where people and/or vehicles need to be temporarily interconnected, it may be difficult and/or expensive to deploy infrastructure-based WLANs. For these environments, infrastructure-less or ad hoc WLANs provide a viable alternative solution. Ad hoc WLANs do not need any fixed infrastructure and require only the mobile nodes to cooperate in a peer-to-peer fashion to form a temporary network in order to exchange data. However, this configuration of the IEEE 802.11 standard is limited to single-hop communication which is only applicable to mobile nodes within a mutual transmission range. Due to increase in processing power and transceiver capability of the mobile nodes, it has become feasible to increase the communication range of temporary network using the mobile nodes themselves as forwarding agents and relying on the upper layers of the protocol stack for multi-hop path formation. Therefore, with mobile nodes acting as routers, they may form the backbone of a spontaneous network that extends the range of the ad hoc WLAN beyond the transmission radius of the source. This latter category of ad hoc WLANs is popularly referred to as a Mobile Wireless Ad Hoc Network (or MANET for short) [16, 28, 31].

2.1.1 *Characteristics of MANETs*

MANETs are self-organizing and dynamic systems in which the network topology can change on-the-fly without the intervention of a system administrator [16]. Although, MANETs inherit many characteristics found in wireless networks they also possesses some unique features which are derive from the nature of the wireless communication medium and the distributed function of the medium access mechanisms [32-35].These features are now considered in turn.

Autonomous and infrastructure-less: The network is autonomous system of mobile nodes that are connected without any infrastructure or centralized administration. Each node acts as an independent router in addition to generating and forwarding messages to other nodes that may not be within the same transmission range [10, 34, 36].

Mobility: The devices in MANETs have no physical boundary and their location changes as they move around. This movement of participating nodes makes the network topology highly dynamic as well as causing the intercommunication patterns between nodes to change frequently in an unpredictable manner [2, 32, 37]. Thus, an ongoing communication session suffers frequent path breaks. As a result, broadcasting and routing protocols for MANETs must handle mobility management efficiently [38].

Limited Resources: Most nodes in MANETs such as laptops, sensors and PDAs suffer from limited resources compared to their wired counterparts. These resources include limited energy, computational power and memory [39, 40].

Energy: Mobile devices in MANETs generally rely on batteries for their energy source. However, battery power and lifetime are finite. Many activities such as wireless signal transmission, reception, retransmission, and beaconing operations all consume battery power, and as nodes in MANETs act as both an end system and a router at the same time, additional energy is required to forward packets for other nodes.

Computational Power: The computing components used in mobile devices, such as memory and processor, are usually constrained by low capacity and processing power. Therefore, minimizing the usage of such resources is an important challenge faced in the design of MANET protocols.

Limited Bandwidth: The available frequency bandwidth of the wireless channel in MANETs is significantly lower compared to their wired counterparts [41]. Since nodes within the same transmission range shared the same wireless channel, the bandwidth available per wireless channel depends on the number of nodes and the traffic they each inject into the network. Thus, only a fraction of the total bandwidth is available for each node. This bandwidth limitation imposes a constraint on routing and broadcasting protocols when maintaining topological information.

Wireless Channel: The wireless communication medium is susceptible to a variety of transmission impediments such as path loss, interference and blockage or fading [42, 43]. Path loss of a signal is expressed as the ratio of the power of the transmitted signal to that of the received signal at the receiver on a given path [44, 45]. Its accurate estimation is critical in design and deployment of MANETs, since it measures the effects of the terrain and the carrier frequency used on signal propagation. Multi-path fading refers to the rapid fluctuations in signal strength when received at the receiver, and is usually caused by propagation mechanisms, particularly, reflection, refraction or diffraction of the transmitted signal. It is one of the major problems associated with radio frequency networks [16].

Similarly, transmission over the wireless communication medium is vulnerable to two main forms of interferences, i.e., adjacent channel and co-channel interference [46, 47]. These barriers generally restrict the data rate, reliability and range of wireless transmission. Therefore, any communication protocol for MANETs should contend with these issues.

***Heterogeneity*:** The large scope of MANET applications shows that the number of partaking nodes can range from several nodes to tens of thousands of nodes. Different scenarios may show different node mobility from static nodes such as static sensor nodes to highly mobile nodes such as vehicles or planes. Moreover, the size, memory, computational power and battery power of these nodes are very different from one another. Therefore, the heterogeneity in network, node mobility and node leads to a varying degree of topology dynamics which can affect the performance and the design of protocols required for MANETs.

***Low Connectivity and Reliability*:** Network connectivity in MANET is obtained by routing and forwarding among different mobile nodes. A particular node may fail to forward the packet due to various conditions like node acting selfishly, overloading, or broken links. These misbehaving nodes and unreliable links pose new challenges in maintaining communication route among network nodes [16]. Furthermore, collision is more likely to occur in wireless networks than wired networks because of the shared channels. The resulting high transmission error rate makes the communication less reliable.

Network Security: MANETs are generally more susceptible to information and physical threats than their fixed wired counterparts. The use of shared broadcast wireless channels means nodes with not enough physical protection are prone to security threats. In addition, due to the distributed and infrastructure-less nature of MANETs, it mainly relies on individual security solution from each mobile node as centralised security control is difficult to implement [32].

2.1.2 *Application of MANETs*

Due to the flexibility, quick and low cost of deployment, MANETs find application many areas from simple civil applications to complicated high risk applications like, emergency operations, tactical and military applications [1, 32, 36]. Below are some useful applications of MANETs.

Tactical Operations: MANETs have primarily been used for tactical network related applications in order to improve battlefield communications and survivability [1, 36]. The dynamic nature of military operations makes it impossible to rely on fixed communication infrastructure on the battlefield. As such, MANETs are used as an important option for military operations as it does not require any infrastructure establishment. Therefore, they can be used during the deployment of forces in an unknown and hostile area, for fast establishment of military communication.

Emergency Services: For emergency services such as search and rescue operation and crowd control, it is critical to find ways to enable the operations of a communication network even when conventional infrastructure-based elements are destroyed or have been disabled as part of the effects of a natural disaster like an earthquake, cyclone or hurricane. MANETs could be deployed to overcome network loss and would be a good solution for coordinating rescue efforts.

Collaborative and Group Communication: Although early MANET applications and deployments were military oriented, non military applications have grown substantially and have become the main focus recently [32]. A MANET is a feasible choice when there is a demand for temporary collaborative computing between a group of users (e.g. University campus or conference venue) as it offers a quick communication platform with minimal configuration [28, 48].

2.2 Broadcasting in MANETs

Broadcasting, the process of transmitting a packet from a source node to all other nodes in the network, is more frequent in MANETs than in wired networks, especially as the basic vehicle for on-demand route discovery. In multi-hop MANETs where most of the nodes might not be within the transmission range of the source node, intermediate nodes need to assist in the broadcast operation by forwarding the packet to other remote nodes in the network.

Broadcasting can be based on two transmission models, the *one-to-all model* and the *one-to-one* model [16]. In the *one-to-all* model, transmission by each node can reach all nodes that are within its transmission radius, while in the *one-to-one* model, each transmission is directed toward only one neighbour (via narrow beam directional antenna or separate frequencies for each node) [16, 28]. The *one-to-all* model of broadcasting is mainly studied in literature [16], and most of this thesis is devoted to that model. An example of this model is the propagation of routing control packets (e.g. route request) in some routing protocols [11, 12]. Broadcasting is also frequently deployed for news distribution (such as alarms and announcements), for resource discovery and advertisement (such as topology discovery and maintenance [49]), and for sensor data dissemination (such as data aggregation [50] and consistency update propagation [51]).

In conventional broadcast settings (i.e. flooding, where every node in the network forwards every uniquely received packet exactly once), the dissemination of packets in this way often consumes valuable network resources such as bandwidth and node power due to redundant transmissions of broadcast packets. These redundant retransmission of packets cause high contention and collision in the network, which lead to waste of limited bandwidth and potentially total collapse of the network, especially when the network is scaled. This phenomenon is referred to as the *broadcast storm problem* [18, 19].

2.2.1 *Broadcast Storm Problem*

The broadcast storm problem is a side-effect of flooding. For example, Figure 2.3 depicts a sample network with five nodes, where if node ***A*** broadcasts a packet, nodes ***B***, ***C*** and ***D*** will receive the packet. Nodes ***B***, ***C*** and ***D*** will then forward the packet and lastly ***E*** will also broadcast the packet. In fact, this case clearly shows the broadcast redundancy inherent with flooding. Forwarding the broadcast packet by nodes ***A*** and ***D*** is sufficient for the broadcast operation to cover all the five nodes.

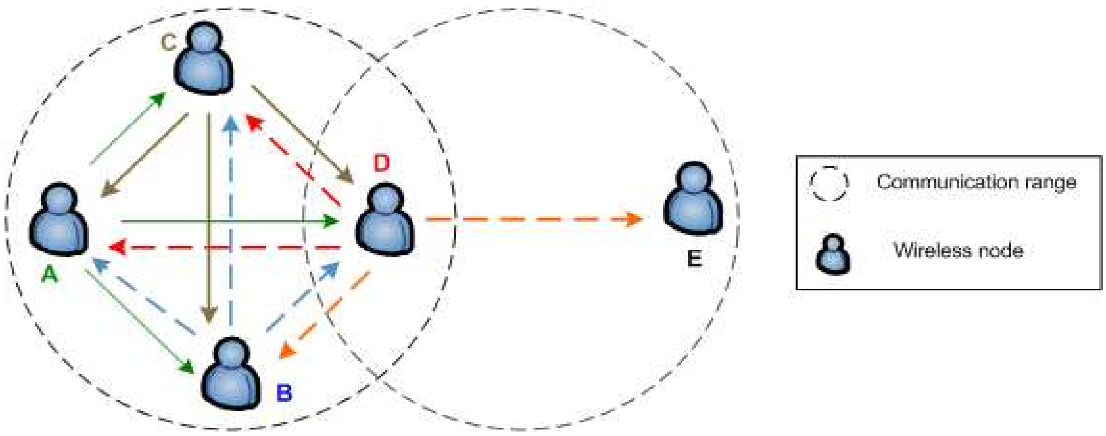

Figure 2.1. A sample of ad hoc network with 5 nodes

However, when the size of the network increases and the network becomes dense, more transmission redundancy will be introduced and these transmissions are likely to cause serious drawbacks (i.e. redundant rebroadcast, contention and collision) which can lead to a total collapse in the operation of the network. These drawbacks are collectively referred to as the *broadcast storm problem* [17-19]. The detail of each of the drawbacks now follows:

Redundant rebroadcast: This phenomenon occurs when a node rebroadcasts packets that neighbouring nodes have already received. The scenario is illustrated using Figure 2.1. When node ***A*** broadcast a packet to nodes ***B***, ***C*** and ***D***, then node ***B*** rebroadcast to ***A***, ***C*** and ***D*** which is clearly redundant as nodes ***A***, ***C*** and ***D*** have received a copy of the packet already from ***A***'s transmission.

Channel Contention: This occurs when a node broadcasts a packet and if the neighbours of the node receive the broadcast packet and try to retransmit the packet, these transmissions may severely contend the shared physical channel with each other. This will cause delay in the dissemination of data packets.

Packet Collision: As nodes compete for shared medium, if more than one node attempts to transmit at one time on the channel, collision is more likely to occur.

2.2.2 *Classification of Broadcasting Schemes*

To mitigate the impact of the broadcast storm problem discussed in Section 2.2.1, several broadcast schemes [18, 19, 52-55] have been proposed. These schemes are broadly categorised into two main approaches: deterministic and probabilistic. Probabilistic or gossiping-based [23] require each node to rebroadcast the packet to its neighbours with a given forwarding probability. Deterministic approaches in contrast, predetermine and select the neighbouring nodes that forward the broadcast packet. On the other hand network coding[2] [56] has been adapted recently as another paradigm to support broadcast applications in wireless networks. The subsequent section will provide a brief description of each of these approaches.

2.2.2.1 Deterministic Schemes

Deterministic schemes typically require some sort of topological knowledge (i.e. global, partial-global or local) of the network to build a fixed backbone that guarantees full coverage of the network for a broadcast operation. The topological knowledge of the network is gathered by maintaining information about nodes neighbourhood via periodic exchange of “hello” packets. The schemes use only a subset of nodes in the network to forward the broadcast packet and the remaining nodes are considered either in the set or adjacent to the nodes that forward the packet. In a similar vein, William and Camp [57] referred to this category as *neighbour knowledge-based algorithms*. Basically, neighbour knowledge-based scheme can be further divided into self pruning and

[2] A method of allowing intermediate nodes in the network to not only forward but also combine their incoming independent packets before forwarding.

neighbour designating methods. Details of the various neighbour knowledge-based schemes are presented below.

Self Pruning Scheme [52, 58, 59]

Broadcasting based on self pruning is the simplest neighbour knowledge-based method which Lim and Kim [58] referred to as flooding with self pruning. In this scheme, each node must have the knowledge of its 1-hop neighbours which is obtained via periodic exchange of “hello” packets. A node includes its list of 1-hop neighbours in the header of each broadcast packet. A node receiving a broadcast packet compares its neighbour list to the sender’s neighbour list. If the receiving node would not reach any additional nodes, it refrains from forwarding the packet; otherwise the node rebroadcast the packet.

Scalable Broadcast Scheme (SBA) [60]

SBA requires that all nodes have knowledge of their neighbours within a 2-hop radius. The neighbour information together with the identity of the node from which a packet is received allows a receiving node to determine if it would reach additional node by rebroadcasting the broadcast packet. 2-hop neighbour information is achievable via periodic exchange of “hello” packet which contains the node’s identifier and the list of known neighbours. After a node receives a “hello” packet from all its neighbours, it has 2-hop topology information centred at itself.

Dominant Pruning (DP) [58]

Like SBA, dominant pruning also requires all nodes to have knowledge of their 2-hop neighbours obtained via “hello” packets. However, unlike SBA, DP requires forwarding nodes to proactively choose some or all of its 1-hop neighbours as rebroadcasting nodes and only those chosen nodes are allowed to rebroadcast. Nodes instruct neighbours to rebroadcast by including their address as part of a list in each broadcast packet header. Whenever 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 Cover Set[3] algorithm to determine which subset of neighbours should

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[3] The algorithm recursively chooses 1-hop neighbours which cover the most 2-hop neighbours and recalculates the cover set until all 2-hop neighbours are covered.

rebroadcast the packet, given knowledge of which neighbours have already been covered by the sender's broadcast.

Multipoint Relaying Scheme [61]

Multipoint relaying also uses 2-hop neighbour knowledge obtained via "hello" packets for routing decision. In this scheme, each node selects a subset of its 1-hop neighbours as multipoint relays (MPRs) sufficient to cover its 2-hop neighbourhood. When a broadcast packet is transmitted by a node, only the MPRs of the given node are allowed to rebroadcast the packet and only their MPRs forward the packet and so on. Using some heuristics, each node is able to locally compute its own MPRs based on the availability of its neighbourhood topology information.

Ad Hoc Broadcast Protocol [62]

The ad hoc broadcast protocol (AHBP) employs an approach similar to multipoint relaying. In AHBP, forward nodes are called Broadcast Relay Gateways (BRGs) and only nodes that are designated as a BRG within a broadcast header are allowed to rebroadcast the packet. BRGs are proactively chosen from each upstream sender which is a BRG itself. The algorithm for selection of BRG set is similar to that of choosing MPRs. The AHBP is also extended to account for high mobility network.

Cluster-Based Algorithms

In cluster-based broadcast schemes, the network is divided into several groups of clusters forming a simple backbone infrastructure. Each cluster has one cluster head that dominates all other members in the cluster. The cluster head is responsible for forwarding packets and selecting forwarding nodes on behalf of the cluster. Two or more overlapping clusters are connected by gateway nodes. Cluster heads and gateway nodes of a given MANET together form a connected dominating set (CDS) [63].

Peng and Lu proposed a CDS-based broadcast algorithm in [64]. It considers the sender of the broadcast packet and the forward nodes with lower node IDs that are selected by the sender to determine a selected forward node's forward node set. Wu and Li [65] also proposed a marking process to determine a set of forward nodes (called gateways) that form a CDS: a node is marked as a gateway if it has two neighbours that are not directly connected. These gateways can be used as forward nodes in a broadcast process. Other enhancements to this category of broadcast schemes are also discussed in [66, 67].

Although clustering can be desirable in MANETs, the overhead associated with the formation and maintenance of clusters is non-trivial in most cases [68]. Therefore, the total number of forwarding nodes is generally used as the cost criterion for broadcasting. The problem of finding the minimum number of forward nodes that forms the minimum connected dominating set is well known to be NP-complete [69].

Hybrid Broadcast Algorithms

Wu and Dai [70] proposed a hybrid broadcast algorithm that combined both self-pruning and neighbour-designating schemes: When a node intents to send a broadcast packet, it will select some forward nodes to partially cover its 2-hop neighbour set. When a node receives the broadcast packet, if it is a selected forward node, it has to relay the packet; if it is not a selected forward node, it still uses self-pruning algorithms to determine its forward/non-forward status.

In general, deterministic schemes are considered not scalable due to the excessive overhead associated with building and maintaining network topological information especially in the presence of high mobility.

2.2.2.2 Network Coding-Based Schemes

Recently, there has been a lot of research interest in the use of network coding to improve transmission efficiency in wireless networks [56, 71-74]. The pioneering work in [56], where intermediate nodes are allowed to process their incoming information flows, has shown that networks that allow intermediate nodes to combine incoming packets before forwarding achieved significant throughput gains over networks with intermediate nodes that only forward packets. For instance, if node *c* receives two packets from nodes *a* and *b* respectively. In order to let *a* and *b* have each other's packet, *c* needs to forward both the packets as a traditional forwarding node. With network coding, *c* only needs to forward one coded packet containing both original packets through the *XOR* operation, and *a* and *b* can decode the message with the help of their own messages through the XOR operation. Support for broadcasting in wireless networks with network coding can also be tackled either using deterministic or probabilistic approaches.

Under probabilistic approaches, authors in [54, 71] have shown that practical coding-based probabilistic schemes significantly outperform non-coding based probabilistic schemes. In these schemes, network coding was adapted to probabilistic approach for supporting all-to-all communication in wireless ad hoc network for both fixed and mobile network scenarios. Packets in this scheme are usually grouped into so-called generations, and only packets of the same generation can be combined [75]. Although, their work has indicated the significant benefit potentials of deploying network coding over a practical wireless ad hoc network environment, since the scheme has to group packets forwarded from various sources into globally unique sets called generations, then solving this in a distributed manner is a hard problem and limits the coding gains. At the same time, the use of a globally unique set of coded packets implies that decoding delay can be large[4].

On the other hand, the authors in [72, 73] applied network coding to deterministic approach using theoretical solutions based on solving linear programs that assume knowledge of the entire network topology. The results have shown significant gains in terms of efficiency and computational overhead over approaches that do not use network coding. Furthermore, practical and deterministic coding-based schemes for support of unicast traffic in wireless networks have also been studied in [74, 76].

Recently, in Yang et al. [77] network coding has been exploited for efficient broadcasting to further mitigate the number of transmissions in the multiple source broadcast application. The authors have combined network coding-based broadcast approach with broadcasting using directional antenna and referred it to as efficient broadcasting using network coding and directional antenna (EBCD), where each node decides its forwarding status using only local information and limited piggybacked broadcast state information. The proposed

[4] Enough information must be received from the various sources before a generation can be decoded at a node.

EBCD approach achieved better performance than the traditional connected dominating set (CDS)-based broadcast and the existing network coding-based broadcasts in terms of energy consumption.

Although network coding has shown a lot of potential benefits along very different dimensions of wireless ad hoc networks, such as throughput, wireless resources and resilience to link failures, its deployment is faced with a number of challenges, such as complexity (i.e. node additional functionality for encoding and decoding packet), security and integration with existing infrastructure (i.e. how could network coding be integrated with existing networking protocols?) [77, 78]. In fact many of the network coding-based schemes suffer from delay accumulation because they need to store several packets to transmit a combination of them. At the same time the encoding time induced at each node during transmission can negatively affect the total time to complete the transmission[78].

2.2.2.3 Probabilistic Schemes

Probabilistic broadcast schemes for MANETs were first suggested in [23, 79] and further investigated in [20, 22, 80-82]. In all schemes under this category, packets are broadcast with a probability p that can be fixed or computed by a node based on the node local density or counter value or its distance/location to the sender. Typical probabilistic schemes are classified into five categories: fixed probabilistic, counter-based, location-based, distance-based and hybrid-based schemes.

Fixed Probabilistic Scheme [53]

In this scheme, every mobile node is allowed to rebroadcast a packet based on a predetermined forwarding probability P. Figure 2.2 outlines the operations of fixed probabilistic scheme. The selection of appropriate forwarding probability determines the effectiveness of the scheme. To determine an appropriate forwarding probability, the authors in [80] have suggested the use of random graphs [69] and percolation theory [83] in MANETs. They claimed that there exists a forwarding probability value $P_n < 1$, such that using P_n, the broadcast packet can reach almost every node, while using a forwarding probability less than P_n will not yield much improvement on the number of covered nodes. Since different MANET topology has different P_n, and there is no existing mathematical model for estimating P_n, many probabilistic schemes use a predetermined value for P_n.

Algorithm: Fixed Probabilistic Scheme (FP)

On receiving a broadcast packet *m* at a node *X*
- **if** packet *m is* received for the first time
    o Forward *m* with a probability *P*
- **else**
    o Drop the packet *m*
- **End Algorithm**

Figure 2.2: A description of the fixed probabilistic scheme.

The studies in [53, 80] have shown that probabilistic broadcast schemes can significantly reduce the inherent effects of the broadcast storm problem but they suffer from poor reachability, especially in sparse network. This poor reachability exhibited is due to the assignment of the same forwarding probability at every node regardless of its number of neighbours [23, 53].

Cartigny and Simplot [81] have proposed some probabilistic schemes where the forwarding probability *P* is computed from the local density *n* (i.e. number neighbours of the node considering rebroadcast). The authors have introduced a fixed value parameter *k* to achieve high reachability for a given network topology. However, these broadcast schemes are uniform because each node in the network determines its forwarding probability based on the fixed efficiency parameter *k* which is not globally optimal.

Counter-Based Scheme [18, 53]

In the counter-based scheme, a node upon the reception of a broadcast packet initiates a random assessment delay (RAD) timer and a counter which counts the number of received duplicate packets. When the timer expires, if the counter exceeds the threshold value, the node assumes all its neighbours might have received the same packet, and will not rebroadcast the packet. Otherwise, the node will broadcast the packet. An outline of the counter-based scheme is presented in Figure 2.3. The selection of an appropriate threshold value is the key to the performance of this technique and it has been shown in [18] that transmission redundancy could be reduced by choosing a threshold value between 2 and 4.

Algorithm: Counter-Based Scheme (CB)

Upon reception of a broadcast packet *m* at a node *X* for the first time

- Initialize the packet counter *c* to 1
- Set and wait for RAD to expire
- While waiting:
    - For every duplicate packet *m* received
    - Increment *c* by 1
- **if** (*c* < *C*) (i.e. *C* is the counter threshold)
    - Forward the packet *m*
- **else**
    - Drop the packet *m*
- **End Algorithm**

Figure 2.3: A description of the counter-based broadcast algorithm.

Distance-Based Scheme [53]

The distance-based scheme allows a node to forward a broadcast packet based on the additional coverage area which is determined by the distance between itself and each neighbouring node that has previously forwarded a given packet. In this scheme, a node upon reception of a broadcast packet for the first time initiates a random assessment delay (RAD) timer. Before the expiration of the RAD timer, the node checks the location of the senders of each received packet. If any sender is closer than a threshold distance value (*D*), the node will not rebroadcast the packet. Otherwise, the node rebroadcasts it when the RAD timer expires [18]. The operation of the scheme is outlined in Figure 2.4.

Algorithm: Distance-Based Scheme (DB)

Upon reception of a broadcast packet *m* at a node *X* for the first time
- Initiate a waiting timer (RAD)
- Before the timer expires:
    - Check the location of the sender of packet *m*
- **if** the sender is closer than the threshold distance D
    - The packet *m* is dropped
- **else**
    - Forward the packet *m* after the RAD expires
- **End Algorithm**

Figure 2.4: A description of the distance-based broadcast algorithm.

Therefore, rebroadcast decision requires the knowledge of geographical locations of all the neighbouring nodes of a particular node. This can be achieved by using GPS receiver, where nodes could include their location information in each packet transmitted. Alternatively, some parameters like signal strength at a node can be used to estimate the distance to the source of a received packet. Although distance-based scheme achieve high reachability they suffer from high number of redundant broadcast packets because a node that has received a broadcast many times may still rebroadcast the packet if all the neighbouring nodes transmission distances are greater than the threshold value.

Location-Based Scheme [18, 53]

In location-based scheme [18, 53], each node is expected to know its own position relative to the sender's position using geo-location technique such as GPS. Upon the reception of a previously unknown packet, the node initiates a waiting timer and accumulates the coverage area that has been covered by the arrived packet. When the waiting timer expires, if the accumulated coverage area is larger than a threshold value, the node will not rebroadcast the packet. Otherwise, the node broadcast the packet. The scheme operation is summarised in Figure 2.5.

Algorithm: Location-Based Scheme (LB)

Upon reception of a broadcast packet *m* at a node *X* for the first time

- Initiate a waiting timer (RAD)
- Before the timer expires:
    - Calculate the coverage area covered by the received packet *m*
- When the waiting timer expires:
- **if** the coverage area is larger than the threshold location L
    - The packet *m* is dropped
- **else**
    - Forward the packet *m*
- **End Algorithm**

Figure 2.5: A description of the location-based broadcast algorithm.

Other enhancements to counter-based, distance-based and location-based algorithms are discussed in [19].

Hybrid Schemes

The schemes under this category combine the features of the fixed probabilistic scheme with any of the other probabilistic broadcast schemes listed above in order to mitigate the inherent problem associated with flooding (i.e. the broadcast storm problem). It can be fixed probabilistic and counter-based or distance-based or location-based. Most recent works [20, 22, 82] on probabilistic broadcasting falls under hybrid schemes and the contributions of this research study also fall under the same category. This section reviews some of the probabilistic broadcast schemes which are more related to this research study. Some of the related schemes are presented below.

Bani-Yassein et al [20] have proposed an adjusted probabilistic flooding scheme which is a combination of fixed probability and knowledge-based approaches. It uses two rebroadcast probability values which are dynamically adjusted according to the local number of neighbours at each mobile host. The probability value changes when the host moves to a different neighbourhood. In a sparse region, the rebroadcast probability is set high while a low probability value is set in dense region of the network. Compared with the fixed probability scheme, the scheme achieves better saved rebroadcast. However, its performance degrades under high traffic load. Similarly, the use of 'hello' packet to acquire neighbourhood information and the distribution of global information (i.e. average neighbours, maximum neighbours) to all nodes induces more overhead.

In [84] the same authors propose a highly adjusted probabilistic flooding scheme as an extension of their previous work. In this scheme, three different rebroadcast probability values are used for three regions of the network (i.e. dense, moderate and sparse) with node located in sparse region assigned a high probability value while the lowest probability value is set for nodes in dense region. This scheme also suffers from the same drawback as its predecessor in terms of overhead associated with gathering neighbourhood information and the distribution of extra global information (i.e. average, minimum and maximum neighbours). Similarly, the determination of optimal values for these parameters is quite difficult.

Zhang and Dharma [22] proposed a dynamic probabilistic scheme which focuses on optimizing route discovery process in AODV routing protocol. The scheme combines the features of probabilistic and counter-based schemes which dynamically adjust the rebroadcast probability *P* at each mobile node based on the value of local packet counters. Therefore, as nodes move to different neighbourhood the value *P* changes, i.e. a packet is rebroadcast with a current probability *P* if the packet is received for the first *N* times (i.e. *N* is the threshold value to indicate whether enough copies of the broadcast packet was received or not). The probability *P* is decrease by a small constant *d* when an additional copy beyond *N* of an existing packet is received, or increased by another small constant *e* if a node did not received anything within the time interval. Finally a fixed lower and upper bound is set for *P*. The algorithm exhibits lower latency, fewer collision, better reachability and higher throughput compared to flooding and fixed probability. Although the scheme achieves superior performance, its evaluation has been based on the route discovery process in the AODV routing protocol rather than a network-wide broadcasting scenario. Moreover, determination of an optimal value for *d* and *e* is quite difficult. Furthermore, there is an overhead associated with the distribution of global network information (i.e. number of nodes) within the network.

In Chen et al [85], a distance-aware counter-based broadcast scheme called "*DIS_RAD*" has been suggested that introduces the concept of distance into counter-based broadcast scheme. The scheme gives nodes closer to the border of the transmission range a higher rebroadcast probability because they can have a high chance of reaching more nodes [13]. A distance threshold is employed to distinguish between interior and border nodes using two distinct RAD values with the border nodes having shorter RADs than the interior nodes. This simple adaptation provides border nodes with higher rebroadcast probability and a lower rebroadcast probability for the interior nodes. Although the approach has superior performance over counter-based scheme it suffers from the limitation of all distance-based schemes (i.e. determination of location information and optimal threshold value).

The main advantages of probabilistic schemes in general are their simplicity and robustness to mobility.

2.3 The Network Simulator (Ns-2)

In recent years, several discrete-event network simulation tools have been suggested for performance analysis of MANETs [86-89]. The commonly used network simulators include Ns-2 [90], GloMoSim [89], QualNet [88], OMNET++[91] and OPNET [87]. Some of the simulators such as Ns-2 and GloMoSim have been developed as part of university research projects and are available for free download, while others such as QualNet (the commercial successor of GloMoSim) and OPNET are available for a fee.

The Ns-2 [90] simulator is one of the most popular discrete-event simulation tools and its architecture is organized according to the OSI reference model [92]. Although it was originally designed for wired networks, Ns-2 has been extended for simulating wireless networks, including wireless LANs, mobile ad hoc networks (MANETs), and sensor networks. It is a popular and powerful network simulation tool, and the number of users has increased greatly over the last decade [93]. This is due to the fact that it is freely available, open source and includes detailed simulations of important operations of such networks [94]. The development efforts of the simulator have been supported by DARPA and NSF [95].

The simulator is written in C++ and a script language called Object Tool command language (OTcl). Ns-2 uses an OTcl interpreter in which the user writes an OTcl script that defines the network topology (number of nodes, links), the traffic in the network (sources, type of traffic and destination), and which protocol it will use. This script is then used by Ns-2 during the simulations. The result of the simulation is an output trace file that can be used for data processing and visualisation using network animator (NAM). NAM is a visualisation tool available in Ns-2 package that can graphically represent packets as they propagate through a network.

The Ns-2 simulator includes radio propagation models that support propagation delay, capture effects, and carrier sense [96, 97]. The default radio models use characteristics similar to the commercial Lucent WaveLAN technology with a nominal bit rate of 2Mb/s and a nominal range of 250 meters with an Omni-directional antenna. Other radio propagation models in Ns-2 include the free space propagation model, the two-ray ground reflection model and the shadowing propagation model [97].

2.3.1 Mobility Model

Since nodes in MANETs are often mobile, modelling their movements is not quite obvious. In order to evaluate the performance of a new protocol, it is necessary to use a *mobility model* that reasonably captures the movement patterns of mobile nodes that eventually utilise the given algorithm [98].

Presently, mobility models used for the evaluations of algorithms proposed for MANETs are grouped into two: trace-driven and synthetic models [98]. Trace-driven are mobility patterns that are observed in real life systems. They provide accurate information especially if they are obtained through long observation period and involve a large number of participants. However, privacy issues with regards to the confidentiality of certain data, time and cost involved may prohibit the collection and distribution of such statistics. On the other hand, synthetic models attempt to represent the behaviours of mobile nodes without the use of traces. They do not provide such accuracy (i.e. in terms of real life system representation) like trace-driven models but they enable researchers to estimate nodes behaviour in the absence of real trace models at low cost and time. In this thesis synthetic mobility models are used. The reasons of this choice are due to limited availability of traces and these traces are related to very specific scenarios which make their validity difficult to generalise. Furthermore, the available traces do not allow for sensitivity analysis of the performance of the algorithm, since the value of the parameters that characterise the simulation scenario can not be varied [99]. Synthetic models have been classified in [100] into entity and group mobility models depending on whether individual nodes or a group of nodes are concerned.

In MANETs, many entity mobility models for the generation of synthetic traces have been proposed [98, 101]. The most widely used of such model is the Random Way-Point (RWP) mobility model [11]. In RWP model, collections of nodes are placed randomly within a confined simulation area. Each node at the beginning of the simulation starts by being stationary for a pause time and then selects a random destination inside the simulation area and moves towards it with a random speed chosen from a uniform distribution (*minimum speed*, *maximum speed*]. Once the node reaches its destination, it pauses for a time interval and then chooses another random destination and speed. All nodes follow and repeat the same procedure until the end of the simulation time. The popularity of RWP model has been attributed to its simplicity and ease of use. However, as shown in [102] it suffers from two significant problems. First, if the *minimum speed* is set to zero or a very small value, the instantaneous node average speed (i.e. a metric that quantifies the aggregate level of mobility) consistently decrease over time. As such the model fails to provide a steady state. Thus, under these situations, the simulation analysis of protocols for MANETs is likely to produce misleading results. Secondly, the level of mobility for RWP goes through oscillations before settling down onto a “steady state”. In general, if the data collected in a simulation run include the initial transient period, it is likely that the results will exhibit considerable errors. This phenomenon is referred to as *initial transient problem*. The suggested method for dealing with this problem was to discard the initial set of observations hoping that the steady state would have set in. However, it is quite difficult to predetermine the length of this transient period.

Recently, various entity mobility models [98, 103] have been proposed which attempt to model better mobility traces than RWP model. However, these models also suffer from non-steady state distribution at the start of the simulation and so the Random Trip mobility model [104] is used in this research to take care of this non-steady node distribution problem.

A random trip mobility model is a generic model for random, independent node movements which is defined by a framework, *Trip, Phase, Path*. A phase describes some state of the mobile node specific to the model which indicates whether the mobile node moves or pauses at a given time. A path is a continuous mapping from an origin point to a destination point while a trip is specified by a path and duration. In random trip model, at a trip transition instant, a mobile node picks a trip destination uniformly at random within the area and samples numeric speed from uniform distribution [minimum speed, maximum speed]. At the end of the trip, the mobile node picks another path according to the model's trip selection rule driven by a Markov chain. This cycle repeats until the end of the simulation time. Unlike other random mobility model, random trip node mobility distribution converges to a steady-state regime from origin of an arbitrary trip and there is no need to discard initial sets of simulation observations.

2.4 Assumptions

The following simplifying assumptions have been used throughout this research and have been widely adopted in the literature [53, 82, 105, 106].

- The number of nodes in a given topology remains fixed throughout the simulation time. Nevertheless, network partitioning may still occur during simulation and so the network may not be connected at all times. However, at no time does a node leave or gets added to the simulation area. This is to allow the behaviour of the proposed algorithms to be studied under the same environments and at the same time to allow direct and fair comparisons between the new algorithms and the existing without losing nodes.

- All mobile nodes are homogeneous, i.e., all nodes are equipped with IEEE 802.11b transceivers.

- All nodes participate fully in the broadcasting protocol of the network. In particular each node participating in the network should be willing to forward packets to other nodes in the network.

- Although, nodes in MANETs may run out of power or switch themselves off to save power. However, in simulated scenarios nodes are assumed to have sufficient power supply to function throughout the simulation time and at no time does a mobile node run out of power or malfunction because of lack of power. This is to allow direct and fair comparisons between the new algorithms and the existing without losing nodes. However, it would be interesting to study the energy consumption as a next step of this research.

- Mobile node transmissions may interfere with each other (i.e. affect each other if they occur in close proximity); however a node always successfully decode a transmission provided it is within transmission range of the source and there is no interfering transmission.

- A broadcast operation or route discovery process can be initiated by any source node which has a packet (i.e. control or data packet) to be transmitted.

Nevertheless, other assumptions will be stated in the subsequent chapters where appropriate.

2.5 Justification of Method of Study

In this research work, extensive simulations are conducted to explore the performance of probabilistic broadcasting in MANETs. This section briefly discusses the choice of simulation as the appropriate mode of study for the purposes of this thesis, justifies the adoption of network simulator (Ns-2) as the favoured simulator and further provides information on the techniques used to minimise the possibility of simulation error.

MANETs face several challenges due to their lack of coordination or configuration prior to set up. These challenges include routing packets in an environment where the topology is changing frequently, wireless communications issues, and resource issues such as limited power and storage. These challenges makes simulation an invaluable tool for understanding the operation of these networks [93]. Whilst real world test (i.e. test beds or real life implementation) and analytical models are crucial for understanding the performance of MANETs protocols, simulation has been chosen as method of study in this research because it provides an environment with specific advantages over the other methods [103]. These include:

- It allows repeatable scenarios evaluation and exploration of a variety of metrics. This aid in the development and refinement of networking protocols by allowing the protocol developer to make changes to the protocol and retest the protocol in the same scenario which will aid in deeper understanding of how the changes affect the performance results.

- It enables the isolation of parameters. This allows the effects of a single parameter, such as mobility, density, data traffic or transmission range, to be studied in details while all other parameters are held constant.

- It also allows a wide variety of scenarios and network configurations to be evaluated on a reasonable scale, time frame and budget.

There are currently a few analytical works on MANETs in general and broadcasting in particular [107]. This is partly due to the existence of flexible and standardized simulators [87, 88, 90, 108], and partly due to lack of common platform to base analytical models on. For broadcasting, the analytical efforts to-date focused on ideal network situations such as ideal MAC and static nodes [109-111] or for small size networks [112]. Moreover, the dynamic nature of MANET topologies complicates analytical modelling which made it unsuitable for the purpose of modelling probabilistic broadcasting with reasonable degree of accuracy. For example, Kurkowski *et al.* [93] conducted a survey of MANET research published in MobiHoc'2000-2005 [113] which shows that 114 out of the 151 published full papers (75.5%) at the conferences used simulation to evaluate their research.

In addition, since the scope of this study of probabilistic broadcasting in MANETs involves numerous mobiles nodes, even a moderate deployment of nodes as an experimental test-bed could entail substantial and unaffordable cost. As such simulation has been chosen as it provides a reasonable trade-off between the accuracy of observation involved in a test-bed implementation and the insight and completeness of understanding provided by analytical modelling.

In order to conduct performance analysis of the suggested solutions, the popular Ns-2 (v.2.29) simulator [90] has been extensively used in this research. Ns-2 has been chosen primarily because it is a proven simulation tool utilised in several previous MANET studies [57, 93, 114] and has been validated and verified in [115, 116]. For instance, It has been shown in [93] that 35 of the 80 papers in MobiHoc'2005 [113] that state the simulator used in their simulation study used Ns-2 (43.8%). While extending the simulator to evaluate the proposed broadcasting schemes, special care has been taken to ensure that the algorithms implemented would function as designed and that the simulator would not exhibit unwanted side-effects. This has been accomplished by validating the simulator and the algorithms implemented/extended in the Ns-2 simulator.

The Ns-2 simulator has been validated using Ns-2 "validation test suite", which consist of automated validation scripts that exercise the various parts of Ns-2 and compare the results with known values from the developer [86]. This validation ensures that the current operating environment operate as the developer intended, the Ns-2 is used as designed and it is executing properly [117].

To validate the proposed schemes extended in Ns-2, fixed value validation technique was used. The fixed value technique exercises the model with input data for which the outcomes are known [118]. The validation consists of running the modified counter-based scheme over a 5 nodes static chain topology on a 1000m x 1000m area as shown in Figure 2.8, in which an intermediate node is allowed to forward a received broadcast packet based on fixed probability $p \le 1$ if the counter value at a node is less than the threshold value. Each node has a transmission range of 100m, and the distance between two successive nodes was between 70m and 80m. The choice of the distance between two successive nodes is to reduce the chances of exposed node problem and also to ensure that a node could communicate with only its 1-hop neighbour. To create a traffic pattern, node 0 was assigned as the source node and generates broadcast traffic at a rate of 4 packets/second for 100 second simulation time. The forwarding probability at the intermediate nodes 1 to 3 was set at $p = 1$ (i.e. simple counter-based scheme) and $p = 0$. The aim of this validation test was to achieve 100% delivery success when the probability at the intermediate nodes is 1 and 0% delivery success when the probability at the intermediate nodes is 0.

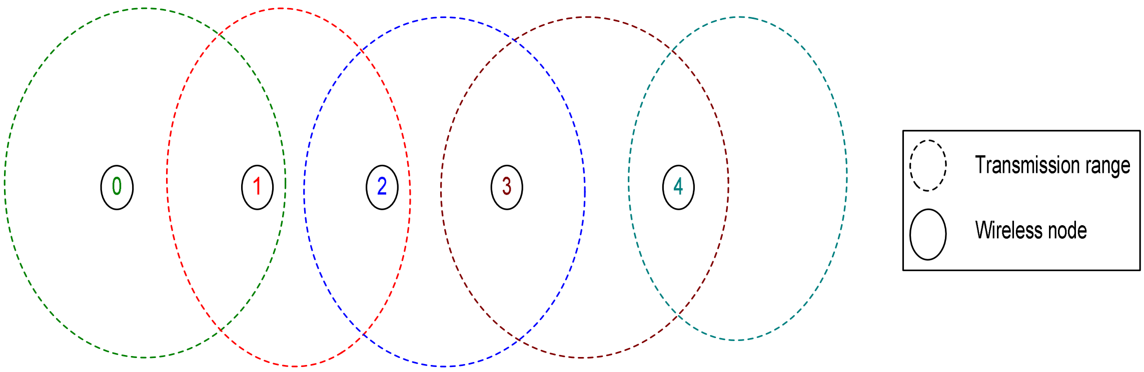

Figure 2.6. A Five nodes chain topology scenario for the validation of the counter-based implementation in the Ns-2 simulator.

2.6 Simulation Model and System Parameters

The study is conducted using Ns-2 [90]. The simulation model consists of two set of scenario files: topology scenario and traffic generation files. The topology scenario files define the mobility model which governs the distribution of mobile nodes within the simulation area over the simulation period. On the other hand, the traffic pattern file contains information such as packet type, data packet size, injection rate of the broadcast packet and the number of traffic flows.

The random trip mobility generator [119] was used to generate all mobility scenarios for this research. The minimum speed of 1m/s is used while the maximum speed is varied from 1m/s to 20m/s in order simulate human speed as well as fast moving vehicle.

A traffic generator was used to simulate constant bit rate (CBR) with a packet payload of 512 byte and a transmission rate of four packets per second for route discovery scenario. CBR was chosen as a communication service due to its simplicity and predictability which gives us a better opportunity to test our algorithms during the experiments. For route discovery process, communication sessions in form of traffic flows were introduced to simulate traffic in the network while for pure broadcast scenario the broadcast injection rate is used. In order to construct a random broadcast traffic pattern, each new packet was assigned a source node randomly chosen from the entire pool of the network nodes.

Nodes are assumed to be equipped with a wireless transceiver operating on IEEE 802.11b wireless standard [120]. The physical radio characteristics of each node such as the transmit power, signal to noise and interference ratio and antenna gain, are chosen to mimic the commercial Lucent OriNOCO Wireless LAN PC Card [121] with a nominal bit rate of 11 Mb/s and a transmission range of 100 meters with an Omni-directional antenna. The IEEE 802.11 MAC layer provides two access methods to the wireless media: the Distributed Coordination Function (DCF) and the Point Coordination Function (PCF) [122] where the former is contention-based and the latter is contention-free. The DCF is the fundamental MAC access method that works in a distributed fashion which makes it suitable for MANETs that have neither infrastructure nor central management. PCF is an optional access method built on top of the DCF relying on a central node and hence is suitable for infrastructure wireless network. DCF is based on the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) scheme. CSMA is a contention-based algorithm which ensures that each node senses the medium before sending, to avoid collisions and retransmissions. In addition to physical carrier sensing the DCF has a virtual carrier sensing phase that exchanges Request-To-Send/Clear-To-Send (RTS/CTS) [33] control packets as a handshaking mechanism between neighbouring nodes before transmitting unicast packets to reduce the probability of collisions due to hidden terminals problem [123].

To gain more realistic signal propagation than with the deterministic free space or two-ray ground reflection models [97], the shadowing model is used for the radio propagation [124].

2.6.1 System Parameters

In this research as well as in other studies [12, 18, 22, 57], the key components of our simulation model includes, simulation area, number of nodes, mobility model, maximum and minimum speeds, and number of traffic flows as well as broadcast rates. All nodes are mobile, identical and operate in a square flat simulation area of size 1000m x 1000m. Each node has a fixed transmission range of 100m in order to simulate a multi-hop network. For all the scenarios, each the simulation runs for a period of 900 seconds to avoid immature termination and to keep the simulation time manageable. Each randomly generated topology represents an experimental trial in which different numbers of trials were first considered and it was observed that the means of 20, 25, 30 and 35 trials are within same confidence interval of 95%. However, the mean values of 30 and 35 trials are almost the same. Therefore, the statistics have been collected throughout this thesis using a 95% confidence interval over 30 randomly generated topologies. The error bars in the graphs represent the upper and lower confidence limits from the means and in most cases they have been found to be quite small such that they are obscured by the symbol itself. For the sake of clarity and tidiness, the error bars have not been included in some of the graphs.

Other simulation parameters used in this study are summarised in Table 2.1 and have been widely adopted in existing MANETs performance evaluation studies [18, 19, 57]. This above settings could represent a real life MANET scenario like students in a University campus or a team of search and rescue operation in a disaster terrain. Although the number students or search team could be larger than the one presented in this scenarios and the operational time could be longer but the chosen values are to keep the simulation time manageable while still generating enough traces for analysis.

Table 2.1. Summary of system parameters, mobility model and protocols used in the simulation experiment

Parameter	Value
Simulator	NS-2 (2.29.3)
Transmission range	100m
Packet size	512 bytes
Interface queue length	50
Topology size	1000m x 1000m
Traffic type	CBR
Number of nodes	20, 40, …, 200
Simulation time	900 seconds
Bandwidth	11 Mbps
Maximum speed	1, 5, 10, … 20m/s
Packet origination rate	1, 10, 20, …, 50packets/sec
Number of trials	30
Confidence interval	95%
MAC type	802.11b
Counter threshold	2 – 6
Propagation model	Shadowing model

In this research study, we focus on three major network operating conditions: network density, traffic load, and mobility (in terms maximum speed) using three different cases by varying one condition while keeping the other two constant in order to avoid the effect of the other conditions on the performance result of the varying condition. These three operating conditions are explained below:

- *Network Density:* This refers to the total number of nodes in the network. It is used to study the effect of varying network density on the performance of the network. When the network density increases, the network connectivity and average hop count also increases which may increase network contention, collision and latency. The simulation area is kept constant in all scenarios from sparse to dense network. Simulation has been performed by deploying 20, 40, 60, …, 200 nodes while fixing the maximum speed to 5m/s and the traffic load to 10 source-destination connections for route discovery scenario and 10 packet per second broadcast injection rate for pure broadcast scenario.

- *Traffic Load:* This is used to study the effect of varying the amount of traffic load on the performance of the network. In the case of route discovery process, traffic load of 1, 5, 10, 15, 20, 25, 30 and 35 source-destination connections were used while broadcast injection rate of 1, 10, 20, 30, …, 70 packets per second were used for some pure broadcast scenarios. The network density is kept to 100 nodes to avoid sparse and dense scenarios with a maximum speed 5m/s to avoid the effect of mobility. In both pure broadcast and route discovery scenarios we managed to run up to 55 source-destination connection and 90 packets per second. However, runs above 35 source-destination connections and 70 packets per second did not show any changes in the overall performance results but need huge amount of time to run.

- *Mobility:* This is used to study the effect varying node mobility (in terms of maximum speed) on the performance of the network. When the maximum speed increases frequent link breaks also increases and more route discovery process initiated. The maximum speeds of 1, 5, 10, 15, and 20m/s were used to simulate human (slow, fast walking and running) speeds as well as vehicle speed. A network density of 100 nodes and traffic loads of 10 source-destination connections and 10 packets per second broadcast injection rate were used to suppress the effect of both network density and traffic load.

2.7 Performance Metrics

In this research, the performance of the new broadcast schemes is measured for both pure broadcast scenario and route discovery process using the following performance metrics which have been widely used in the literature [18, 22, 53, 82, 105, 125].

Reachability (RE): The percentage of network mobile nodes that receive a given broadcast packet over the total number of nodes that is reachable, directly or indirectly.

End-to-end delay (Broadcast): The elapsed time between when a broadcast is initiated and its reception by the last node in the network.

Routing overhead: The total number of RREQ packets generated and transmitted during the entire simulation period. For packet sent over multiple hops, each transmission over one hop is counted as one transmission.

Collisions rate: The total number of control packets dropped by the MAC layer as a result of collisions per unit of the simulation time.

Normalised Throughput: The ratio of the number of data packets successfully received at the destinations per unit simulation time over the theoretical throughput (i.e. the total number of data packets generated per second).

End-to-end delay: The average delay a data packet experiences to cross from source to destination. This includes all possible delays caused by buffering during route discovery delay, queuing at the interface queues and retransmission over one hop is counted as one transmission.

2.8 Summary

This chapter has discussed the background and related work on broadcasting in mobile ad hoc networks. It has also presented the characteristics of MANETs and suggested why their dynamic and infrastructure-less nature might make them applicable in a number of areas.

Broadcasting in MANETs has been discussed along with the performance drawbacks of the broadcast storm problem. This has been extended by discussion of the different categories of existing broadcast schemes which have been proposed to reduce the effect of this issue.

We have described the different routing protocols developed for MANETs with a particular emphasis on route discovery process in AODV as a common example of the use of broadcasting services. We then explained the fundamental phases of AODV routing protocol, where both route discovery and maintenance operations have been briefly outlined.

After describing the existing probabilistic broadcast schemes along with their relative merits, the chapter has briefly described Ns-2 simulator that is used to conduct the performance analysis of the proposed broadcast schemes and discussed the choice of simulation as a tool of study in this research. Finally, the chapter has outlined the performance evaluation metrics used and some assumption that apply throughout this research study.

The probabilistic broadcast schemes have shown great potential in mitigating the broadcast storm problem associated with flooding due to their simplicity, scalability and robustness to node mobility, compared to deterministic schemes. However, the performance of most of these schemes including fixed probabilistic and counter-based scheme, rely on the appropriate selection of the broadcast decision parameters, i.e., forwarding probability or counter threshold, or distance threshold. The next chapter will examine the effect of different counter threshold values and forwarding probability values on the performance of counter-based and fixed probabilistic schemes respectively taking into account important system parameters such as network density and traffic load.

Chapter 3

Performance Analysis of Counter-Based and Fixed Probabilistic Broadcast Schemes

3.1 Introduction

Counter-based and fixed probabilistic approaches to broadcasting have been suggested in [18, 19, 80] as a means of mitigating the detrimental effects of the broadcast storm problem associated with flooding. In counter-based scheme, the predefined threshold *C* is the key parameter in this approach and its appropriate selection can have significant impact on the performance of the technique. Similarly, the selection of appropriate forwarding probability dictates the performance merit of fixed probabilistic scheme just like the threshold value *C* is to counter-based scheme. Despite the importance of these key parameters, there has been so far barely any attempt to analyse the effect of these key parameters on the performance of the two approaches together.

Motivated by the above observation, this chapter evaluates the effect of different threshold values on the performance of the counter-based scheme and the different forwarding probability values on the fixed probabilistic scheme, using extensive Ns-2 simulations under a varying network density and traffic load.

The remaining part of this chapter is organised as follows: Section 3.2 analyses the performance of the counter-based scheme while Section 3.3 analyses that of the fixed probabilistic scheme. Finally, Section 3.4 concludes the chapter.

3.2 Analysis of the Counter-Based Broadcast Scheme

This section investigates the effect of the counter threshold on the performance of counter-based scheme. The original implementation of the counter-based scheme of the Ns2.1b7a simulator [90] which is implemented according to the specification in [18], has been modified and implemented on Ns-2 (2.29.3) simulator [90] in order to realise different counter threshold values. The main modifications are done to *cbflood.cc*, *cbflood.h* and *cbflood.tcl* files in the *CBFLOOD* folder of the simulator which include defining and setting threshold variable such the *cbflood.cc* can interface with the *cbflood.tcl* to accept different threshold values. Other folders modified among others include *MAC* folder to configure it as IEEE 802.11b; *MOBILE* folder to configure the propagation model (i.e. shadowing model); *TRACE* folder to incorporate the counter value into the packet trace format. The counter threshold values have been varied from 2 to 6 with an increment of 1 per simulation trial. The performance analysis of counter-based scheme over varying counter threshold values has been conducted using the simulation model and parameters as outlined in Chapter 2 (see Section 2.6). The analysis focus on the effect of network density and traffic load on the performance of different counter threshold values for counter–based scheme. The performance metrics used for the analysis includes the number of retransmitting nodes, collision rate and reachability; and the metrics have been defined in Chapter 2 (see Section 2.7).

3.2.1 *Effects of Network Density*

This section presents the performance impact of network density on counter-based scheme over different threshold values. The network density has been varied by deploying 20, 40, 60, …, 200 nodes over a network topology of 1000m x 1000m. Each node in the network moves according to random trip mobility model with minimum and maximum speeds of 1m/s and 5m/s respectively. In each simulation trial, a broadcast injection rate of 10 packets per second has been used to ensure sufficient traffic within network which can give better network connectivity. Each new broadcast packet assigned a source node randomly chosen from the entire pool of network nodes in order to create a random traffic pattern. In all figures presented in this section, the x-axis represents the variations of network operating conditions (i.e. node density or load) while the y-axis represents the results of the performance metric of interest.

3.2.1.1 Number of Retransmitting Nodes

Figure 3.1 shows the effects of density on the performance of different counter threshold values together with flooding in terms of number of retransmitting nodes. The figure reveals that the number of retransmitting nodes for a given threshold value increases with increasing network density. A low threshold value (i.e. C = 2) requires least number of retransmissions while those utilising higher threshold values (i.e. C = 5, 6) require the largest number of rebroadcasts. This indicates that a low threshold value results in fewer retransmitting nodes. In fact threshold values greater than 4 behave almost similar to flooding because most of the nodes retransmit the packets. For example in Figure 3.1, for a network of 100 nodes about 40% of the nodes retransmit for the threshold value 2 while around 98% of the nodes retransmit for threshold value 6.

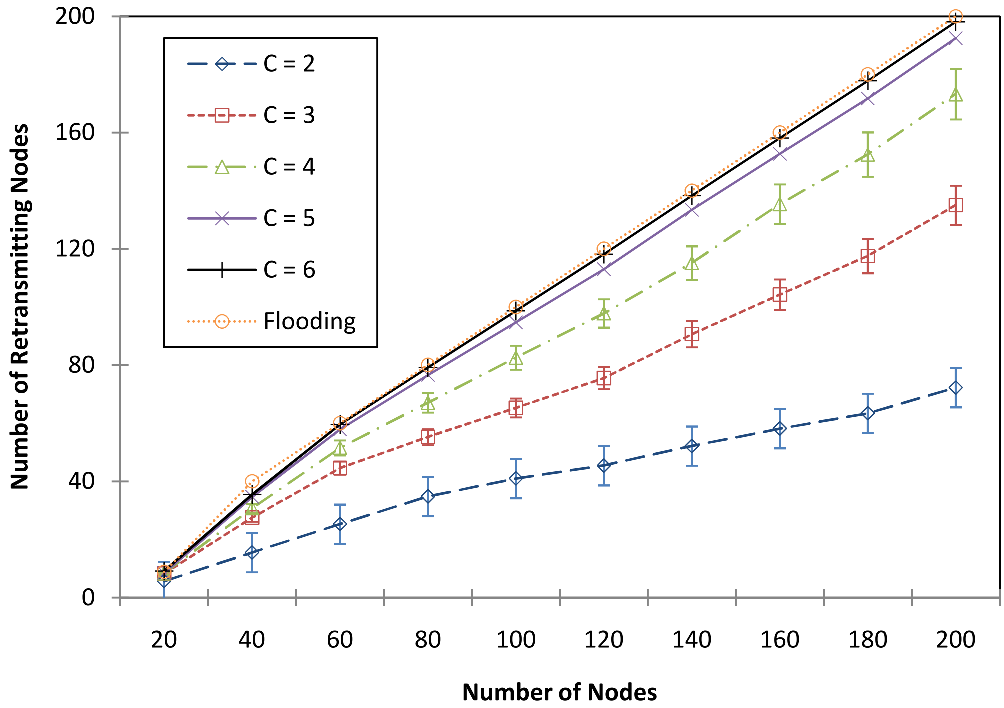

Figure 3.1. Number of retransmitting nodes vs. number of nodes placed over 1000mx 1000m area when a broadcast rate of 10 packets/sec is used for different threshold values.

3.2.1.2 Reachability

Figure 3.2 depicts the reachability performance achieved by the different threshold values over a varying network density. The figure shows that reachability increases with increase in network density. For example, reachability achieved by threshold value 2 increases from 26% for 20 nodes to 98% for 100 nodes while that of threshold value 6 increases from 45% to 99.9% for 20 and 100 nodes respectively. This is because as number of nodes increases there is more likelihood that nodes are located within the transmission range of each other and thus resulting in a better network connectivity.

Figure 3.2 also reveals that low threshold value (i.e. C = 2) achieves the least reachability in sparse to medium networks (20 to 80 nodes). But as the density increases reachability improves for all threshold values. As in Figure 3.1, for threshold values 4 and above, the counter-based scheme converges to flooding in terms of reachability performance. This is because the higher the threshold values, more nodes retransmit the broadcast packets. Therefore, to maintain a high reachability in sparse networks, a higher threshold value is required while to maintain reachability in dense networks, a low threshold value can be used. Thus, reachability improves with increased network density.

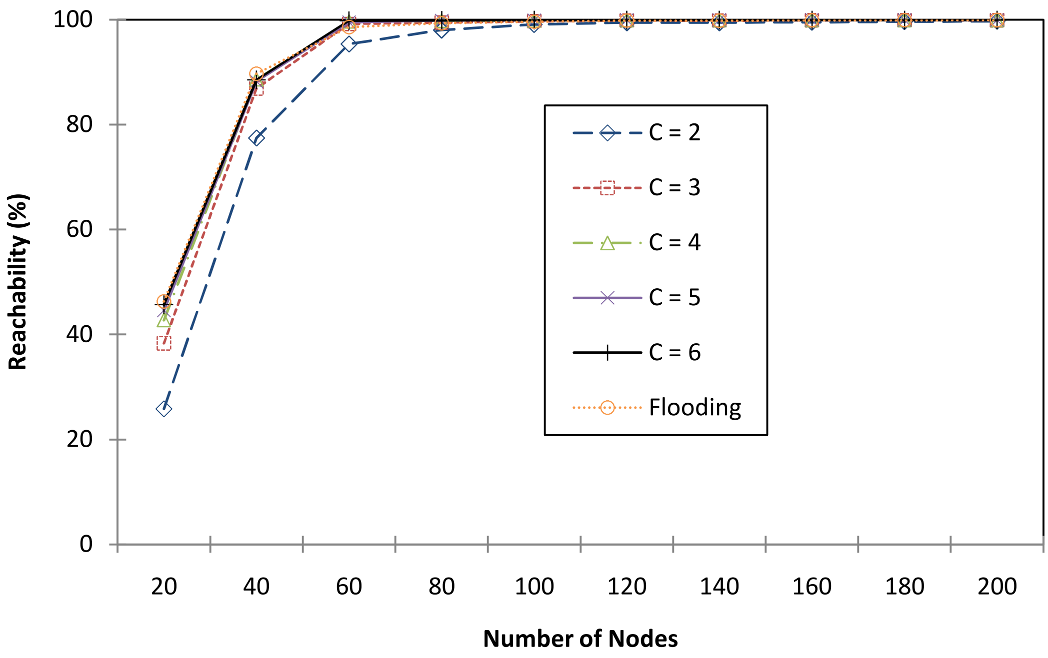

Figure 3.2. Reachability vs. number of nodes placed over 1000mx1000m area when a broadcast rate of 10 packets/sec is used for different threshold values.

3.2.1.3 Collision Rate

Figure 3.3 shows the effects of network density on the performance of different threshold values in terms of average collision rate. The figure illustrates that the collision rate for a given threshold value increases almost linearly as network density increases. This is due to the fact that increasing the network density increases the chances of two or more nodes within the same transmission range transmitting at the same time, leading to a possible increase in the number of collisions. For example in Figure 3.3, when the number nodes is increased from 100 to 200 nodes, the collision rate for threshold values 2 and 6 increases by approximately 550% and 435% respectively. In contrast, the collision rate for flooding increases by as much as 375% for an increase from 100 to 200 nodes.

The figure also reveals that for a given network size, the number of collision incurred by the different threshold values increases as the threshold value increases. As can be seen in Figure 3.3, for a network with 100 nodes, the collision rate for threshold value 3 increases by a factor of around 3 compared to threshold value 2 while the collision rate increases by a factor of 5 for threshold value 5 compared to threshold value 2. Similar to Figures 3.1 and 3.2, for threshold values of 4 and above, the counter-based scheme behave similar to flooding as most of the nodes are involved in packet retransmission.

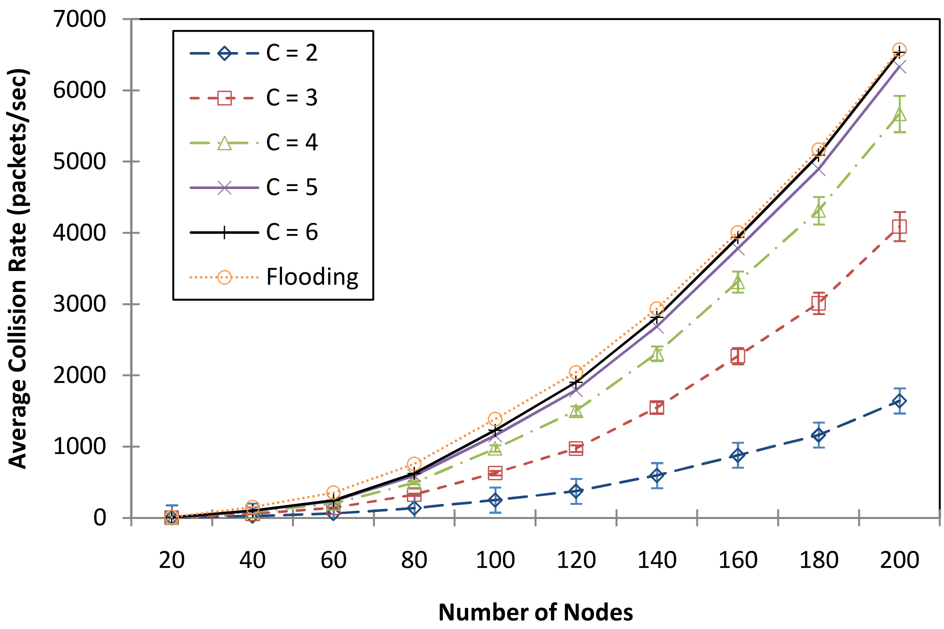

Figure 3.3. Average Collision rate vs. number of nodes placed over 1000mx1000m area when an injection rate of 10 packets/sec is used for different threshold values.

3.2.2 *Effects of Traffic Load*

In this section, 100 nodes are placed over a network topology of 1000mx1000m area and each node in the network moves according to random trip mobility model with minimum and maximum speeds of 1m/s and 5m/s respectively. To investigate the impact of traffic load, the injection rates of 1, 10, 20, 30, 40 and 50 packets per second have been used with each new broadcast packet assigned a source node randomly chosen from the entire pool of network nodes.

3.2.2.1 Number of Retransmitting Nodes

The results in Figure 3.4 show the effects of offered traffic load on the network performance for different threshold values in terms of number of retransmitting nodes. As expected, the number of retransmitting nodes for a given threshold value almost remain constant over different traffic loads. This is due to the use of fixed number of nodes (i.e. 100 nodes) in this simulation scenario. Nevertheless, a low threshold value (i.e. *C*=2) requires the least number of retransmissions while high threshold values (i.e. *C*=5, 6) require the largest number of retransmissions. For example in Figure 3.4, around 41% (41 nodes) of nodes retransmit when *C* = 2 while about 65% of the nodes retransmit for *C* = 3 and around 84%, 94% and 98% of the nodes retransmit for *C* = 4, 5 and 6 respectively. Therefore, the higher the threshold values the higher the number of retransmitting nodes.

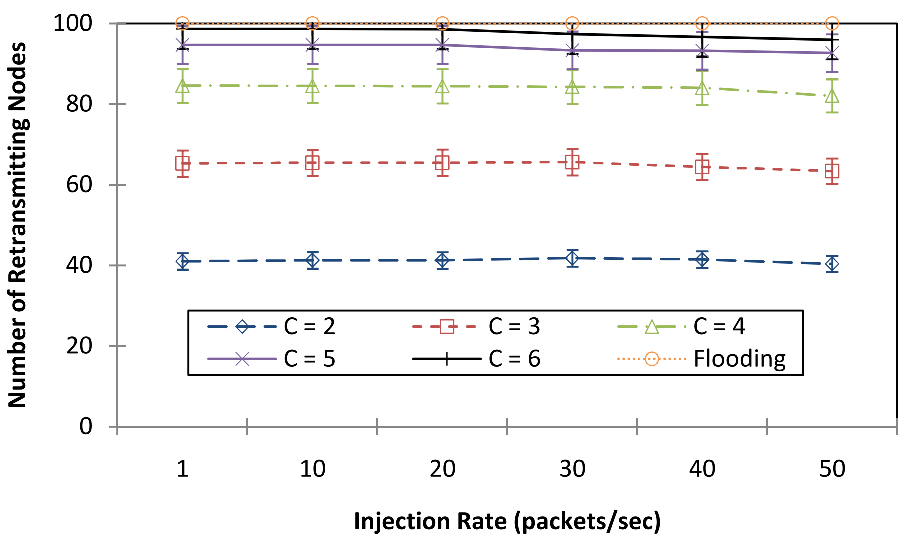

Figure 3.4. Number of retransmitting nodes vs. broadcast injection rates in a network of 100 nodes placed over 1000mx1000m area for different threshold values.

3.2.2.2 Reachability

Figure 3.5 reveals that reachability decreases with increased broadcast injection rate, i.e. a heavier load will result in a lower reachability performance. This is true for all threshold values and flooding, because a high broadcast rate leads to more contention and collision among broadcast packets. For example, flooding is the most affected as reachability falls to around 85% at a broadcast rate of 50packets/sec. Moreover, to maintain a better reachability a low threshold value is required especially in dense network. The figure also reveals that a low threshold value is advantageous when the injection rate is over 20 packets per second.

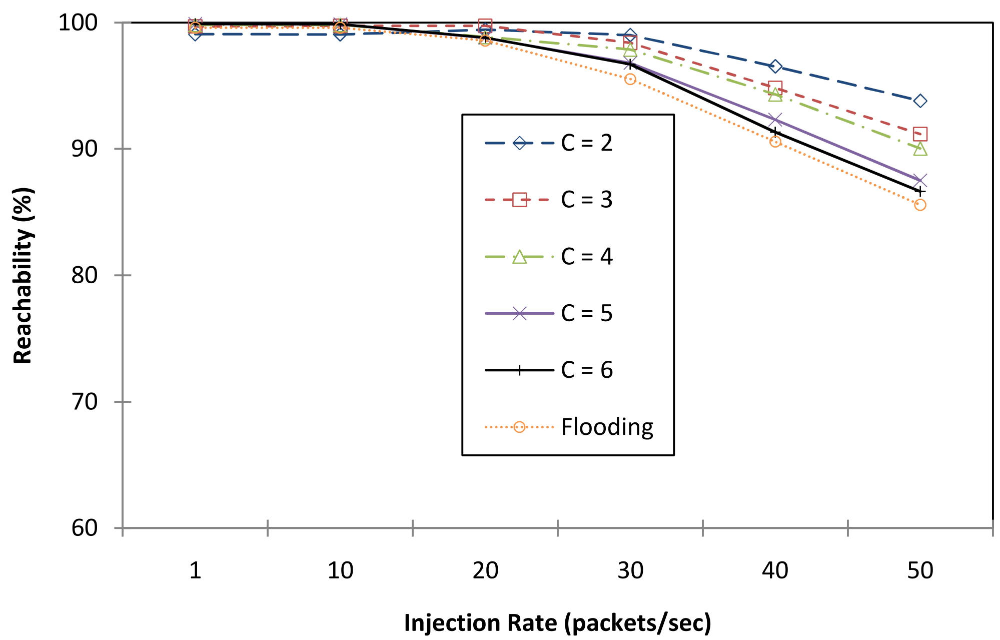

Figure 3.5. Reachability vs. broadcast injection rates in a network of 100 nodes placed over 1000mx1000m area for different threshold values.

3.2.2.3 Collision Rate

The result in Figure 3.6 reveals that when the offered load increases, the average collision rate of all the threshold values and flooding also increases. This is because, when the injection rate is increased, the number of broadcast packet generated and transmitted also increases. Thus, the probability of two or more nodes transmitting at the same time within the same transmission range increases. This in turn leads to an increase in the collision rate. However, for a given injection rate, the average collision rate of the counter-based scheme with a threshold value 2 is much lower compared with the other threshold values and flooding. For example at an injection rate of 50 packets per second, the collision rate for C = 6 increases by approximately 220% compared with that of C = 2.

Similar to Figures 3.4 and 3.5, the figure also depicts that for threshold values greater that 4 the behaviour of the counter-based scheme converges to flooding.

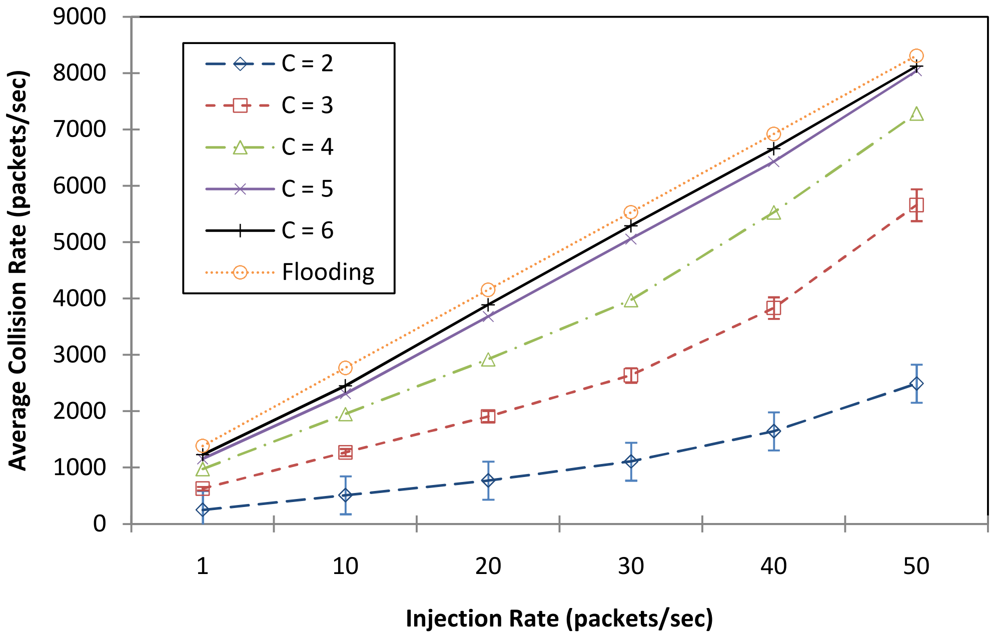

Figure 3.6. Average Collision rate vs. broadcast injection rates in a network of 100 nodes placed over 1000mx1000m area for different threshold values.

3.3 Analysis of Fixed Probabilistic Broadcast Scheme

This section examines the effect of the forwarding probability on the performance of fixed probabilistic broadcast scheme. The original fixed probabilistic broadcast scheme specification in [18] have been modified and implemented on Ns-2 (2.29.3) simulator [90] in order to incorporate the different forwarding probabilities. The probability values have been varied from 0.1 to 1.0 with an increment of 0.1 per trial. The performance analysis of fixed probabilistic scheme over varying probability values has been conducted using the simulation model and parameters as outlined in Chapter 2 (see Section 2.6). The performance of fixed probabilistic scheme has been assessed over two network conditions, network density and traffic load, in order to identify the effect of each operating condition over varying forwarding probability values. The performance metrics used for the analysis are the same with those used in Section 3.2.

3.3.1 *Effects of Network Density*

In this section, the network density has been varied by increasing the number of nodes placed over a network topology of 1000m x 1000m area. Each node in the network moves according to random trip mobility model with minimum and maximum speeds of 1m/s and 5m/s respectively. For each simulation trial an injection rate of 10 packets per second has been used.

3.3.1.1 Number of Retransmitting Nodes

As earlier stated in Section 3.1, if the forwarding probability is set to 1 then the fixed probabilistic scheme is reduced to simple flooding. The Figure 3.7 shows that the number of retransmitting nodes for any given forwarding probability value increases as the number of nodes increases. Similarly, the fixed probabilistic scheme with a low forwarding probability value (e.g. P = 0.1) requires least number of retransmitting nodes while those with high forwarding probability values (e.g. P=0.9 and 1.0) require the largest number of retransmitting nodes. This is due to the fact that increasing the forwarding probability increases the chances of two or more nodes within the same transmission range transmitting at the same time, leading to possible increase in the number of retransmitting nodes. For example in Figure 3.7, for a network of 100 nodes around 21% of the nodes retransmit for forwarding probability *P* = 0.3 while 89% of the nodes retransmit for *P* = 0.9.

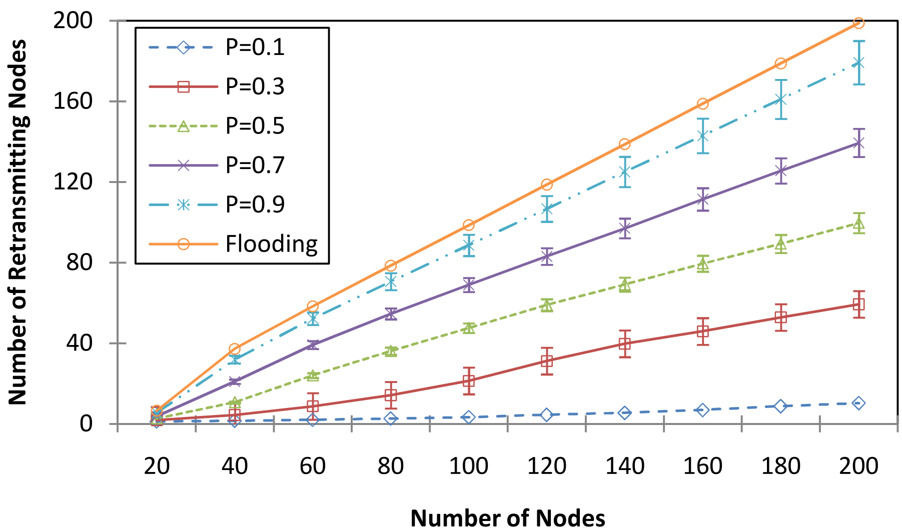

Figure 3.7. Number of retransmitting nodes vs. number of nodes placed over 1000mx 1000m area when an injection rate of 10packets/sec is used for different probability values.

3.3.1.2 Reachability

The results in Figure 3.8 depict that reachability increases with increased network density for various forwarding probability values. For example, reachability for the forwarding probability value P = 0.3 increases from approximately 16% for a network of 20 nodes to around 68% for 100 nodes. In contrast, for P = 0.9 reachability increases from around 30% to 99% for 20 and 100 nodes density respectively. This is because as density increases there is more likelihood that more nodes are located within the same transmission range of each other and thus resulting in a better network connectivity. The Figure also reveals that a low forwarding probability value (e.g. P = 0.1) achieves the lowest reachability for various network densities. This is because the lower is the forwarding probability value the lesser is the chance of a node retransmitting its received broadcast packet. However, as the density increases reachability improves for all the forwarding probability values but at different rates. Similarly, the figure shows that to maintain a high reachability in sparse networks, a higher forwarding probability value is required while to maintain high reachability in dense networks, a low forwarding probability value can be used. For example to maintain 100% reachability in a network of 120 to 200 nodes, a forwarding probability value of 0.5 is sufficient. To achieve high reachability in a network of 40 – 100 nodes, a high forwarding probability value (0.9) is required.

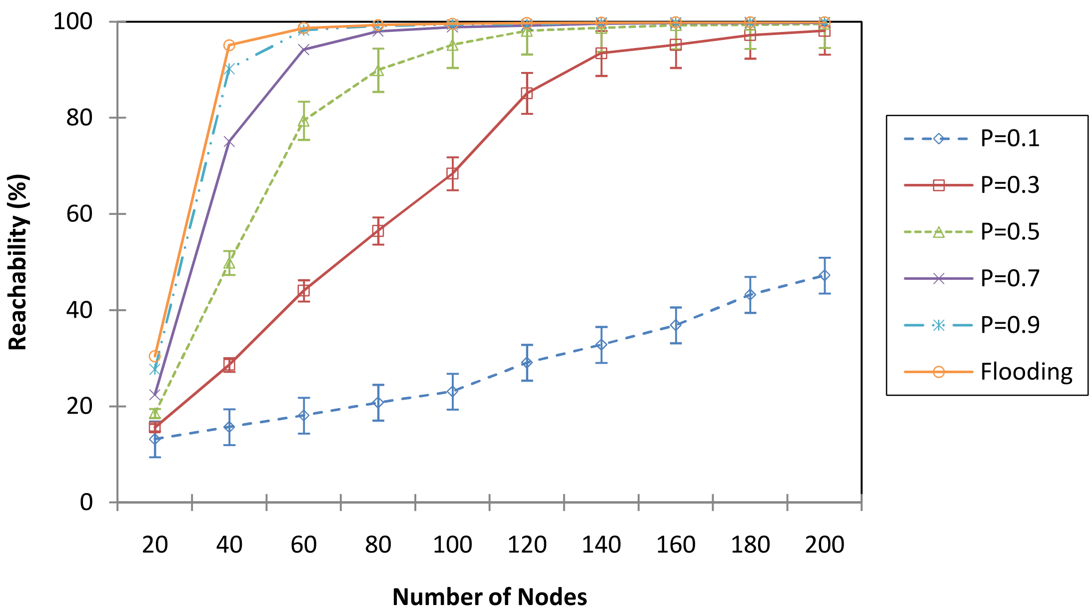

Figure 3.8. Reachability vs. number of nodes placed over 1000mx1000m area when an injection rate of 10 packets/sec is used for different probability values.

3.3.1.3 Collision Rate

The results in Figure 3.9 demonstrate that the collision rate for given forwarding probability value increases almost linearly with increased network density. This is due to the fact that increasing the network density increases the chance of two or more nodes being within the same transmission range transmitting at the same time, leading to a possible increase in the number of collisions. For example in Figure 3.9, when the network density is increased from 100 to 200 nodes, the collision rate for forwarding probability values 0.3 and 0.9 increases by approximately 700% and 390% respectively.

The results also reveals that for a given network density, the number of collision incurred by the different forwarding probability values increases as the forwarding probability value increases. For instance, for a network of 120 nodes, the collision rate for the forwarding probability P=0.3 increases by a factor of around 3 when the forwarding probability increases to P=0.5. Moreover, the collision rate increases by a factor of 4 when forwarding probability value increases to P=0.7.

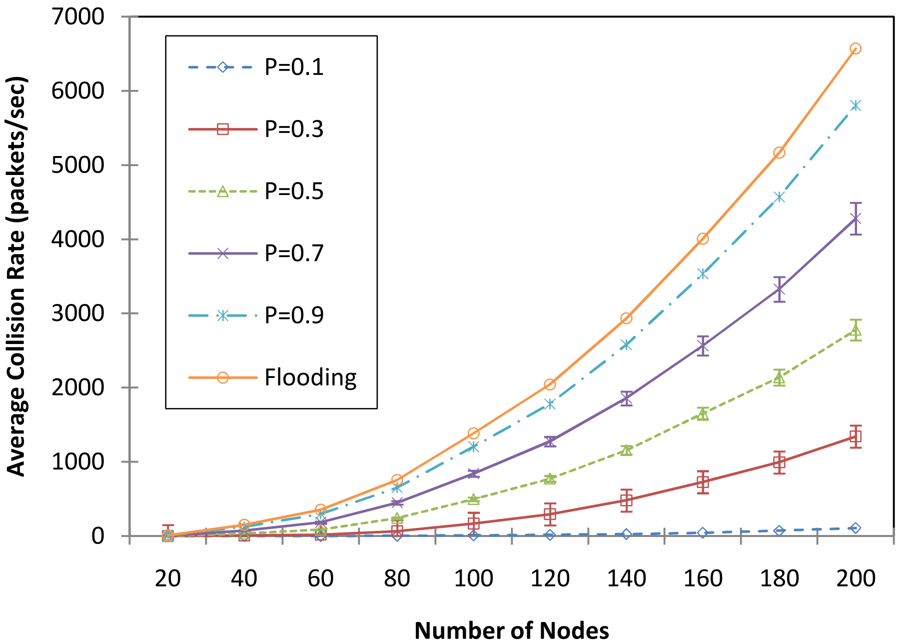

Figure 3.9. Average Collision rate vs. number of nodes placed over 1000mx1000m area when an injection rate of 10 packets/sec is used for different probability values.

3.3.2 *Effects of Traffic Load*

To investigate the impact of traffic load, the packet injection rates of 1, 10, 20, 30, 40 and 50 packets per second have been used with a network density of 100 nodes and a maximum node speed of 5m/s.

3.3.2.1 Number of Retransmitting Nodes

Figure 3.10 shows that the number of retransmitting nodes for any given forwarding probability value remains constant over varying traffic loads. Nevertheless, the lower forwarding probability value (e.g. P = 0.1) requires the lowest number of retransmitting nodes while the higher forwarding probability values (e.g. P = 0.9, 1.0) requires the largest number of retransmitting nodes. For example in Figure 3.10, around 49% (49 nodes) of the nodes retransmit when P = 0.5 while around 68% of the nodes retransmit when P=0.7 and 89% of the nodes retransmit when P=0.9. Therefore, the higher is the forwarding probability the more is the number of retransmitting nodes.

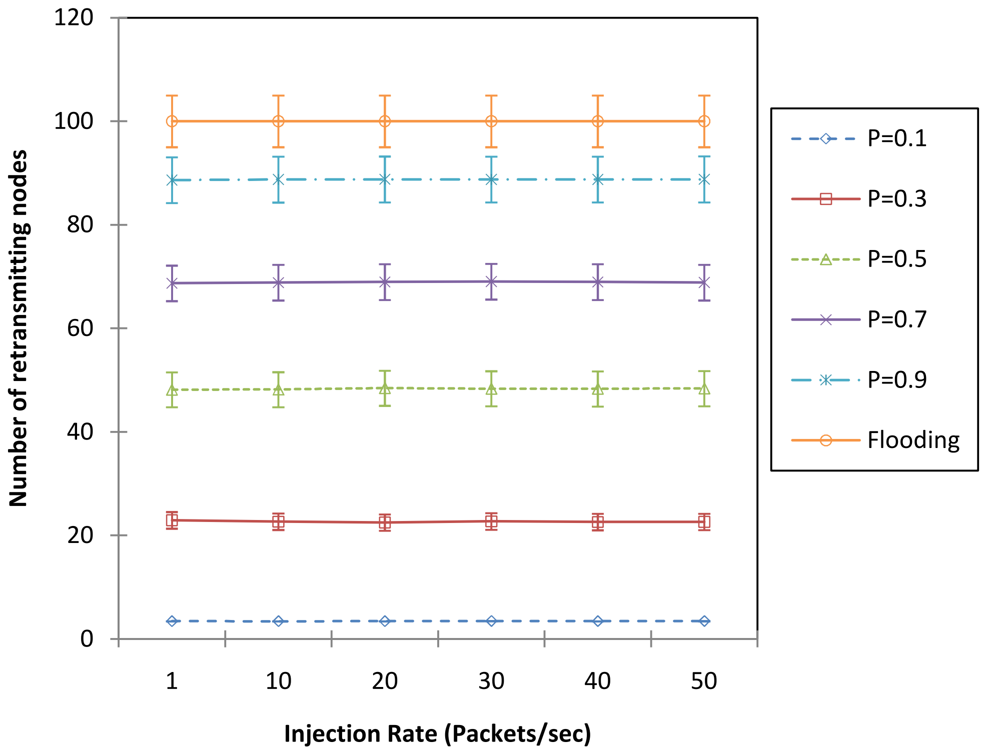

Figure 3.10. Number of retransmitting nodes vs. broadcast injection rates in a network of 100 nodes placed over 1000mx1000m area for different probability values.

3.3.2.2 Reachability

According to Figure 3.11, reachability decreases with increase in injection rate, i.e. a heavier load will result in a lower reachability. This is because a high injection rate leads to more contention and collision among broadcast packets. For example, flooding is the most affected where reachability falls to around 85% at 50packets/sec injection rate.

The figure also shows that a forwarding probability of P=0.7 is quite advantageous when the injection rate is over 20 packets per second. This is due to the fact that when the probability is set high (e.g. greater than 0.7), more redundant transmissions of the broadcast packets induce a huge amount of packet contention and collisions causing some of the broadcast packets to fail to reach most of the nodes in the network.

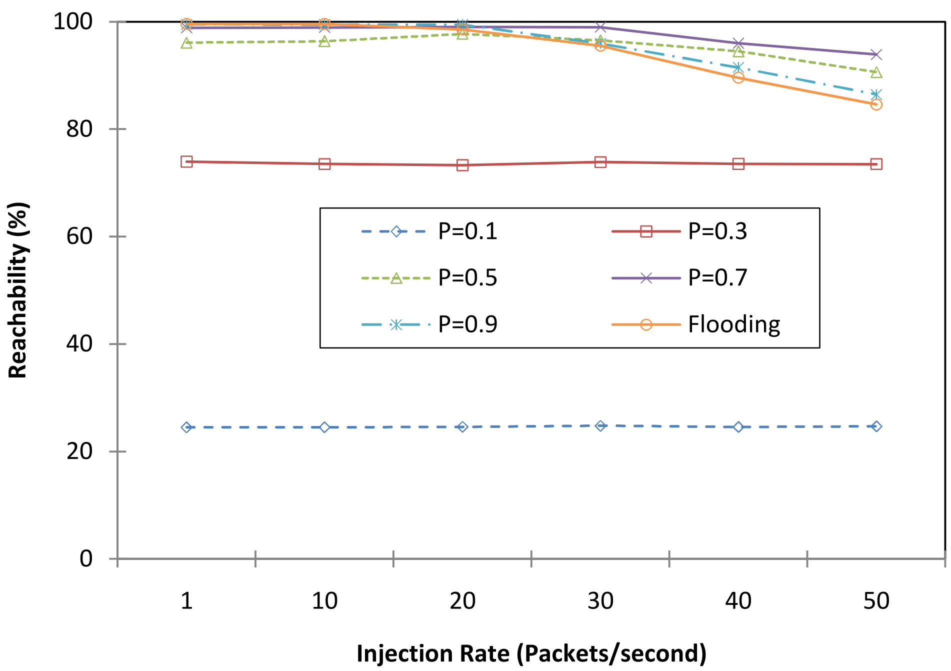

Figure 3.11. Reachability vs. broadcast injection rates in a network of 100 nodes placed over 1000mx1000m area for different probability values.

3.3.2.3 Collision Rate

Figure 3.12 reveals that when the offered load increases, the average collision rate of all the forwarding probability values and flooding also increases. This is because, when the broadcast rate increases, the number of broadcast packet generated and transmitted also increases. Thus, the probability of two or more nodes transmitting at the same time within the same transmission range is increased which leads to an increase in the collision rate. However, for a given injection rate, the average collision rate of the counter-based scheme with forwarding probability P= 0.1 is much lower compared with that of other forwarding probability values and flooding. For example at an injection rate of 50 packets per second, the collision rate for *P*=0.9 increases by approximately 635% when compared with that of P=0.3.

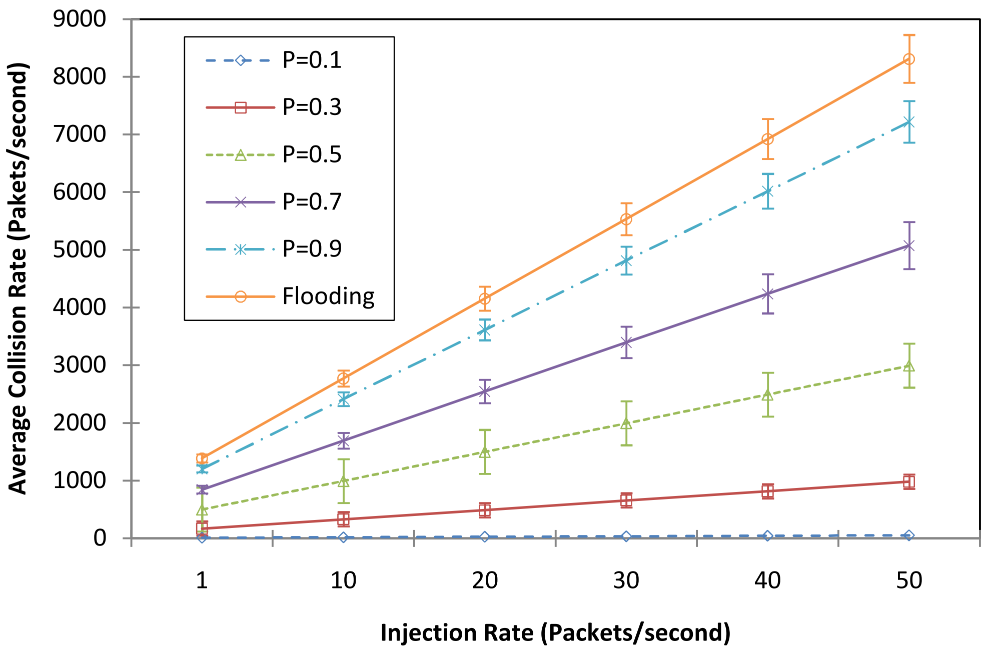

Figure 3.12. Average collision rate vs. broadcast injection rates in a network of 100 nodes placed over 1000mx1000m area for different probability values.

3.4 Conclusions

This chapter has conducted a performance analysis of counter-based and fixed probabilistic broadcast schemes to assess the effects of network density and traffic load over different counter threshold and forwarding probability values.

The results have revealed that network density and offered traffic load have significant impact on the performance of the two schemes in terms of number of retransmitting nodes, reachability and collision rate. Furthermore, the results have shown that the selection of an appropriate threshold and forwarding probability values dictates the achieved performance output of counter-based and fixed probabilistic schemes.

In counter-based scheme, number of retransmitting nodes (Figure 3.1), reachability (Figure 3.2) and collision rate (Figure 3.3) increases with increase in counter threshold value. The results have shown that a threshold value of 3 can minimise the number of retransmitting nodes and collision rate without sacrificing reachability in moderate to dense network. However, in sparse network reachability degrades. In general, counter-based achieves better reachability performance than fixed probabilistic scheme. On the other hand, the analysis on fixed probabilistic scheme have shown that reachability (Figure 3.8), collision rate (Figure 3.9) and number of retransmitting nodes (Figure 3.7) increases as the forwarding probability increases. Thus, a forwarding probability of 0.5 can minimise the number of retransmitting nodes and collision rates with a relatively acceptable reachability in dense network. The main advantage of fixed probabilistic scheme is its reduction of redundant retransmissions. However, it suffers from poor reachability.

Thus, neither of the two schemes independently is adequate in reducing the number of redundant retransmissions and at the same time ensures most of the nodes receive the broadcast packet (reachability). The subsequent chapter will introduce a new broadcast technique which combines the features of counter-based and fixed probabilistic scheme, leading to an improved hybrid broadcast scheme.

Chapter 4

Probabilistic Counter-Based Broadcast Scheme

4.1 Introduction

As was discussed in Chapter 3, both counter-based and fixed probabilistic schemes can reduce the detrimental effects of broadcast storm. The counter-based scheme often achieves better reachability while a probabilistic scheme often reduces the number of redundant rebroadcast at the expense of reachability.

Despite the advantages of these schemes, there has been little work so far to determine the merits of hybrid-based broadcast scheme that combine the desirable features of the counter-based and fixed probabilistic schemes. In an effort towards filling this gap, this chapter proposes a new broadcast scheme which provides a framework for the development of such hybrid broadcast schemes.

The rest of the chapter is organised as follows. Section 4.2 describes the proposed probabilistic broadcast scheme. Section 4.3 analyses the effects of various network operating conditions on the performance of the proposed broadcast scheme. Finally, Section 4.4 summarises the findings of the chapter.

4.2 The New Broadcast Scheme

The new scheme simply referred to Probabilistic Counter-based Broadcast Scheme (PCBS), combines the features of two probabilistic schemes, namely, the counter-based approach and fixed probabilistic approach. It makes use of one set of network information, i.e. neighbourhood information of the mobile nodes. One of the simplest techniques for neighbourhood information estimation is the use of packet counter. At each node a counter is maintained for every received broadcast packet. The counter is increased whenever a new copy of the broadcast packet is received. A high packet counter values entails that the number of neighbours of the current node is high while a low packet counter means a small number of neighbours. Therefore, the new scheme employs a packet counter as a mechanism to estimate the density for each node in the network.

Basically, the new scheme operates as follows. A node upon reception of a previously unseen packet initiates a counter *c* that records the number of times a node receives the same packet. Such a counter is maintained by each node for each broadcast packet as stated above. After waiting for a Random Assessment Delay (RAD) time, which is randomly chosen from a uniform distribution between 0 and T_{max} seconds, where T_{max} is the highest possible delay interval. If *c* reaches a predefined threshold *C*, the node is inhibited from rebroadcasting the packet. Otherwise, if *c* is less than the predefined threshold *C*, the packet is rebroadcast with a rebroadcast probability *P*. The broadcast scheme is divided into two phases: the rebroadcast decision phase and the forwarding probability assignment phase.

The rebroadcast decision criterion is similar to that of conventional counter-based scheme, where the key rebroadcast decision parameter is the threshold value *C* as discussed in Chapter 3. However, the forwarding probability assignment phase of the conventional counter-based scheme has been modified to incorporate the assignment of a fixed forwarding probability value to a node.

The rebroadcast decision phase is triggered whenever a node needs to communicate with other nodes in the network or receive a broadcast packet. The source node transmits the broadcast packet to all its 1-hop neighbours. Each neighbouring node that receives the broadcast packet initialise a counter and wait for a RAD time during which it increment its counter for every received copy of the same broadcast packet. After the expiration of the RAD time, the node compares its *c* value against the threshold value. If the *c* value is less than the threshold value, the scheme proceeds to the second phase where the forwarding probability is assigned. Otherwise, the broadcast packet is dropped and the scheme exit.

Unlike the fixed probability scheme where each node is automatically assigned a fixed forwarding probability value, the forwarding probability assignment phase is triggered only if the rebroadcast decision phase is satisfied. Otherwise, the phase is skipped. Figure 4.1 present an outline of the algorithm.

Algorithm: Probabilistic Counter-based Broadcast Scheme (PCBS)

Forwarding Nodes

On hearing a broadcast message *m* at a node *X*

- Initialize the packet counter *c*
- Set and wait for RAD to expire
- While waiting:
  - o For every duplicate message *m* received
  - o Increment *c* by 1
- **if** ($c < C$) (i.e. *C* is the counter threshold)
  - o set the forwarding probability to *P*
- **else**
  - o Drop the message *m*
  - o Goto Exit
- Generate a random number R_n over the range *[0,1]*
- ***If*** ($R_n < P$)
  - o Broadcast the message *m*
- ***else***
  - o Drop the message *m*
- Exit

Figure 4.1: An outline of the new broadcast scheme that combine the features of both counter-based and fixed probabilistic schemes.

The forwarding probability *P* and the threshold value *C* are crucial parameters that greatly affect the performance of the algorithm. As shown in Chapter 3, few rebroadcasts can be saved when choosing $C \geq 6$, especially in sparse network. In fact, the scheme with $C \geq 6$ behaves almost similar to flooding. Whilst many rebroadcasts could be saved when choosing C equals to 3. Therefore, this result is used to set the threshold value in the new scheme.

Similarly, the analysis on forwarding probabilities that has been conducted in Chapter 3 for fixed probabilistic scheme has shown that a larger P incurs more redundant retransmission while a smaller P leads to lower reachability. Similar to what is reported in [23, 57], the forwarding probability of around 0.65 can significantly reduce the number of retransmission as well as collision rate. Despite this insight a further analysis is conducted in the next section to determine the appropriate forwarding probability value for counter-based scheme. This is because the forwarding probability suggested from the analysis in both chapter 3 and [23, 57] is directly in relation to fixed probabilistic scheme. Thus, the suggested probability value might not yield a similar performance when applied to the new scheme.

4.2.1 *Selection of Forwarding Probability P*

In order to gain a deep understanding on the effects of different forwarding probabilities on counter-based scheme, we conduct an extensive Ns-2 [90] simulations to determine the appropriate forwarding probability value for our new scheme. The previous counter-based broadcast scheme implementation used in Chapter 3 has been further modified to incorporate the different forwarding probability values.

The performance analysis of the different forwarding probability values has been conducted using the simulation model and parameters as outlined in Chapter 2 (see Section 2.6). The performance metrics used for the analysis includes the number of retransmitting nodes, collision rate and reachability; and the metrics have been defined in Chapter 2 (see Section 2.7). The simulation scenario is designed to assess the impact of network density on the performance of counter-based scheme over different forwarding probabilities. The network density has been varied by deploying 80, 120, 160 and 200 nodes over a fixed area of 1000m x 1000m for different forwarding probabilities. Each node moves according to random trip mobility model [104] with a speed chosen uniformly between 1 and 5m/sec. The broadcast injection rate of 10 packets per second and a packet size of 512 bytes have been used. In the figures presented in this section, the x-axis represents the variations of forwarding probabilities, while the y-axis represents the results of the performance metric of interest.

Number of Retransmitting Nodes:

The results in Figure 4.2 reveals that the number of retransmission nodes for a given network size (i.e. a given number of nodes) increases almost linearly with increased forwarding probabilities. This is due to the fact that increasing the forwarding probability increases the chances of two or more nodes within the same transmission range transmitting at the same time, resulting in a possible increase in the number of retransmitting nodes. For example from the figure when the forwarding probability is increased from *P* = 0.5 to *P* = 1.0, the number of retransmitting nodes for a 120 nodes network increases by approximately 56% while for 160 and 200 nodes networks the number retransmitting nodes increases by as much as 90% and 102% respectively.

Figure 4.2 also demonstrates that for a given forwarding probability the number of retransmitting nodes increases as the number of nodes increases. As can be seen in Figure 4.2, the number of retransmitting nodes at *P* = 1 increases by up to 75% when the number of nodes increases from 120 to 200 nodes.

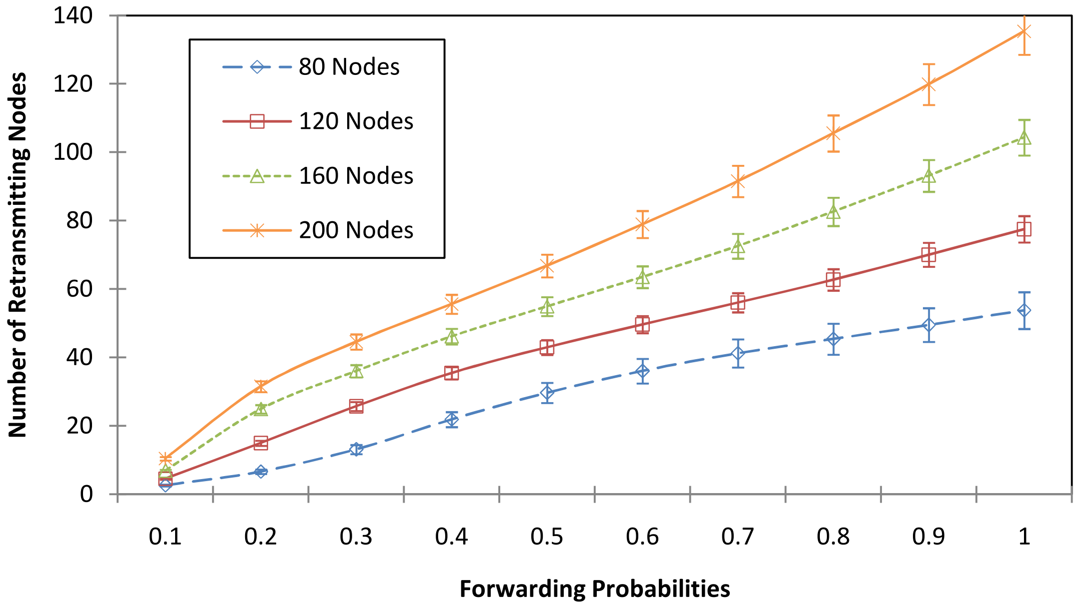

Figure 4.2: Number of retransmitting nodes vs. forwarding probabilities for different network densities.

Reachability:

The results in Figure 4.3 show that reachability increases with an increase in the forwarding probability given various network densities. For example, reachability achieved by 120 nodes network increases from 29.5% for the forwarding probability P=0.1 to 99.8% for P=1.0 while the reachability achieved by a 200 nodes network increases from around 48% to 99.9% for P=0.1 and 1.0 respectively. This is because increasing the forwarding probability increases the chances of more nodes transmitting a broadcast packet, resulting in a possible increase in the number of nodes that receives the broadcast packet.

Figure 4.3 also reveals that lower network density (i.e. 80 nodes) achieves the least reachability performance using lower forwarding probabilities (P=0.1 to 0.5). However, as the forwarding probability increases reachability improves for all network densities. For example, as depicted in Figure 4.3, the reachability achieved using P= 0.2 increases from 36% for 80 nodes to 91% for 200 nodes. This is because increasing the network density increases the chances of more nodes to be within the same transmission range of each other and resulting in more nodes receiving the broadcast packet.

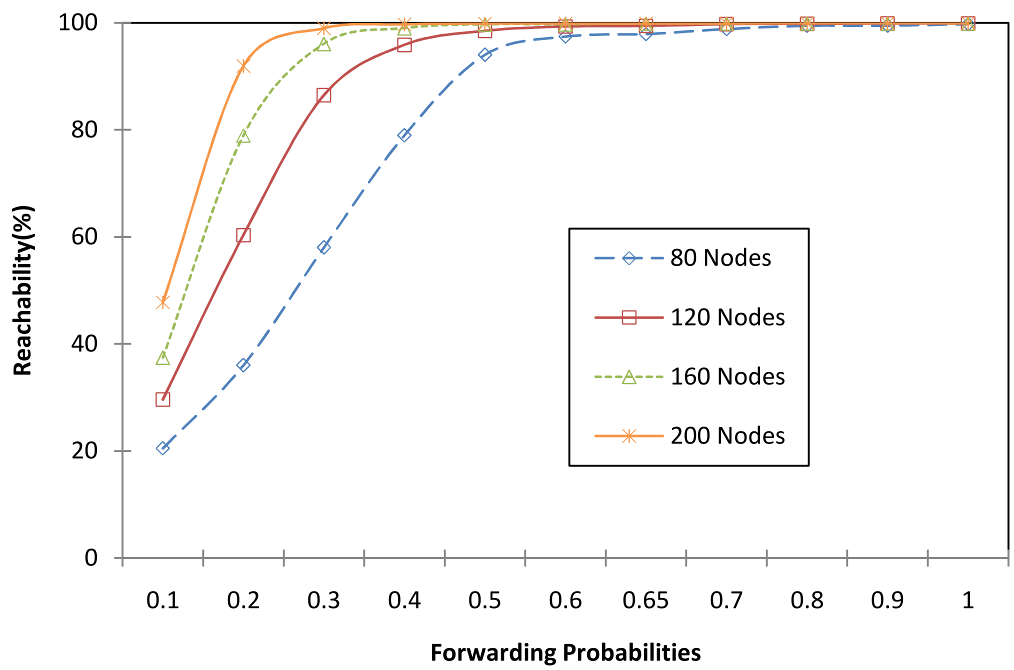

Figure 4.3: Reachability vs. forwarding probabilities for different network densities.

Collision Rate:

Figure 4.4 shows that the collision rate for a given network density increases almost linearly with increased forwarding probabilities. This is due to the fact that increasing the forwarding probability increases the chances of two or more nodes within the same transmission range transmitting at the same time, resulting in an increase in the number of collisions. For example in Figure 4.4, when the forwarding probability is increased from P=0.5 to 1.0, the collision rate for 160 and 200 node networks increased by approximately 230% and 221% respectively.

The figure also shows that for a given forwarding probability, the number of collisions incurred by the different network densities increases as the network density increases. As can be observed in Figure 4.4, for P=1.0, the collision rate for 120 nodes increases by approximately 265% when the network density is increased to 200 nodes.

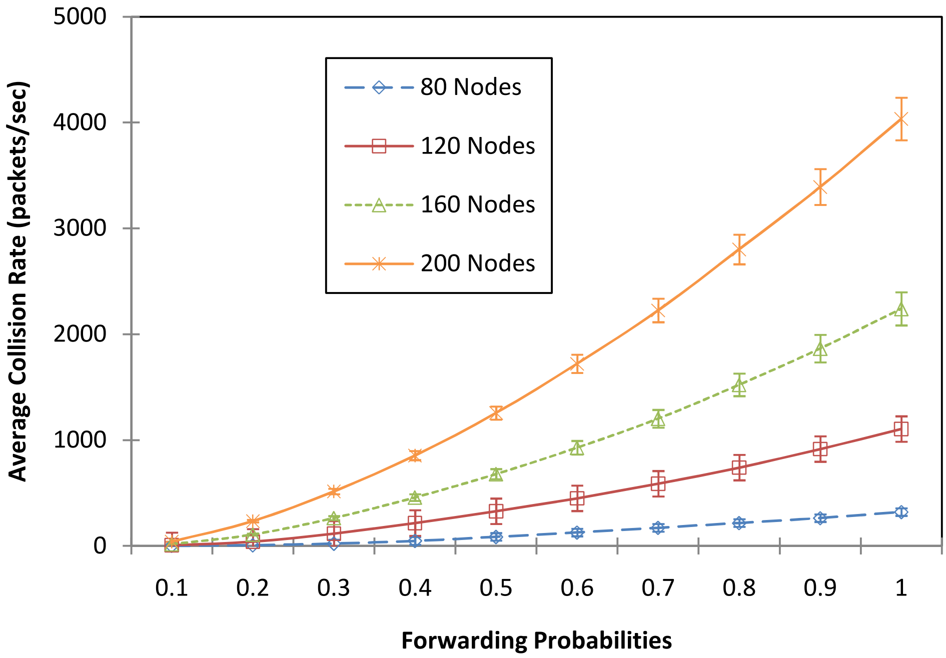

Figure 4.4: Average collision rate vs. forwarding probabilities for different network densities.

The above results have revealed that for a given network density considerable savings can be achieved in terms broadcast packet transmission and collisions without sacrificing reachability, provided that an appropriate forwarding probability is used. For example, the results have revealed that using a forwarding probability of around 0.5 in a moderate to dense network (120 – 200 nodes) can reduce the number of retransmitting nodes as well as rate of collisions while still guaranteeing good performance level in terms of reachability. Although, the analysis considered the effect of different network densities only, the results of other network operating conditions such as network load and mobility are presented in appendix A for interested readers.

4.3 Performance Evaluation

This section presents the performance evaluation of the new proposed probabilistic broadcast scheme using the same simulation model and parameters as outlined in Chapter 2 (Section 2.6).The performance metrics that have been used to conduct the performance evaluation include the reachability, average collision rate, number of retransmitting and end-to-end delay. These metrics have been defined in Chapter 2 (Section 2.7).

To evaluate the performance of the new probabilistic broadcast scheme (simply referred to as probabilistic counter-based broadcast scheme (PCBS, for short)), the previous counter-based broadcast scheme implementation used in Section 4.2.1 have been further modified and implemented on the same Ns-2 (2.29.3) simulator [90] in order to incorporate a single forwarding probability value. The results are compared against the counter-based scheme (CB, for short), fixed probabilistic scheme (FP, for short) and flooding.

The simulation scenarios consist of two different network settings, each designed to assess the impact of a particular network operating condition on the performance of the protocols. First, the impact of network density is assessed by deploying a different number of mobile nodes over a topology of 1000m x 1000m. The second simulation scenario investigates the effects of an offered load on the performance of the broadcast schemes by varying the number of packet injection rate for each simulation scenario.

4.3.1 *Impact of Network Density*

The network density has been varied by changing the number of nodes placed in a 1000m x 1000m area of each simulation scenario. Each node moves according to random trip mobility model [104] with a speed chosen between 1 and 5m/sec. For each simulation trial, a broadcast injection rate of 10 packets per second is used.

4.3.1.1 Number of Retransmitting Nodes

Figure 4.5 shows the number of retransmitting nodes required by the each of the four schemes as the network density increases. The figure illustrates that the required number of retransmitting nodes in all the four broadcast schemes increases with increased number of nodes. Furthermore, the figure reveals the clear advantage of PCBS over CB, FP and flooding. For instance, compared with the CB and flooding, the required retransmitting nodes in PCBS can be reduced by approximately 33% and 166% respectively when the number of nodes is relatively small (e.g. 40 nodes). The performance advantage of PCBS over the other schemes is further increased in dense networks. For example, in Figure 4.5, when the number of nodes increases to 200 nodes, the required retransmitting nodes in PCBS is reduced by as much as 105% and 203% less than FP and flooding respectively. Clearly, PCBS is more scalable than the other schemes.

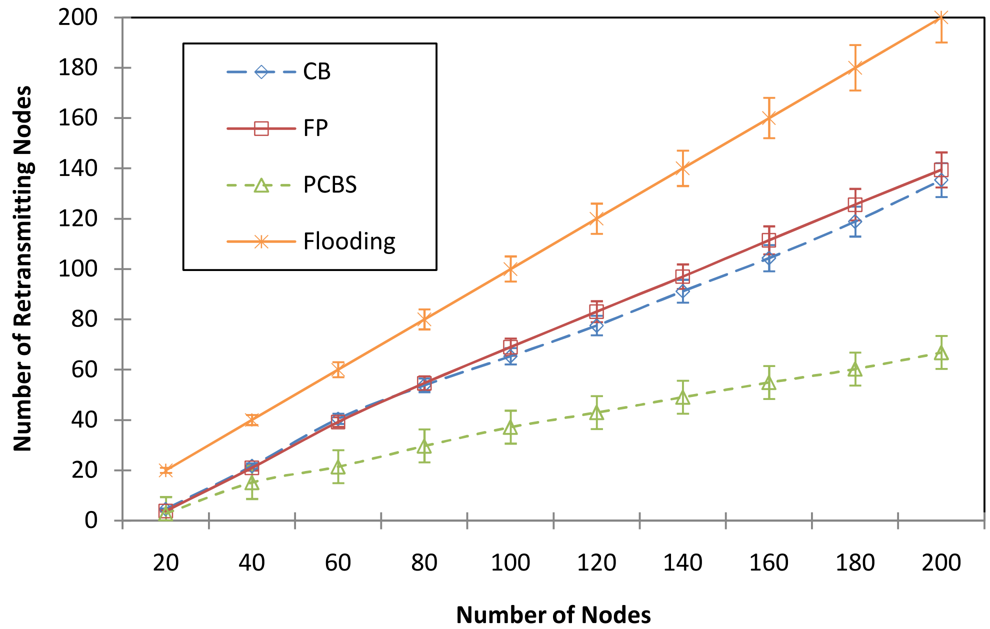

Figure 4.5: Number of retransmitting nodes vs. number of nodes placed over 1000m x 1000m area using 10packets/sec broadcast injection rate.

4.3.1.2 Reachability

Figure 4.6 illustrates the reachability achieved by the four broadcast schemes when the number of nodes is varied. The figure shows that reachability increases with increased number of nodes. For instance, reachability achieved by FP increases from 21% for 20 nodes to 98% for 120 nodes while the reachability achieved by PCBS increases from 25% to 98% for 20 and 120 nodes respectively. As expected, flooding has the best reachability performance compared to the other schemes. PCBS achieved one of the least reachability performances in sparse network (i.e. 20 to 60 nodes) but in dense network it achieves a reachability performance that is comparable to flooding.

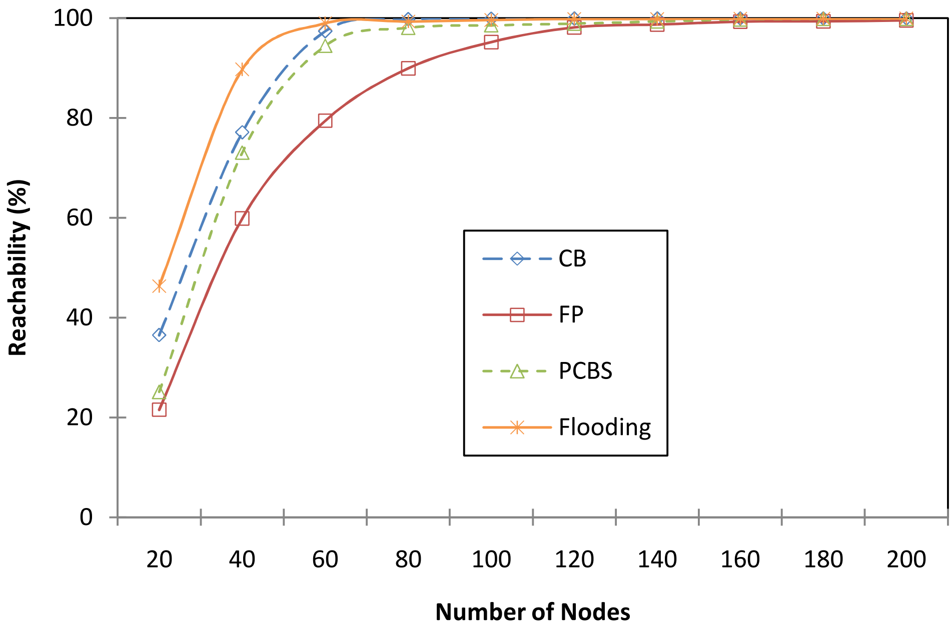

Figure 4.6: Reachability vs. number of nodes placed over 1000mx1000m area using 10packets/sec broadcast injection rate.

4.3.1.3 Collision Rate

Figure 4.7 show that the number of collisions incurred by the broadcast schemes increases with increased number of nodes. The figure also reveals that as the number of nodes increases the advantage of PCBS over the FP, CB and flooding becomes more noticeable, confirming the scalability feature of the PCBS approach. In fact, the probability of two more nodes transmitting at the same time is significantly reduced using PCBS. This is because most of the nodes within the same transmission range have been made to probabilistically suppress their broadcasts. For instance, Figure 4.7 depicts that the collision rate of PCBS is reduced by approximately 134%, 148% and 281% for 200 nodes compared against the CB, FP and flooding respectively.

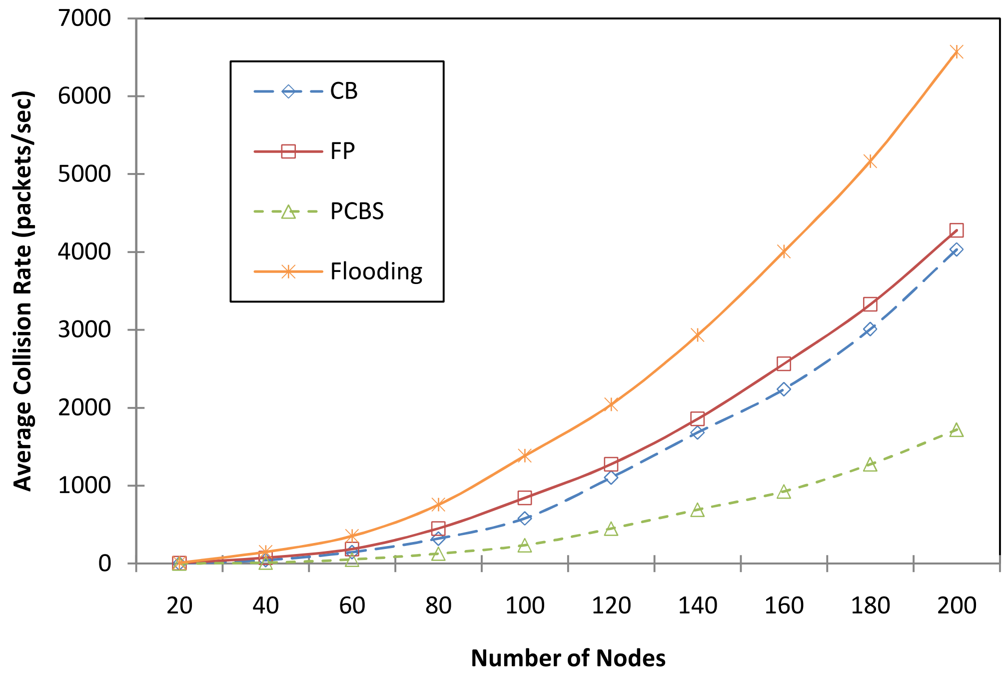

Figure 4.7: Average collision rate vs. number of nodes placed over 1000mx1000m area using 10packets/sec broadcast injection rate.

4.3.1.4 End-to-End delay

The result in Figure 4.8 shows that the end-to-end delay incurred by the broadcast schemes increases with increased network density. Figure 4.8 also reveals that PCBS incurred the least end-to-end delay compared to the other schemes in sparse to dense network. This is due to the few number of retransmission nodes required by PCBS which leads to low contention and collision within the network. In general, contention and collision increases with increasing network density regardless of the scheme used. On the contrary, flooding incurs the least end-to-end delay in sparse network (i.e. 20-40 nodes).

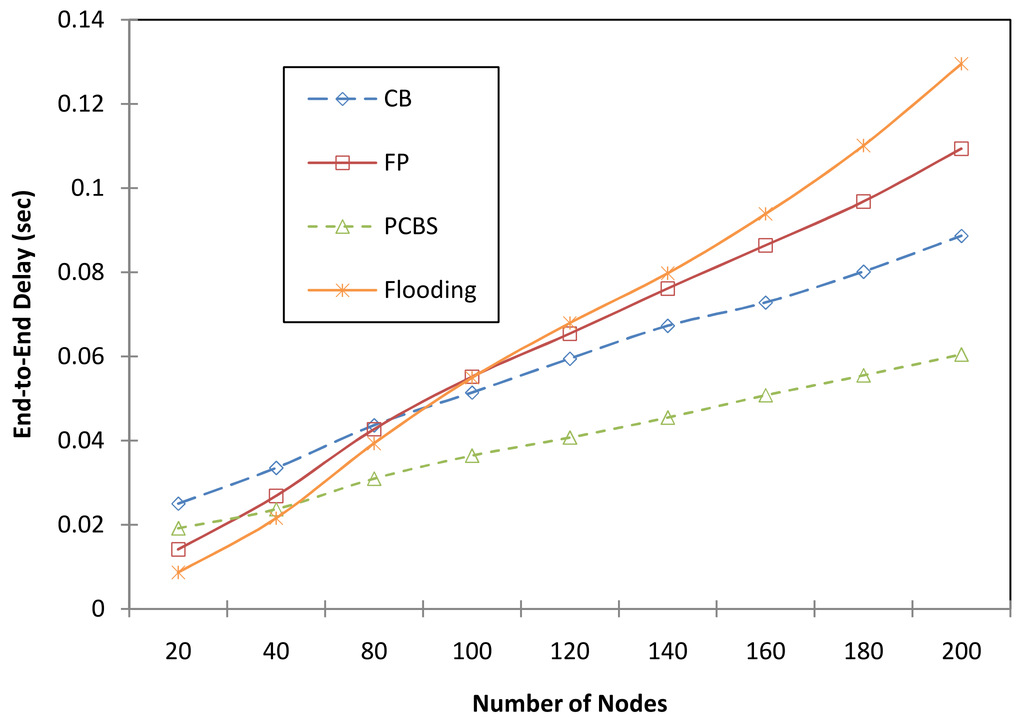

Figure 4.8: End-to-end delay vs. number of nodes placed over 1000mx1000m area using 10packets/sec broadcast injection rate.

4.3.2 *Impact of Offered Load*

In this section, the effects of offered load on the performance of the broadcast schemes have been investigated, where the offered load is varied by increasing the broadcast injection rate from 1 to 70packets/second. The topology for each simulation scenario consists of 100 nodes placed on a flat area of 1000m x 1000m, each moving according to random trip mobility model with a speed chosen between 1 and 5m/sec. The purpose of this study is to measure the effect of load on the broadcast schemes and also illustrates the general limits of each broadcast scheme for a given broadcast injection rate. This will provide a cursory indication of which broadcast scheme reacts best over a range of network traffics (i.e. broadcast injection rate).

4.3.2.1 Number of Retransmitting Nodes

The results in Figure 4.9 depict the effects of offered traffic load on the performance of the broadcast schemes in terms of number of retransmitting nodes. As the number of nodes and the topology area remain fixed, one might expect the number of retransmitting nodes to remain constant in Figure 4.9 as well. In fact, to some extent CB and PCBS follow this trend. However, a careful examination of Figure 4.9 reveals that both CB and PCBS shows different trend (i.e. not constant only) which include both increasing and decreasing trend. For broadcast injection rate of 1 – 40 packets per second, both schemes shows a constant trend while both shows an increasing trend for injection rate of 50 -60 packets per second and a decreasing trend for 70 packets per second injection rate. Essentially, this is because higher traffic forbids redundant packets to be delivered during the RAD, therefore more nodes rebroadcast which further congest the network resulting in this snowball effect. In the case of flooding and FP, the number of retransmitting nodes falls as the network becomes congested, which directly demonstrates the effect of collisions and queue overflows in congested network. Nevertheless, PCBS requires the least number of retransmissions than the other broadcast schemes.

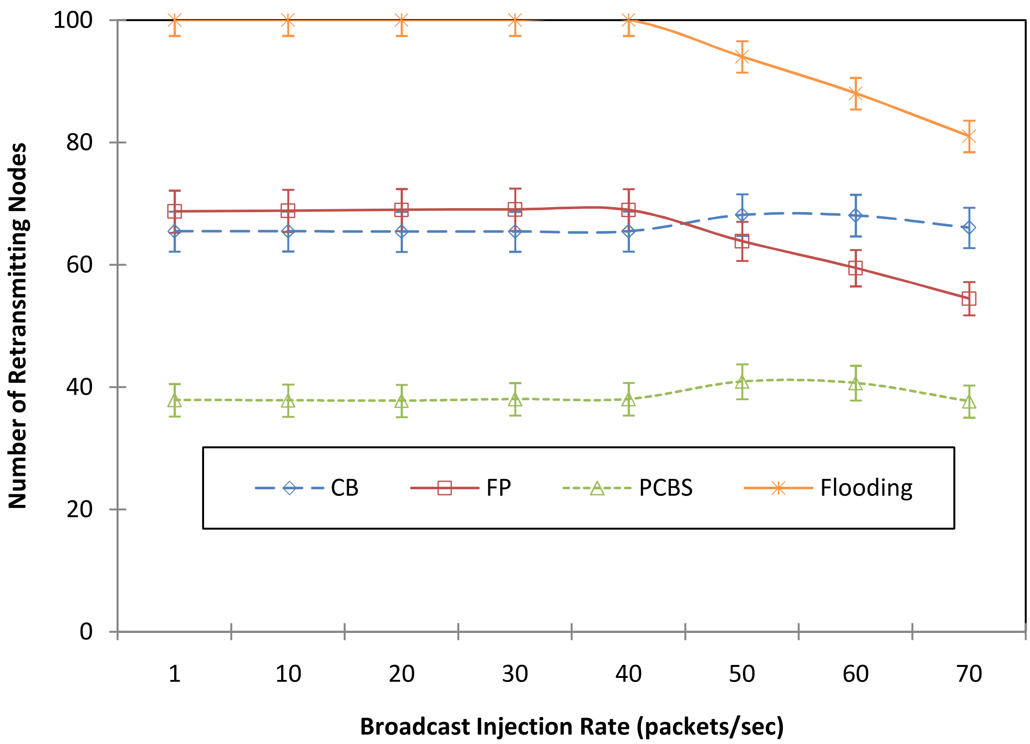

Figure 4.9: Number of retransmitting nodes vs. offered load for a network of 100 nodes placed in 1000mx1000m area.

4.3.2.2 Reachability

Figure 4.10 depicts the reachability performance of the four broadcast schemes over varying offered load. The figure shows that each scheme suffers as the network becomes more congested, i.e., reachability decreases with increased injection rate. Thus, heavier load results in a low reachability performance. This is true for all the broadcast schemes, because a high injection rate means more contention and collision among broadcast packets. For example, flooding is the most affected where reachability falls to around 80% at a 70packets/sec injection rate. Comparing Figure 4.10 to Figure 4.5 reveals the relationship between performance in congested networks and the number of redundant retransmission: i.e., broadcast schemes that minimise the number of redundant retransmissions deliver the most packets in congested networks. Thus, PCBS achieved better reachability performance in congested network.

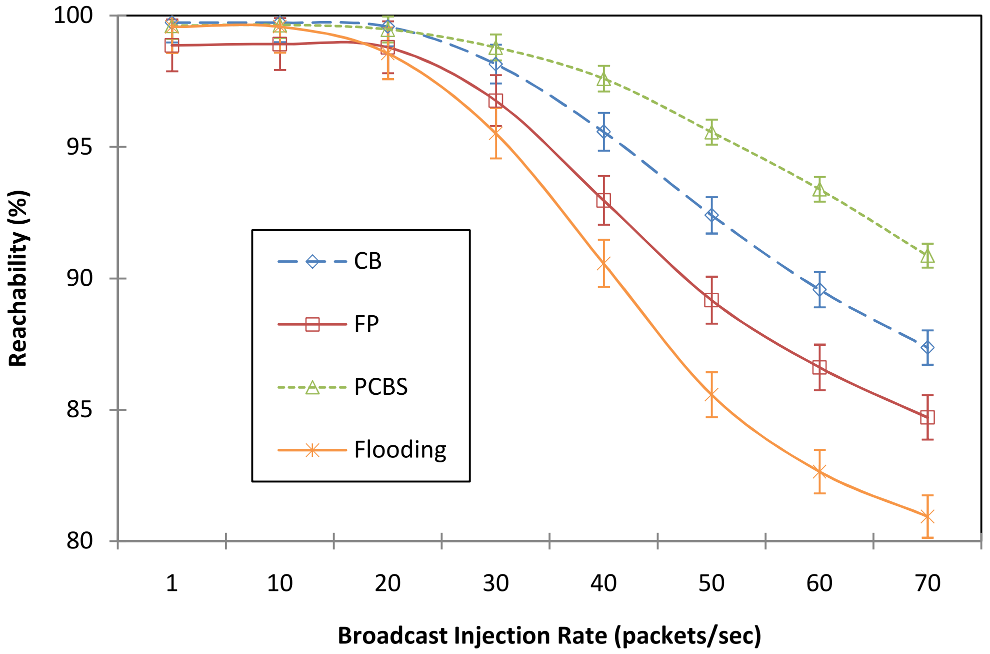

Figure 4.10: Reachability vs. offered load for a network of 100 nodes placed in 1000mx 1000m area.

4.3.2.3 Collision Rate

The results presented in Figure 4.11 depict the average collision rate under varying offered load (i.e. injection rates). When the offered load increases, the collision rate in all the broadcast schemes is also increased. This is because as broadcast injection rate increases the number of broadcast packets generated and disseminated increases. As a result, the probability of two or more nodes within the same transmission range transmitting at the same time increases which leads to an increase in the collision rate. Nevertheless, for a given injection rate, the collision rate in PCBS is much lower than in CB, FP and flooding. For instance, at an injection rate of 60 packets per second, the collision rate in PCBS is reduced by approximately 57%, 66% and 79% compared to the CB, FP and flooding respectively.

Figure 4.12 on the other hand shows the effect of offered load on both collision rate and reachability in a single graph. When the offered load increases, the collision rate in all schemes is also increased while the reachability achieved by all the schemes decreases. The results have shown that schemes with low average collision rate achieve better reachability than schemes with high average collision rate. That is broadcast schemes that minimise the average collision rate deliver the most packets in congested networks.

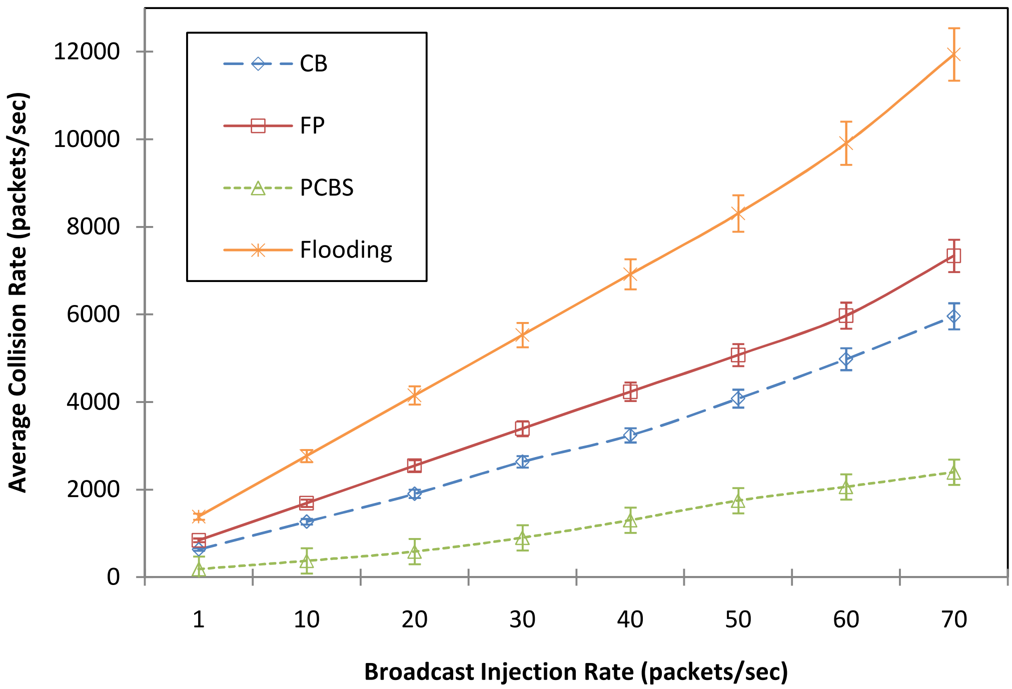

Figure 4.11: Average collision rate vs. offered load for a network of 100 nodes placed in 1000mx1000m area.

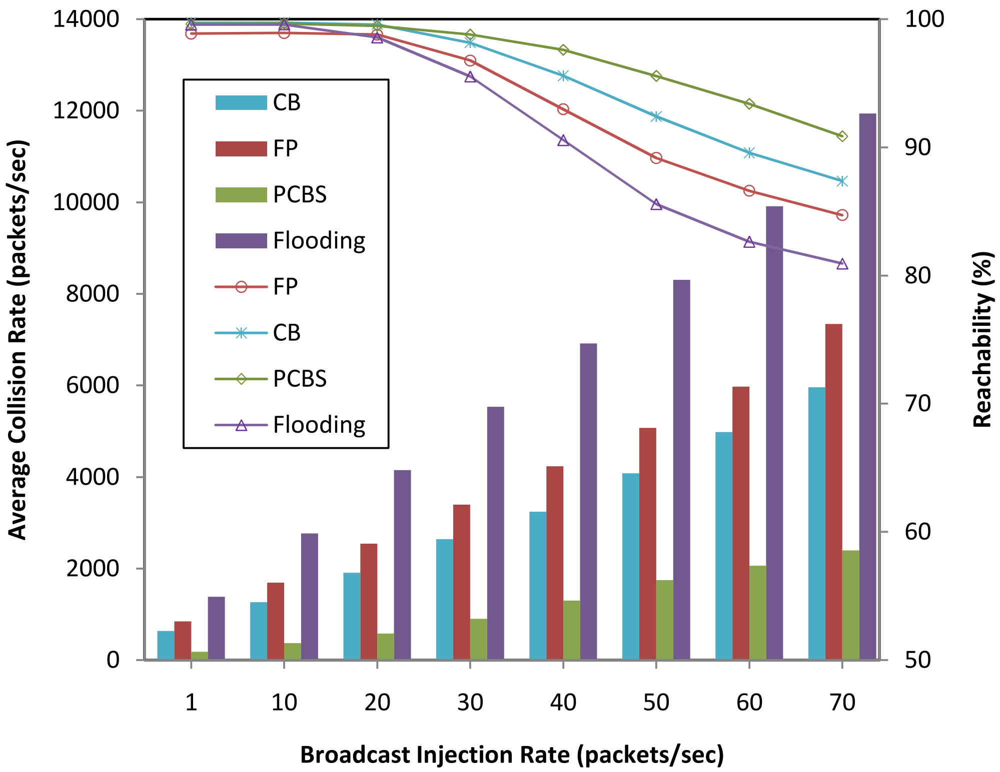

Figure 4.12: Reachability and Average collision rate vs. offered load for a network of 100 nodes placed in 1000m x 1000m area.

4.3.2.4 End-to-End Delay

Figure 4.13 show that all the broadcast schemes incur a comparable end-to-end delay when the offered load is less than 30 packets per second. However, the performance difference among the four schemes is noticeable at offered load greater than 30 packets per second. In Figure 4.12, the PCBS maintains a steady end-to-end delay for a traffic rate of 1-40 packets per second beyond which the end-to-end delay rose sharply to around 0.69s. The other broadcast schemes also exhibit similar trend but with different rising point. In FP and flooding, the end-to-end delay rise sharply as the traffic rate exceed 30 packets per second while in CB the sharp rise becomes more noticeable as the injection rate exceed 40 packets per second. For example, at injection rate of 60 packets per second, the delay in PCBS is reduced by approximately 20%, 40% and 46% compared against CB, FP and flooding respectively.

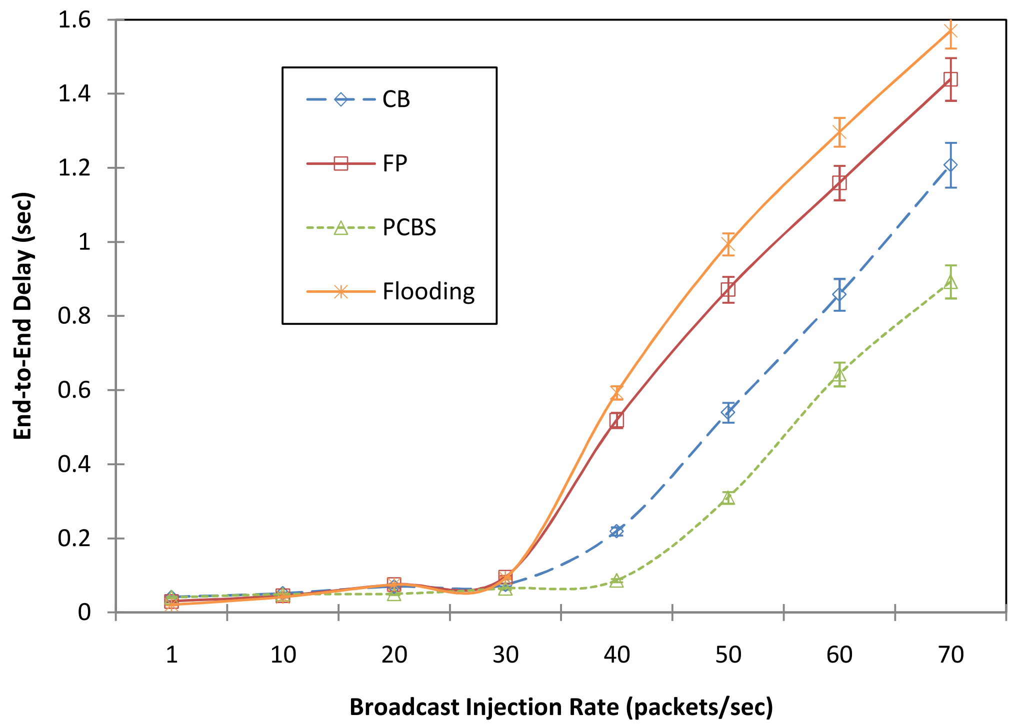

Figure 4.13: End-to-end delay vs. offered load for a network of 100 nodes placed in 1000m x 1000m area.

4.4 Conclusions

This chapter has presented a new broadcast scheme referred to as Probabilistic Counter-Based Broadcast Scheme (PCBS), which combines the features of counter-based and fixed probabilistic broadcast approaches. The scheme exploits the use of packet counter and probability at mobile nodes to reduce the retransmission of broadcast packets.

Simulation runs have been carried out to compare the performance of PCBS against that of counter-based (CB, for short), fixed probabilistic (FP, for short) and flooding. The performance analysis has shown that under varying network density and traffic load, PCBS outperforms the other schemes (i.e., CB, FP and flooding) in terms of number of retransmission nodes, average collision rate, reachability and end-to-end delay in most of the considered cases. Although, the performance of all the schemes degrades with increased injection rate, PCBS shows better resilience in high injection rate settings as it manages to reduce packet collision and channel contention by minimising the redundant transmissions.

Despite the superiority of PCBS over other schemes, its use of single fixed forwarding probability for all nodes in the network regardless of whether the node is in sparse or dense region of the network has make it inflexible in a typical MANET scenario where regions of varying node density co-exist in the same network. The solution to overcome the inflexibility of PCBS will be discussed in Chapter 5.

Chapter 5

Adjusted Probabilistic Counter-based Broadcast Scheme

5.1 Introduction

Mobility and reconfiguration are some of the key features that uniquely distinguished MANETs from other networks. The devices in MANETs have no physical boundary and their location changes as they move around. As such, the network topology in MANETs is highly dynamic due to node mobility which often resulted in frequent changes in the node distribution in this network [105, 126]. Therefore, the forwarding probability used in probabilistic broadcast schemes for the dissemination of broadcast packets should be set dynamically to reflect the local neighbourhood information of a given node, i.e., the packet counter value of a given node which determine whether the node is located in a sparse or dense region [22, 82].

As discussed in Chapters 3 and 4, the effect of broadcast storm can be reduced by allowing each node in the network to rebroadcast a received broadcast packet with a given forwarding probability. However, to achieve a significant reduction of the number of retransmission nodes without sacrificing reachability, the forwarding probability should be set high for a sparse network and low for a dense network. Similarly, both PCBS and its constituents (i.e., CB and FP) rely on the use of predetermined forwarding probability value which is unlikely to be optimal in other settings.

In order to significantly reduce the broadcast redundancy without sacrificing network reachability for a given network topology, the forwarding probability at a node should be adjusted and dynamically set according to the counter value of the given node. To achieve this, a new probabilistic broadcast approach referred to Adjusted Probabilistic Counter-based Scheme (APCBS, for short) is proposed in this chapter.

The rest of the chapter is structured as follows. Section 5.2 describes the proposed adjusted probabilistic counter-based broadcast scheme. Section 5.3 analyses the effects of various network operating conditions on the performance of the proposed broadcast scheme. Finally, section 5.4 summarises the findings of the chapter.

5.2 Adjusted Probabilistic Counter-Based Broadcast Scheme

Similar to PCBS (see Chapter 4), the APCBS algorithm combines the functionalities of FP and CB schemes, and also makes use of neighbourhood information which is estimated using packet counter. As in CB and PCBS, the APCBS partitions the network into two parts (i.e. sparse and dense networks) using the threshold value. The first part encompasses nodes with counter values less than the threshold value and this is the part where broadcast packet forwarding is considered highly desirable. On the other hand, the second part (dense network) consists of nodes with packet counter value greater than the threshold value and in this case where rebroadcast of packet need to be minimised because no much additional coverage can be gained by forwarding the packet [18]. Therefore, both the nodes within the two parts of the network are allowed to forward the broadcast packet with a forwarding probability dynamically determined using the counter value at the forwarding node and the threshold value.

The broadcast decision phase and the forwarding probability assignment phase of APCBS are both triggered in the same manner as in PCBS. Unlike the PCBS where each node is assigned a predetermined forwarding probability value, the nodes dynamically compute their forwarding probabilities using a probability function which depends on the packet counter value at a given node (i.e., local density) and the threshold value. An outline of the algorithm is presented in Figure 5.1.

Algorithm: Adjusted Probabilistic Counter-based Broadcast Scheme (APCBS)

Forwarding Nodes

On hearing a broadcast packet at a node *Y*

- Initialize the packet counter *c*
- Set and wait for RAD to expire
- While waiting:
  - For every duplicate broadcast packet received
  - Increment *c* by 1
- **if** ($c < C$) (i.e. *C* is the counter threshold)
  - Set the forwarding probability, $P \rightarrow f(c)$
- **else**
  - Set the forwarding probability, $P \rightarrow f(c)$
- Generate a random number R_n over the range *[0,1]*
- ***If*** ($R_n < P$)
  - Rebroadcast the broadcast packet
- ***else***
  - Drop the broadcast packet
- Exit

Figure 5.1: An outline of the adjusted probabilistic counter-based scheme.

The important factor in both PCBS and APCBS is the selection of the forwarding probability value *P*. Although larger *P* incurs more redundant rebroadcasts while a smaller *P* leads to lower reachability depending on the network density. Therefore, APCBS adjusts the forwarding probability dynamically by the use of the function *f(c)* which is defined in the next section.

5.2.1 *The Forwarding Probability in APCBS*

Let *c* be the counter value (i.e. number of neighbours) of a given node *Y* and let *C* be the counter threshold value. The forwarding probability at node *Y* is defined as follows:

$$f(c) = \begin{cases} e^{-(\frac{c}{C})} & ; \quad c \le C \\ e^{-(\frac{c+2}{C})} & ; \quad Otherwise \end{cases} \tag{1}$$

As shown in equation (1), the function takes into account mobile node 1-hop information (i.e. c value) and the threshold value to compute an appropriate forwarding probability value for a given node. As in Chapter 4 and also based on the analysis in chapter 3, the *C* value of 3 is used in the computation of *f(c)* and throughout the chapter.

The forwarding probability function *f(c)* uses an exponential function because earlier observations from the previous chapters (i.e. chapter 3 and 4) has shown that a high forwarding probability value incurs more redundant retransmissions while a low forwarding probability leads to low reachability. Moreover, nodes with few numbers of neighbours should be assigned a high rebroadcast probability while those with high number of neighbours should be assigned a low rebroadcast probability. Therefore, as the number of neighbours increases, the rebroadcast probability should decreases. Based on the above features and specifications identified for the forwarding probability, an ideal mathematical function that can fit into these requirements is the exponential function. Figure 5.2 depicts a graph of forwarding probabilities against counter value (i.e. number of neighbours) in APCBS. The figure shows the trend of different node counter value with their corresponding probability values.

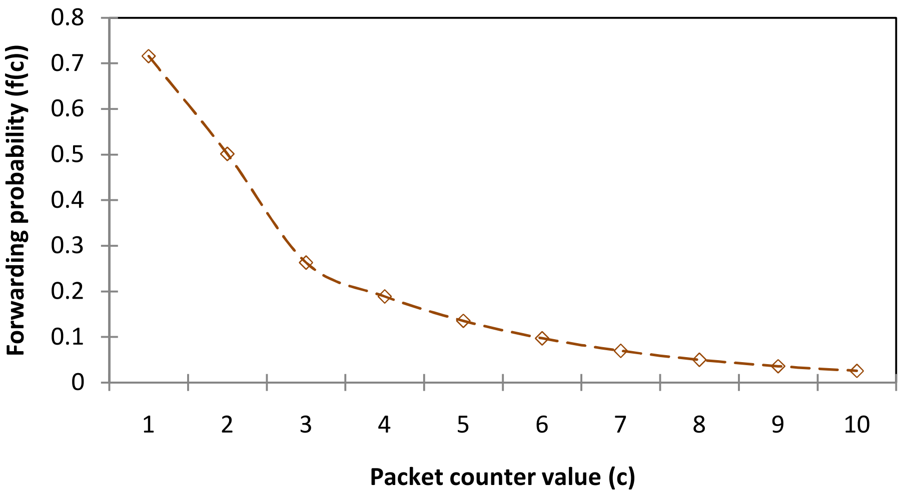

Figure 5.2: Forwarding probability for different packet counter values

5.3 Performance Evaluation

This section presents the performance evaluation of the new proposed probabilistic broadcast scheme using the same simulation model and parameters as outlined in Chapter 2 (Section 2.6).The performance metrics that have been used to conduct the performance evaluation include the reachability, average collision rate, number of retransmitting and end-to-end delay. These metrics have been defined in Chapter 2 (Section 2.7).

To evaluate the performance of the adjusted probabilistic counter-based broadcast algorithm (i.e. APCBS), the previous PCBS implementation used in Chapter 4 have been modified and implemented on the same Ns-2 simulator [90] in order to incorporate the forwarding probability function of the APCBS algorithm. The results are compared against the PCBS (Chapter 4), counter-based scheme (CB, for short), fixed probabilistic scheme (FP, for short) and flooding.

The simulation scenarios consist of two different settings, each specifically designed to assess the impact of a particular network operating condition on the performance of the protocols. First, the impact of network density is assessed by deploying a different number of mobile nodes over a fixed topology area of 1000m x 1000m. The second simulation scenario investigates the effects of an offered load on the performance of the broadcast schemes by varying the number of packet injection rate for each simulation scenario.

5.3.1 *Impact of Network Density*

The network density has been varied by changing the number of nodes deployed over a 1000m x 1000m area of each simulation scenario. Each node moves according to random trip mobility model [104] with a speed chosen between 1 and 5m/sec. For each simulation trial, a broadcast injection rate of 10 packets per second is used.

5.3.1.1 Number of Retransmitting Nodes

Figure 5.3 shows the number of retransmitting nodes required by each of the five schemes as the network density increases. The figure illustrates that the required number of retransmitting nodes in all the five broadcast schemes increases with increased number of nodes. In addition, the figure reveals the clear advantage of APCBS over PCBS, CB, FP and flooding. For instance, compared with the PCBS, the required retransmitting nodes in APCBS can be reduced further by approximately 10% when the number of nodes is relatively large (e.g. 180 nodes). This performance is attributed to the use of different forwarding probabilities for each counter value at a given node which results in the reduction of number of retransmitting nodes. Thus, the performance advantage of APCBS over the other schemes is further increased. For example, in Figure 5.3, when the number of nodes increases to 200 nodes, the required retransmitting nodes in APCBS is reduced by as much as 125% and 131% less than that in CB and FP respectively.

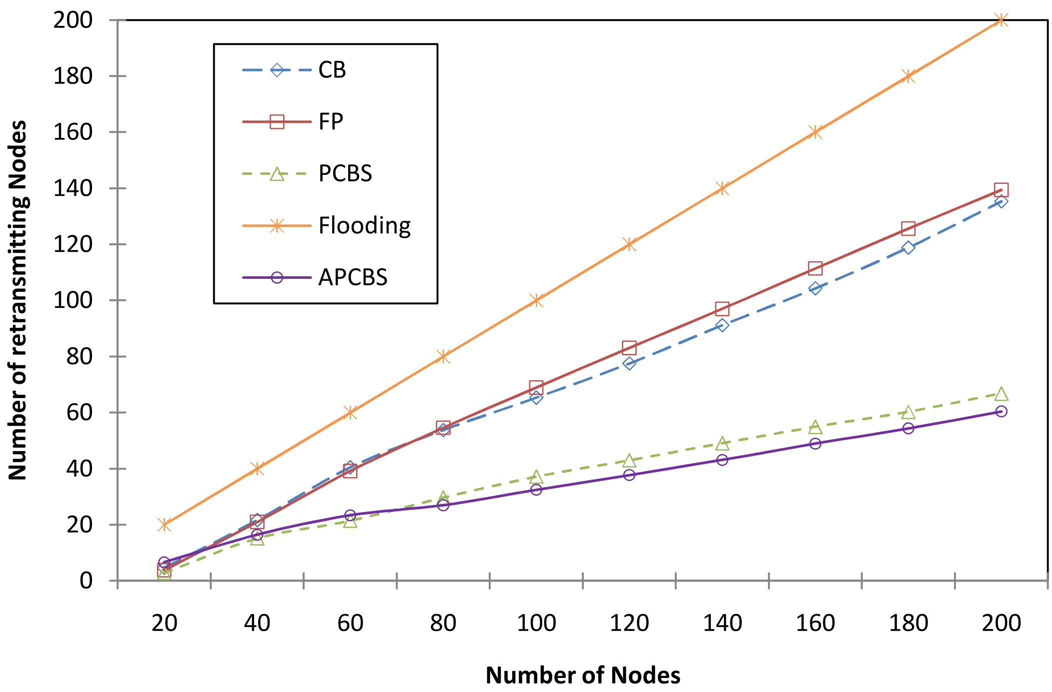

Figure 5.3: Number of retransmitting nodes vs. number of nodes placed over 1000m x 1000m area using 10 packets/sec broadcast rate.

5.3.1.2 Reachability

The result in Figure 5.4 depicts the reachability achieved by the five broadcast schemes when the number of nodes is varied. The figure shows that reachability increases with increased number of nodes. For instance, reachability achieved by PCBS increases from 25% for 20 nodes to 98% for 120 nodes while the reachability achieved by APCBS increases from 36% to 99% for 20 and 120 nodes respectively. As expected, flooding has the best reachability performance compared to the other schemes. Unlike in Figure 4.6, APCBS achieved the highest reachability performance in sparse network (i.e. 20 to 80 nodes) compared to FP, PCBS and CB. APCBS achieved a reachability performance that is comparable to flooding in network with 40 – 200 nodes. This reachability performance improvement is as result of appropriate assignment of forwarding probability to nodes based on their counter value.

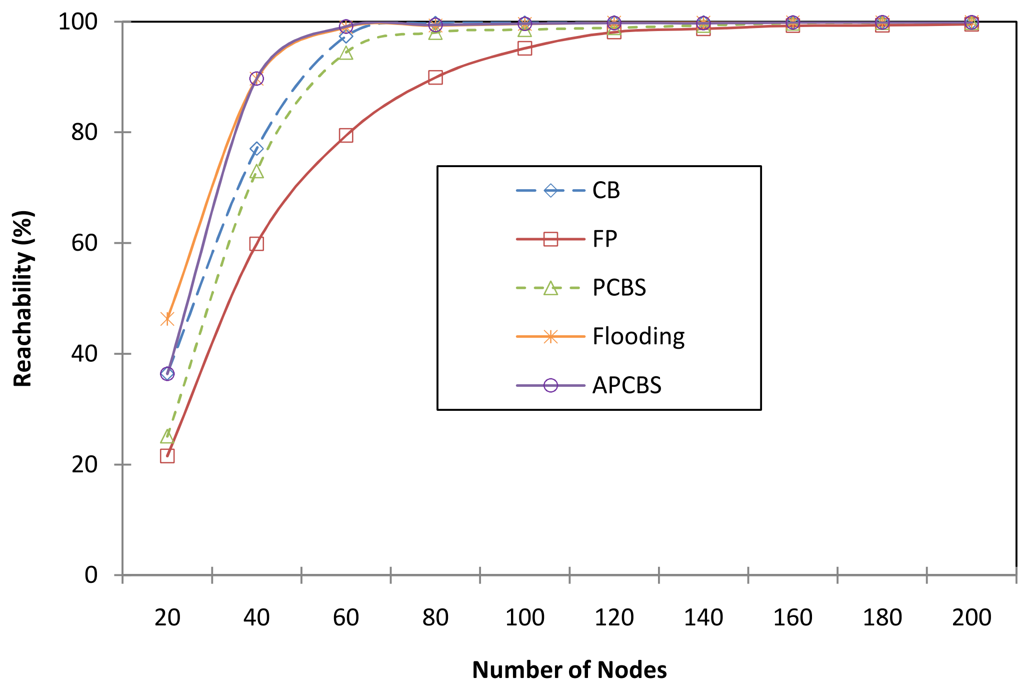

Figure 5.4: Reachability vs. number of nodes placed over 1000mx1000m area using 10 packets/sec broadcast injection rate.

5.3.1.3 Collision Rate

Figure 5.5 show that the number of collisions incurred by the broadcast schemes increases with increased number of nodes. The figure also reveals that as the number of nodes increases the advantage of APCBS over the PCBS and other schemes becomes more noticeable. Therefore, the probability of two more nodes transmitting at the same time is significantly reduced when using the APCBS approach. This is because most of the nodes within the same transmission range have been made to probabilistically suppress their broadcasts by assigning them different forwarding probabilities based on their counter value. For instance, Figure 5.5 depicts that the collision rate of APCBS is reduced by approximately 25% for 200 nodes compared against the PCBS.

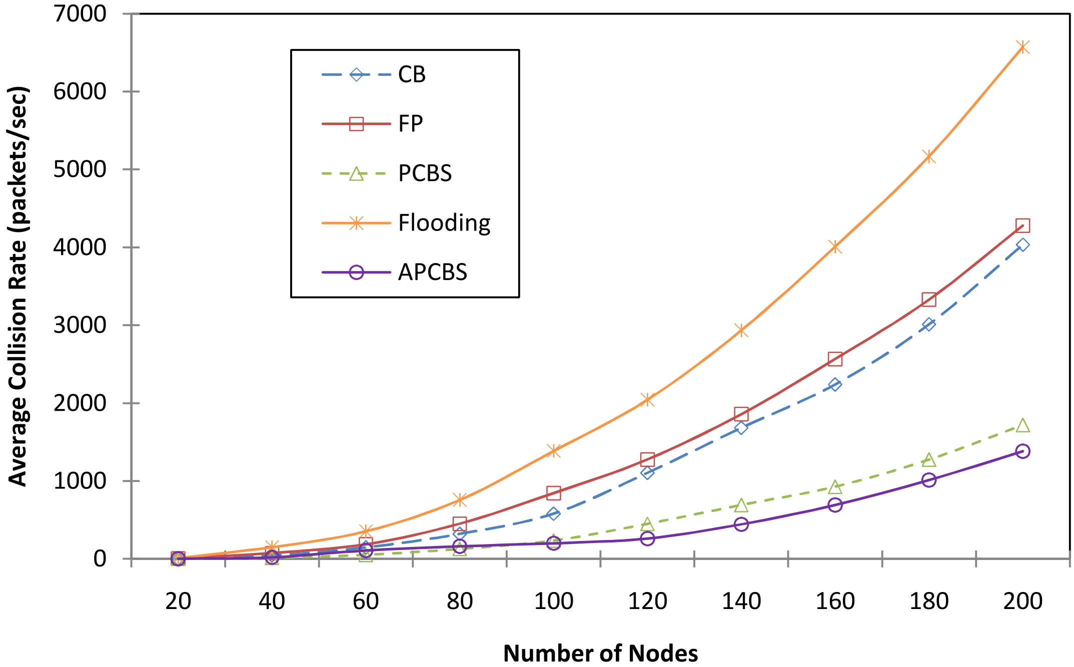

Figure 5.5: Average collision rate vs. number of nodes placed over 1000mx1000m area using 10 packets/sec broadcast injection rate.

5.3.1.4 End-to-End Delay

The result in Figure 5.6 shows that the end-to-end delay incurred by the broadcast schemes increases with increased number of nodes. The figure also reveals that APCBS incurred the least end-to-end delay compared to the other schemes in sparse to dense network. This is due to the few number of retransmission nodes required by APCBS which leads to low contention and collision within the network. In general, contention and collision increases with increasing network density regardless of the scheme that is used. For instance, the end-to-end delay incurred by APCBS is reduced by approximately 15% for 200 nodes when compared against that of PCBS. In contrast, flooding incurs the least end-to-end delay in sparse network (i.e. 20-40 nodes).

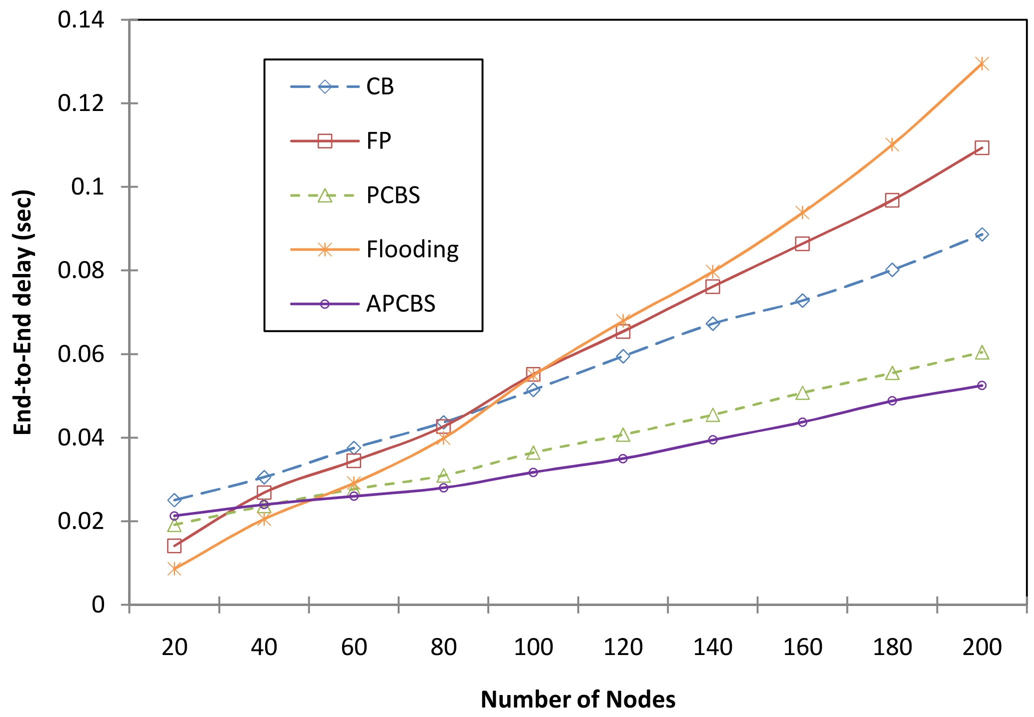

Figure 5.6: End-to-end delay vs. number of nodes placed over 1000mx1000m area using 10 packets/sec broadcast injection rate.

5.3.2 *Impact of Offered Load*

In this section, the impact of offered load on the performance of the broadcast schemes have been investigated where the offered load is varied by increasing the broadcast injection rate from 1 to 70 packets per second. The topology for each simulation scenario consists of 100 nodes placed on a flat area of 1000m x 1000m area, each moving according to random trip mobility model with a speed chosen between 1 and 5m/s. The purpose of this study is to measure the effect of load on the broadcast schemes and also illustrates the general limits of each broadcast scheme for a given broadcast injection rate. This will provide a cursory indication of which broadcast scheme reacts best over a range of network traffics (i.e. broadcast injection rate).

5.3.2.1 Number of Retransmitting Nodes

The results in Figure 5.7 depict the effects of offered traffic load on the performance of the broadcast schemes in terms of number of retransmitting nodes. As the number of nodes and the simulation area remain constant, one might expect the number of retransmitting nodes to remain constant in Figure 5.7 as well. In fact, to some extent APCBS, CB and PCBS follow this trend.

However, a careful examination of Figure 5.7 reveals that CB, PCBS and APCBS shows different trend (i.e. not constant only) which include both increasing and decreasing trend. For broadcast injection rate of 1 to 40 packets per second, both schemes shows a constant trend while both shows an increasing trend for broadcast injection rate of 50 to 60 packets per second and a decreasing trend for 70 packets per second broadcast injection rate. In essence, this is because higher traffic forbids redundant packets to be delivered during the RAD, therefore more nodes rebroadcast which further congest the network resulting in this irregular trend. In the case of flooding and FP, the number of retransmitting nodes falls as the network becomes congested, which directly demonstrates the effect of collisions and queue overflows in congested network. Nevertheless, APCBS requires the least number of retransmissions than the other broadcast schemes.

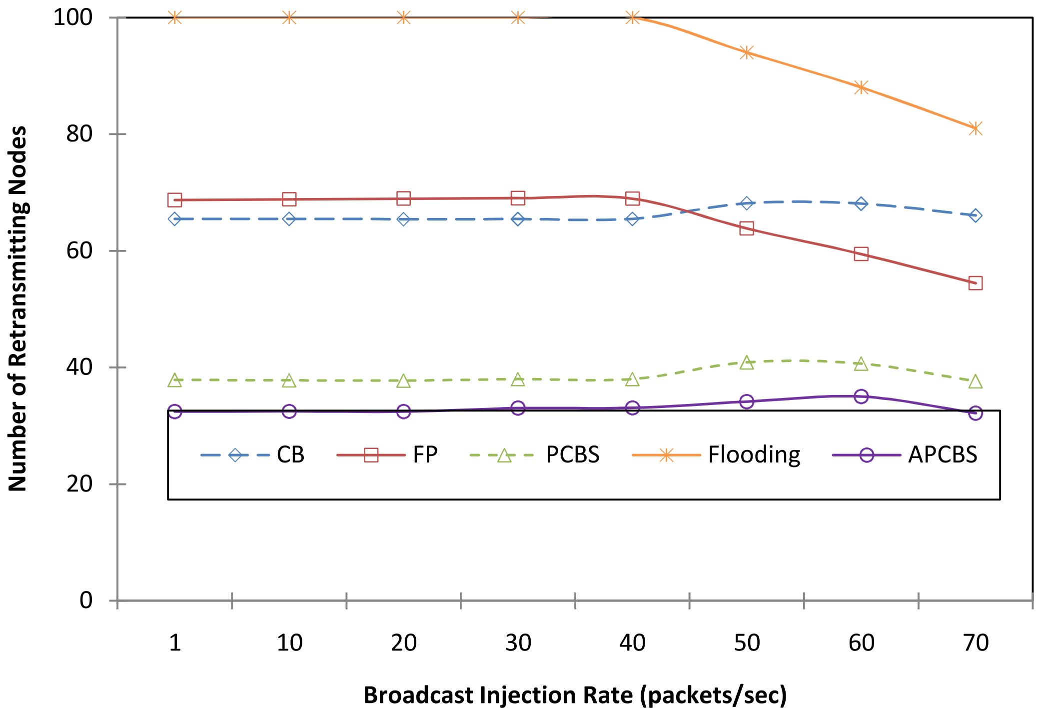

Figure 5.7: Number of retransmitting nodes vs. offered load for a network of 100 nodes placed in 1000mx1000m area.

5.3.2.2 Reachability

Figure 5.8 shows the reachability achieved by the broadcast schemes over varying offered load. The figure shows that each scheme suffers as the network becomes more congested, i.e., reachability decreases with increased broadcast injection rate. Thus, a heavier load results in a lower reachability performance.

This is true for all the broadcast schemes, because a high broadcast injection rate means more contention and collision among broadcast packets. For example, flooding is the most affected where reachability falls to around 80% at a 70packets/sec broadcast injection rate. Comparing Figure 5.8 to Figure 5.3 reveals the relationship between performance in congested networks and the number of redundant retransmissions: i.e., broadcast schemes that minimise the number of redundant retransmissions deliver the most packets in congested networks. Thus, APCBS achieved better reachability performance in a congested network.

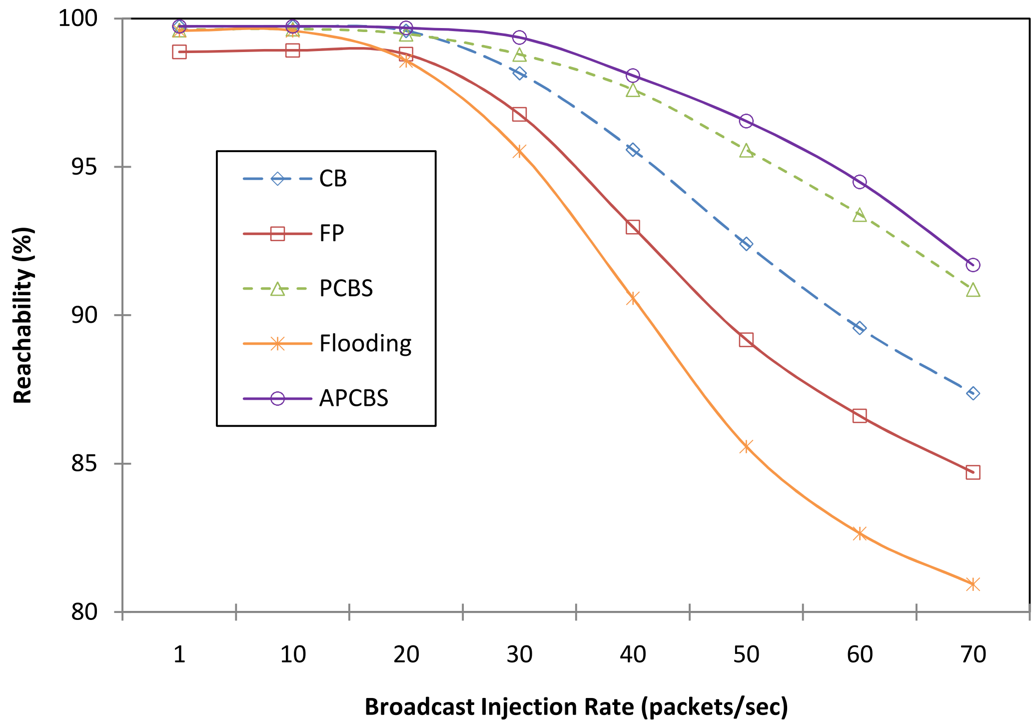

Figure 5.8: Reachability vs. offered load for a network of 100 nodes placed in 1000mx 1000m area.

5.3.2.3 Collision Rate

The results presented in Figure 5.9 depict the average collision rate under varying offered load (i.e. broadcast rates). When the offered load increases the collision rate in all the broadcast schemes also increases. This is because, as the broadcast injection rate increases, the number of broadcast packets generated and disseminated increases. As a result, the probability of two or more nodes within the same transmission range transmitting at the same time increases which leads to an increase in the collision rate. Nevertheless, for a given injection rate, the collision rate in APCBS is much lower than in PCBS. For instance, at a broadcast injection rate of 70 packets per second, the collision rate in APCBS is further reduced by approximately 37% compared to the PCBS.

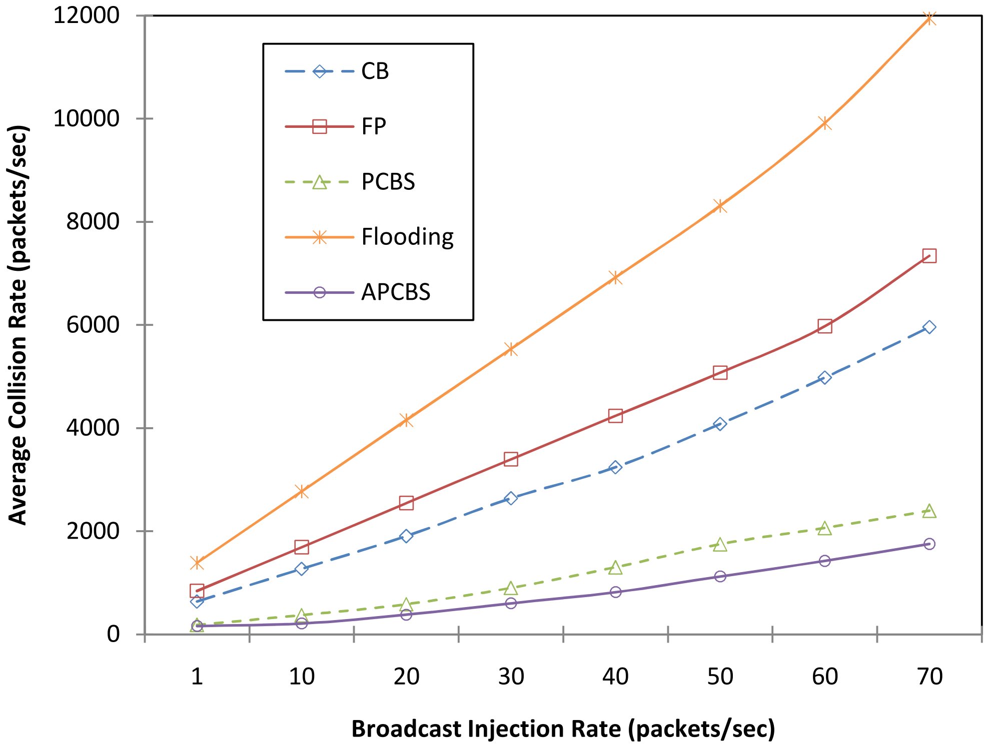

Figure 5.9: Average collision rate vs. offered load for a network of 100 nodes placed in 1000m x 1000m area.

Figure 5.10 on the other hand shows the effect of offered load on both collision rate and reachability in a single graph. When the offered load increases, the collision rate in all schemes is also increased while the reachability achieved by all the schemes decreases. The results have shown that broadcast schemes that minimise average collision rate achieve better reachability in congested networks. As a result, APCBS performs better than the other schemes.

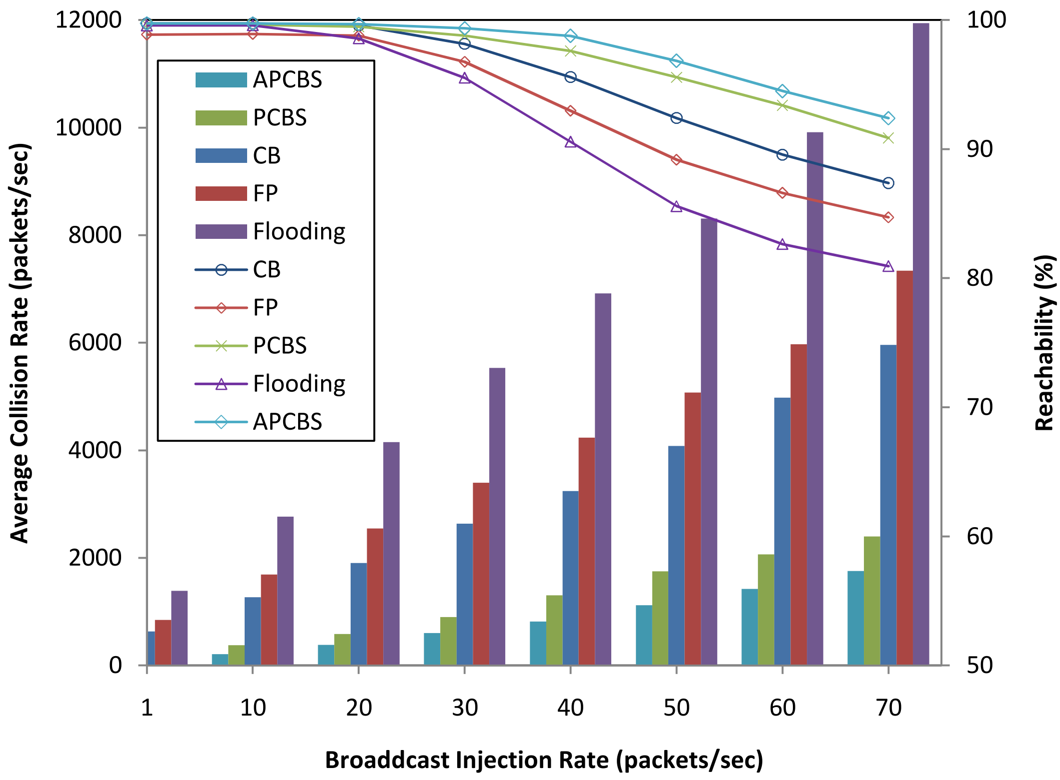

Figure 5.10: Average collision rate and Reachability vs. offered load for a network of 100 nodes placed in 1000m x 1000m area.

5.3.2.4 End-to-End Delay

Figure 5.10 show that all the broadcast schemes incur a comparable end-to-end delay when the offered load is less than 30 packets per second. However, the performance difference among the broadcast schemes is noticeable at offered load greater than 30 packets per second. In Figure 5.10, the APCBS and PCBS maintains a steady end-to-end delay for an injection rate of 1-40 packets per second beyond which the end-to-end delay rose sharply. The other broadcast schemes also exhibit similar trend but with a different rising point. In FP and flooding, the end-to-end delay rose sharply as the traffic rate exceed 30 packets per second while in CB the sharp rise becomes more noticeable as the broadcast rate exceed 40 packets per second. For instance, at broadcast injection rate of 70 packets per second, the delay in APCBS is further reduced by approximately 16% compared against PCBS.

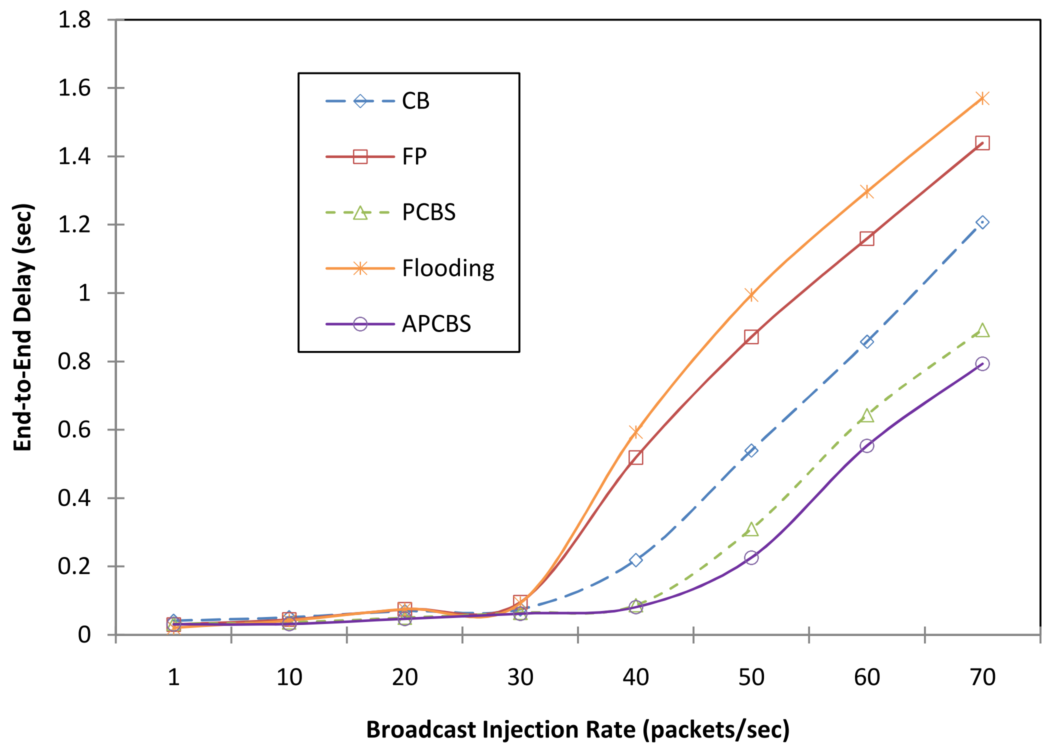

Figure 5.11: End-to-end delay vs. offered load for a network of 100 nodes placed in 1000mx1000m area.

5.4 Conclusions

In this chapter, a new broadcast scheme referred to as APCBS was proposed which dynamically computes the forwarding probability at a node using a mathematical function. It exploits the use of a packet counter and probability at a given node to reduce the dissemination of broadcast packets. The chapter has compared the performance of APCBS against that of other broadcast schemes suggested and considered in the previous chapters.

The performance analysis have revealed that APCBS outperforms the PCBS, CB, FP and flooding in terms of number of retransmitting nodes, end-to-end delay and collision rate in most of the considered cases of the network density and traffic load. Although, the performance of all the schemes degrades with increased broadcast injection rate, the proposed APCBS shows a better resilience in high broadcast injection rate settings as it manages to reduce packet collision and channel contention by minimising the redundant retransmissions.

This chapter has evaluated the performance of APCBS and other broadcast schemes in the context of pure broadcast scenario. However, investigating the performance merits of these broadcasting algorithms in real applications, such as route discovery process is lacking. Chapter 6 of this thesis evaluates the performance of APCBS and existing schemes as a route discovery mechanism using AODV as base routing protocol.

Chapter 6

Performance Analysis of Adjusted Probabilistic Counter-Based Route Discovery

6.1 Introduction

The performance evaluation of most existing probabilistic broadcast schemes suggested for MANETs [18, 19, 57, 82], including the ones that have been discussed in the previous chapters have focused on "pure" broadcast scenarios with relatively a little investigation on their performance impact on particular real applications such as route discovery process in routing protocols. A number of MANETs routing protocols [12, 127, 128] employs flooding for the propagation of routing control packets, such as Route Request (RREQ) during route discovery process. Despite that, a little effort has been made so far to evaluate the performance of these alternative broadcast schemes on other contexts such as route discovery process.

Motivated by the above observation, this chapter evaluates the performance of the Adjusted Probabilistic Counter-Based Broadcast Scheme (APCBS) introduced in Chapter 5, when used as a route discovery mechanism in the well-known Ad hoc On Demand Distance Vector (AODV) routing protocol. The performance of the route discovery approach based on APCBS, referred to here as Adjusted Probabilistic Counter-Based Route discovery (APCBR, for short) will be compared against that of the route discovery based on flooding used in the traditional AODV [12], fixed probabilistic (FP for short), and counter-based (CB, for short).

The rest of the chapter is organised as follows. Section 6.2 presents an overview of route discovery process in AODV. Section 6.3 describes the proposed APCBR and presents its algorithm. Section 6.4 describes the simulation environment. Section 6.5 analyses the effects of various network operating conditions on the performance of the proposed APCBR. Finally, section 6.6 summarises the findings of this chapter.

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

A routing protocol is a fundamental component needed for the efficient operation of a MANET [129]. The main goal of a routing protocol is to establish and maintain paths between nodes in order to deliver a packet from source to destination. A path in a MANET consists of an ordered set of intermediate nodes that transport a packet across a network from source to destination by forwarding it from one node to the next. The unique characteristics of MANETs, such as those outlined in Section 2.1.1, make routing in these networks a challenging task [105]. In particular, the mobility of nodes results in a highly dynamic network with rapid topological changes causing frequent route failures. As a result, a MANET environment needs an effective routing protocol that can dynamically adapt to frequent changes in network topology, and should also be designed to be bandwidth-efficient by reducing the routing control overhead to make available more bandwidth for actual data communication.

Considerable research effort has been dedicated to developing routing protocols for MANETs [11, 12, 23, 130]. These protocols can be classified into three main categories based on the route discovery and routing information update mechanisms: *proactive (or table driven)*, *reactive (or on-demand driven)* and *hybrid*. *Proactive routing protocols* such as those depicted in [11, 131] attempt to maintain consistent and up-to-date information about routes from every node to every other node in the network. In disparity, r*eactive routing protocols* such as those described in [132, 133] establish routes only when they are required while *hybrid* approaches [127, 134, 135] integrate proactive and reactive routing components. Reactive protocols can adjust quickly to route changes and use less bandwidth and battery power by avoiding unnecessary periodic updates of routing information at each node. Ad hoc on-demand distance vector (AODV)

[132], dynamic MANET on-demand routing (DYMO) [136] and dynamic source routing (DSR) [133] are typical and well-known examples of routing protocols in this category.

AODV is the best-known and most studied MANET routing protocol [136, 137]. It is reactive in nature, requesting and establishing routes only when needed and maintaining only those that remain active. The AODV routing mechanism consists of two phases; *route discovery* and *route maintenance*.

6.2.1 Route Discovery

When a source node wants to send data to a destination and does not already have a valid route to the destination, it initiates a route discovery process[5] in order to locate the destination. A route request (RREQ) packet is broadcast throughout the network via simple flooding and in a managed fashion using expanding ring search [12]. The RREQ packet contains the following main fields: source identifier, source sequence number, broadcast identifier, destination identifier, destination sequence number (created by the destination to be included along with any route information it sends to requesting node), and time-to-live. To prevent excessive transmission of the RREQ packets, the source node optimizes its search by using an expanding ring search. In this search process, increasingly larger neighbourhoods are included to find the destination. A time-to-live field (TTL) in the header of the RREQ packet control the search. The destination sequence number is used by AODV to ensure loop-free routes which also contain most recent route information [131].

Each intermediate node that forwards an RREQ packet creates a reverse route back to the source node by appending the next hop information in its routing table. Once the RREQ packet reaches the destination or an intermediate node with a valid route, the destination or intermediate node responds by sending a unicast route reply (RREP) packet to the source node using reverse route. The validity of a route at the intermediate is determined by comparing its sequence number with the destination sequence number. Each node that participates in forwarding the RREP packet back to the source creates a forward route to the

[5] This is a process of creating a route to a destination when a node needs a route to it.

destination by appending the next hop information in the routing table. However, nodes along the path from source to destination are not required to have knowledge of which nodes are forming the path.

Figure 6.1 depicts an example of route discovery process. It shows how the path is determined from the source node (node 2), to the destination node (node 9). Node 2 propagates a route request packet to its neighbours, nodes 1, 3, and 4. These nodes, in turn, disseminate the route request to their neighbours while collecting route data. The route request, along with the path to the source node, is eventually received by the destination node, node 9. Base on the route data that has been collected during the route discovery process, the destination node is able to send its reply message back along the shortest route, as shown by the RREP route.

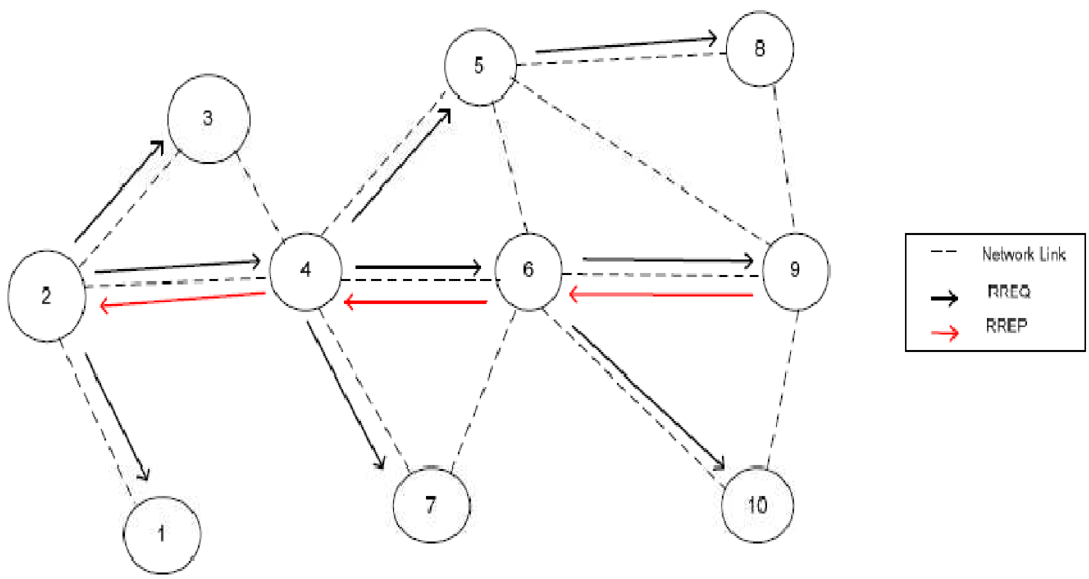

Figure 6.1. Illustration of route discovery process in AODV

6.2.2 Route Maintenance

The second phase of AODV routing mechanism is the route maintenance phase. Route maintenance is the process of responding to changes in topology that happen after a route has initially been created. After the route discovery process and as long as a discovered route is used, it has to be maintained. To maintain paths, intermediate nodes along the path continuously monitor the active links and maintain an up-to-date list of their 1-hop neighbours (by means of a periodic exchange of "hello" packets). The routing table entries include a destination, the next hop toward the destination, and a sequence number.

Routes are only updated if the sequence number of the incoming message is larger than the existing number. Routing table also maintain a route expiration time. Each time that route is used to forward data packet, the expiration time is updated to the current time plus ACTIVE_ROUTE_TIMEOUT[6]. After the time expires, the routing table is no longer valid [138]. When a broken link occurs or a node receives a data packet for a destination it has no forwarding route for, it must respond with creation of a Route Error (RERR) message. The RERR message holds a list of all of the unreachable nodes.

Figure 6.2 shows the maintenance process due to a broken link. The link between node 6 and node 9 has broken. Node 6 creates a RERR message and propagates it back to node 2. The source node can either try to find a new route by initiating a new route discovery for the destination if there is no intermediate node with an alternative path to destination, or the intermediate node may try to repair the route locally.

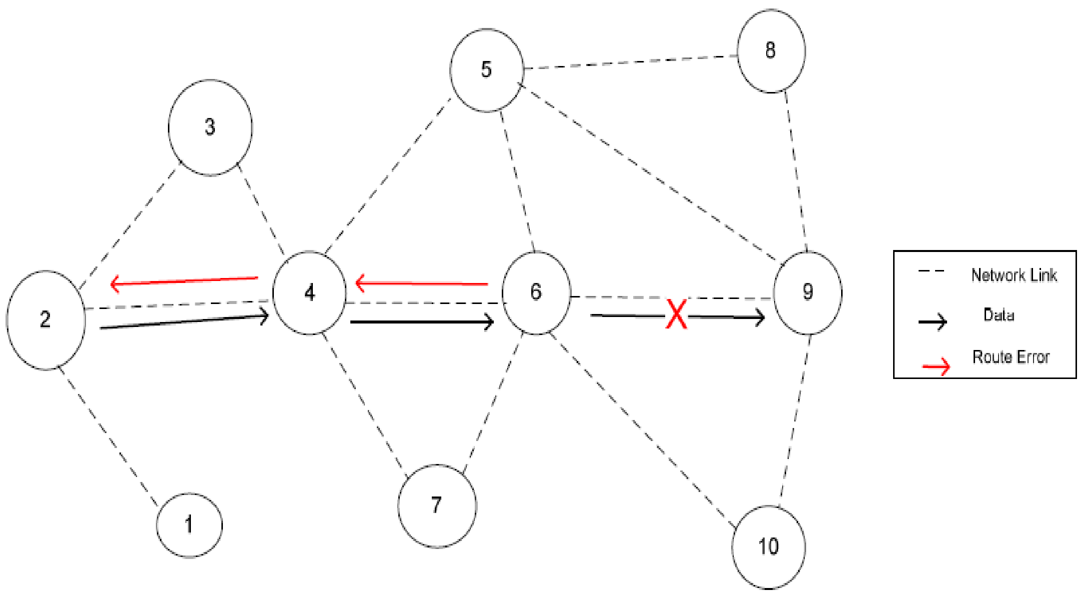

Figure 6.2. Illustration of route maintenance in AODV

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[6] It is the timer value attached with each route entry and if a route is not used or refreshed within this time period, the route is considered stale and purged.

6.3 Adjusted Probabilistic Counter-Based Route (APCBR) Discovery

In APCBR, a route discovery is initiated whenever a source node wishes to send data to another node but it does not have a valid route to destination or an active route to a destination has been broken. The source node broadcasts an RREQ packet to all its 1-hop neighbours. However, unlike the fixed probabilistic route discovery, each neighbouring node that receives the RREQ packet initiates a counter *c* that records the number of times a node receives the same RREQ packet and a Random Assessment Delay (RAD) timer which is randomly chosen from a uniform distribution between 0 and T_{max} seconds, where T_{max} is highest possible delay interval. Such a counter is maintained in each node for each RREQ packet. During RAD period, *c* is incremented for each duplicate of the RREQ packet received. After the expiration the RAD timer, if *c* exceeds a predefined counter threshold *C* (*C* is the same as in APCBS), the node forwards the RREQ packet with a probability P_1. Otherwise, if *c* is less than or equal to the predefined *C*, the RREQ packet is forwarded with a probability P_2.

Both P_1 and P_2 are dynamically computed using the forwarding probability function used in APCBS (in Chapter 5). The process of RREQ packet dissemination continues in a similar vein until the RREQ packet is received by the destination or a node with a valid route to the destination. The destination replies by sending a Route Reply (RREP) packet. The RREP packet is unicast towards the source node along the reverse path set-up by the forwarded RREQ packet. An outline of the algorithm is presented in Figure 6.3.

Algorithm: Adjusted Probabilistic Counter-based Route Discovery (APCBR)

```
Upon receiving an RREQ packet at node Y

If (the RREQ packet is received for the first time)
        Initialise the packet counter c to 1
        Set the RAD timer
        Add the RREQ packet ID to the received packet list and wait for RAD to
        expire
            While waiting step:
                    -   For every duplicate RREQ packet received
                    -   Increment c by 1
        if (c ≤ C)
                set the forwarding probability to high: P → P2
        else
                set the forwarding probability to low: P → P1
        end if

        Generate a random number Rn over the range [0,1]
        If (Rn < P)
                Rebroadcast the RREQ packet
        else
                drop the RREQ packet
        end if

else
        // the RREQ packet is a duplicate packet
        if (waiting for RAD timer to expire)
                Go to while waiting step
        else
                drop the RREQ packet
        end if
end if
```

Figure 6.3: A brief outline of APCBR route discovery algorithm

6.4 Simulation Environment

The goal of the following simulation experiment is to evaluate the performance of APCBR discovery mechanism in AODV routing protocol under various network operating conditions. The AODV routing protocol has been chosen among the other existing MANETs routing protocols as it is one of the most widely studied and analysed as indicated in [105]. Although AODV is more than a decade old but it is still the building block upon which recent routing protocols are built. For example, the Dynamic MANET On-demand (DYMO) [128] routing protocol uses the same route discovery mechanism as that of the AODV routing protocol. Moreover, DYMO simplifies AODV while still retains its basic mode of operation.

Each mobile nodes in our scenarios moves according to random trip mobility model [104] deployed in a topology of 1000m x 1000m area. The maximum speed is varied for each simulation scenario from 1m/s to 20m/s. Each simulation experiment is run for a period of 900sec. Data flows of Constant Bit Rate (CBR) packets each with 512 bytes size have been used. The nodes use a sending rate of 4 packets/sec with different number of traffic flows (i.e. source-destination connections) ranging from 1 to 35 traffic flows. The simulation parameters that have been used in this study are summarised in Table 6.1.

Table 6.1: Summary of system parameters used in the simulation experiment

Simulation Parameter	Value
Simulator	NS-2 (2.29.3)
Transmission range	100m
Packet size	512 bytes
Interface queue length	50 packets
Topology size	1000m x 1000m
Number of nodes	20, 40, …, 200
Simulation time	900 seconds
Traffic type	CBR
Maximum speed	1, 5, 10, … 20m/s
Number of trials	30
Confidence interval	95%
MAC type	802.11b
Counter threshold	3
Flows	1, 5, 10, … 35
Sending rate	4 packet/second

6.5 Performance Evaluation

To evaluate the performance merit of APCBS algorithm for route discovery, the implementation of the AODV routing protocol in the Ns-2 simulator [90] has been modified to incorporate the functionality of the APCBS, CB and FP algorithms. In what follows, the modifications of the traditional AODV for the three algorithms are referred to as APCBR-AODV, CB-AODV and FP-AODV. The simulation results of APCBR-AODV are compared against the CB-AODV, traditional AODV and FP-AODV.

The performance analysis of the APCBR route discovery has been conducted using the simulation model and parameters outlined in Chapter 2 (Section 2.6) and the simulation setup outlined in Section 6.3. The performance metrics that have been used for the performance analysis include the routing overhead, collision rate, network throughput and end-to-end delay. These metrics have been defined in Chapter 2 (see Section 2.7).

The simulation scenarios in this chapter consist of three different settings, each specifically designed to assess the impact of a particular network operating condition on the performance of the protocols. First, the impact of network density is assessed by varying the number of mobile nodes placed on an area of fixed size 1000m x 1000m. The second scenario evaluates the impact of offered traffic load on the resulting routing protocols by providing a different number of traffic flows (i.e. source-destination connections) for a fixed number of nodes placed on a 1000m x 1000m topology area. The last scenario investigates the effects of node mobility on the performance of the route discovery algorithms by varying the maximum speed of a fixed number of mobile nodes placed on a fixed topology of 1000m x 1000m area.

6.5.1 *Impact of Network Density*

In this section, the network density has been varied by changing the number of nodes deployed over a 1000m x 1000m area for each simulation scenario. Each node moves according to random trip mobility model [104] with a speed chosen between 1 and 5m/sec. For each simulation trial, 10 randomly selected source-destination connections (i.e. traffic flows) are used.

Routing Overhead:

Figure 6.4 show that the routing overhead generated by each of the routing protocols increases almost linearly as the network density increases. The results also reveal that for a given network density, the routing overhead generated by APCBR-AODV is lower compared with that by CB-AODV, FP-AODV and AODV. The good performance behaviour of APCBR-AODV is due to the fact that the forwarding probability at a node is set according to its local counter value and the threshold value. Thus, the number of redundant retransmissions of RREQ packets is significantly reduced, and as a consequence the overall routing overhead is reduced.

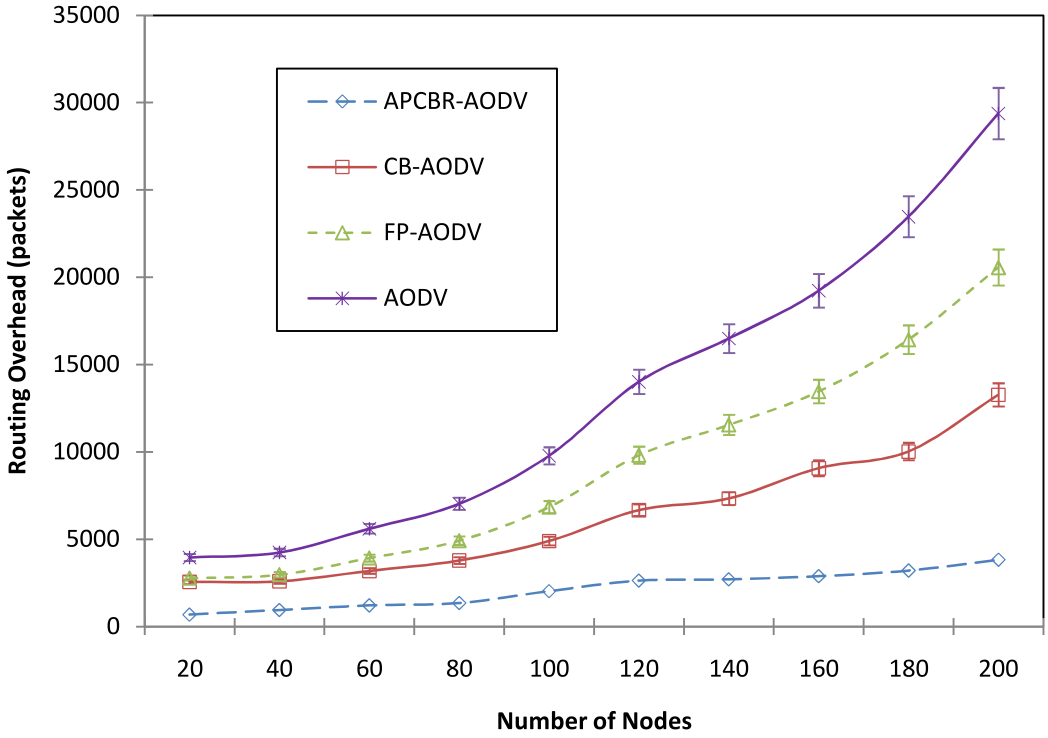

Figure 6.4: Routing overhead versus number of nodes placed over a 1000mx1000m area.

Similarly, Figure 6.5 depicts the performance of the routing protocols in terms of routing overhead measured in bytes. Even though APCBR-AODV has registered the lowest routing overhead in terms of number of packets transmitted as shown in Figure 6.4, the reduction in the routing overhead by APCBR-AODV is further increased when measured in terms of number of bytes transmitted. For example for a network with 120 nodes, the routing overhead of APCBR-AODV is approximately 430% lower than that of AODV when measured in terms of the number of packets transmitted. On the other hand, it is about 450% lower than that of AODV when measured in terms of number of transmitted bytes.

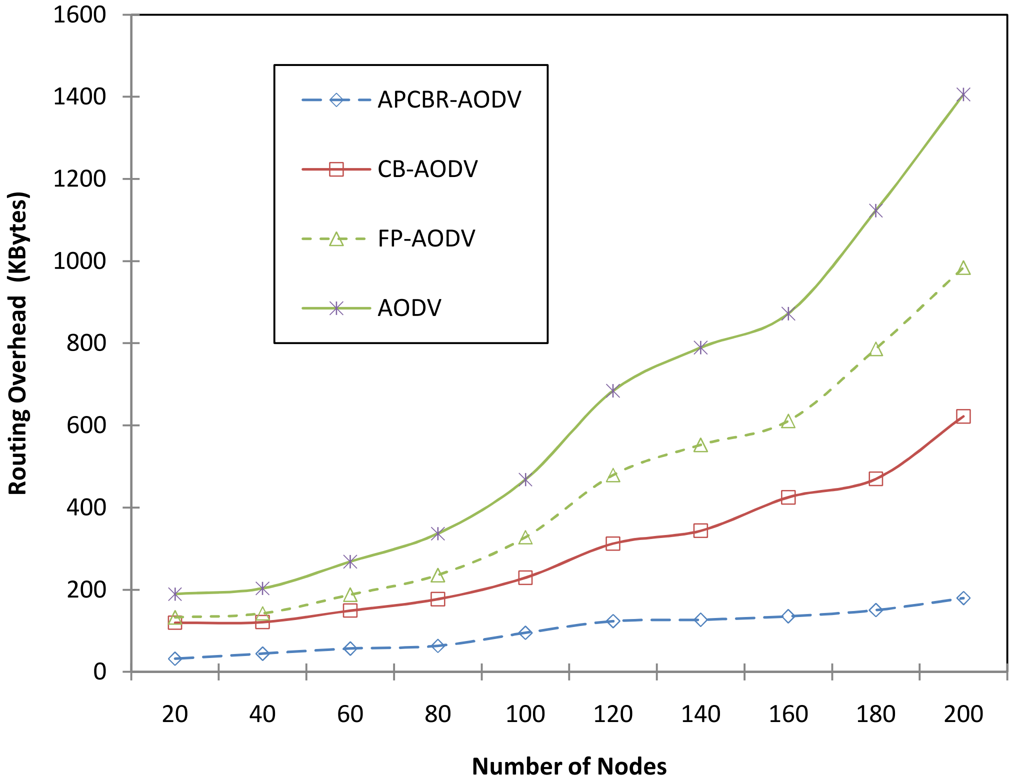

Figure 6.5: Routing overhead in terms of bytes versus number of nodes placed over a 1000mx1000m area.

Collision Rate:

The result in Figure 6.6 shows that the number of collisions incurred by the routing protocols increases with number of nodes increases. Since data and control packets share the same physical channel, the collision probability is increased when the dissemination of RREQ packets is not appropriately controlled. The figure also reveals that for a given network density, APCBR-AODV outperforms CB-AODV, FP-AODV and AODV. For instance, the collision rate of APCBR-AODV is approximately 257% lower than that of CB-AODV.

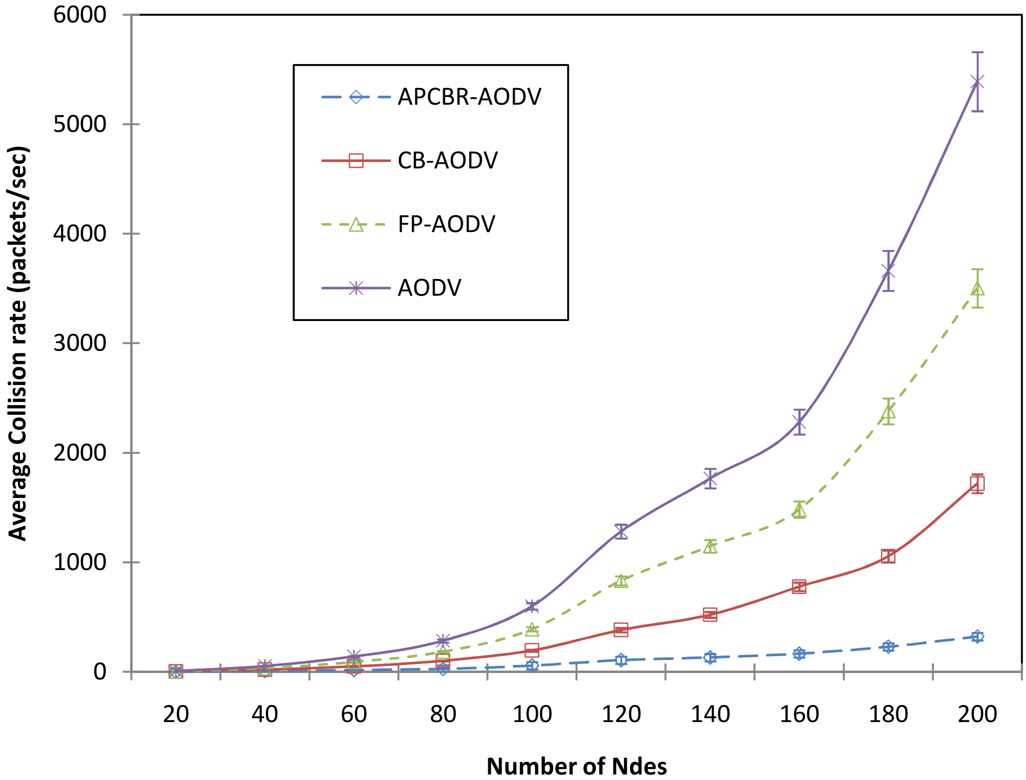

Figure 6.6: Average collision rate versus number nodes placed over a 1000mx1000m area using a maximum node speed of 5m/sec.

Normalised Network Throughput:

In Figure 6.7, the results shows that the normalised throughput for each of the routing protocols is low when the network density is set low (i.e. 20 nodes). This is due to the poor network connectivity associated with sparse networks. On the other hand, in a dense network where excessive redundant retransmissions of control packets (e.g. RREQ packets) is predominant, channel contention and packet collisions increase thereby lowering the bandwidth available for data transmission. Therefore, if measures are taken to control the redundant retransmissions of RREQ packets in a dense network, the degradation of the throughput can be reduced. As shown in Figure 6.7, APCBR-AODV outperforms CB-AODV, FP-AODV and AODV when the network is relatively dense. The improved performance of APCBR-AODV in a dense network is due to the significant reduction in the number of retransmissions of RREQ packets by dynamically computing the appropriate forwarding probability for each node using its local counter value.

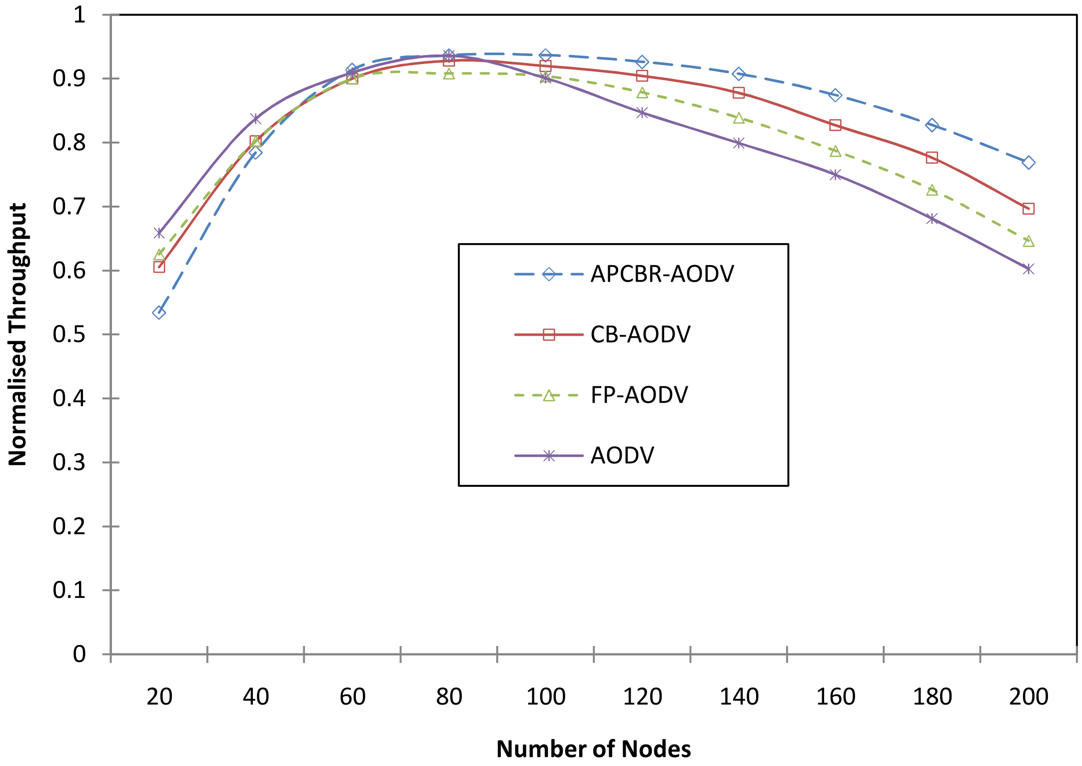

Figure 6.7: Normalised network throughput versus number of nodes placed over a 1000mx 1000m area using a maximum node speed of 5m/sec.

End-to-End Delay:

Figure 6.8 shows that the end-to-end delay for each of the routing protocols is relatively high for both sparse and dense networks. In a sparse network, the RREQ packets fail to reach their respective destinations because of poor network connectivity. On the other hand, in a relatively dense network, most of the originated RREQ packets fail to reach their destinations due to the increased chance of channel contention and packet collisions caused by excessive redundant retransmissions of the RREQ packets. This potentially increases the time required for data packets to cross from the source to destination. In a sparse network, APCBR-AODV achieves a comparable performance to AODV while FP-AODV outperforms CB-AODV. However in a dense network, APCBR-AODV performs better than all the other three protocols. This is due to the significant reduction in both the routing overhead and the collision rate as shown in Figures 6.5 and 6.6 respectively.

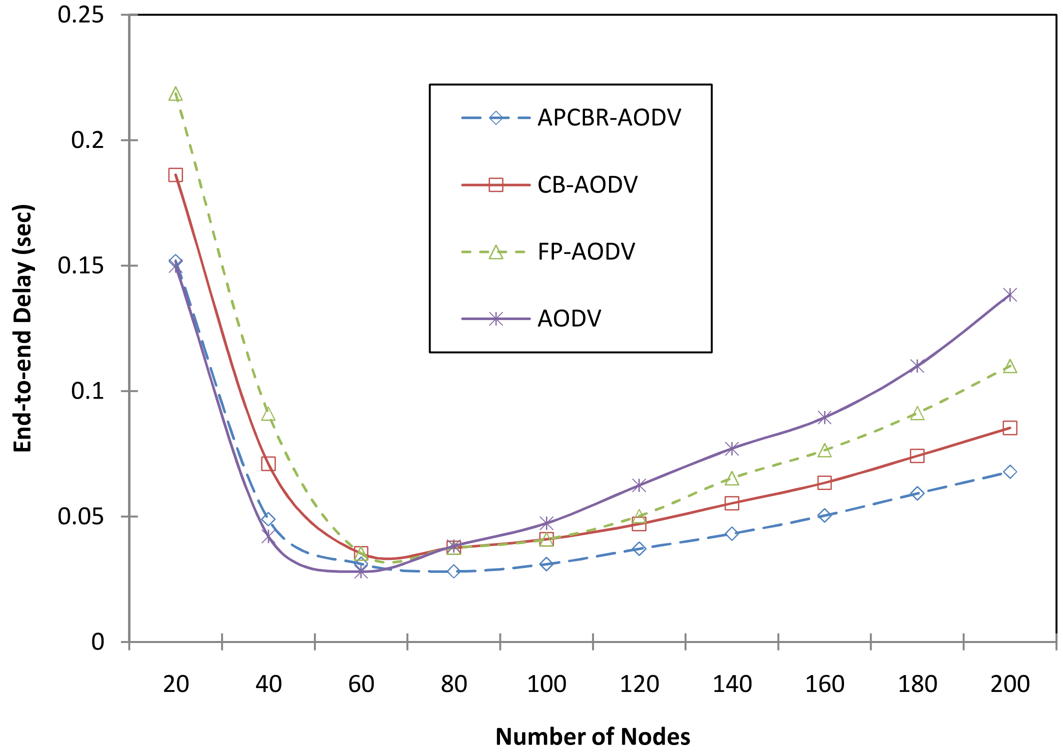

Figure 6.8: End-to-end delay versus number nodes placed over a 1000m x 1000m area using a maximum node speed of 5m/sec.

6.5.2 *Impact of Offered Load*

This section has considered different numbers of source-destination pairs (flows, for short) over a 100 node network. The offered load has been varied over the range 1, 5, 10… 35 flows while a maximum speed of 5m/s is used.

Routing Overhead:

The results in Figure 6.9 show that the routing overhead generated by each of the routing protocols increases as the number of flows increases. The larger the number of source-destination connections in a network the more RREQ packets generated. For instance, when the number of connections increases from 15 to 20, the routing overhead generated by APCBR-AODV, CB-AODV, FP-AODV and AODV increases by approximately 94%, 85%, 101% and 101% respectively. Figure 6.9 also reveals that the routing protocols have comparable performance level for 1 and 5 offered loads. However, the APCBR-AODV outperforms the CB-AODV, FP-AODV and AODV in the other offered loads (i.e. 10 – 35).

Similarly, Figure 6.10 depicts the routing overhead generated in terms bytes by the four routing protocols. The results from the figure follow a similar trend to

Figure 6.9. Therefore, the results in both Figures 6.9 and 6.10 also reveal that APCBS-AODV has a clear performance advantage over CB-AODV, FP-AODV and AODV across all offered loads in terms of both packets and bytes. This is because APCBR-AODV implements a route discovery mechanism with a relatively fewer number of nodes participating in the forwarding of the RREQ packets.

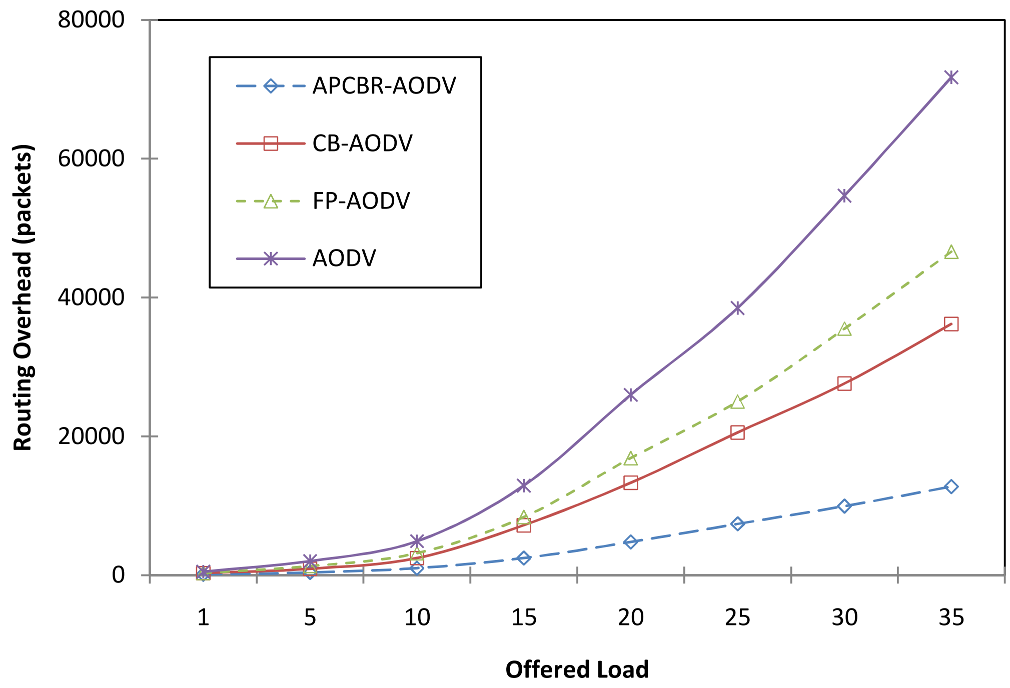

Figure 6.9: Routing overhead in terms of number of packets against offered load for a network of 100 nodes placed in 1000mx1000m area.

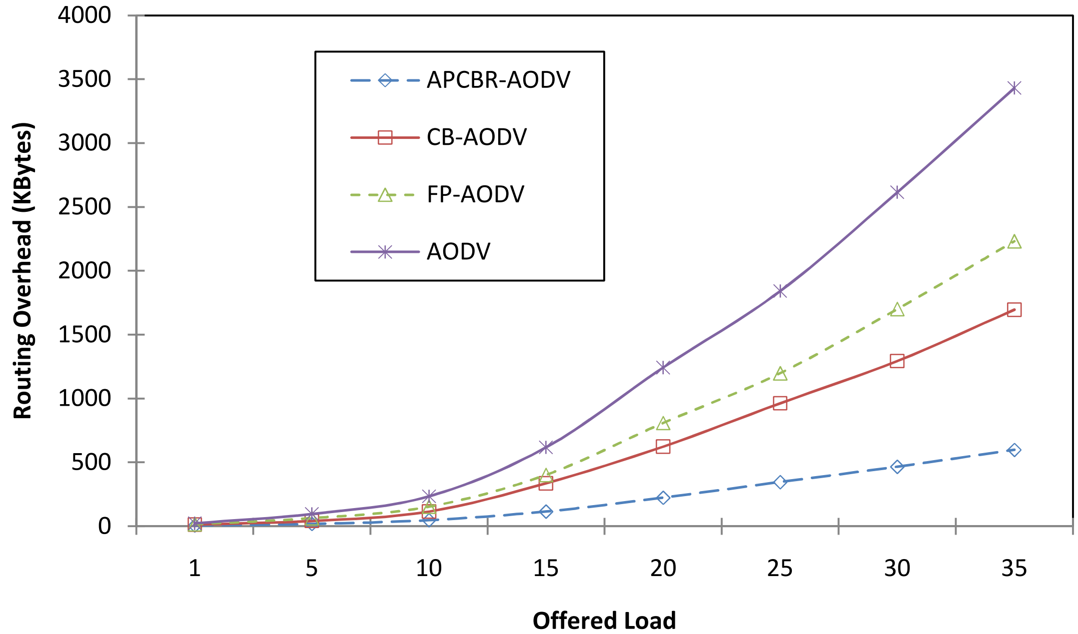

Figure 6.10: Routing overhead in terms of bytes against offered load for a network of 100 nodes placed in 1000mx1000m area.

Collision Rate:

Similar to the routing overhead generated by the protocols as shown in Figures 6.9 and 6.10, the number of collision incurred by the protocols increases as the offered load increases. This is because when the offered load is increased by increasing the number of flows, the number of RREQ packets generated and transmitted increases. As a result, the packet collision rate is increased. It can also be observed from Figure 6.11 that APCBR-AODV outperforms CB-AODV, FP-AODV and AODV for all offered loads considered. This is because a large number of RREQ packets are dropped due to the use of appropriate forwarding probabilities, thereby reducing the channel contention.

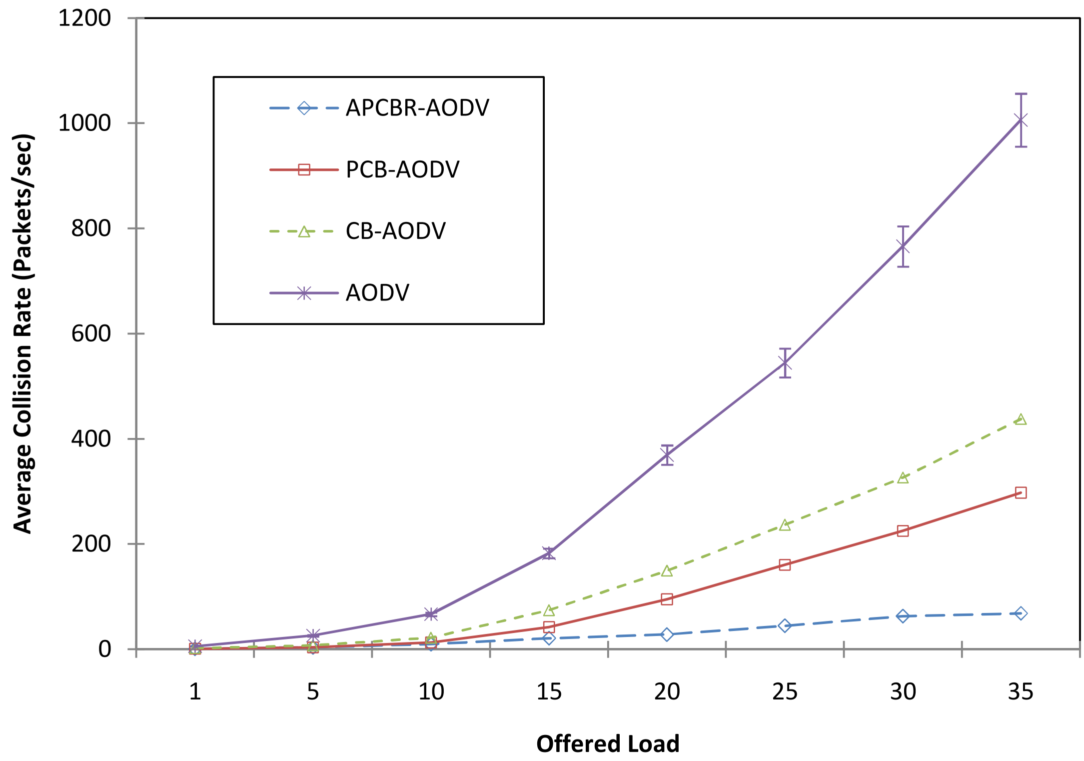

Figure 6.11: Average collision rate versus offered load for a network of 100 nodes placed in 1000mx1000m area.

Normalised Network Throughput:

Figure 6.12 reveals that the normalised network throughput for all the routing protocols decreases as the offered load increases. This is because when the offered load increases the number of nodes initiating route discovery operations also increases. As a consequence, more RREQ packets are generated and transmitted, causing an increase of the channel contention and packet collisions. This phenomenon reduces the number of data packets delivered at their destinations, thereby causing degradation of the overall network throughput. Nonetheless, it can be seen from the figure that the superiority of APCBR-AODV over the other routing protocols becomes more noticeable when the offered load increases.

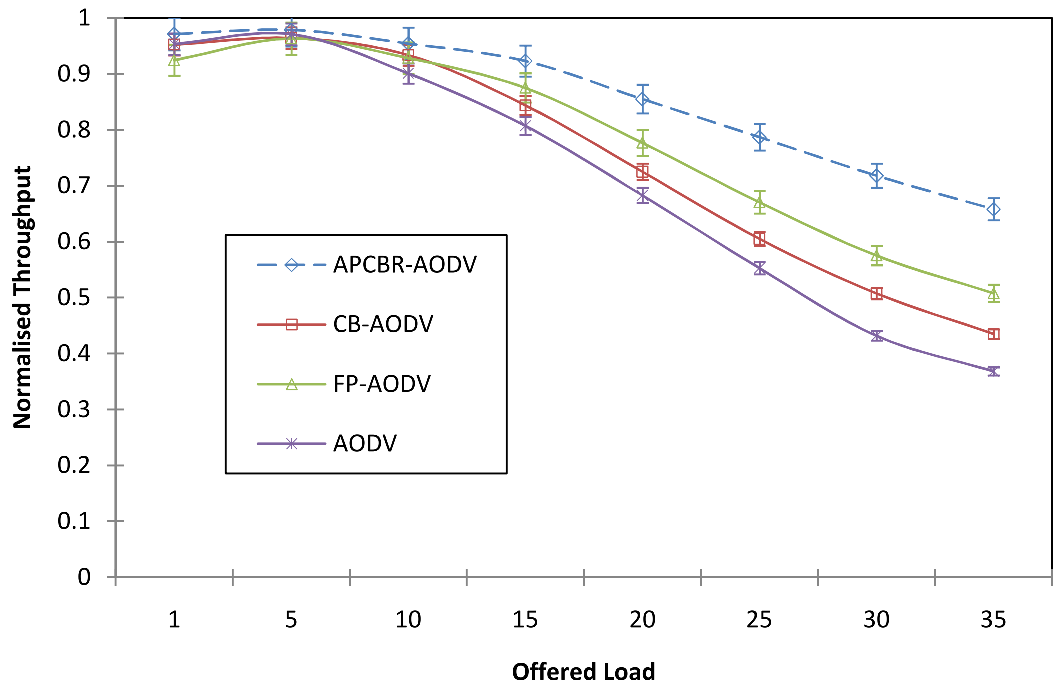

Figure 6.12: Normalised throughput versus offered load for a network of 100 nodes placed in a 1000mx1000m area.

End-to-End Delay:

Figure 6.13 shows that the end-to-end delay of each of the protocols is slightly affected by increasing the offered load from 1 to 10 flows. However, the delay of each of the protocols increases sharply when the offered load increases from 10 to 35 flows. This is because when the number of flows is larger than 10, the network generates more number of routing control packets (e.g. RREQ packet), as a result the channel contention and packet collisions increases. This phenomenon results in a significant increase of the end-to-end delay of the protocols. The figure also shows that APCBR-AODV performs better than the other three versions of AODV when the offered load is increased. For instance, the end-to-end delay of APCBR-AODV is less than that of the CB-AODV, FP-AODV and AODV by approximately 41%, 75% and 110% respectively at an offered load of 35 flows.

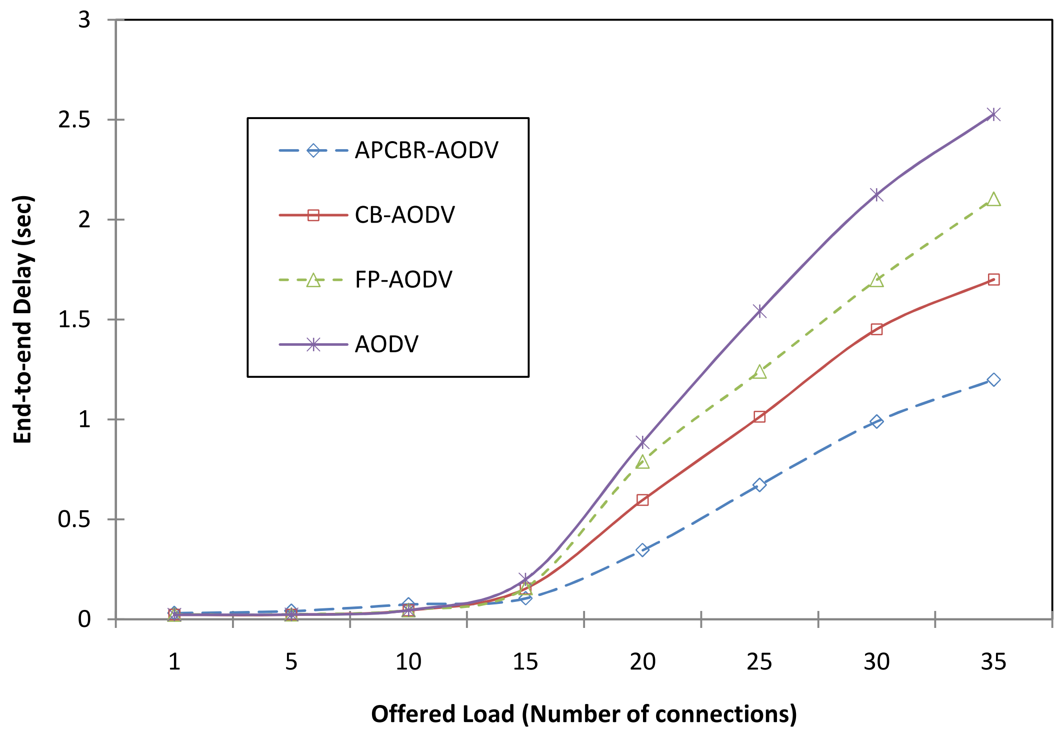

Figure 6.13: End-to-end delay versus offered load for a network of 100 nodes placed in a 1000mx1000m area.

6.5.3 *Impact of Node Mobility*

In this section, the maximum speed of 100 nodes placed in an area of 1000m x 1000m size has been varied from 1, 5, 10, …, 20m/s. An offered load of 10 flows has been considered in each simulation scenario.

Routing Overhead:

Figure 6.14 depicts that the routing overhead generated by the four routing protocols increases with increased maximum node speed. This is because when node mobility increases, the network topology changes frequently, thus more RREQ packets are generated and disseminated to maintain broken paths or to establish new paths. These activities potentially increased the overall routing overhead. For example, the routing overhead of APCBS-AODV, CB-AODV, FP-AODV and AODV increases by approximately 127%, 123%, 202% and 202% respectively when the node speed is increased from 1m/sec to 5m/sec. Correspondingly, across all maximum node speed, APCBS-AODV performs better than CB-AODV, FP-AOV and AODV.

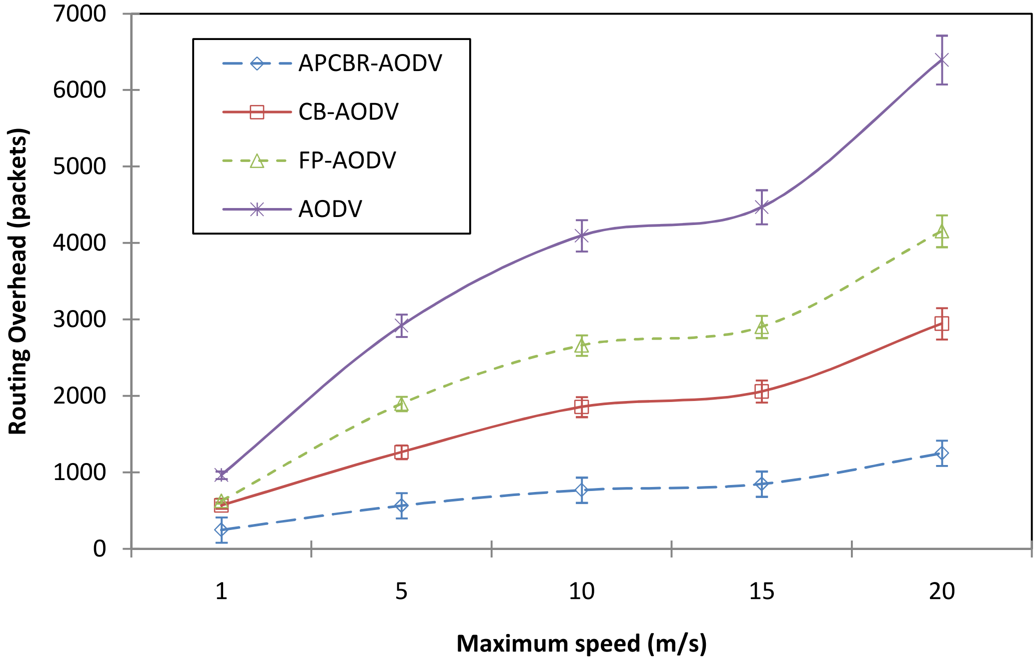

Figure 6.14: Routing overhead in terms of number of packets versus maximum node speed for a network of 100 nodes placed in a 1000mx1000m area.

Similarly, in Figure 6.15, the routing overhead measured in terms of bytes is plotted against the maximum node speed. The performance behaviour of each of the routing protocols in Figure 6.14 is similar to that in Figure 6.15. The routing overhead of each of the routing protocols increases with increased maximum node speed.

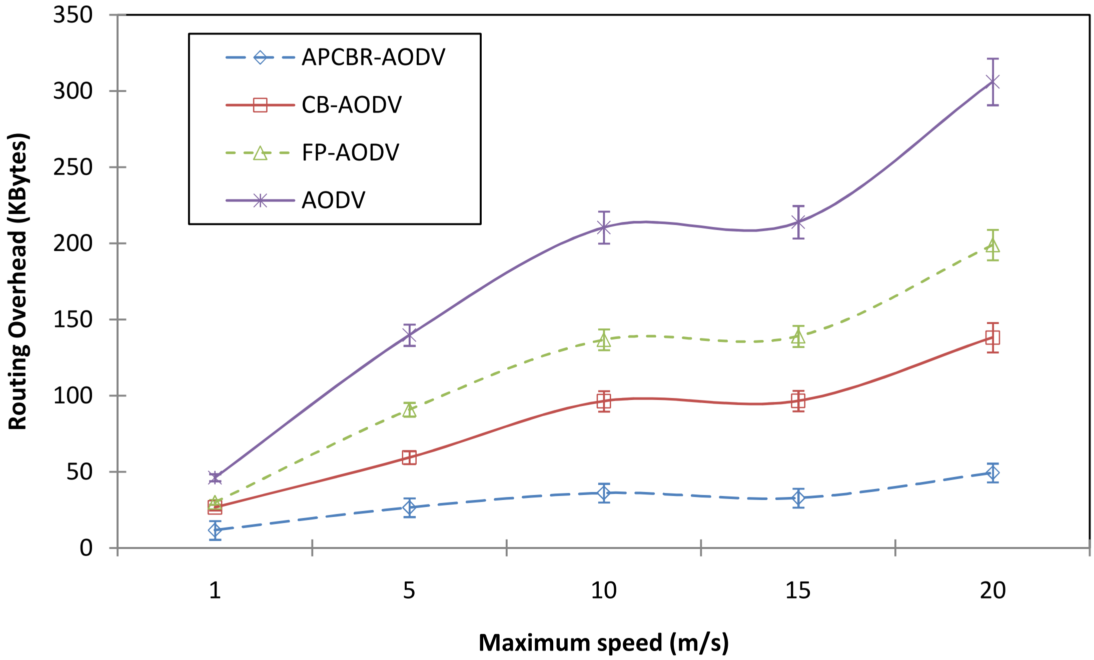

Figure 6.15: Routing overhead in terms of bytes versus maximum node speed for a network of 100 nodes placed in a 1000mx1000m area.

Collision Rate:

The result in Figure 6.16 shows that the number of collision for each of the protocols increases as the node mobility increases. This is due to the increase in the frequency of broken routes which leads to an increase in the number of RREQ packets generated and disseminated. For instance, when the maximum node speed increases from 1m/sec to 5m/sec, the collision rate of APCBR-AODV, CB-AODV, FP-AODV and AODV increases by around 180%, 145%, 250% and 251% respectively. The figure also reveals that the collision rate in APCBR-AODV is significantly reduced when compared against those of CB-AODV, FP-AODV and AODV.

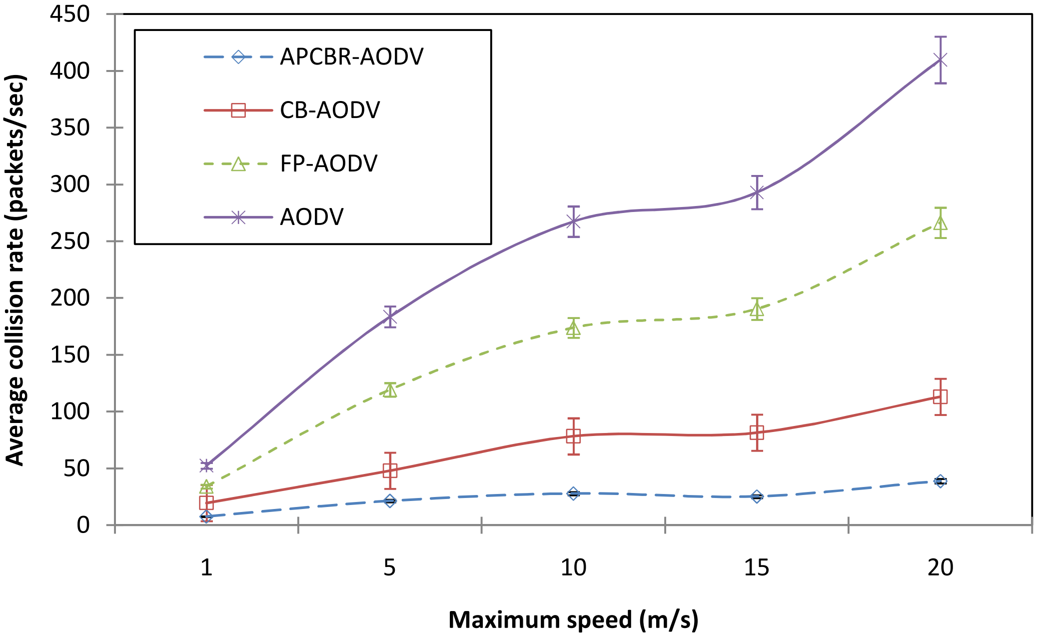

Figure 6.16: Average collision rate versus maximum node speed for a network of 100 nodes placed over 1000mx1000m area.

Normalised Network Throughput:

Figure 6.17 shows that the normalised network throughput achieved by each of the protocols degrades with increased node mobility. This could be due to several reasons including the following: Firstly, when node mobility increases, the network topology changes more frequently and unpredictably which leads to frequent path breaks. Secondly, the broken routes resulting from the frequent topology changes trigger more new route discovery and maintenance operations which increases the number of RREQ packets generated and disseminated in the network. As a consequence the probability of packet collisions increases. Even though APCBR-AODV performs relatively better than the other three protocols (i.e. CB-AODV, FP-AODV and AODV), its superiority over the three protocols becomes more noticeable when the node mobility is relatively high.

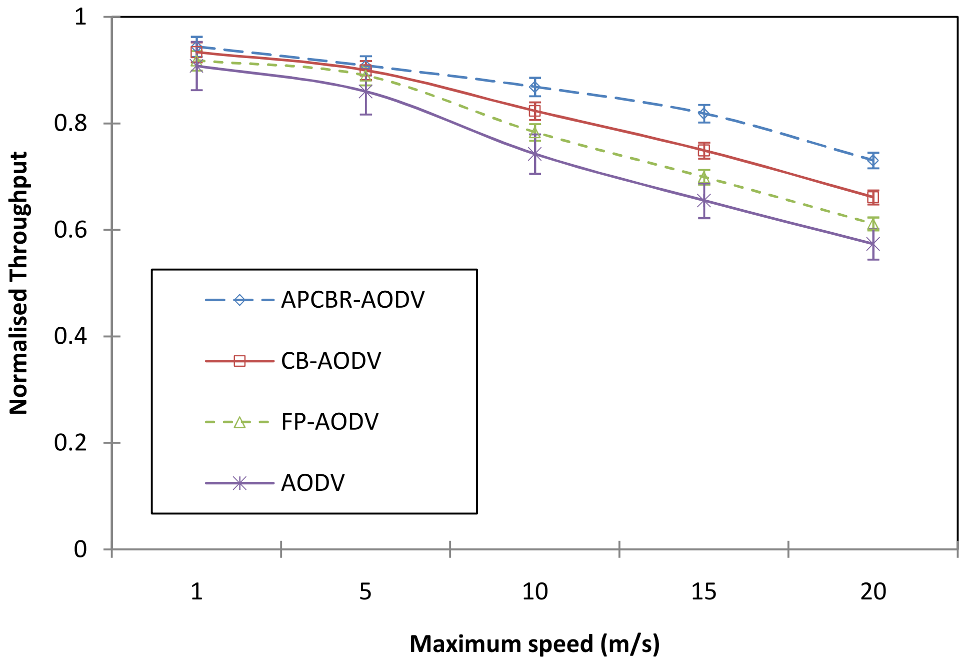

Figure 6.17: Normalised throughput versus maximum node speed for a network of 100 nodes placed in a1000mx1000m area.

End-to-End Delay:

Figure 6.18 depicts the average end-to-end delay experienced by data packets transmitted from source to destination of each of the protocols against the maximum node speed. The figure shows that the end-to-end delay incurred by each of the protocols increases with increased maximum node speed. This is due to the frequent path breaks associated with increased node mobility. When the frequency of path breaks increases the end-to-end delay of data packets waiting to be transmitted also increases. This is because new paths need to be established. Moreover, frequent path breaks can lead to stale routes at mobile nodes which can result in an overall increase in the end-to-end delay of data packets. Nevertheless, across all node speeds considered the delay incurred in APCBR-AODV is shorter than those in CB-AODV, FPAODV and AODV.

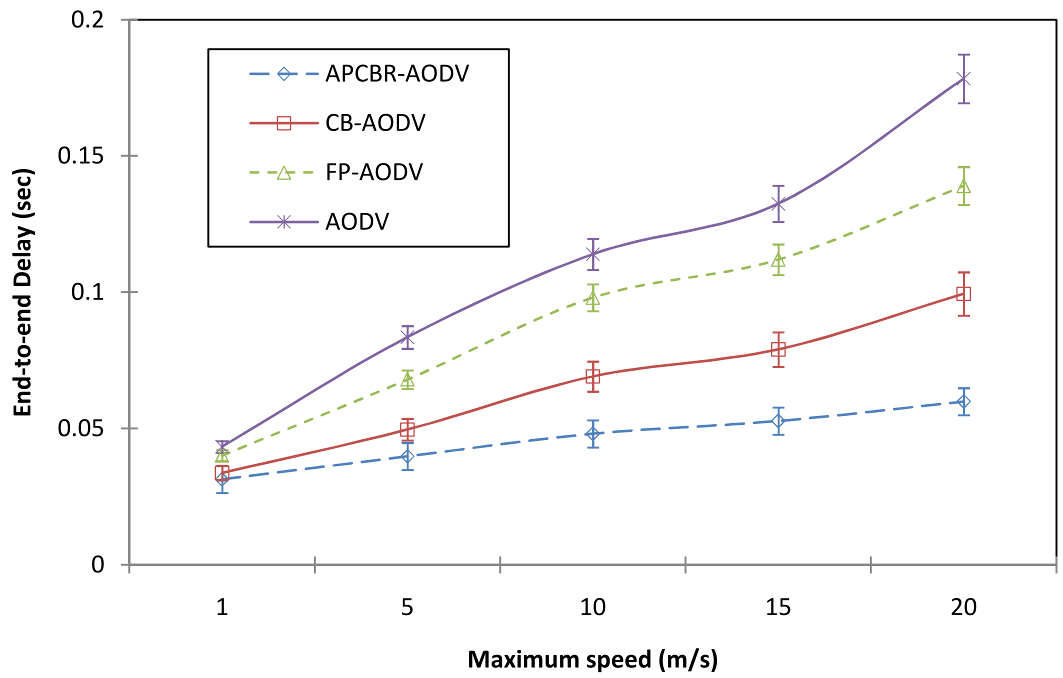

Figure 6.18: End-to-end delay versus maximum node speed for a network of 100 nodes placed in a 1000mx1000m area.

6.6 Conclusions

The new broadcast scheme, APCBS proposed earlier in Chapter was used to develop a route discovery algorithm referred to as Adjusted Probabilistic Counter-Based Route (APCBR) discovery. In APCBR, the forwarding probability at a node is dynamically computed based on its neighbour density (using packet counter) and its threshold value. The performance of the resulting AODV routing protocol (referred to as APCBR-AODV) has been compared against the traditional AODV that uses flooding as well as the AODV versions that employ counter-based broadcasting (referred to as CB-AODV) and fixed probabilistic (FP-AODV).

The simulation results have shown that for all considered network densities, APCBR-AODV outperforms the other three versions of the AODV routing protocol in terms of routing overhead (in packets and bytes) and collision rate. In terms of normalised network throughput and end-to-end delay, APCBR-AODV again outperforms the other versions of AODV particularly in a dense network.

Similarly, APCBR-AODV achieved superior performance with respect to the considered metric over other versions of AODV for all offered load considered. Furthermore, the results have shown that APCBR-AODV is relatively superior over the other three routing protocols in terms of routing overhead and average collision rate across all considered node speeds. Whist, the performance in terms of network throughput and end-to-end delay of APCBR-AODV is better than that of CB-AODV, FP-AODV and AODV for most node speeds.

Chapter 7

Conclusions and Future Work

7.1 Introduction

The recent advances in wireless technology and mobile computing devices have stimulated considerable interest in mobile ad hoc networks (MANETs) among the research community [28, 39, 96, 139]. The communication capability of each device in such network is restricted by its wireless transmission range, since a device cannot directly communicate beyond this range. Broadcasting is extensively used in a wide range of applications in MANETs including route discovery process in many well-known routing protocols [11, 12], address resolution and dissemination of data in sensor network.

The provision of efficient broadcast algorithms that can cope with frequent topology changes and limited shared channel bandwidth is one of the most challenges of research in MANETs and are crucial to the basic operations of the network [96]. The simplest broadcasting method is *flooding,* where each node in the network forwards every received packet exactly once. Although flooding guarantees that a given packet reach every node in the network, it often generates excessive redundant retransmissions in the network [17-19]. To reduce the broadcast storm problem associated with flooding, a number of schemes have been suggested [18, 20-23] which can be categorised into *deterministic* and *probabilistic*. The deterministic schemes [24-27] require global or near-global network topological information to build a virtual backbone that covers all the nodes in the network and are considered not scalable because of the excessive overhead associated with building and maintaining network topological information especially in the presence of mobility. Probabilistic schemes in disparity are considered more scalable than the deterministic scheme, since 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 smaller overhead and demonstrate superior adaptability in changing environments when compared to deterministic schemes. However, most of the proposed probabilistic schemes are inadequate in reducing the number of redundant retransmissions while still guarantee that most of the nodes receive the broadcast packets. In some cases, the schemes require the use additional hardware devices for distance measurement or location identification [18] in order to reduce the redundant retransmissions. The aim of this research is to propose new probabilistic hybrid-based algorithms to improve broadcasting in MANETs by reducing the number of redundant retransmissions while still guarantee that most of the nodes receive the broadcast packets without the use of any additional hardware devices.

7.2 Summary of the Results

The current research has suggested new probabilistic broadcast algorithms that can reduce broadcast redundancy, collision rates and improve end-to-end packet delay. The major contributions made by this thesis can be summarised as follows:

- Although fixed probability and counter-based schemes [18] were the earliest suggested solutions to broadcast storm there has been so far hardly any attempt to analyse the effect of different forwarding probability and counter threshold values on the performance of the two approaches taking into account important operating conditions in MANETs, such as node mobility, traffic load and network density. Motivated by this observation, the first part of this research has analysed the performance of counter-based and fixed probabilistic schemes using different threshold and forwarding probability values under varying network density and traffic load.

- In this performance analysis, the existing counter-based and fixed probabilistic schemes implementations in the Ns2.1b7a simulator [90] designed according to the specification in [18], have been modified and implemented on Ns-2 (2.29.3) simulator [90] in order to incorporate different counter threshold and forwarding probability values. The extensive simulation analysis has revealed that for a given network setup under varying network density and traffic load, considerable savings can be achieved in terms of broadcast retransmission and collision rate without sacrificing the overall reachability, provided that appropriate threshold (*C*) and forwarding probability (*P*) values are selected for counter-based and fixed probabilistic schemes respectively. Similarly, the results have shown that the higher the threshold value the higher the number of retransmitting nodes. For instance, under varying offered load for a *C* range of 2 – 6 the number of retransmitting nodes increases from around 41% to 98%. Furthermore, in sparse networks, reachability improves with increased *C* or *P* values. For example, as *C* increases from 2 to 6 the reachability also increases from around 26% to 45% while as *P* increases from 0.1 to 0.9 reachability achieved is in range of 12% to 30%.

- It can be noted that both the counter-based and fixed probabilistic schemes can reduced the negative impact of broadcast storm by allowing each node to rebroadcast a received broadcast packet based on a given threshold or forwarding probability value. In counter-based scheme, a packet is rebroadcast only when the number of copies received at a particular node is less than the threshold value while in probabilistic scheme a node rebroadcasts a packet according to a pre-defined forwarding probability. The counter-based scheme achieves better reachability while probabilistic scheme reduces the number of redundant rebroadcast at the expense of reachability. However, despite the advantages of these schemes, there has not been any study that has suggested a hybrid-based broadcast scheme that combines the desirable features of the two schemes. Motivated by this, the second part of this research proposes a new probabilistic broadcast scheme that aims to further reduce the redundant retransmissions by limiting the dissemination of broadcast packets.

- In this new broadcast scheme, referred to as Probabilistic Counter-Based Scheme (PCBS) each neighbouring node that receives a broadcast packet initialises a counter and waits for a random assessment delay time during which it increments its counter for every received copy of the same broadcast packet. After the expiration of the random assessment time, the node compares its counter value against the threshold. If the counter is less than the threshold, the packet is rebroadcast with a forwarding probability p. Otherwise, the broadcast packet is dropped.

- Numerous simulation experiments have been conducted on the PCBS and the performance results have been compared against those of counter-based (CB), fixed probabilistic (FP) and flooding under two key network operating conditions, network density and offered load. Simulation results have shown that PCBS outperforms CB, FP and flooding in terms of the number of retransmission nodes, average collision rate, reachability and end-to-end delay in most considered cases. For example, under high injection rate (i.e. 60 packets per second) the collision rate in PCBS is around 57% and 79% lower compared to CB and flooding.

- In the PCBS approach, the forwarding probability at a given node when the actual counter value is less than the threshold is predetermined regardless of its actual counter value while a broadcast packet is automatically dropped whenever the counter value at a node is greater than the threshold. However, the node distribution in MANETs often changes frequently and as a consequence the forwarding probability used for the dissemination of broadcast packets should be set dynamically to reflect the local neighbourhood information (actual counter value) at a given node. Motivated by this observation, a new Adjusted Probabilistic Counter-Based Broadcast Scheme (APCBS) has been described. APCBS dynamically adjusts and computes the forwarding probability at a node using a function which depends on the actual counter value for the packet (i.e., local density) and the threshold value. The function computes the forwarding probability of a packet as the negative exponential of the ratio of the actual counter value (c) to threshold (C) values if $c < C$. Otherwise, the packet forwarding probability is computed as $e^{-(\frac{c+2}{C})}$.

- Extensive simulation experiments have been conducted to compare the performance of APCBS against PCBS, CB, FP and flooding. The performance impact of different network densities and offered loads has been examined in the simulation experiments. The results have revealed that in most circumstances APCBS exhibit a superior performance compared to the other schemes in terms of retransmitting nodes, end-to-end delay and collision rates. For instance, the collision rate and end-to-end delay incurred by APCBS is further reduced by approximately 25% and 15% compared to PCBS for a 200 nodes network, while the reachability performance of APCBS is comparable to that of flooding for a 40 to 200 nodes network which is the maximum nodes considered in this research. Furthermore, under high traffic rate the collision rate in APCBS is further reduced by approximately 37% compared to PCBS.

- The performance of most existing broadcast algorithms including our new APCBS and PCBS have been analysed in "pure" broadcast scenarios where a given packet is destined to all network nodes. As a consequence, there has been hardly any investigation on the performance impact of broadcasting on real applications such as route discovery process in routing protocols. In an effort to address this shortcoming, the last part of this research has conducted a performance analysis of the well-known AODV routing protocol when our new APCBS is used as a route discovery mechanism. The new resulting route discovery algorithm is referred to here as Adjusted Probabilistic Counter-Based Route discovery (APCBR for short) while the resulting AODV protocol as APCBR-AODV.

- The performance of APCBR-AODV has been compared against that of AODV equipped with a route discovery process based on Counter-Based broadcast (CB-AODV), Fixed Probabilistic (FP-AODV) and flooding (AODV) under wide range of system parameters including network density, offered load and node mobility. The simulation results have shown that in most cases APCBR-AODV exhibit superior performance advantage in terms of routing overhead, collision rate, network throughput and end-to-end delay compared to CB-AODV, FP-AODV and the traditional AODV. For instance, under high mobility the routing overhead in APCBR-AODV can be lower by up to 56%, 60% and 74% compared to CB-AODV, FP-AODV and AODV respectively.

7.3 Directions for Future Work

In the course of this research, several interesting issues and open problems have been identified that could be pursue in future investigations. Some of these are briefly outlined below.

- This research has presented an extensive performance analysis of probabilistic broadcast algorithms for pure broadcast and application scenarios (e.g. route discovery) based on the reactive AODV routing protocols. It would interesting to investigate the impact of these broadcasting algorithms when used as a route discovery mechanism in other reactive routing protocols, such as DSR [11] and Dynamic MANET on demand (DYMO) [128]. In addition, the effects of these algorithms on the performance of proactive and hybrid routing protocols, such as OLSR [130] and ZRP [127] could also be examined. A potential area where the probabilistic broadcast algorithms could be useful in proactive and hybrid routing protocols is in the advertisements process of the routing tables.

- Most existing studies including the one described in this research have relied on simulations in order to conduct the performance analysis of the algorithms proposed for MANETs. However, simulation cannot cover all possible scenarios (e.g. MANETs with a large number of nodes) due to time and resource constraints. A potential work for the future would be to develop analytical models for the broadcast and route discovery algorithms that can capture the interactions among the important system parameters and quantitatively assess their impact on network performance [111].

- In addition to broadcasting, there are other forms of collective communication in MANETs. These include one-to-many (multicasting) [140], all-to-all (gossiping) [141] and all-to-one (reverse broadcasting) [142]. A future research direction would be to examine the benefit of extending the proposed broadcast algorithms to other types of collective communication. For instance, reverse broadcasting can be used to gather information from every host in the network to a static/mobile centre as in sensor network. However, the arrangement for reverse broadcasting is often complicated since finding the centre node and then subsequently sending the data to that node involves two rounds of broadcasting operations.

- Similar to route discovery process, resource discovery is a challenging task in MANETs because of the unpredictable mobility of nodes. Resource discovery is crucial to the design of MANETs as nodes do not have any prior knowledge of the resources available in the network. There are two approaches that have been suggested for resource discovery: *push* and *pull* [143, 144]. In the *push* approach, resources are pushed through the network so that they reach nodes that have requested the resources. In the *pull* approach, a node floods the network with a resource request. Upon finding the node which has the requested resource, a routing path is created to connect the resource to the request originator. It would be interesting to explore the impact of the proposed algorithms when implemented as resource discovery approach in MANETs, especially as a *pull* resource discovery approach.

- Although simulation has been a valuable tool for the performance evaluation of a MANET system, it often requires certain simplifying assumptions in order to keep the complexity of the various models (e.g. radio propagation models or mobility models) at a manageable level. As a result, the model might not capture important factors that might affect system performance. So far, there has been little activity in the deployment [145, 146] and performance measurements of actual MANET systems. Provided adequate computing resources are made available to materialise an actual MANET configuration in the future, it would be useful to conduct real experimental measurements and verify the simulation results reported in this research. Apart from instilling confidence in the existing work, the results collected from such deployments could be particularly valuable for the realistic calibration of future simulation models.

- The performance analysis of the proposed broadcast and route discovery schemes in this research has been conducted assuming CBR traffic that relies on UDP. A natural extension of this research work would be to explore the performance behaviour of the proposed schemes for other traffic types such as VBR and those that rely on TCP.

Appendix A

Performance Analysis of Different Probabilities on Counter-Based Scheme

A.1 Impact of Offered Load on the Performance of Different Forwarding Probabilities

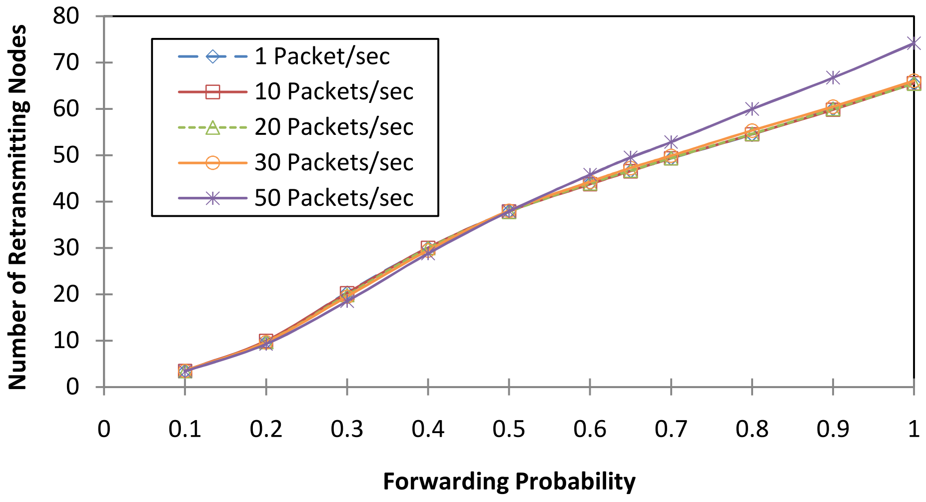

Figure A.1: Number of retransmitting nodes vs. forwarding probabilities for different broadcast injection rates.

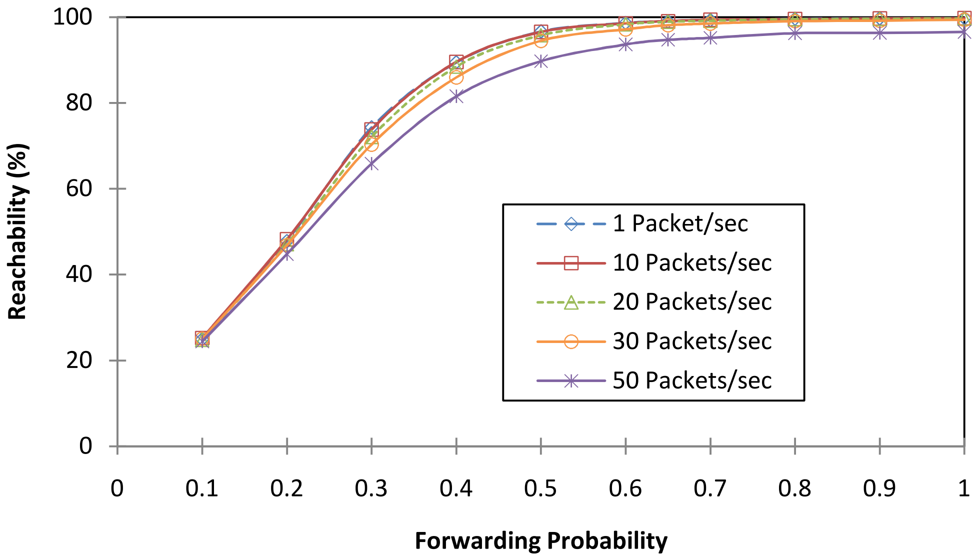

Figure A.2: Reachability vs. forwarding probabilities for different broadcast injection rates.

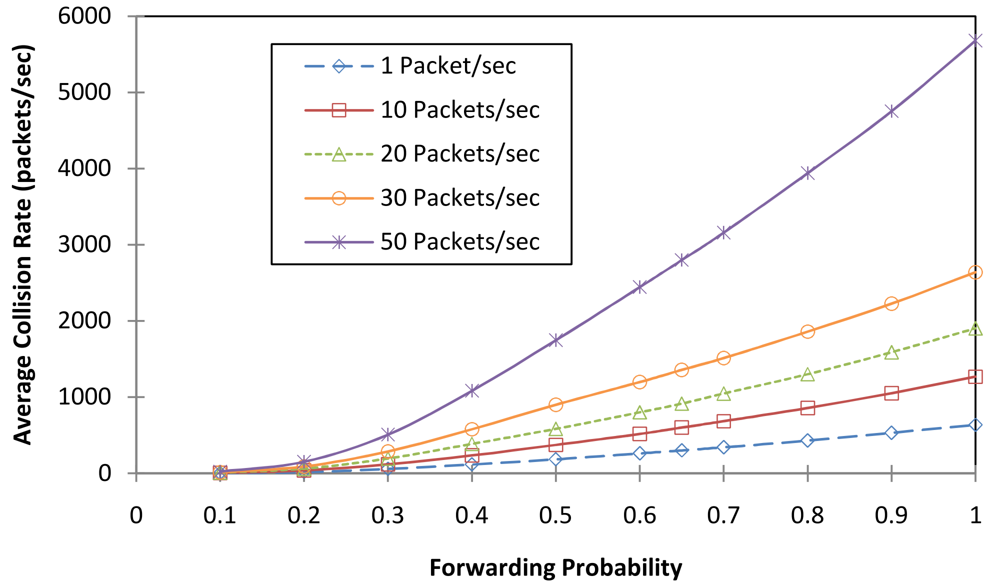

Figure A.3: Average collision rate vs. forwarding probabilities for different broadcast injection rates.

A.2 Impact of Mobility on the Performance of Different Forwarding Probabilities

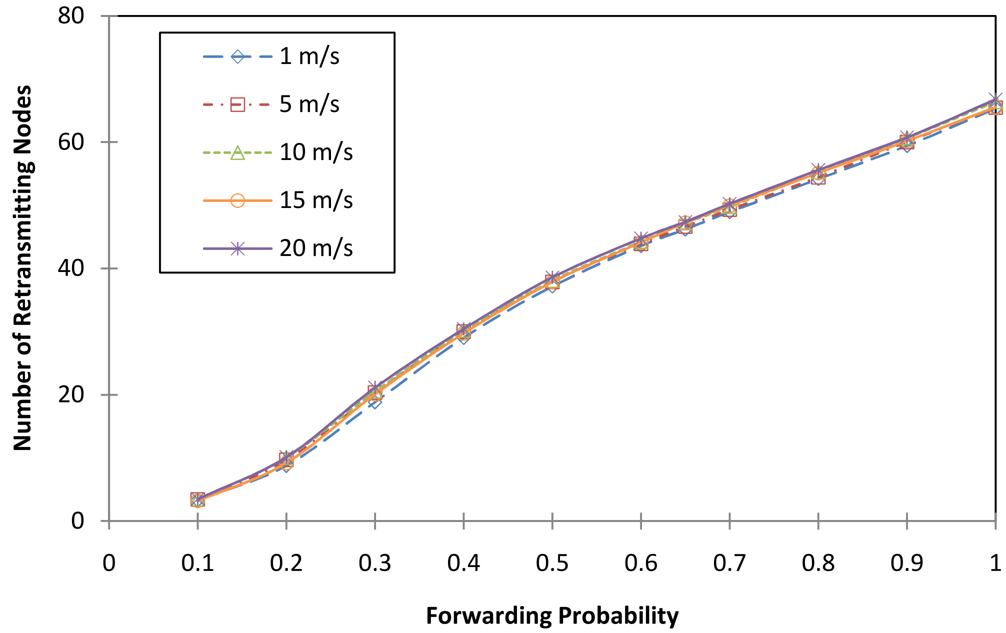

Figure A.4: Number of retransmitting nodes vs. forwarding probabilities for different node speed.

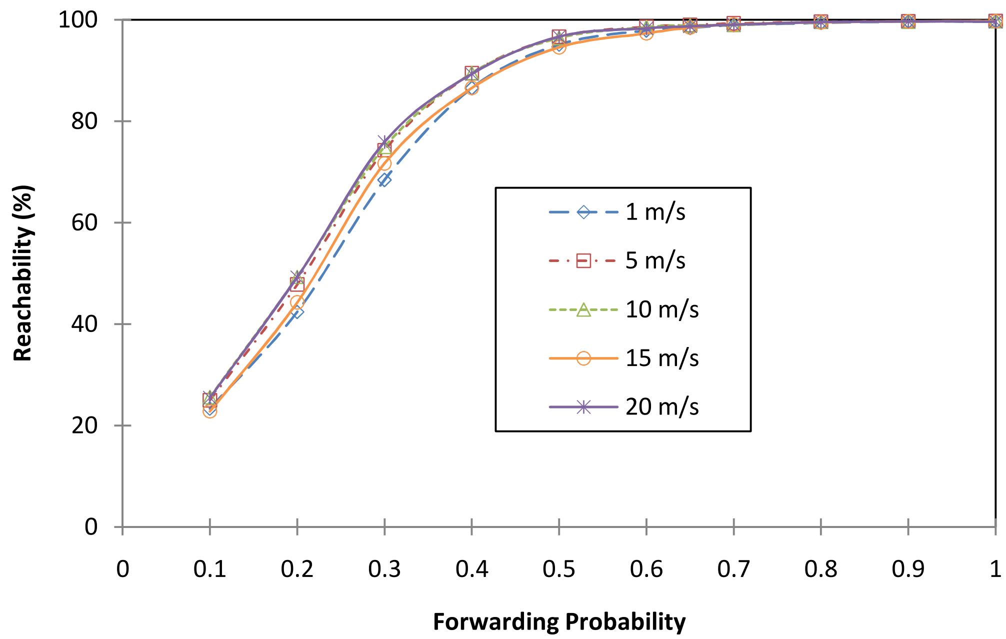

Figure A.5: Reachability vs. forwarding probabilities for different node speed.

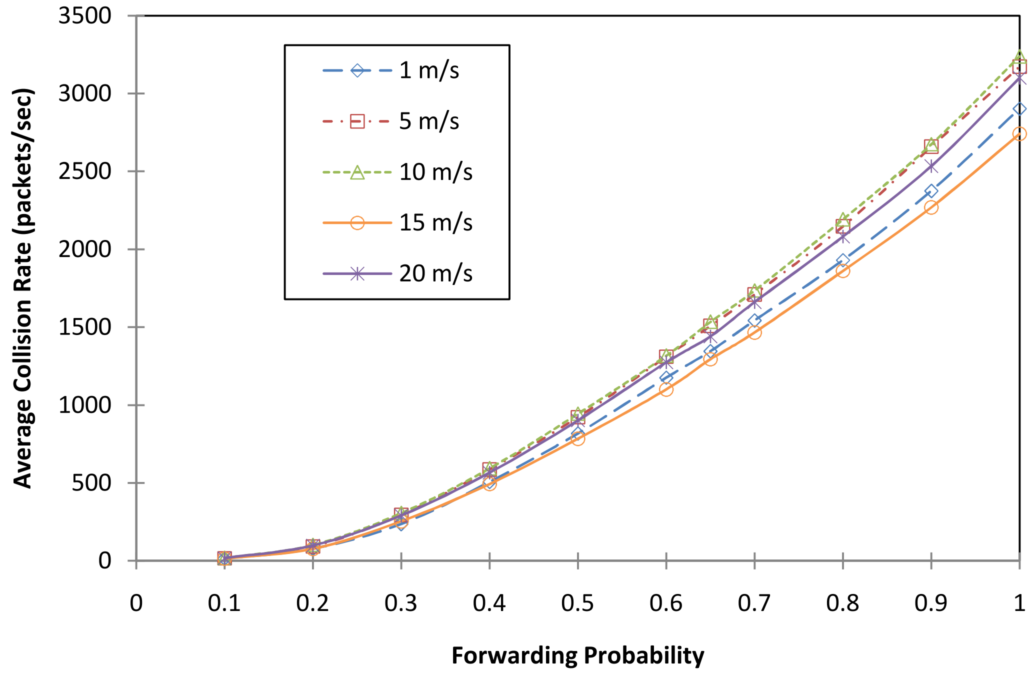

Figure A.6: Average collision rate vs. forwarding probabilities for different node speed.

Appendix B

Performance Analysis of PCBS

B1 Impact of Mobility on the Performance of PCBS

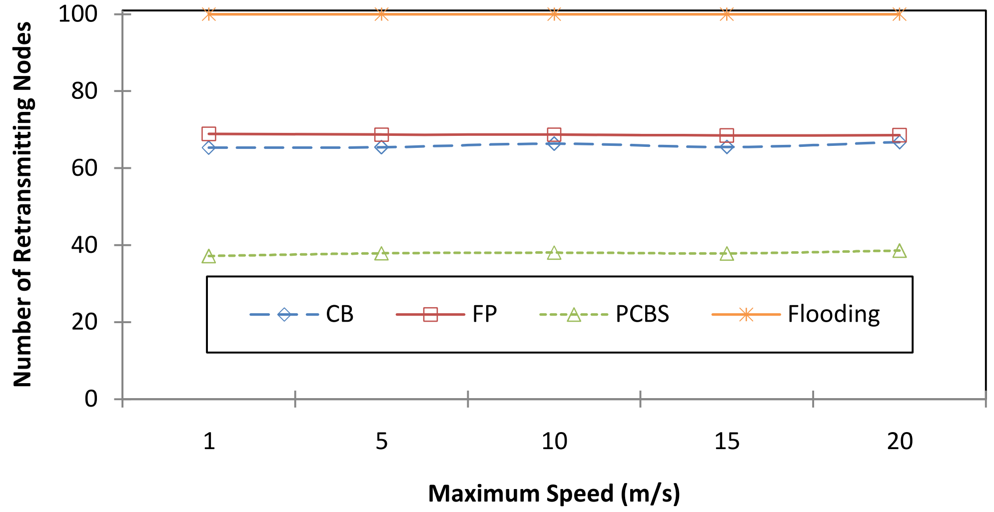

Figure B.1: Number of retransmitting nodes vs. maximum node speed for a network of 100 nodes placed in 1000mx1000m area.7.7

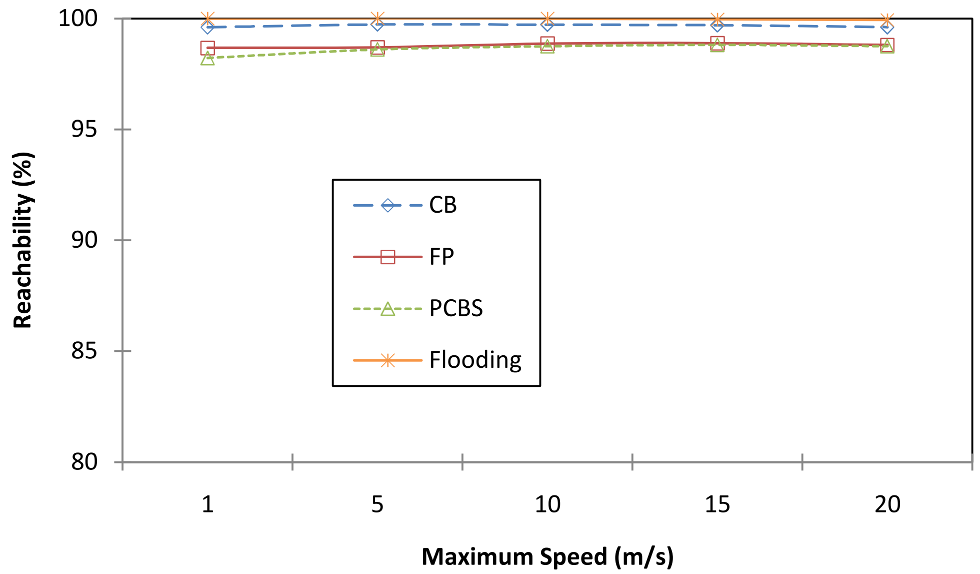

Figure B.2: Reachability vs. maximum node speed for a network of 100 nodes placed in 1000mX1000m area.

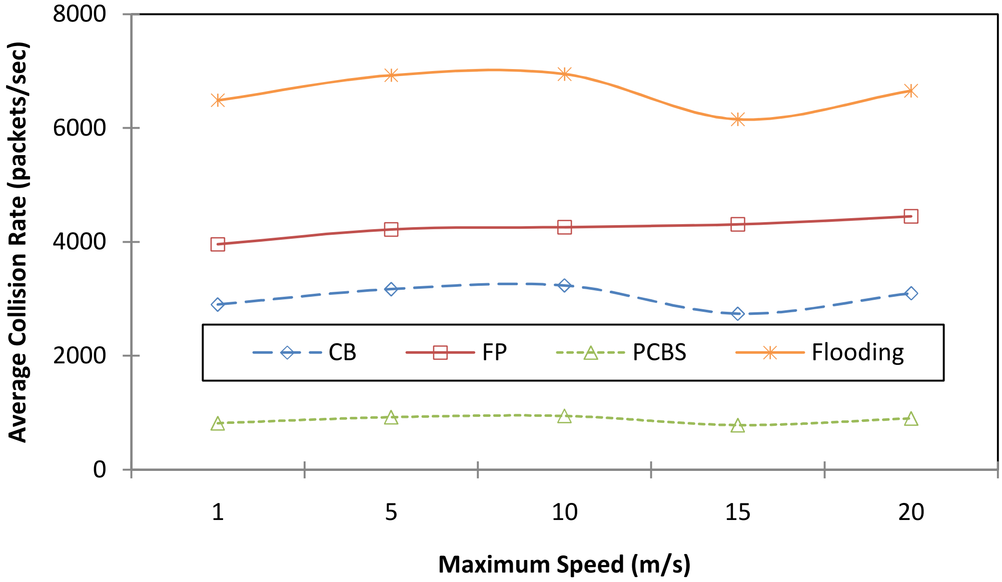

Figure B.3: Average collision rate vs. maximum node speed for a network of 100 nodes placed in 1000mX1000m area.

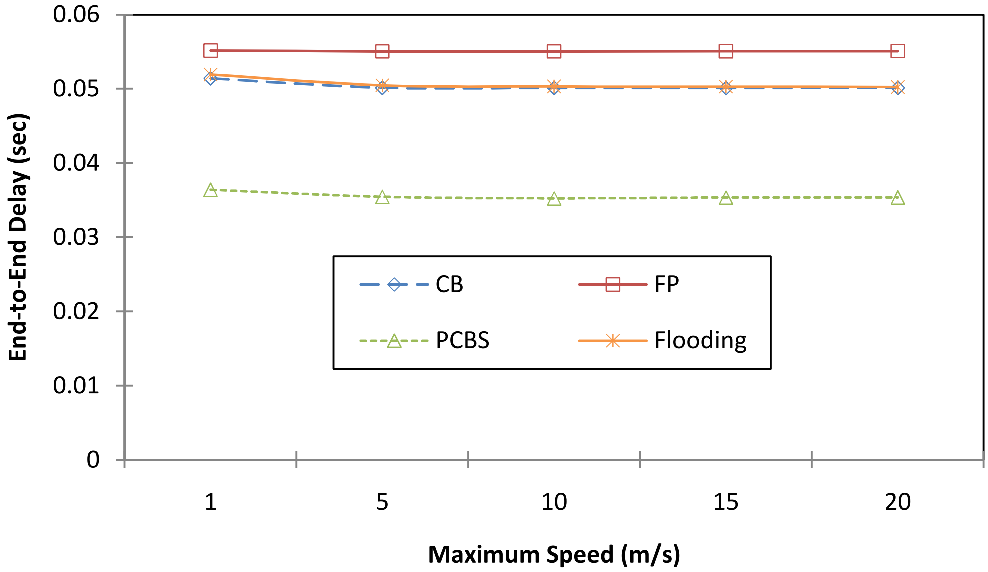

Figure B.4: End-to-end delay vs. maximum node speed for a network of 100 nodes placed in 1000mX1000m area.

Appendix C

Publications during the Course of this Research

- M. Aminu, M. Ould-Khaoua and L. Mackenzie, “Performance Analysis of an Adaptive Probabilistic Counter-Based Broadcast Scheme for Mobile Ad Hoc Networks”, Accepted for publication in the International Journal of Simulation Systems Science and Technology (IJSSST), vol. 10, no. 1-A, 2010.

- J. Abdulai, M. Ould-Khaoua, L.M. Mackenzie and M. Aminu, “A Dynamic Probabilistic Route Discovery for Mobile Ad Hoc Networks”, International Journal of Communication Networks and Distributed Systems, vol. 4, issue 1, pp. 108 – 130, 2010.

- M. Aminu, M. Ould-Khaoua, L. Mackenzie, C. Perkin and J. Abdulai, “Dynamic Probabilistic Counter-Based Route Discovery for Mobile Ad hoc Networks”, To appear in the Proceedings of the 2nd IEEE International Conference on Adaptive Science & Technology, to be held between 14 – 16 December 2009 at Protea Hotel, Accra, Ghana.

- M. Aminu, M. Ould-Khaoua and L. Mackenzie, “An Improved Rebroadcast Probability Function for an Efficient Counter-Based Broadcast Scheme in MANETs”, 25th Annual UK Performance Engineering Workshop (UKPEW’09), 6 - 7 July 2009, University of Leeds, UK, pp. 156 - 167, July 2009.

- M. Aminu, M. Ould-Khaoua, L. Mackenzie, C. Perkin and J. Abdulai, “Probabilistic Counter-Based Route Discovery for Mobile Ad hoc Networks”, Proceedings of the 5th International Wireless Communication and Mobile Computing Conference (IWCMC 2009), 21 -24 June 2009, Leipzig, Germany, pp. 1335 – 1339, ACM, 2009.

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