QoS Enhancement in Wireless Multi-Hop Ad Hoc Networks

A Thesis submitted in fulfilment of the requirements for the
Degree of Doctor of Philosophy (Ph.D.)

By

Oussama Alsabek

Department of Electronic and Computer Engineering
College of Engineering, Design and Physical Sciences
Brunel University, London
United Kingdom

October 2018

Abstract

Wireless ad-hoc multi-hop networks such as wireless mesh networks (WMNs) and mobile ad hoc networks (MANETs), have shown a tremendous growth due to the huge demand of mobile users and connectivity strive over the last two decades. Yet, Quality of Service (QoS) of these networks, when traditional protocols such as Transmission Control Protocol (TCP) and Ad hoc On-demand Distance Vector (AODV) are employed, has shown unsatisfactory performance. Throughput unfairness that leads to starvation is a major problem in WMNs backhaul where nodes that are few hops away from the gateway get minimal chance to transmit to the gateway. Additionally, routing in MANETs without considering mobility, residual energy, and congestion impacts QoS severely. This thesis presents designated and tested solutions to enhance the QoS in wireless mesh and mobile ad-hoc networks. These include enhancing throughput with maintaining fairness among nodes in WMNs, and designing efficient routing schemes that able to provide better QoS in terms of packet delivery ratio, delay, network lifetime and energy consumption.

Enhanced Adaptive Delayed Acknowledgement Mechanism (EADAM) is proposed to enhance the throughput for all active flows in a static chain topology alongside with maintaining fairness among the flows. This mechanism utilises a mathematical model for calculating appropriate TCP delayed acknowledgement timeout with reference to the number of hops between a source and a destination node called Adaptive Delayed Acknowledgement Mechanism (ADAM). An optimum throughput fairness on a chain topology for a number of active flows has been achieved by implementing a TCP delayed acknowledgement timeout model that allows Paralleled transmission among the individual flows, which leads to a significant throughput enhancement. The proposed mechanism EADAM has been tested in Network Simulator NS2. Then validated by comparing to ADAM. A throughput enhancement ratio of up to 35% has been achieved.

Mobility and Energy Aware AODV (MEA_AODV) is a novel route discovery scheme that is mobility and energy aware for AODV in MANETs proposed to improve QoS performance in terms of throughput, Packet Delivery Ratio (PDR), network life time, overall overhead, average delay of an existing scheme called Average Link Stability and Energy Aware (A-LSEA). MEA_AODV relies on two important factors: Link Life Time (LLT) and Residual Energy (RE). Two schemes have been implemented: Selective Energy_ Mobility and Energy Aware AODV (SRE_MEA_AODV) and Selective Link Life Time_ Mobility and

Energy Aware AODV (SLLT_MEA_AODV). The two proposed schemes have been tested in NS2, and then evaluated in comparison with AODV and A-LSEA. The evaluation confirms that SRE_MEA_AODV dramatically outperforms A-LSEA and AODV in term of all the QoS aspects. A throughput enhancement of up to 120% compared to AODV and up to 53% compared to A-LSEA achieved with SRE_MEA_AODV.

A congestion aware routing scheme has been proposed to provide end-to-end guarantees in a route discovery scheme for AODV in MANETs. This scheme improves QoS by controlling the congestion that occurs because of unmanaged node buffer while deciding on forwarding the RREQ packet in the rout discovery process. In this work, the queue length (QL) for the forwarding node is used as a criterion to measure congestion in the node's buffer. The proposed scheme has been implemented in two schemes called: Firstly, Adaptive Managed Buffer_ route discovery scheme for AODV (AMB_AODV). Secondly, Adaptive Managed Buffer and Selective Remaining Energy route discovery scheme for AODV (AMB_SRE_AODV). The two proposed schemes have been evaluated in comparison with standard AODV. The evaluation shows that PDR has improves to up to 27.9% and 31.2% with AMB_AODV and AMB_SRE_AODV respectively. In addition, throughput enhancement of up to 18.73% and 42.7% achieved with AMB_AODV and AMB_SRE_AODV respectively compared with standard AODV.

List of contents

List of Figures

Acknowledgements

First and foremost, my most humble gratitude to the creator. Only with His blessings and perseverance that was bestowed upon me; without his blessing and mercy, this thesis would not have been possible.

My special gratitude and appreciations to my PhD principal supervisor, Dr Rajagopal Nilavalan who been a tremendous inspiration and support throughout my PhD journey. His dedication, guidance and encouragement in my research had great contribution toward completing my PhD.

My deepest appreciation to my second supervisor, Professor Jonathan Loo with whom I started my PhD journey.

My deepest gratitude and appreciations to my parents who sacralised their lives for my success.

My sincere gratitude to my family: wife and daughters, brothers and sister for their support, love and prayers throughout my PhD journey. Words cannot express their sacrifices and inspiration that had led me to what I am today.

My sincere gratitude to all my friends and colleagues who had contributed directly or indirectly in completing my PhD thesis.

Author's Declaration

The work described in this thesis has not been previously submitted for a degree in this or any other university and unless otherwise referenced it is the author's own work.

List of abbreviations

ACK	Acknowledgement
ADAM	Adaptive Delayed Acknowledgement Mechanism
AMB_AODV	Adaptive Managed Buffer_ route discovery scheme for AODV
AMB_SRE_AODV	Adaptive Managed Buffer and Selective Remaining Energy route discovery scheme for AODV
AODV	Ad hoc On-demand Distance Vector
AP	Access Point
A-LSEA	Average Link Stability and Energy Aware
awnd	advertised window
CBR	Constant Bit Rate
CFP	Contention Free Period
CS	Carrier Sensing
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
CTS	Clear To Send
CW	Contention Window
DSDV	Destination-Sequenced Distance Vector
DCF	Distributed Coordination Function
DSDV	Destination Sequenced Distance Vector
DSR	Dynamic Source Routing
EADAM	Enhanced Adaptive Delayed Acknowledgement Mechanism
F-LSEA	Fixed Link Stability and Energy Aware
FTP	File Transfer Protocol
LSEA	Link Stability and Energy Aware
LLT	Link Life Time
LLT_{avg}	average Link Life Time
MAC	Medium Access Control
MANET	Mobile Ad-hoc Network

MEA-AODV	Mobility and Energy Aware AODV
NS2	Network Simulator-2
OLSR	Optimised Link State Routing
OSI	Open Systems Interconnections
PDR	Packet Delivery Ratio
QoS	Quality of Service
QL	Queue Length
RE	Remaining Energy
RE_{avg}	Average Remaining Energy
RREP	Route Reply
RREQ	Route Request
RERR	Route Error
RTS	Request To Send
RTT	Round Trip Time
SLLT_MEA_AODV	Selective Link Life Time_ Mobility and Energy Aware AODV
SRE_MEA_AODV	Selective Energy_ Mobility and Energy Aware AODV
ssthreesh	Slow Start Threshold
TCL	Tool Command Language
TCP	Transmission Control Protocol
Thr	Threshold
UDP	User Datagram Protocol
WLAN	Wireless Local Area Network
WPAN	Wireless Personal Area Network
WMNs	Wireless Mesh Networks
WSNs	Wireless Sensor Networks
WiMax	Worldwide interoperability for Microwave Access

Chapter 1

Introduction

1.1 Introduction

In this chapter, a general brief background to the investigated problems is presented. Then, the motivation behind the work and the aim and objectives of this research are described. In addition, the major contributions of this work and its research methodology are explained. Finally, the structure of the chapters of this thesis briefly outlined.

1.2 General Background

In recent years, wireless ad-hoc networks have emerged as the new communication paradigm in the new modern world. Their growth and deployments have tremendously widespread due to their importance role in turning the world into a small village. Wireless mesh networks (WMNs) and mobile ad hoc networks (MANETs) are most popular two types of these networks. They have gained their popularity because of the wide range of connectivity application and the usefulness that they provide to the end user.

Wireless Mesh Networks (WMNs) are multi-hop networks classified into three categories: Infrastructure-less WMNs, infrastructure WMNs, and hybrid WMNs. Infrastructure-less WMNs consist of mesh clients that can communicate only with each other directly in an ad hoc manner. Infrastructure WMNs where a hierarchal architecture is existed consist of a backbone of mesh routers and mesh clients, mesh clients access the wireless network through mesh routers only. Mesh routers, then, can serve as bridges to connect the wireless network to the internet. Finally, hybrid WMN is similar to infrastructure WMN; however, a mesh client can access the wireless networks through another mesh client [1].

1.3 Motivations

The work presented in this thesis is motivated by the following issues in WMNs and MANETs:

- In wireless mesh networks (WMNs), the throughput unfairness is a critical problem in such wireless multi hop environments where the closest nodes to the gateway get a higher chance to transmit and receive data, whereas the further nodes get minimum chance to transmit and receive. An adaptive delayed acknowledgement mechanism

(ADAM) proposed in [2] to overcome the unfairness issue in chain topology that stated earlier. The mechanism is based on two main factors: the advertised window and delayed ACK for each flow. This mechanism has managed to improve fairness index. However, the achieved per flow throughput is relatively low. Therefore, an enhancement to this technique is required to improve throughput.

- In MANETs, mobile nodes are free to move and form themselves with any mean of centralization. Any node can function as a sender, receiver or relaying node. Moreover, beside mobility, these nodes are mostly battery-based devices, which means power constrain affects the overall performance of MANETs. Hence, routing in MANETs is a challenging task. Classical routing protocols such as AODV or DSR do not consider the node' mobility or residual energy when they used to find a route between a source and a destination node. Consequently, frequent route failure, retransmission and packet dropping occur which lead to throughput and packet delivery ratio to degrade, increase of control overhead and delay, and eventually network life time is reduced. A position based routing and energy aware called average link stability and energy aware routing protocol (A-LSEA) proposed in [3]. QoS performance in terms of throughput, PDR, network life time, overall overhead, average delay have improved. However, the QoS can be enhanced further by modifying the computational logic in the aforementioned work.
- Route breakage is a serious issues that routing in MANETs experiences. This issue leads to packet dropping and poor QoS of the entire network. It is mainly due to three main reasons: Congestion, high node mobility and the limited residual energy of the node. The node in MANETs is completely free to move in any direction, which results a topology change, and congestion may occur. A common congestion scenario is when some intermediate node' buffers get filled. Thus, these nodes when participating in new routes, these routes are likely to break. Hence, a new route discovery scheme that takes into consideration the buffer status in addition to mobility and remaining energy is needed.

1.4 Scope of the thesis

The aim of the research presented in this thesis is to design and implement solutions to enhance the QoS in wireless mesh and mobile ad-hoc networks. These include enhancing throughput with maintaining fairness among nodes in WMNs, and designing efficient routing schemes that able to provide better QoS in terms of packet delivery ratio, delay, network life time and energy consumption.

The objectives to the aim of this research are summarized as follows:

1. To design a transport layer mechanism that eliminates the starvation that exists in WMNs chain topology and enhances the throughput for all active flows.

2. To design a routing discovery schemes for AODV protocol for MANETs that efficiently work in such challenging environment. These routing should enhances the overall QoS of the network. In other words, schemes that enhance PDR and throughput, reduce the delay and overhead, and enhance the network lifetime. The route selection schemes take into consideration the node mobility by using link lifetime LLT and node remaining energy RE as two important factors when selecting a route between a source and destination.

3. To design a route discovery scheme for AODV in MANETs that improves QoS by controlling the congestion that occurs because of unmanaged node buffer while selecting the route.

4. To combine the three factors of congestion, mobility and remaining energy in one route discovery scheme.

1.5 Research contributions

The main contributions of this research are summarized as follows:

1) A novel transport layer mechanism proposed called Enhanced Adaptive Delayed Acknowledgement Mechanism (EADAM) is proposed to enhance the all flows throughputs and maintaining fairness across all flows in chain topology. EADAM has the following properties:
    (i) The proposed mechanism is an enhancement to ADAM [2].
    (ii) This mechanism utilises the delayed ACK technique with factor of two and an advertised window awnd set to one.

(iii) It improves throughput to multiple flows in a chain topology alongside with guaranteeing optimum fairness index among all of those flows.

2) A novel route discovery scheme that is mobility and energy aware for AODV in MANETs called Mobility and Energy Aware AODV (MEA_AODV) has been implemented. The proposed work is based on A-LSEA [3]. Similar to the later, MEA_AODV relies on two important factors: Link Life Time (LLT) and Residual Energy (RE). It shares position based information through Hello messages, then calculates LLTs between the forwarding node and its neighbours. Then, average link life time LLT_{avg} is calculated. Simultaneously, the forwarding node obtains all its neighbours' residual energies through Hello messages, calculates the average energy RE_{avg}. A-LSEA performs a dual checks of the its own LLT_i and RE_i with LLT_{avg} and RE_{avg}.If (LLT_i and RE_i) are greater than (LLT_{avg} and RE_{avg}) the RREQ packet is rebroadcasted, otherwise it is discarded.

The proposed scheme MEA_AODV utilises the same methodology of A-LSEA to find LLT_{avg} and RE_{avg} at each forwarding node in the route discovery process. However, the method of calculating these LLT_{avg} and RE_{avg} is different. The proposed scheme calculates the first average in the same way that A-LSEA does. Then performs first check by comparing the node first parameter (LLT or RE) with its correspondent average. The computation of the second average excludes any node that did not pass the first check. Once the two averages calculated then the node compares its own parameters (LLT_i and RE_i) with (LLT_{avg} and RE_{avg}). Again, If (LLT_i and RE_i) are greater than or equal to (LLT_{avg} and RE_{avg}) the RREQ packet is rebroadcasted, otherwise it is discarded.

Based on the computation philosophy of MEA_AODV, Two schemes have been implemented:

- Selective Remaining Energy Mobility and Energy Aware AODV (SRE_MEA_AODV).
- Selective Link Life Time Mobility and Energy Aware AODV (SLLT_MEA_AODV).

These two schemes are called selective because they are selective when they come to calculate the second average parameter.

3) A congestion aware routing scheme has been proposed to provide end-to-end Guarantees in a route discovery scheme for AODV in MANETs. This scheme improves QoS by controlling the congestion that occurs because of unmanaged node buffer while deciding on forwarding the RREQ packet in the rout discovery process. In this work, the queue length (QL) for the forwarding node is used as a criterion to measure congestion in the node's buffer. It is compared with a predetermined threshold (Thr). When QL exceeds Thr the node is considered congested and unable to participate in the route. Therefore, the RREQ is discarded. Otherwise. The node forwards RREQ. The proposed scheme has been implemented in two schemes called:

- ❖ Adaptive Managed Buffer route discovery scheme for AODV (AMB_AODV)
- ❖ Adaptive Managed Buffer and Selective Remaining Energy route discovery scheme for AODV (AMB_SRE_AODV)

1.6 Thesis organisation

This thesis is organised into six chapters, where Chapter 1 is the introductory chapter for this research, Chapter 2 is the background, Chapter 3 to Chapter 5 are the contribution of the research and Chapter 6 is the conclusion and future works. An overview of all the chapters are briefly described as below:

Chapter 1 briefly introduces the research background, motivations behind the research. Then clearly it states the aim and objectives of this research followed by the research contributions and finally concludes with the thesis organisation.

Chapter 2 introduces to some background information and elaborates the taxonomy of wireless mesh networks WMNs and mobile ad-hoc networks MANETs. Then, overview on QoS challenges in WMNs and MANETs explained. A TCP overview is stated. Finally, an overview on routing protocols in MANETs focusing on AODV is presented.

In Chapter 3, a brief introduction to WMNs and their architectures and congestion control and fairness issue. Related work on fairness is listed. Then, the proposed technique called EADAM to enhance throughput is explained. The chapter ends with a comprehensive performance evaluation of the proposed scheme.

Chapter 4 provides a brief introduction to MANETs and routing protocols used with MANETs elaborating the main challenges of mobility and energy. It shows related work on mobility aware and energy aware routing. Then, it presents two route discovery scheme that are mobility and energy aware called SRE_MEA_AODV and SLLT_MEA_AODV. The chapter ends with a comprehensive performance evaluation of the proposed schemes.

Chapter 5 addresses the congestion issue in MANETS during route discovery process. It presents a novel scheme that adaptively selects forwarding nodes based on their buffer status. Then, it combines this technique with the SRE_MEA_AODV that proposed in chapter 4 to propose a congestion, mobility and energy aware route discovery scheme that guarantees stability and QoS in the selected route.

Finally, Chapter 6 concludes the research findings of the thesis and suggests future work to be carried out in connection with the presented research.

Chapter 2

Background: WMNs & MANETs, Qos challenges, TCP & Routing

2.1 Introduction

Wireless networks, over the last two decades, have shown a tremendous growth due to the huge demand of mobile users and connectivity strive. Wireless ad hoc mutli-hop networks such as mobile ad hoc networks MANETS, wireless mesh networks WMNs and wireless sensor networks WSNs are different technologies that have been proposed and evolved as promising networks to accommodate this demand.

In order to gain a better understanding of wireless networks (whether WMNs or MANETs) it is important to describe the characteristics of open systems interconnection (OSI) model proposed by the international standards organization (ISO), which is shown in Figure 2.1 [4]. In this model, there are conceptually seven layers:

- Physical layer (PHY): To deals with the hardware of the network.
- Data Link layer (MAC): For controlling data transmission between two nodes. Medium Access Control protocol, here, provides fair access by sharing the allocated radio channels.
- Network layer: This layer is responsible of routing data packets from source to destination node (AODV for example).
- Transport layer: This layer is mainly about assuring reliability when data transferred from an end to another (the common protocol here is Transmission Control Protocol TCP).
- Session layer: This layer coordinates with transport layer to provide reliable data delivery.
- Presentation layer: For data encryption and decryption.
- Application layer: Provides a mean of interpretation between the software and the network.

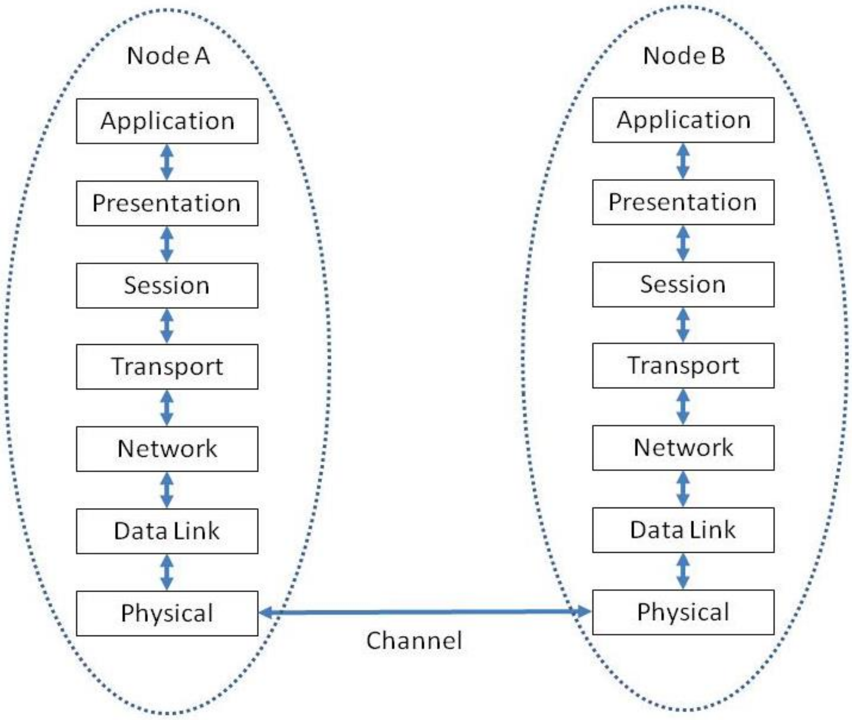


Figure 2.1 OSI Layered architecture model in networks [4]

In this chapter, a taxonomy of WMNs and MANETs is outlined. Then, overview on QoS challenges in WMNs and MANETs explained. A TCP overview is stated. Finally, an overview on routing protocols in MANETs, focusing on AODV, is presented.

2.2 Wireless mesh networks WMNs

Wireless Mesh Networks are emerging networks have brought a great attention from prospective stakeholders of communication due to their novel characteristics in wireless networks. Self-organised, self-configured, easy deployment and minimal setup requirements are some of these characteristics of WMNs that make WMNs cost-efficient and well-adopted connection technologies for wide range of applications [1].

2.2.1 WMNs architecture

The main components in WMNs are two types: mesh clients and mesh routers. A mesh client is an end-user such as a laptop or mobile phone or even a pc, while a mesh router is a dedicated node that provides connectivity with other mesh routers or access points or mesh clients. Additionally, some mesh routers equipped with multiple radios in order to allow simultaneous connections [5] . In addition to clients and routers connectivity, mesh routers may function as bridges or gateways to the internet backbone.

WMNs can be categorized in three possible architectures: infrastructure-based, infrastructure-less and hybrid WMNs.

2.2.1.1 Infrastructure based WMNs

The most common architecture in WMNs where mesh routers form the backbone of the network. The meshing among wireless routers and access points creates a wireless backhaul communication system, mesh clients access the wireless network through mesh routers only. Mesh routers, then, can serve as bridges to connect the wireless network to the internet [5]. This architecture is illustrated in Figure 2.2.

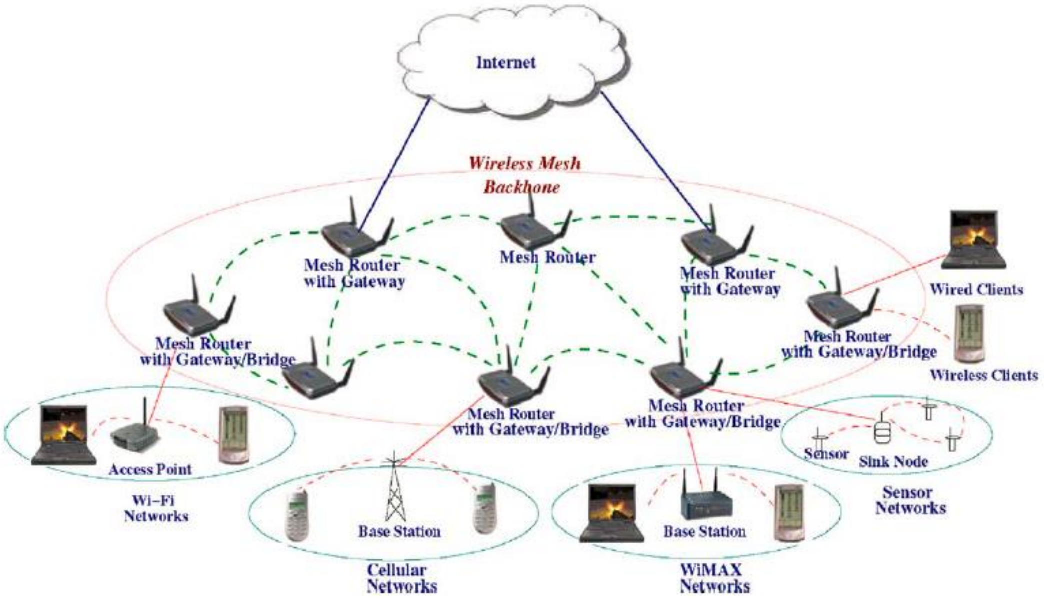


Figure 2.2 WMNs infrastructure based architecture [1]

2.2.1.2 Infrastructure-less WMNs

In infrastructure-less wireless mesh networks each mesh client communicates with another without the need of mesh routers. Hence, the mesh client performs extra tasks such as routing between a source node and a destination node [1]. This architecture is illustrated in Figure 2.3.

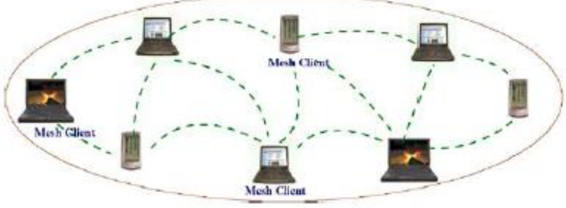


Figure 2.3 WMNs infrastructure-less architecture [1]

2.2.1.3 Hybrid WMNs

This architecture is more complex where the previous two have merged together. Mesh clients can communicate with each other via direct communication or through a mesh router. This is illustrated in Figure 2.4.

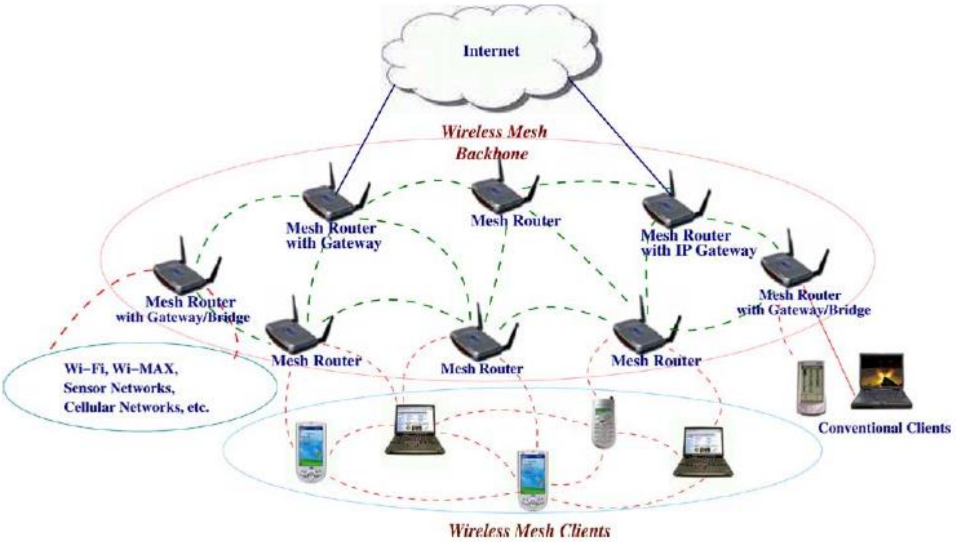


Figure 2.4 WMNs hybrid architecture [1]

2.2.2 WMNs features

Wireless mesh networks are multi-hop networks that facilitate linking two nodes which are in coverage range to each other by using other intermediate nodes as relaying nodes. WMNs support ad-hoc wireless networking represented in self-configured and self-healing that make these networks deployable. Additionally, mobility is supported especially with mesh clients. Moreover, WMNs support the compatibility with other wireless technologies such as WiMAX and Zig-Bee [1] [6].

2.2.3 WMNs Applications

WMNs have become promising solutions to many civilian networking applications due to their characteristics and features that previously mentioned [1] [6]. Some of those applications are:

- **Broadband home networking:** Providing home broadband without relying on access points APs in WLAN IEEE802.11 as shown in Figure 2.5(a).
- **Community and neighbourhood networking:** Connecting community different parts without necessarily using the internet as shown in Figure 2.5(b).
- **Enterprise networking:** WMNs can be used to connect nodes in an office or in multiple offices in different building replacing old solution of using a wired Ethernet network as shown in Figure 2.6.

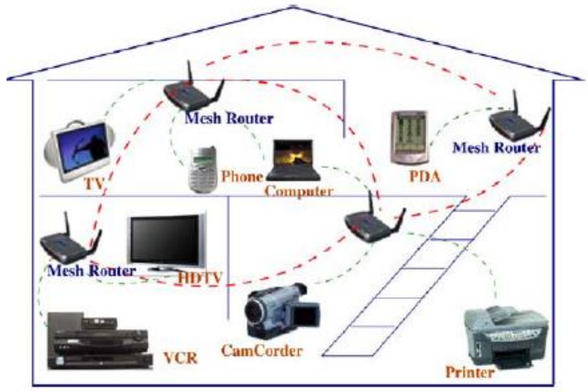
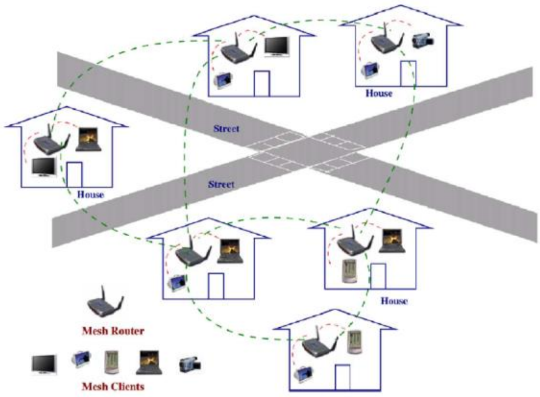
 	

Figure 2.5(a) WMNs for Broadband home [1]	*Figure 2.5(b) WMNs for community networking [1]*

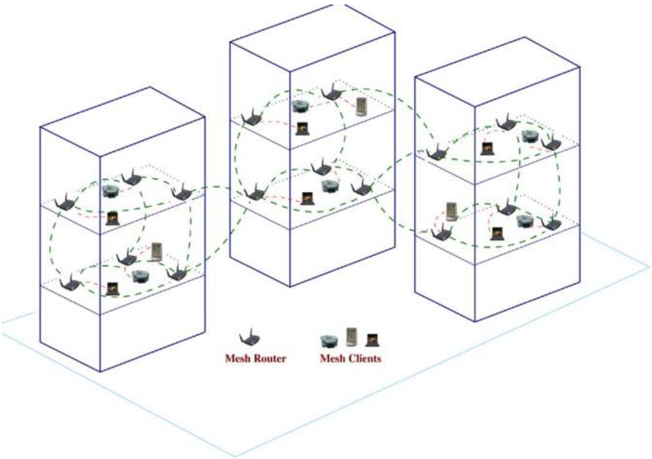


Figure 2.6 WMNs for Enterprise networking [1]

- **Metropolitan networking:** Providing better QoS connectivity to wider area comparing with other wireless networks (Figure 2.7).

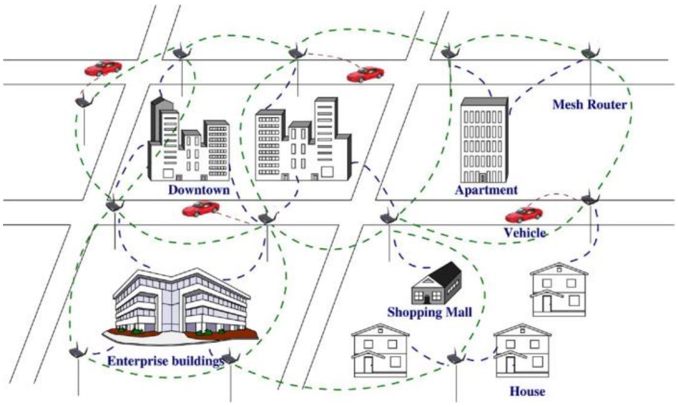


Figure 2.7 WMNs for metropolitan networking [1]

- **Intelligent transportation system:** WMNs can be used within a transportation system to provide ability to control these systems and provide real time information to the system' users as shown in Figure 2.8.

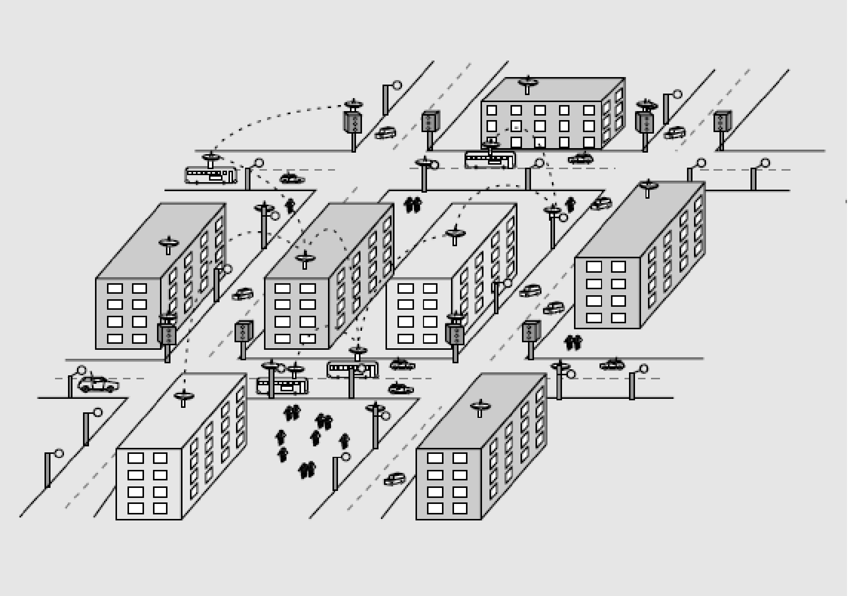


Figure 2.8 WMNs for Intelligent transportation systems [6]

- **Security surveillance:** WMNs can be deployed in a public places such as Campuses, train stations, airports..etc, to provide connectivity that feeds security information such as images and videos.

2.3 Mobile ad-hoc networks MANETs

2.3.1 MANETs overview

Mobile ad hoc networks are multi-hop communication networks consisted of mobile nodes that are totally free to move anywhere anytime. MANETs are self-configuring and organising networks where nodes communicate in peer-to-peer manner without any form of centralization as shown in Figure 2.9. Moreover, MANETs paradigms have formed the basis to other wireless networks such as wireless mesh networks WMNs, wireless sensor networks WSN, and wireless vehicular ad hoc networks VANETs [7].

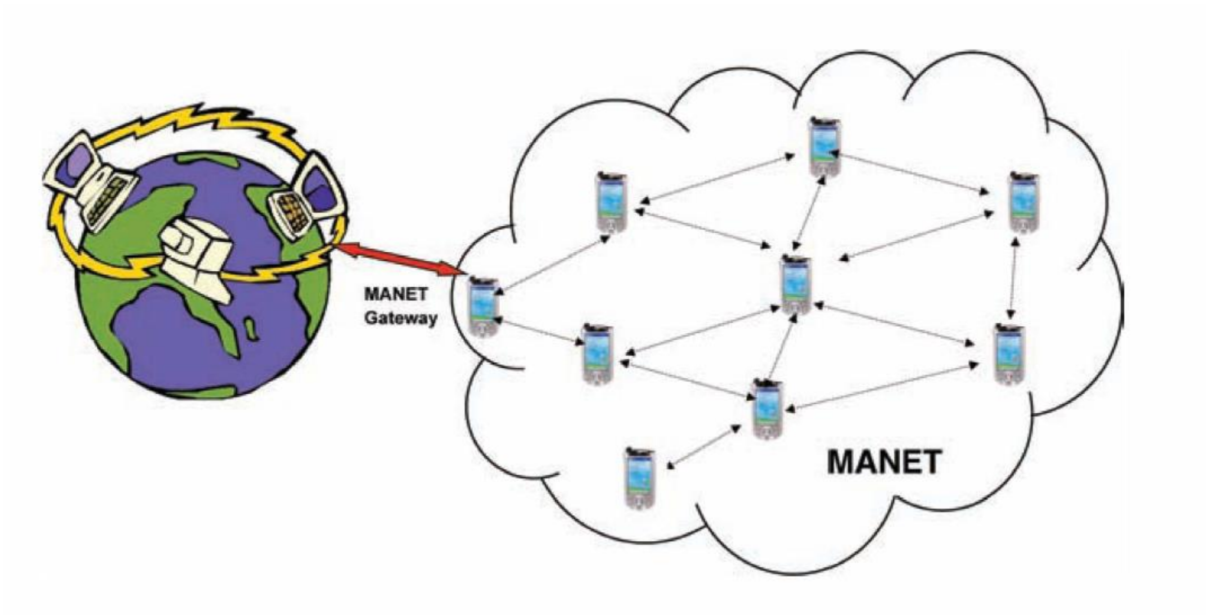


Figure 2.9 MANET topology [7]

2.3.2 MANETs features and characteristics

MANETs are infrastructure-less networks. Unlike infrastructure network, mobile nodes communicate with peers and eventually to the internet purely in multi hop decentralized fashion. The topology changes rapidly and arbitrarily. Therefore, MANETs have been cost effective solutions to connect end users to the internet, or to fast and easy network deployments [7] [8].

2.3.3 MANETs applications

Because of the aforementioned characteristics of MANETs, a range of applications of these type of networks is outlined briefly as follows [8]:

- **Military applications:** MANETs can be perfect solution to battlefields where fast and easy deployment is desired. They can provides communication among the soldiers and their headquarters. Additionally, coordination is also facilitated when these wireless infrastructure-less networks are deployed.
- **Civilian applications:** These include connecting rural areas where infrastructure does not exist, crisis and emergencies such as earthquakes, and other civilian applications outlined with WMNs such as metropolitan networking.

2.4 QoS challenges in WMNs and MANETS

In this section, the most important QoS challenges in wireless mesh networks WMNs and mobile ad hoc networks MANETs are outlined. These form the research contributions that presented in the coming chapters.

1. **Starvation in WMNs backhaul**. In infrastructure WMNs, mesh routers relay upstream traffics from lower tiers to upper tier in the backhaul then traffic is relayed to the gateways that in turn, relays it to the internet. The main issue, here, is that nodes that are close to the gateway gets greater chance of transmitting their traffic than those that further away. Thus, nodes that are few hops away from the gateway experience starvation. This issue happens mainly due to the poor performance of TCP protocol when employed in such wireless environment. [2] [9]. The solution has two folds: maintain fairness and maximizing throughput.
2. **Routing in MANETs due to high Mobility.** High mobility and unpredictable topology changes lead to frequent link breakage. Thus, routing in MANETs is a challenging task. Therefore, classical route discovery schemes when employed in MANETs should be redesigned [7].
3. **Routing in MANETs with energy constrain.** As mobile nodes are battery based, the residual energy of the node should also be taken into consideration during route selection process [3] [10].
4. **Routing in MANETs with congestion in node's buffer**. A node's buffer status is crucial factor that indicates to congestion state in that node. Thus, if such node has been selected while route is discovered then a route failure likely to occur.

2.5 Transmission Control Protocol TCP

2.5.1 Overview

TCP is one of the most dominant transport layer protocol traditionally employed in wired networks for the internet due to its high degree of reliability of data packet delivery between two ends. Data packet segments sent by a source node has to be acknowledged by returning ACKs by the receiver node. This reliability is achieved through flow control technique in TCP by using two windows: congestion window *cwnd* at the source and advertised window awnd at the receiver side. The advertised window indicates the number of data bytes beyond the acknowledged data the source can send to the destination. This information is appended to the header of each TCP (data or control) segment sent to the source, while the congestion window functionality is to keep increasing until a packet loss is detected. In this way, the conventional TCP mechanisms attempt to chock up the channel and perform well in wired networks [11].

Round trip time (RTT) is an important factor in TCP mechanisms. It represents the time from a data packet sent by the source node to reach the destination node and an acknowledgement ACK is received by the sender in return. Additionally, a timer is used for each segment sent to spot segment loss. If the timer expires before an ACK is received, this implies segment loos. The receiver returns a duplicate ACK when an out of order segment arrives. This to alert the sender that the received segment does not match with expected sequence number.

Four traditional congestion control mechanisms have been implemented of TCP to mitigate congestion and reduce packet drops commonly known as slow start, congestion avoidance, fast retransmit, and fast recovery [12].

Slow start and congestion avoidance are two algorithms used at the sender. In the initial stage of a TCP connection, the advertised window *cwnd is set to one. In slow start phase, cwnd is incremented by one* by each successful ACK received by the sender. However, this *cwnd* increase is capped by the slow start threshold *ssthreesh.* On the other hand, if *ssthreesh* is reached, then congestion avoidance phase is triggered to work on keeping the flow going and preventing congestion to occur. This is performed by incrementing *cwnd* by one for each RTT [12].

Fast retransmission and fast recovery are the other two algorithms that work together when a packet loss is identified. Upon receiving three duplicate ACK, fast retransmission is triggered and performed by sending what is expected to be lost. Then, the fast recovery phase takes over. Here, *cwnd* is reduced by half and increase it gradually until no more duplicate ACK is received [12].

Several TCP variants have been proposed base on the aforementioned congestion control mechanisms. These variants are TCP Tahoe, TCP Reno, TCP New Reno, TCP SACK and TCP Vegas [13].

2.5.2 TCP Variants

2.5.2.1 Tahoe

In the Tahoe version [13], TCP reacts to a packet loss - detected by the fast retransmission scheme or after a timeout- by setting the *ssthreesh* to half of the *cwnd* and decreasing *cwnd* to one. After receiving the ACK for the retransmitted packet the source enters the slow start phase and the transmission window can be increased exponentially with the slow start scheme while (*cwnd* <= *ssthreesh*). Afterwards, the sender enters the congestion avoidance phase and the window is increased by l/*cwnd* for each received acknowledgement. The main drawback of Tahoe is that when a packet loss is detected, the TCP behaviour becomes very slow [14].

2.5.2.2 Reno

In the Reno version [15], the fast recovery scheme is additionally used. With this scheme, the source retransmits the lost packet after receiving three duplicate ACKs and sets ssthresh to half of the current cwnd. Cwnd is then set to ssthresh plus 3 times the packet size. Each time another duplicate ACK is received, cwnd is incremented by the packet size and a packet is transmitted if allowed by the new value of cwnd. When the next ACK arrives that acknowledges new data, cwnd is set to ssthresh. If loss was detected with the timeout scheme then the same procedures used in the Tahoe version are used here as well.

2.5.2.3 New Reno

The TCP New-Reno [14] is an enhanced version of TCP Reno with fast re-transmission in a scenario with multiple data packet loss in a single window. Unlike in the fast re-transmit state in TCP-Reno, TCP New-Reno remains in the state of fast recovery until all outstanding data packets are acknowledged at a period of fast recovery. Hence, the reduction of congestion window is not required as frequently as in TCP-Reno.

2.5.2.4 TCP SACK

TCP selective acknowledgment (SACK) version [16] has been proposed to mitigate throughput degradation due to multiple segment losses within the same congestion window. TCP SACK selectively acknowledges data packets that has been received successfully. This helps the sender to resend only lost packets. TCP SACK is good option in satellite internet access [13].

2.5.2.5 TCP Vegas

TCP vegas is an enhancement version to Reno and New Reno that focus on congestion avoidance aspect. The rationality of Vegas is congestion avoidance before packet lose occurs. Thus, congestion is detected in real time based on the value of RTT [13].

2.5.3 TCP in wireless multi-hop networks

TCP is a connection-oriented transport layer protocol that provides reliable, in-order delivery of data to the TCP receiver. On the other hand, channel contention, signal fading, mobility , and limited energy are well known characteristics of wireless multi-hop networks [11]. Due to these characteristics of Wireless Multi-hop networks, traditional TCP when used in this environment, it causes a serious performance degradation. This poor performance is mainly presented in throughput drop.

The impacted throughput in wireless environment when the traditional TCP is employed is due to the misbehaviour of TCP congestion control mechanism. According to TCP, if packet loss occur, congestion control mechanism is triggered. However, packet loss in wireless networks is not necessarily to be a result of congestion as explained earlier. Rather, it could be caused by other factors related to this environment. Therefore, TCP' misinterpretation of packet loss in wireless-multi hop networks affects the throughput severely [11] [17].

Fairness is an important issue in wireless mesh networks. The throughput unfairness is a critical problem in wireless multi hop environments where the nearest nodes to the gateway get a higher chance to transmit and receive data, whereas the further nodes get less and less chance to transmit and receive. The unfairness in multi-hop networks is mainly due to two layers mechanisms interacting over a wireless multi-hop network: MAC (IEEE802.11b, for instance) and transport (TCP) layers. In [2] an adaptive delayed acknowledgement mechanism (ADAM) was proposed to overcome the unfairness issue that stated earlier. The mechanism is based on two main factors: the advertised window and delayed ACK for each flow. This mechanism utilises a mathematical model for calculating appropriate TCP delayed acknowledgement timeout with reference to the number of hops between a source and a destination node.

2.6 Routing in MANETs

Routing protocols in MANETs are classified depending on different creteria. Protcol design is the classical creteria for routing protocol. They are classified into proactive, reactive, and hybrid. Other classification include hirarchical routing, geographical position based, unicast and multicast, mobility aware, power or energy aware. A routing protocol often is listed in more than one category [18].

2.6.1 Proactive routing

In proactive routing, such as DSDV and OLSR, tables that contain information about all nodes updated regularly on a periodical basis. When a source node seeks a route to a distention, the forwarding node or the routers have immediate information about the desired route. This make this type of routing fast and desired for real time application that require QoS guarantee. However, the disadvantages of proactive routing are the necessity of maintaining updated information even if not needed, and the relatively higher level of energy consumption due to the large amount of overhead produced [18].

2.6.2 Reactive routing

Reactive routing or on demand routing, such as AODV, utilises route request and rout reply mechanisms. Hence, finding a route between a source and destination requires broadcasting messages to discover a route rather than depending on pre-built routing tables. Yet, the routing tables are built during the route discovery process. Route discovery is performed by broadcasting a route request to all neighbours nodes which in turn rebroadcast the message until a valid route to the destination is found. At this stage, a route reply is issued to the source node. Once the source node receives the route reply, then the route has been established and data start to be sent over that route. If any failure occur while data being sent, then error message is issued by the incapable node to inform the source of that the route is no longer available.

The reactive routing has proven to be effective in terms of reducing the control overhead which contribute to improve scalability and QoS. However, route discovery process can cause undesirable delay [19].

2.6.3 Hybrid routing

Hybrid routing combines the aforementioned two routing approaches to benefit from the advantages of these techniques. This routing utilises node zoning in order to reduce the overhead traffic across the network, which contributes to the overall network scalability [18] [19].

2.7 Summary

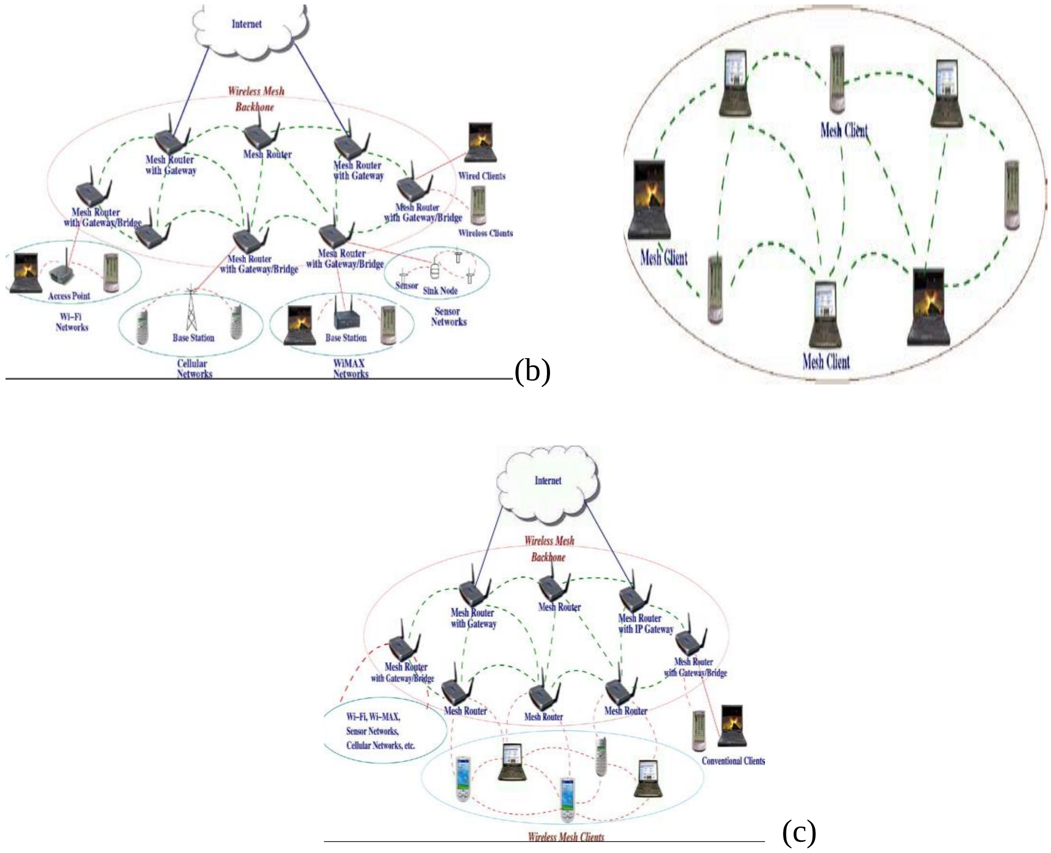
In this chapter, a taxonomy of WMNs and their toplogies of infrastucture, infrastructure-less and hyprid WMNs is presented. Then, an elaboatation on WMNs features and several applications in modern civilasation is explained. Similarly, a brief of MANETs with their applications is outlined. Then, an overview on QoS challenges in WMNs and MANETs is explained. A TCP overview and its variants is stated. Finally, an overview on routing protocols in MANETs classified into proactive, reactive and hyprid, focusing on AODV, is presented.

Chapter 3

Throughput and Fairness enhancement in Wireless Mesh Networks

3.1 Introduction

Wireless Mesh Networks have gained a huge popularity for the last few years due to their advantages of self-organizing, rapid deployment, and easy maintenance. Wireless Mesh Networks (WMNs) are multi-hop networks classified into three categories: Infrastructure-less WMNs, infrastructure WMNs, and hybrid WMNs. Infrastructure-less WMNs consist of mesh clients which can communicate only with each other directly in an ad hoc manner (Figure 3.1,a). Infrastructure WMNs where a hierarchal architecture is existed consist of a backbone of mesh routers and mesh clients, mesh clients access the wireless network through mesh routers only. Mesh routers, then, can serve as bridges to connect the wireless network to the internet (Figure 3.1, b). Finally, hybrid WMN is similar to infrastructure WMN; however, a mesh client can access the wireless networks through another mesh client (Figure 3.1, c) [1].



(b) (a)

(c)

Figure 3.1 WMNs architectures [1]

Congestion control is a key issue in Wireless Mesh Networks. The issue of congestion has been identified in all kinds of computer networks as a result of heavy traffic load in networks where a lack of resources and unmanaged traffic conditions are existed. Hence, congestion control purpose is to prevent or reduce any overloading or congestion may occur all over the network nodes and links. Provided that WMNs are multi-hop networks using radio channels as a medium to perform the communications among nodes, this makes the task of congestion control is more sophisticated [20].

Congestion control has been studied with combination with TCP (Transmission Control Protocol) in wired networks. TCP is the transport layer protocol whose main characteristic is transmission reliability. This characteristic is interpreted in TCP through retransmission if any packet lose happens. The case of packet lose or drop means, according to TCP, that congestion has happened. This is true in wired networks. However, it is not true in the multiple hop wireless networks such as MANETs or WMNs. Thus, a vast amount of research has been conducted in attempt to enhance the performance of TCP over multi-hope wireless networks [21], [22], [23], [24].

Fairness is an important issue in wireless mesh networks. The throughput unfairness is a critical problem in wireless multi hop environments where the nearest nodes to the gateway get a higher chance to transmit and receive data, whereas the further nodes get less and less chance to transmit and receive. The unfairness in WMNs is mainly due to two layers mechanisms interacting over a wireless multi-hop network: MAC (IEEE802.11b, for instance) and transport (TCP) layers. Moreover, the contention on the wireless medium among different flows leads to a serious unfairness where the nearest to the gateway get more bandwidth while other flows which are a few hops away may starve [25], [9], [26]. Thus, solutions have been proposed in the literature to address the unfairness issue. Those proposals can be classified according to their functionalities as: Mac layer [9], network layer [27], transport layer [28], or cross layer techniques [26], [29]. In addition, some of which is distributed while others are centralized.

In this chapter, a novel end-to-end transport-layer technique is proposed that not only assures fairness in WMNs, but also improves the throughput for all the active flows that transmit simultaneously to the gateway, which is in turn connected to the internet.

3.2 Current research

Fairness index is a vital metric used in the research to quantify the fairness in the networks. It is a scalar measure of fairness and discrimination for resource allocation to analyse fairness performance. The fairness index is defined as:

$$\text{Fairness Index} = \frac{\left(\sum_{i=1}^{N} \eta i\right)^2}{N \sum_{i=1}^{N} \eta i^2} \qquad (3.1)$$

where, ηi is the throughput of flow i

N is the number of flows. If all of throughput ηi are equivalent, the fairness index reaches the maximum value of one.

Serious TCP performance degradation and unfairness issue in wireless mesh networks has been tackled from different perspectives. One of these perspectives is queue management. RED (Randomly Early Detection) [30] is a congestion avoidance mechanism proposed in wired networks that works at the network layer scheme. It works on calculating the average queue size at the gateway in order to detect potential congestion and then comparing it to predetermined thresholds; min and max. NRED is an extension to RED but in a distributed manner [27]. NRED monitors the node neighbour's queue size by implementing a distributed drop probability across the node neighbours keeping the queue size under control. The scheme seems to solve the unfairness problem partially. However, complex calculations are required in order to calculate the drop probability, and unreliability exists when packets drop is simply allowed when a threshold is exceeded. In [31] another queue level proposal has been proposed called EQMMN (Enhanced Queue Management for Multi-hop Networks) as an enhancement to an existing queuing mechanism QMMN. The main point of the proposed technique is the differentiation between active TCP and UDP flows. Specific evaluation scenario shows a little improvement to fairness index. However, the fairness index is not satisfactory. Moreover, the rationality of such mechanisms is to assure fairness by dropping some packets from the buffer of the nearest flow to the gateway in order to give chance to further flows to get chance of occupying space in that buffer. On the other hand, this is not acceptable from reliability's point of view.

Flow rate control and load balancing are other perspectives to deal with unfairness in wireless mesh networks. ARC (Aggregate Rate Control) and PFRC (Per Flow Rate Control) are two centralized mechanisms proposed in [32] implemented at the gateway-side. The former is to assure fair rate allocation for all flows at the gateway, while the later does the same as ARC but with weighted fairness support. Their achievement is quiet good in terms of fairness. However, complex implementation needs to be applied to the gateway. GWLB (Gateway Load Balancing) is another centralized scheme that attempts to solve the fairness problem by balancing the TCP traffic across multi gateways [28]. The fairness index achieved is still quite low, and the existence of multi gateway constrains the efficiency of the scheme.

Cross-layer solutions have been proposed in literature. Ye et al. [26] proposed a TCP-MAC cross-layer solution. Their technique, CCLE (Counter Cross-Layer ECN), is based on CLE (Cross-Layer ECN). Whereas CLE is a scheme that makes use of RTS count as a metric to trigger TCP congestion control mechanism, CCLE comes with the idea of prioritizing the TCP flows according to their distance from the gateway. In other words, at the gateway, a priority method is implemented in order to calculate the probability of each flow that in turn sets the ECN (Explicit Congestion Notification) bit in that TCP flow. Their results show fairness improvement comparing with other work. However, the complexity and the modification to the MAC protocol stack make it difficult to deploy. Another cross-layer proposal for multi path routing in WMNs called PDR (Path Diversity Retransmission) presented in [33]. The key idea is to separate the original packets from the retransmitted packets into two different paths. PDR requires adding a classifier between TCP and IP layers to differentiate between the two packet types. Fairness and throughput have been enhanced comparing with original multi path and single path routing. However, fairness index does not reach 0.7 in the best cases, and packet loss rate has not taken into consideration.

Adjustment to MAC layer minimum contention window (CW_{min}) is another approach to solve the fairness problem in wireless multi-hop networks. Ling et al [34] used a probability model to analyse the relation between TCP and MAC layer parameters in order to solve the TCP flow unfairness, then a scheme called F-MAC was proposed. The later scheme is based on increasing CW_{min} of the nearest flow to gateway when a certain condition assures. Similarly, increasing CW_{min} of the closest node to the gateway to a value that greater than its neighbours is a suggested solution to overcome starvation in WMNs [25]. This kind of solution is valid only in certain cases; it requires, also, a change to the MAC layer protocol.

Fairness has been investigated through another important approach which is scheduling. Since scheduling plays an important role in WMNs, some research has focused on that topic and linked it to fairness. A classification of fair scheduling by the degree of fairness, scheduling control, and metrics and mechanisms used in scheduling has been shown in [35]. Then, a centralized round robin scheduling scheme that assumes multi gateways in the networks has been proposed. The scheme is an enhancement to a pure scheduling technique where a requirement table has been proposed. This table is maintained by each mesh router then it is used later at the gateways to produce the scheduling. The enhanced scheme proposed is quite useful in the case of multi gateways only. However, this is not always the available case.

Moreover, keeping the requirement table updated brings unnecessary overheads to the network. Another round robin scheduling scheme to improve per-flow fairness at the MAC layer has been proposed in [9]. The scheme allocates a separate buffer for each flow then packets are sent alternatively from those buffers. The delay after back off algorithm, originally in DCF, has been eliminated in order to achieve a better bandwidth utilisation. However, this scheme requires a modification to the MAC (DCF) protocol. Another technique called Probabilistic Control on Round robin Queue (PCRQ) proposed in [36]. PCRQ is a scheduling scheme that proposes three algorithms in the link layer level to control the packets in three steps: input, in and output queues. The technique shows improvement in fairness index comparing with FIFO scheduling, RR and Shagdar's method [9]. However, no clear throughput improvement has been made. Nor, its deployment is limited because of the modification it requires to the link layer.

3.3 The proposed work

3.3.1 Problem statement

In IEEE 802.11 mesh networks, nodes that are close to the gateway get better opportunities to send and receive data while nodes that are few hops away from the gateway may starve. This is the unfairness problem. To elaborate on this issue let us take a simple chain network topology with three source nodes and a gateway for the purpose of the study.

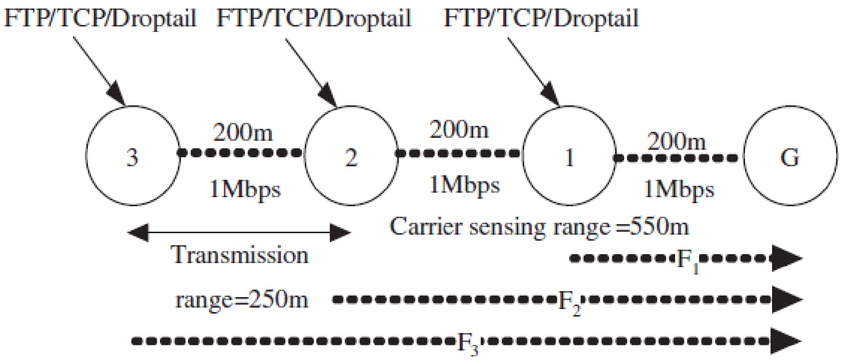


Figure 3.2 A chain network topology with three source nodes [2]

In Figure 3.2, there are three source nodes (1, 2, and 3) and a gateway (G), the distance between any two nodes on the chain including G is 200 m, bandwidth is 1 Mbps, transmission range is 250 m, carrier sensing range is 550 m. Nodes 1, 2 and 3 generate flows F1, F2 and

F3 respectively and simultaneously to the gateway. Flow1' throughput that runs from node 1 to G is the highest while Flow3' throughput degrades severely as shown in Figure 3.3.

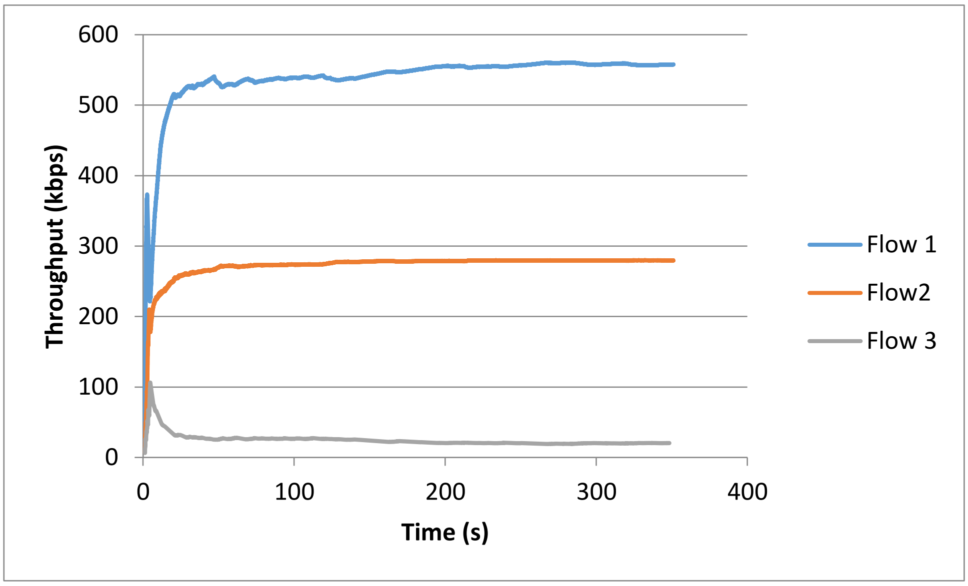


Figure 3.3 TCP Flows throughput with standard 802.11

3.3.2 Adaptive Delayed ACK Mechanism

In [2] an adaptive delayed acknowledgement mechanism was proposed to overcome the unfairness issue that stated earlier. The mechanism is based on two main factors: the advertised window and delayed ACK for each flow. As the throughput in TCP flow control can be given as follows:

$$\text{Throughput} = \frac{\min(cwnd\ ,awnd)}{\text{RTT}} \qquad (3.2)$$

where *cwnd* and *awnd* are the congestion and advertised window respectively. RTT is the Round Trip Time and it denotes the duration from the time of a TCP data segment leaves the sender until an ACK segment is received by that sender.

From (3.1) since *cwnd* is adjusted automatically by congestion control algorithm, we can see that throughput is mainly influenced by two parameters: *awnd* and RTT.

To achieve fair throughput, ADAM was proposed with the delayed ACK factor of 2. This means that the TCP receiver returns an ACK segment upon receiving two data segments if the delayed ACK times has not expired, or it returns an ACK segment upon receiving only one data segment and the delayed ACK timer expires. As RTT value is determined by the time when the ACK is returned to the sender. As a result, throughput is determined by RTT as we can see from equation (3.2). Therefore, RTT is determined by ACKs either upon receiving two data segments or upon the timer expiry. As for the first case, RTT and ACKs will not be stable because data segments are received in unpredictable way due to issues like interference, congestion window, etc. In the second case, relying on the timer expiry can provide more accuracy. In other words, delayed ACK is generated only upon the timer expiry. So, by choosing proper values for the delayed ACK time-out for each flow, perfect fairness can be achieved. Hence, in Adaptive Delayed ACK Mechanism (ADAM), the receiver returns an ACK segment only upon the delayed timer expiry. Thus, only one data segment can be sent in each round trip time. This means that *awnd* is chosen as one segment, which means that throughput is controlled by the value of the delayed ACK time-out.

In order to understand how ADAM choses the RTTs values (or the delayed ACK time-out) for achieving perfect throughput fairness (1:1:1) among the three flows let us consider a chain topology consists of three flows F1, F2 and F3 transmit simultaneously to a gateway (G) as shown in Figure 3.4. T_F denotes to the time of sending a data segment from a node to the next node. T_{ACK} denotes to the time of returning an ACK from one node to the next one. RTT_1 then can be:

$$RTT1 = Tf + Tack \qquad (3.3)$$

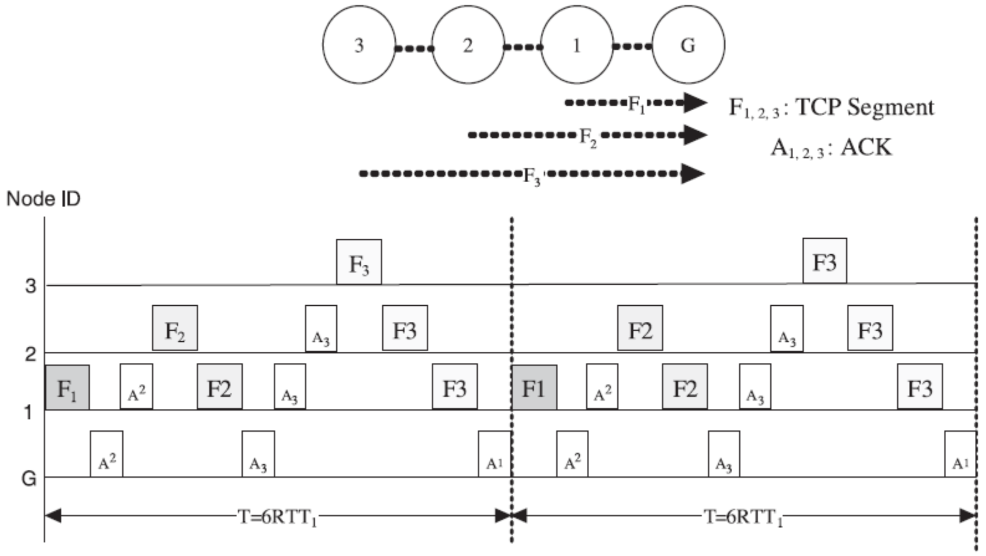


Figure 3.4 TCP Flows fair scheduling with ADAM [19]

The ideal fair scheduling can be achieved in this scenario is when node1 transmits the F1 data segment to G in T_F then waits. Node2 then transmits F2 data segment to N1 in T_F, then N1 relays that segment to G in another T_F. Node3 then transmits F3 data segment to node2 in T_F, node2 relays that data segment to node1 in T_F, and node1 relays it to G in another T_F. At this stage, G will return an ACK for F1 to node1 in T_{ACK}, which will enable node1 to send the next F1 data segment. Here, the gateway (G) will return F2 ACK that after two T_{ACK} will trigger node2 to send the next F2 data segment. Similarly, G will release an ACK for F3 which after three T_{ACK} will trigger node3 to send the next F3 data segment. So, the cycle (T) consists of six times of RTT_1. Furthermore, as can be seen from above, for F1 to transmit the next data segment after successfully sending the first one, it will have to be differed for five times RTT_1. And for F2 to transmit the next data segment after successfully sending the first one, it will have to be differed it for four times RTT_1. Similarly, F3 has to be differed 3 times RTT_1 before it sends the next data segment to the gateway.

ADAM scheduling can achieve perfect throughput fairness where the transmission of a flow's segment is differed by the delayed ACK mechanism for a designated period of N times of RTT1. (Where is N = 5, 4, 3 for F1, F2 and F3 respectively).

In order to formulate the throughput when ADAM is applied we need to consider a chain network consisted of N+1 nodes (N nodes + G). The nodes are denoted by i ; i = 1, 2, 3, …., N. together with N flows (F_i ; where is i=1, 2, 3,…, N) that transmit from nodes to gateway (G) represented in Figure 3.5. In this figure, d is the distance between nodes. R is the transmission range. Let assume D_i is the distance between node i and G. then

$$\mathrm{D}i = i * d \qquad (3.4)$$

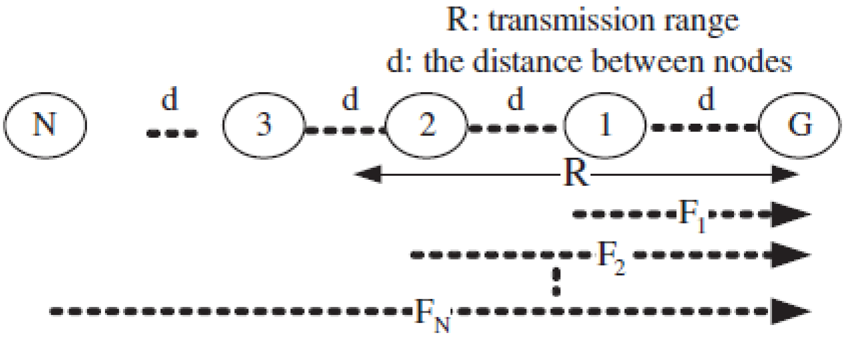


Figure 3.5 A chain network of N+ 1 node and N flows [2]

Also, let H_i denotes the number of hop counts that are necessary for node i to send data to the gateway. H_i will be given as follows:

$$\mathrm{H}i = \left[\frac{\mathrm{D}i}{\left[\frac{\mathrm{R}}{\mathrm{d}}\right] * \mathrm{d}} \right] \qquad (3.5)$$

By substituting Eq (3.4) in Eq (3.5):

$$\mathrm{H}i = [\ \frac{i*d}{\mathrm{R}}\ ] \qquad (3.6)$$

H_s is the sum of hop counts of all nodes which is given as:

$$Hs = \sum_{i=1}^{N} Hi \qquad (3.7)$$

RTT_i is the round trip time for node *i* to send a data segment to G and receive an ACK segment from G without delayed ACK.

$$\mathrm{RTT}i = Hi * RTT1 \qquad (3.8)$$

In the case of only one node in the network that sends continuously to G then maximum achievable throughput denoted by $\boldsymbol{\eta}_{\max}$ is given:

$$\eta\mathrm{max} = \frac{1*\mathrm{segment\ size}}{\mathrm{RTT1}} \qquad (3.9)$$

When perfect throughput fairness is desirable (1:1:1) then the cycle T is given as:

$$T = \sum_{i=1}^{N} RTTi = Hs * RTT1 \qquad (3.10)$$

Let $\boldsymbol{\eta}_{\mathrm{fair}}$ be the fair throughput for every node, then

$$\eta\mathrm{fair} = \frac{1*\mathrm{segment\ size}}{\mathrm{T}} = \frac{\eta\mathrm{max}}{Hs} \qquad (3.11)$$

$\boldsymbol{\eta}_{\mathrm{fair}}$ is achieved when the delayed ACK time-out value is carefully chosen, as mentioned earlier. This value is given as:

$$DATj = T - RTTj \qquad (3.12)$$

where DAT_j is the delayed ACK time-out value applied to node j.

Figure 3.6 shows the performance of ADAM technique in comparison to the standard 802.11 in the scenario of four nodes chain topology. In this figure, F1, F2 and F3 represent the 802.11 flows' throughput, whereas ADAM_F1, ADAM_F2 and ADAM_F3 represent the three flows' throughput using ADAM.

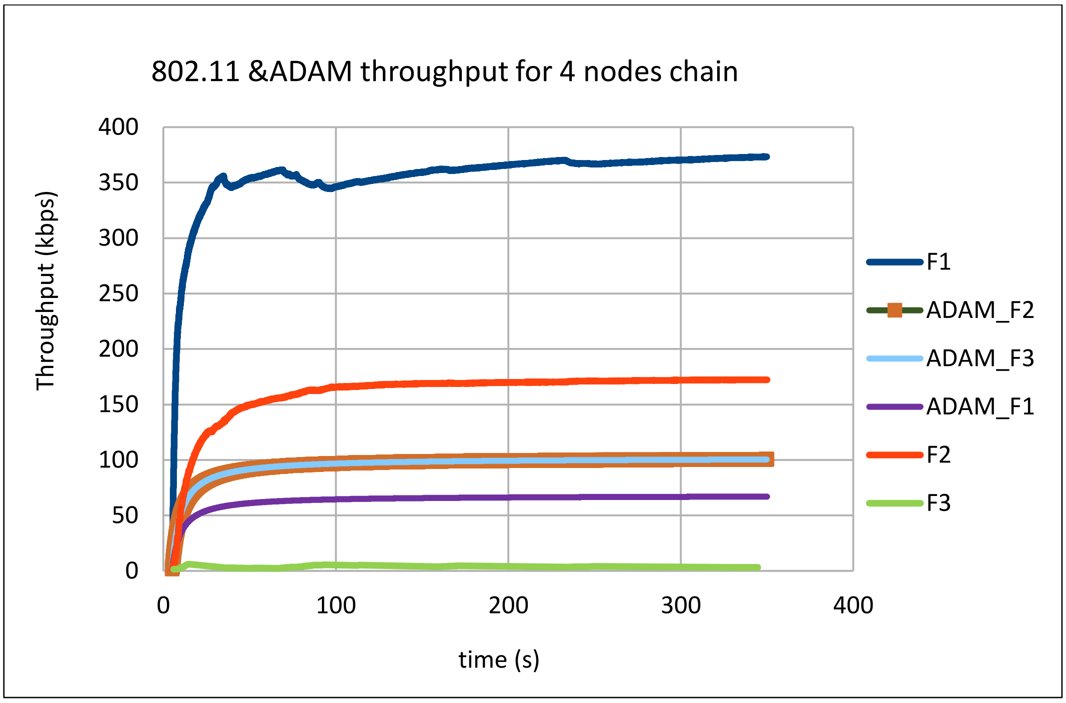


Figure 3.6 TCP Flows throughput with standard 802.11 & ADAM

3.3.3 Enhanced Adaptive Delayed Acknowledgement Mechanism (EADAM)

In this section the proposed work called Enhanced Adaptive Acknowledgement Mechanism (EADAM) is presented. EADAM uses ADAM to propose a new mechanism that not only assures fairness in WMNs, but also enhances the throughput of all active flows that transmit to the gateway. This mechanism utilises the delayed ACK technique with factor of 2 and an advertised window *awnd* set to one. This value of *awnd* enforces the sender not to send more than one data segment in each RTT, which means that the receiver returns an ACK for each data segment only when the delayed ACK timer expires. Thus, the timer expiry value is crucial in this mechanism.

The main idea in Enhanced Adaptive Delayed Acknowledgement Mechanism (EADAM) is to reduce the cycle T by allowing some kind of transmission parallelism among the individual flows. This has been illustrated in Figure 3.7. The scheduling diagrams In Figure 3.7 represent the network scenario of Figure 3.4; a chain topology of three nodes and a gateway. F1, F2 and F3 are three flows transmitting from node1, node2 and node3 respectively. The way how ADAM works has been shown in Figure 3.7(a). The possibility of reducing the cycle T is then shown in Figure 3.7(b), (c) and (d). Here, the time schedule of EADAM (Figure 3.7 (d)) is shown as the final step of gradually minimizing the cycle T from the starting point which is ADAM (Figure 3.7(a)).

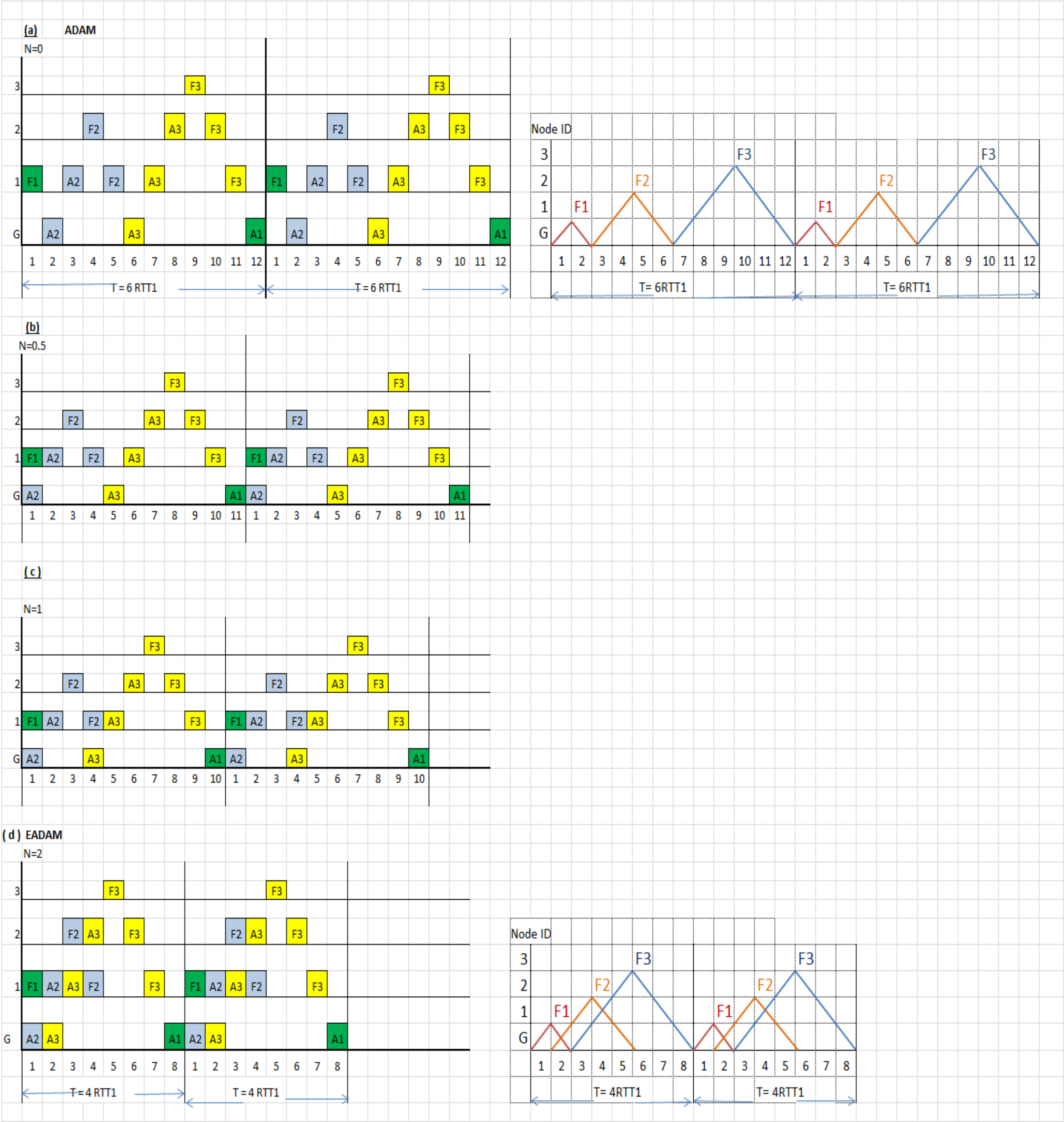


Figure 3.7 TCP Flows fair scheduling with ADAM & EADAM

In EADAM for three flows illustrated in (Fig 3.7 (d)), when node1 transmits the F1 data segment to G in T_F, node1 relays A2 (F2 ACK) for the previous F2 segment in T_{ACK} to G simultaneously. Then, node2 transmits F2 data segment to N1 in T_F, and at the same time node2 relays A3 (F3 ACK) for the previous F3 segment in T_{ACK} to node1. As a result, the cycle is reduced from 6 RTT1 to 4 RTT1. Furthermore, as can be seen from above, for F1 to transmit the next data segment after successfully sending the first one, it will have to be differed for **three** times RTT_1. In addition, for F2 to transmit the next data segment after successfully sending the first one, it will have to be differed for **two** times RTT_1. Similarly, F3 has to be differed **one** RTT_1 before it sends the next data segment to the gateway.

By manipulating equation (3.12) to Adam and EADAM, the following values for delayed ACK time-out value applied to nodes 1, 2 & 3 respectively can be obtained:

Table 3.1 Delayed ACK time-out values for three flows in ADAM & EADAM

	ADAM	**EADAM**
D1	5 RTT1	3 RTT1
D2	4 RTT1	2 RTT1
D3	3 RTT1	1 RTT1

To generalize for the case of more than three flows, the TCP Flows fair scheduling diagram with EADAM in Fig 3.7 (d) on the right side has been developed to the general enhanced ADAM timing diagram that represents a variety of number of flows from 1 to 11 flows (Figure 3.8). In this figure, each coloured triangle represents a flow. The cycle for each scenario can be read on the horizontal axes. For example, for three flows it is 4 (8 divided by 2), and for 5 flows the cycle is 9. The following tables summarize the values of T in ADAM and EADAM for the considered number of flows presented in Figure 3.8.

Table 3.2 comparison between the cycle (T) value in ADAM and EADAM for odd number of flows

No of flows	T with ADAM (RTT1)	T with EADAM (RTT1)
3	6	4
5	15	9

7	28	16
9	45	25
11	66	36

Table 3.3 comparison between the cycle (T) value in ADAM and EADAM for even number of flows

No of flows	T with ADAM (RTT1)	T with EADAM (RTT1)
2	3	2.5
4	10	6.5
6	21	12.5
8	36	20.5
10	55	30.5

The calculation of the delayed ACK time-out value for different number of flows in the proposed technique is produced using the following two equations:

$$\boldsymbol{Di(n)} = \left(1 + \frac{\boldsymbol{(n+1)(n+1)-4}}{\boldsymbol{4}} - i\right) \mathbf{x}\ \mathrm{RTT1} \qquad \mathrm{n} = 1,\ 3,\ 5,\ 7,\ \boldsymbol{\ldots.} \qquad (3.13)$$

$$\boldsymbol{Di(n)} = \left(1 + \frac{\boldsymbol{(n+1)(n+1)-3}}{\boldsymbol{4}} - i\right) \boldsymbol{x}\ \mathrm{RTT1} \qquad \mathrm{n} = 2,\ 4,\ 6,\ 8,\ \ldots. \qquad (3.14)$$

n denotes to the total number of flows, *i* is the considered node

Equation (3.13) is for odd number of flows, whereas equation (3.14) is for even number of flows.

By using equation (3.13) for odd total number of flows, the following table can be obtained:

Table 3.4 values of Di(n) for a variety of odd total number of flows in EADAM

	3 flows	**5 flows**	**7 flows**	**9 flows**	**11 flows**
D1	3 RTT1	8 RTT1	15 RTT1	24 RTT1	35 RTT1
D2	2 RTT1	7 RTT1	14 RTT1	23 RTT1	34 RTT1
D3	1 RTT1	6 RTT1	13 RTT1	22 RTT1	33 RTT1
D4		5 RTT1	12 RTT1	21 RTT1	32 RTT1
D5		4 RTT1	11 RTT1	20 RTT1	31 RTT1
D6			10 RTT1	19 RTT1	30 RTT1
D7			9 RTT1	18 RTT1	29 RTT1
D8				17 RTT1	28 RTT1
D9				16 RTT1	27 RTT1
D10					26 RTT1
D11					25 RTT1

Similarly, by using equation (3.14) for even total number of flows, Table 3.5 can be obtained:

Table 3.5 values of Di(n) for a variety of even total number of flows in EADAM

	2 flows	**4 flows**	**6 flows**	**8 flows**	**10 flows**
D1	1.5 RTT1	5.5 RTT1	11.5 RTT1	19.5 RTT1	29.5 RTT1
D2	0.5 RTT1	4.5 RTT1	10.5 RTT1	18.5 RTT1	28.5 RTT1
D3		3.5 RTT1	9.5 RTT1	17.5 RTT1	27.5 RTT1

D4		2.5 RTT1	8.5 RTT1	16.5 RTT1	26.5 RTT1
D5		1.5 RTT1	7.5 RTT1	15.5 RTT1	25.5 RTT1
D6			6.5 RTT1	14.5 RTT1	24.5 RTT1
D7			5.5 RTT1	13.5 RTT1	23.5 RTT1
D8				12.5 RTT1	22.5 RTT1
D9				11.5 RTT1	21.5 RTT1
D10					20.5 RTT1

In the next section, by testing this technique, the proposed mechanism is shown as promising technique to improve the throughput.

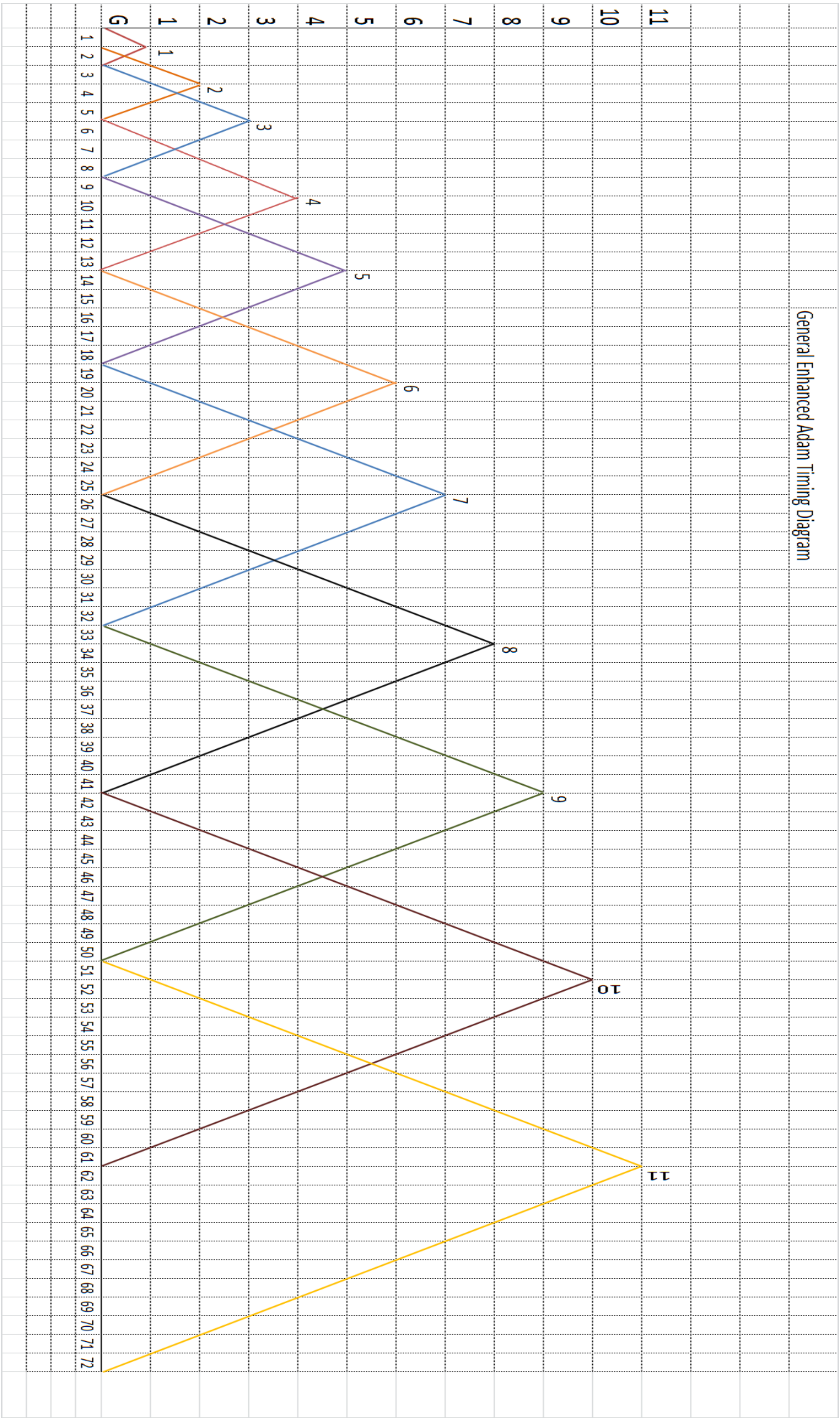


Figure 3.8 The general EADAM timing diagram for a variety of number of flows from 1 to 11 flows

3.3.4 Numerical results and analysis from the proposed work

The proposed mechanism is implemented in NS2 platform for comparing EADAM with ADAM.

3.3.4.1 Three flows only scenario

The scenario in Fig 3.2 is implemented in NS2. This scenario represents a four nodes chain topology; node1, node2 and node3 that transmit continuously to the gateway (G). F1, F2 and F3 are the three active flows from the three nodes to the gateway. The distance between adjacent nodes is 200 m. The transmission range is 250 m, and the carrier sensing range is 550 m. Each link has a bandwidth of 1 Mbps. The application is FTP and the TCP is Reno. The simulation time is 350 s run five times with five different seeds. Table 3.6 shows the simulation parameters for this scenario.

Table 3.6 NS2 three flows simulation parameters

Environment parameter	**Value**
Channel type	Wireless channel
Radio propagation model	Two Ray Ground
MAC type	802.11
Transmission range	250 m
Carrier sensing range	550 m
Interface queue type	Drop Tail/ PriQueue
Max packet in ifq	100
Application	FTP
Agent type at source node	TCP/Reno
Agent type at destination node	TCPSink/DelAck
AWND	1

Four different packet sizes have been tested: 128 B, 256 B, 512 B and 1024 B. Aggregated throughput have been collected from the above scenario. Throughput and Fairness index obtained from EADAM and ADAM for the four packet sizes are shown in Figure 9 and Figure 3.10 respectively.

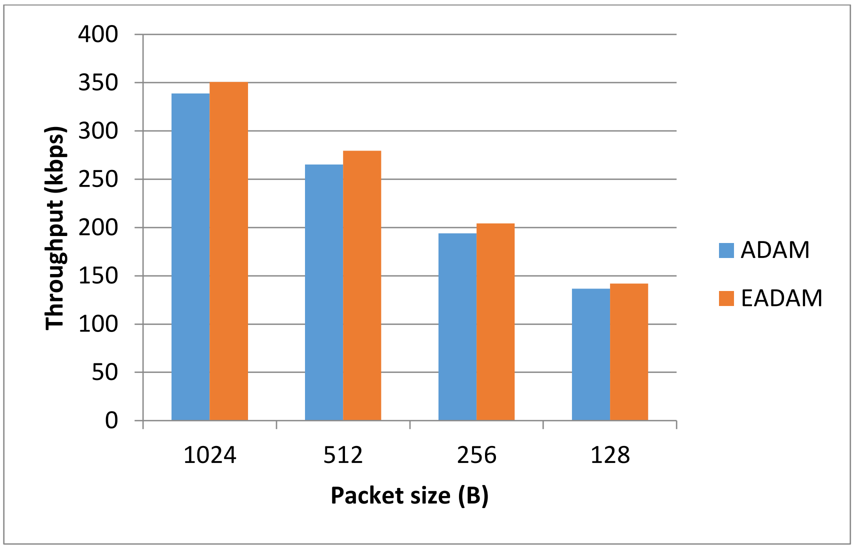


Figure 3.9 Throughput comparison between EADAM & ADAM

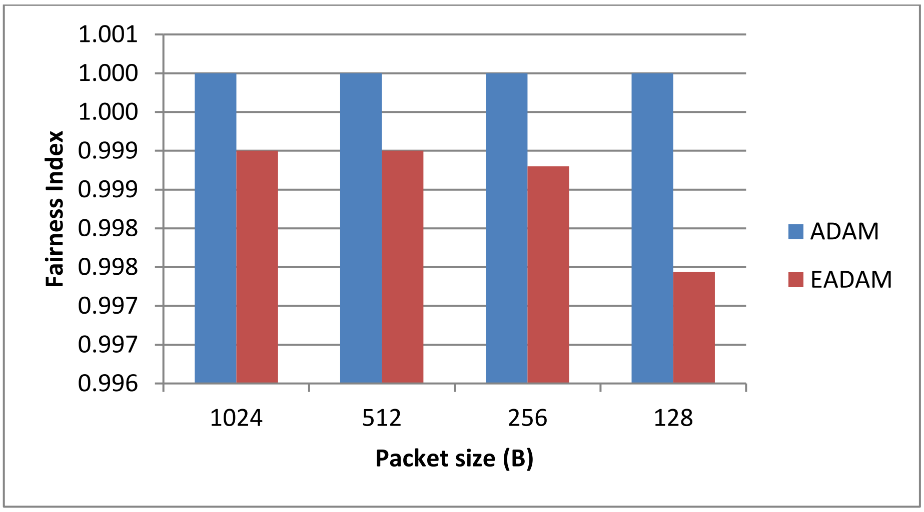


Figure 3.10 Fairness Index comparison between EADAM & ADAM

From these two figures, it is clear that the throughput in EADAM has improved from ADAM while the fairness index has been maintained above 0.997.

To evaluate the performance enhancement of the proposed technique (EADAM) with the ADAM in terms of throughput and Fairness, the Throughput and Fairness Index Enhancement Ratios have been calculated using the following two equations:

$$Throughput\ Enhancement\ Ratio = \frac{\text{throughput (EADAM)} - throughput(ADAM)}{throughput(ADAM} * 100\% \qquad (3.15)$$

$$Fairness\ Enhancement\ Ratio = \frac{\text{fairness index (EADAM)} - fairness\ index(ADAM)}{fairness\ index(ADAM} * 100\% \qquad (3.16)$$

The Throughput and Fairness Index Enhancement Ratio for 3 flows with four different packet sizes (1024, 512, 256, 128) B is shown in Figure 3.11.

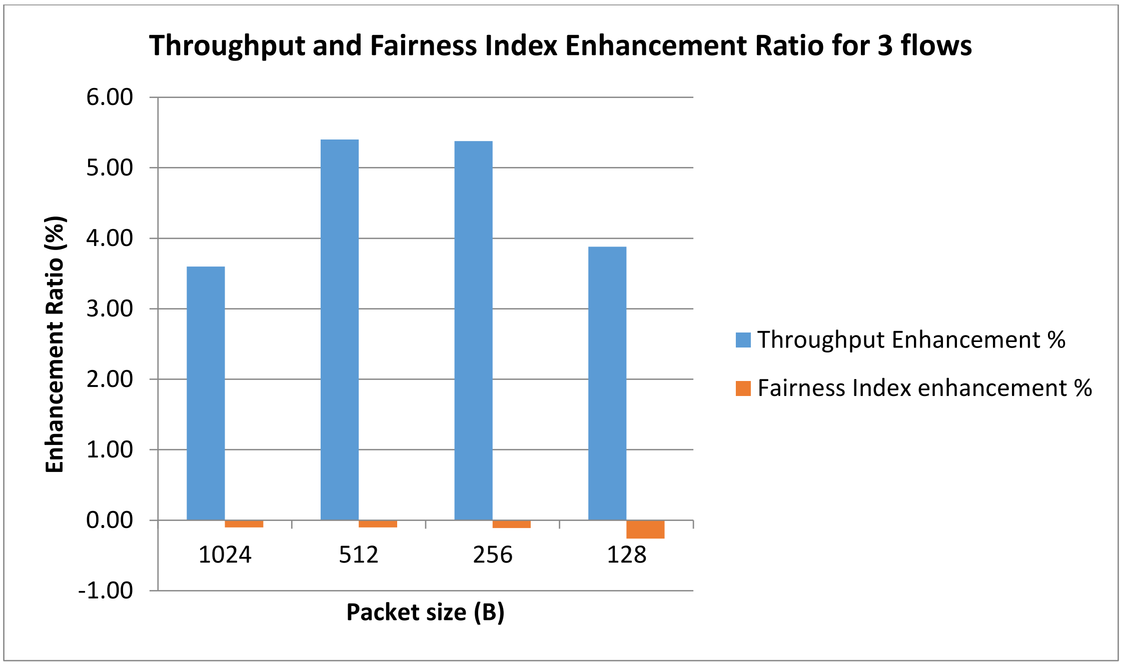


Figure 3.11 Throughput and Fairness Index Enhancement Ratio for 3 flows with four different packet sizes

3.3.4.2 Over three flows scenarios

3.3.4.2.1 Packet size = 128 B

Extending the above scenario to include: 4, 5, 6, 7, 8, 9 flows, the throughput and Fairness index obtained from EADAM and ADAM for packet size = 128 B are shown in Figure 3.12 and Figure 3.13 respectively.

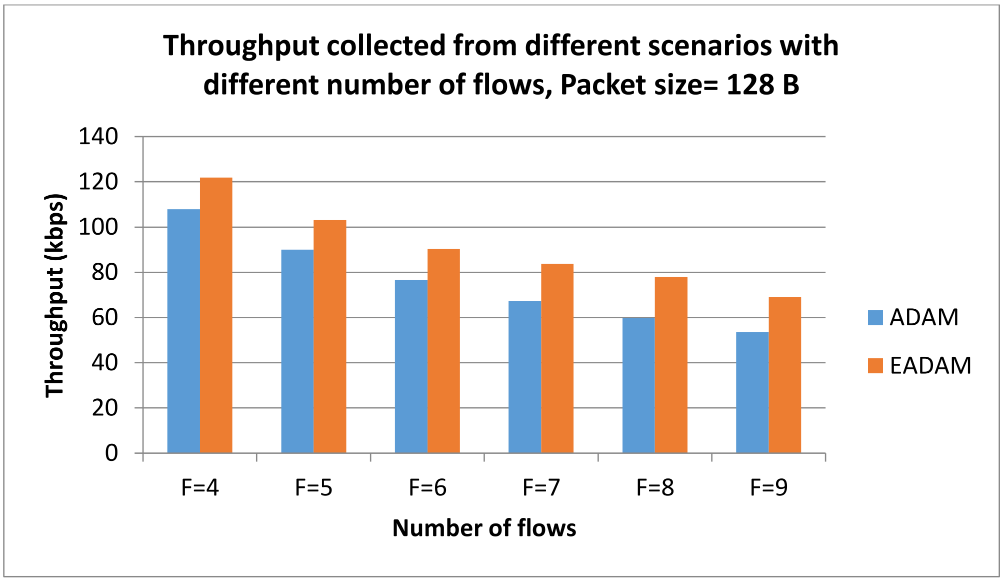


Figure 3.12 Throughput collected from different scenarios with different number of flows _Packet size= 128 B

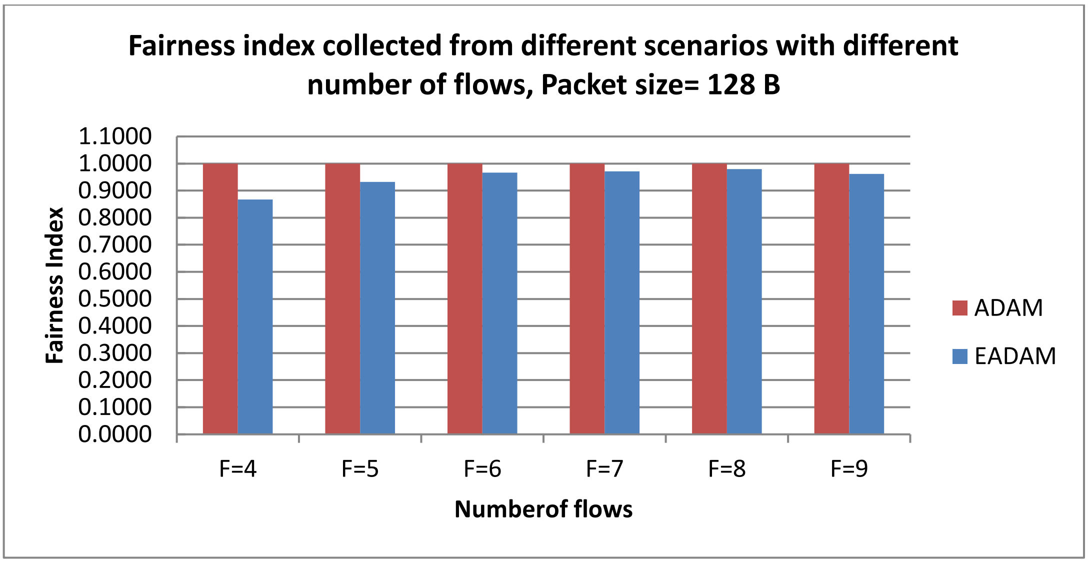


Figure 3.13 Fairness Index collected from different scenarios with different number of flows _Packet size= 128 B

In these scenarios as Figure 3.12 and Figure 3.13 show, it is clear that the throughput in EADAM has improved from ADAM while the fairness index has been maintained.

The Throughput and Fairness Index Enhancement Ratio for different number of flows scenarios with packet size = 128 B has been calculated using equations (3.15) & (3.16) and shown in Figure 3.14.

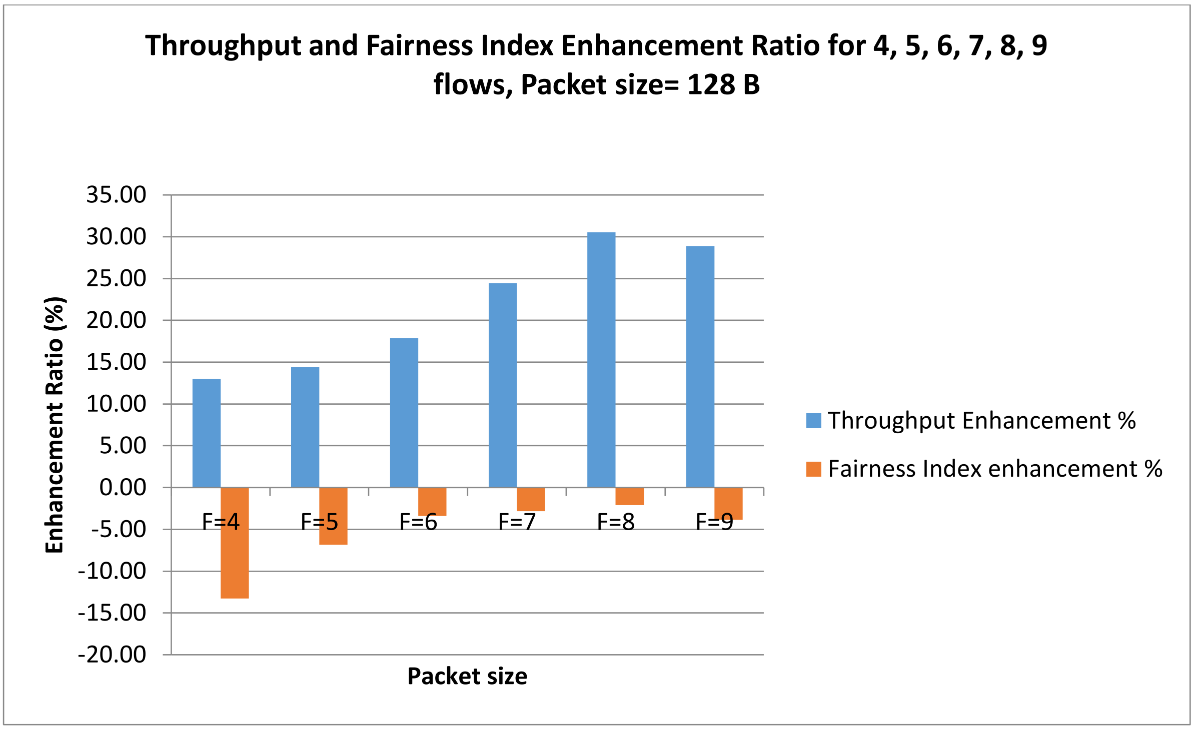


Figure 3.14 Throughput and Fairness Index Enhancement % for 3 flows with packet size= 128 B

3.3.4.2.2 Packet size = 256 B

The proposed (EADAM) and ADAM techniques with 256 B packet size have been tested with the previous different number of flows scenarios. The throughput and Fairness index obtained from EADAM and ADAM for packet size = 256 B are shown in Figure 3.15 and Figure 3.16 respectively. Figure 3.17 shows the Throughput and Fairness Index Enhancement Ratio for different number of flows with packet size= 256 B.

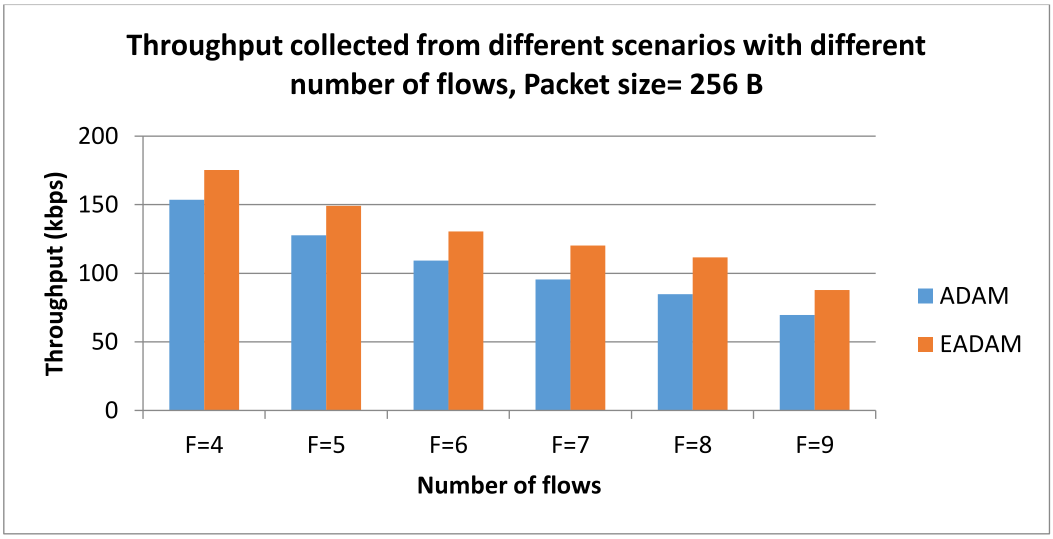


Figure 3.15 Throughput collected from different scenarios with different number of flows _Packet size= 256 B

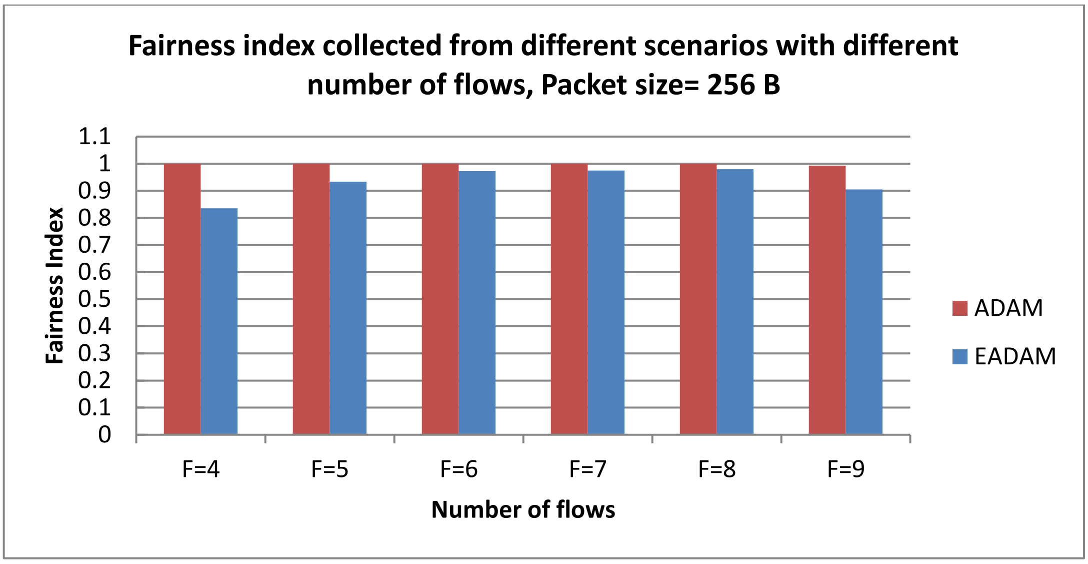


Figure 3.16 Fairness Index collected from different scenarios with different number of flows _Packet size= 256 B

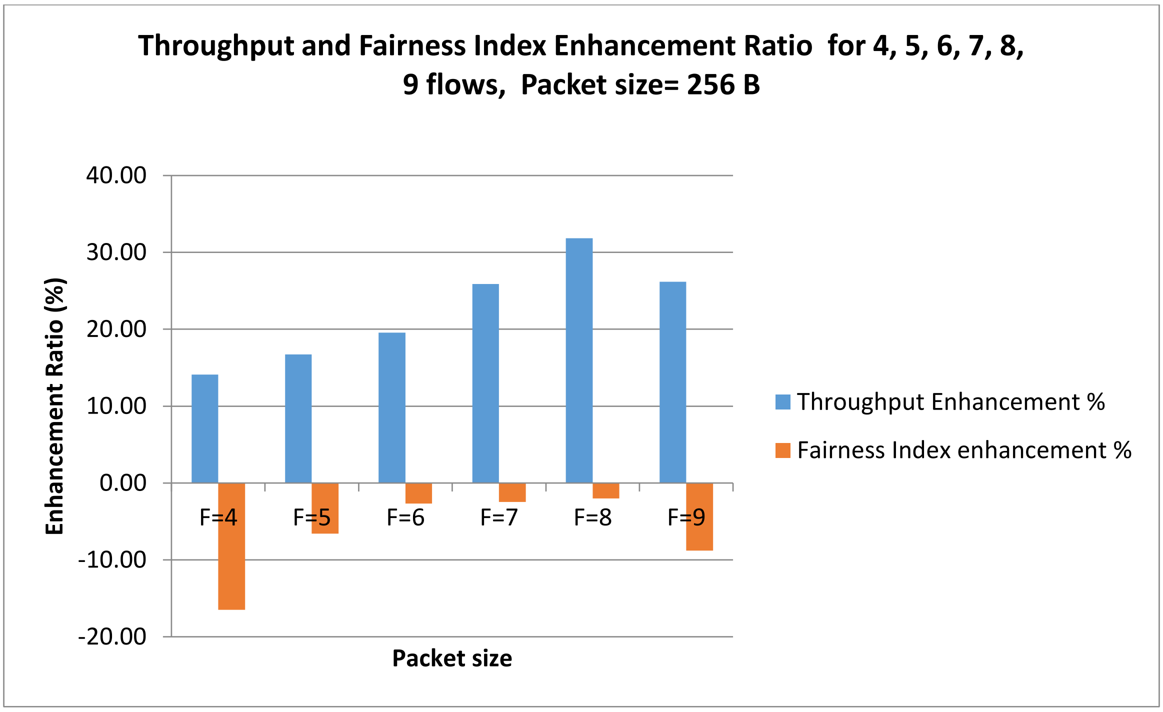


Figure 3.17 Throughput and Fairness Index Enhancement Ratio for 3 flows with packet size= 256 B

3.3.4.2.3 Packet size = 512 B

EADAM and ADAM techniques again have been tested with the previous different number of flows scenarios with 512 B packet size. The throughput and Fairness index obtained from EADAM and ADAM for packet size = 512 B are shown in Figure 3.18 and Figure 3.19 respectively.

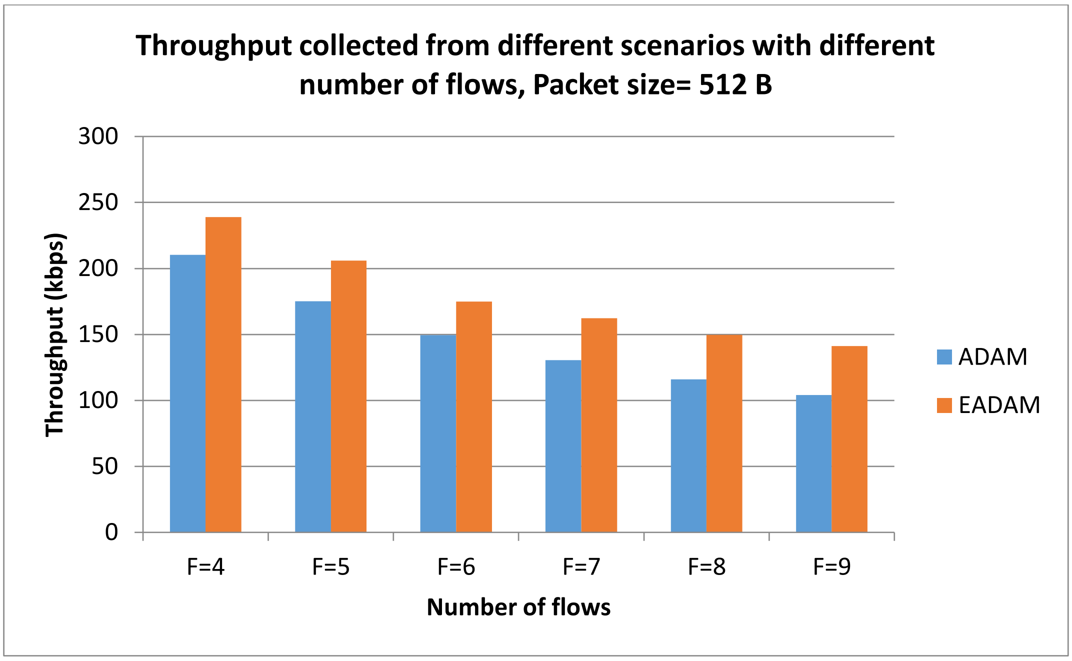


Figure 3.18 Throughput collected from different scenarios with different number of flows _Packet size= 512 B

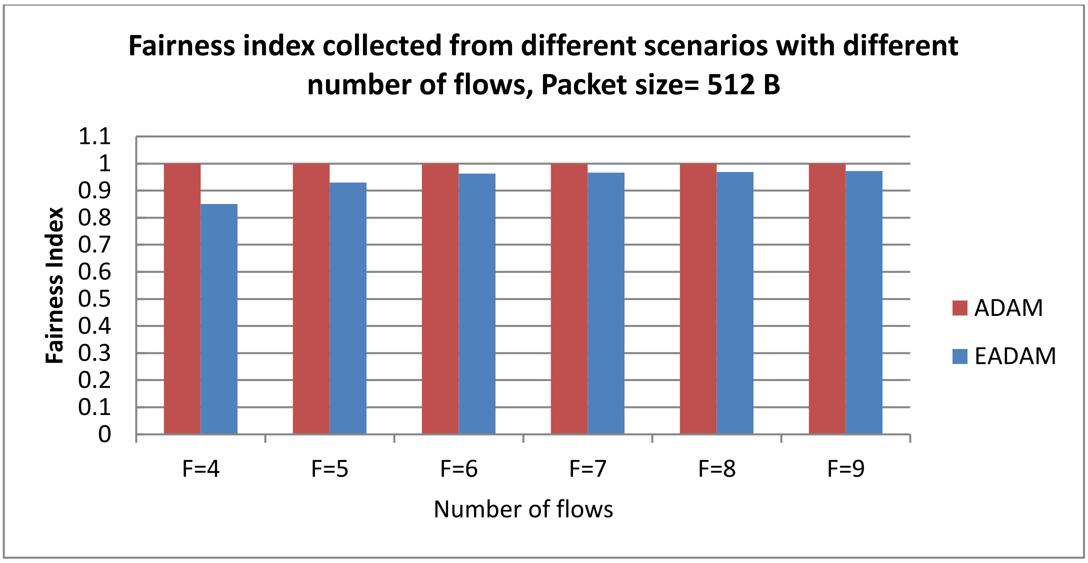


Figure 3.19 Fairness Index collected from different scenarios with different number of flows _Packet size= 512 B

The Throughput and Fairness Index Enhancement Ratio for different number of flows scenarios with packet size = 512 B has been calculated using equations (3.15) & (3.16) and shown in Figure 3.20.

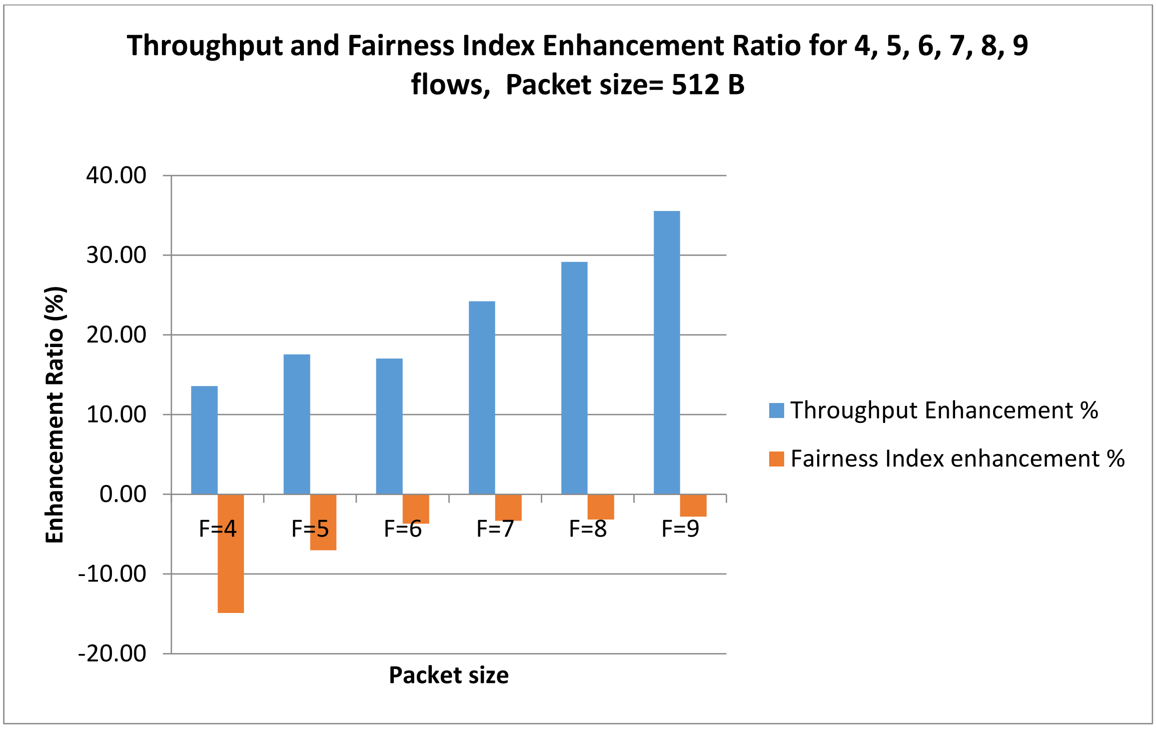


Figure 3.20 Throughput and Fairness Index Enhancement Ratio for 3 flows with packet size= 512 B

3.4.2.4 Packet size = 1024 B

Finally, EADAM and ADAM techniques again have been tested with the previous different number of flows scenarios with 1024 B packet size. The throughput and Fairness index obtained from EADAM and ADAM for packet size = 1024 B are shown in Figure 3.21 and Figure 3.22 respectively. Enhancement ratio of Throughput and Fairness are shown in Figure 3.23.

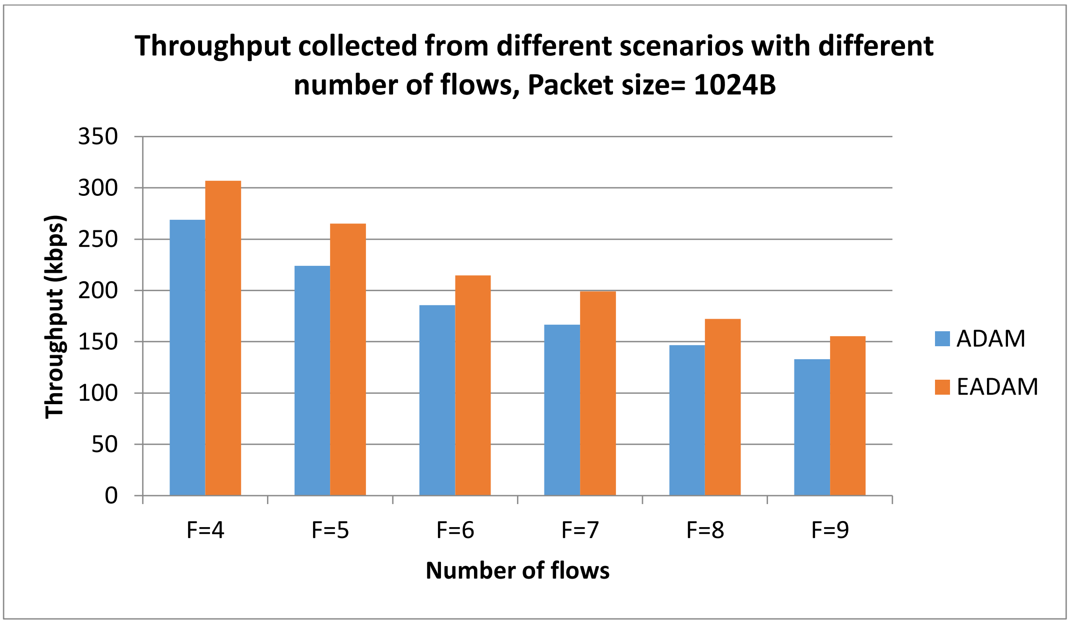


Figure 3.21 Throughput collected from different scenarios with different number of flows _Packet size= 1024 B

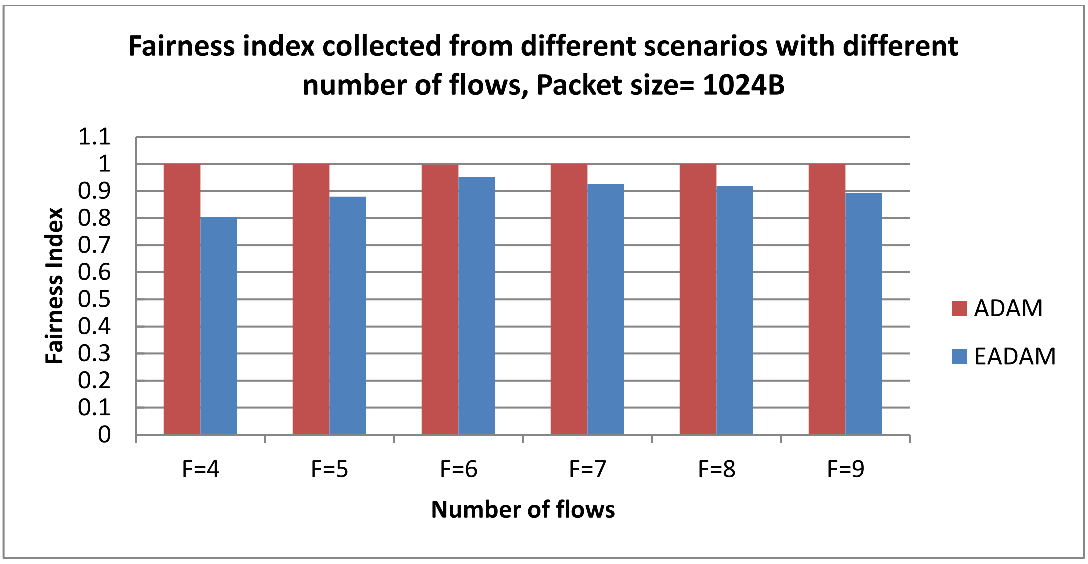


Figure 3.22 Fairness Index collected from different scenarios with different number of flows _Packet size= 1024 B

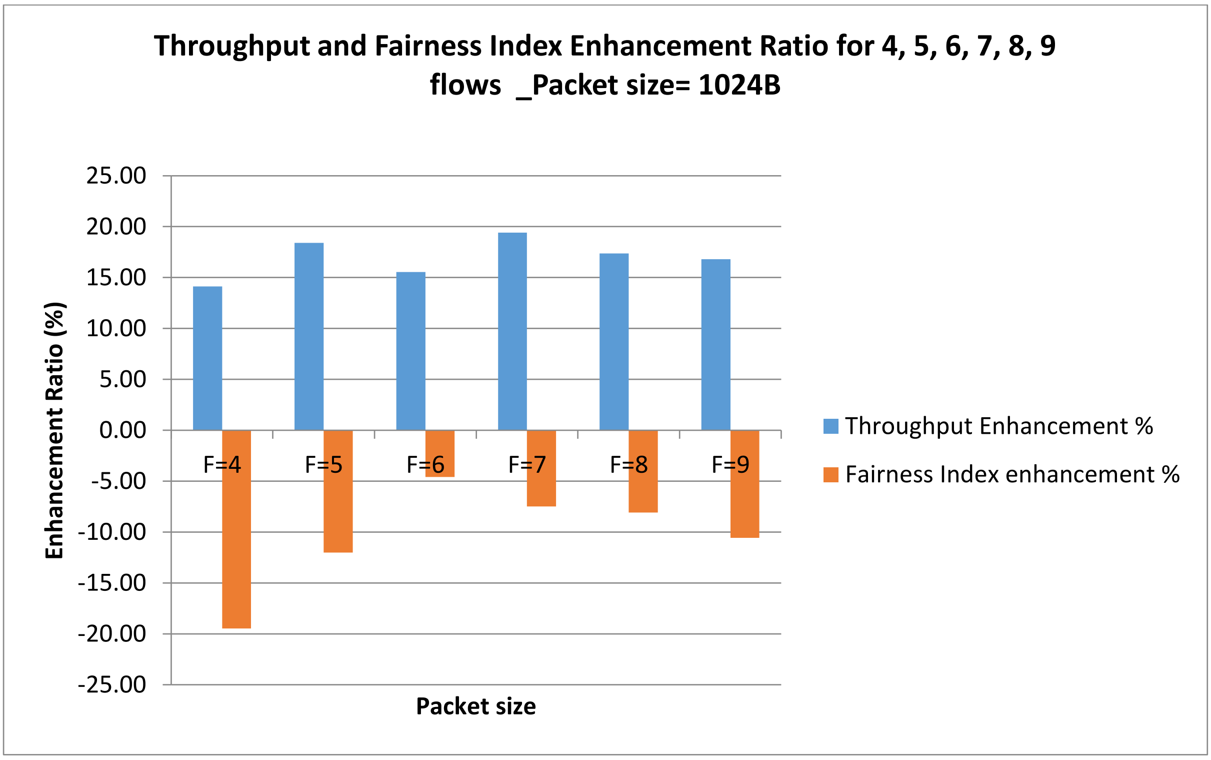


Figure 3.23 Throughput and Fairness Index Enhancement Ratio for 3 flows with packet size= 1024 B

3.4.3 An analysis comparison

Figure 9 to Figure 3.23 are summarized in the Figure 3.24 and Figure 3..25 Figure 3.24 presents the throughput enhancement ratios calculated with equation (3.15) for different number of flows (3 to 9) with four different packet sizes, while Figure 3.25 shows the fairness enhancement ratios calculated with equation (3.16) for the same scenarios.

As can be seen the throughput enhancement ratio is excellent as it ranges from 3.6% to 35.57% when the fairness index enhancement ratio, that is presented with negative values, is still in the range of -0.10% to -16.49%.

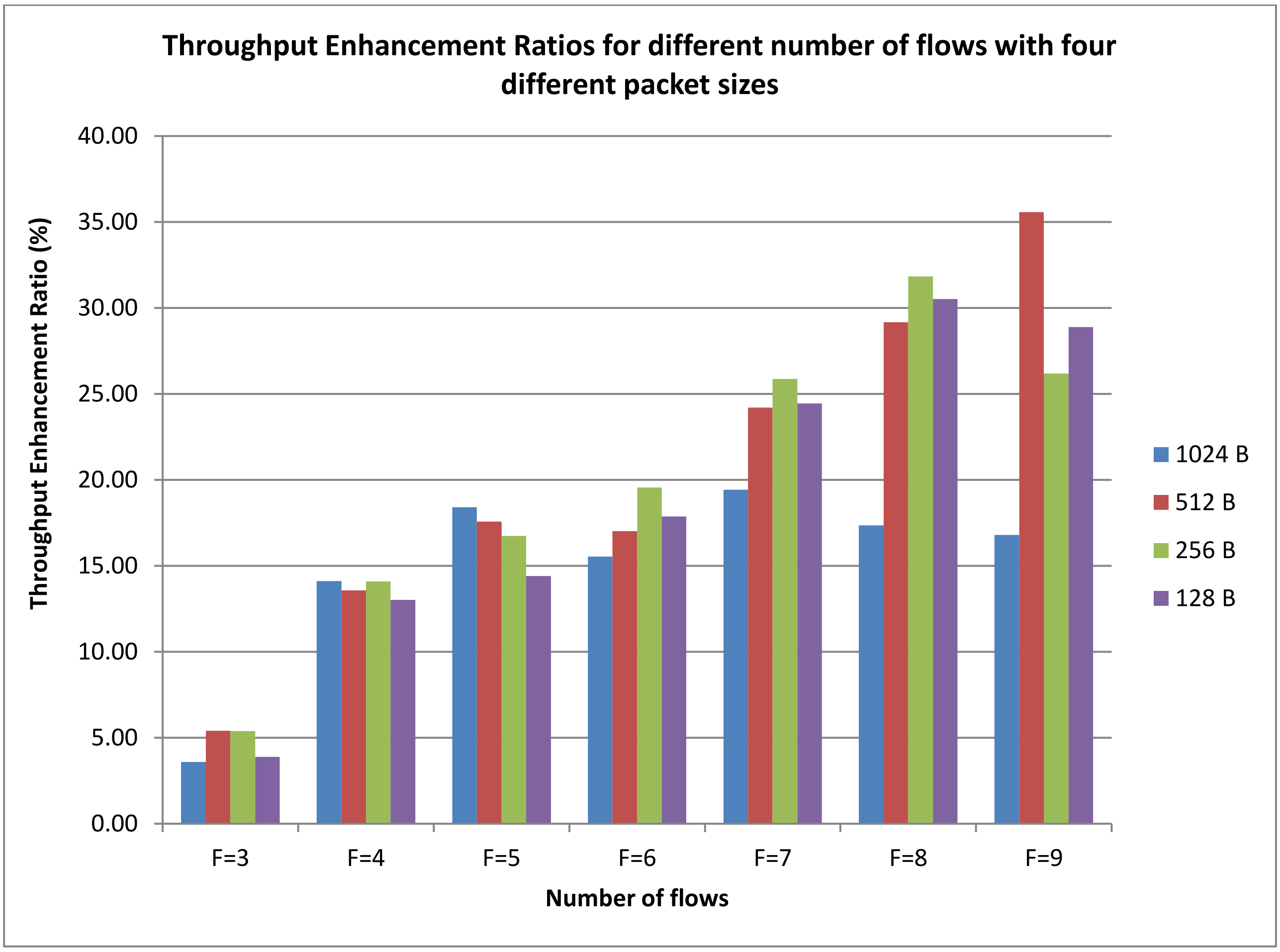


Figure 3.24 Throughput Enhancement Ratios for different number of flows with four different packet sizes

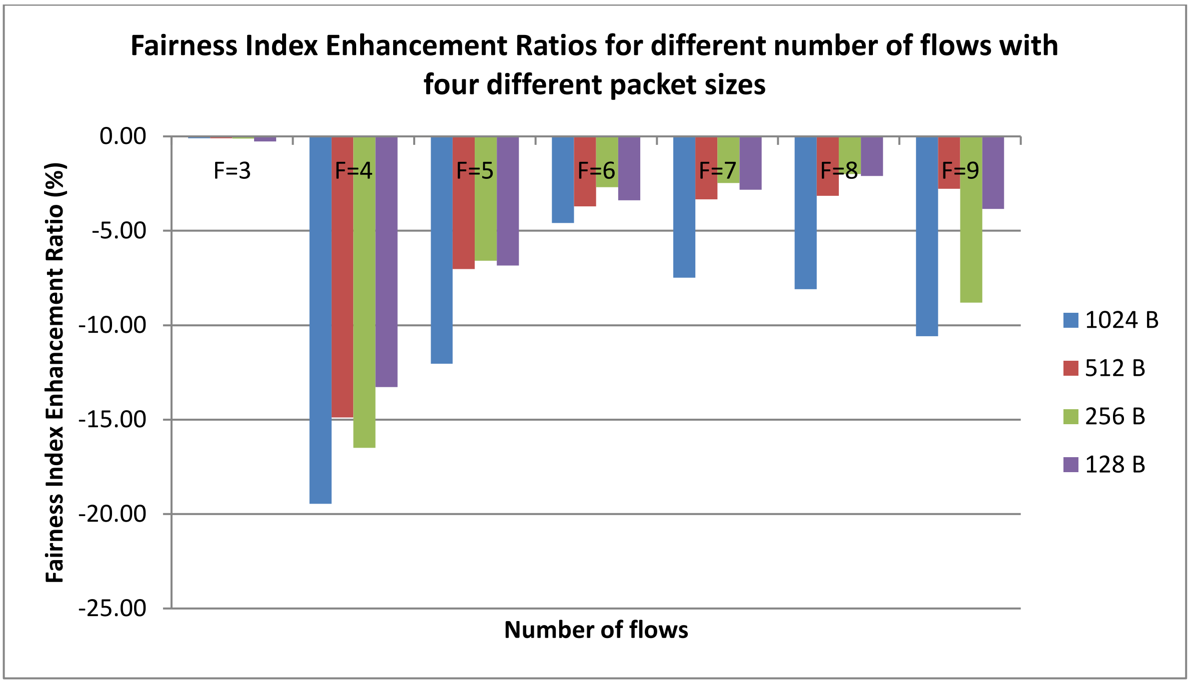


Figure 3.25 Fairness Index Enhancement Ratios for different number of flows with four different packet sizes

3.5 Summary

Throughput unfairness that leads to starvation is a major problem in WMNs backhaul where nodes that are few hops away from the gateway get minimal chance to transmit to the gateway.

Enhanced Adaptive Delayed Acknowledgement mechanism (EADAM) is proposed to enhance the throughput for all active flows in a static chain topology alongside with maintaining fairness among the flows. This mechanism utilises a mathematical model for calculating appropriate TCP delayed acknowledgement timeout with reference to the number of hops between a source and a destination node called ADAM. An optimum throughput fairness on a chain topology for a number of active flows has been achieved by implementing a TCP delayed acknowledgement timeout model that allows Paralleled transmission among the individual flows, which leads to a significant throughput enhancement. The proposed mechanism EADAM has been implemented in NS2. Then validated by comparing to ADAM. A throughput enhancement ratio of up to 35% has been achieved.

Chapter 4

Mobility and Energy Aware Route-Discovery Scheme for AODV in Wireless Mobile Ad-Hoc Networks

4.1 Introduction

Mobile Ad-Hoc Networks are wireless infrastructure-less networks where all nodes communicate in multi-hop manner without any centralisation. Packets are forwarded among mobile nodes from source to destination. The topology of these networks changes rapidly and unpredictably [19] as shown in Figure .

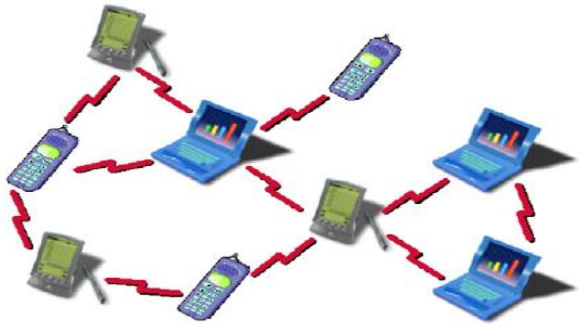


Figure 4.1 MANET example [18]

Routing in MANETs is a challenging task due to the dynamic and mobile topology of these networks. Routing protocols originally were classified as proactive (or table-driven) and reactive (On demand) protocols. The main difference between these two categories is the way of the routing information is built. With proactive protocols, routing information is maintained and updated periodically at every single node in the network which makes route establishment process fast. However, the huge amount of routing information exchanged here leads to unnecessary overheads which in turn leads to bandwidth degrade and extra node energy consumption. On the other hand, in reactive routing protocols, such as AODV, route discovery process to a route from a source to a destination happens when needed. This saves network resources [18]. Mobility is one of the complex issues that challenge routing protocols in MANETS [37] [38]. Another issue is the limited energy associated with the individual mobile nodes. Hence, a vast amount of recent research focused on these two issues in order to improve the QoS of routing in MANETs [37] [39] [40] [41].

In this chapter, two novel Mobility and Energy Aware Route-Discovery schemes for AODV in MANETs are proposed. These schemes do not only improve throughput in

MANETs, but also reduce average energy consumption, overheads and delay across the entire network. Thus, network life time improves.

4.2 Current research

Classical routing protocols, such as AODV and DSR, have evolved to new versions where main issues of mobility and energy constrain have been considered. In [38], a scheme called MA-AODV is proposed. In this scheme, each node computes its own mobility. Then, it uses this information to decide on whether to take part in the established route between source and destination during route discovery process. However, the mobility calculation bases are not clear, and performance evaluation is too limited.

An enhancement to AODV called H-MAODV has been proposed in [42]. In this work, mobility is considered in the form of relative velocity and distance between each node and a one hop neighbour. A factor f_{ij} computed at the route discovery process at every single node that receives RREQ, then the factor is compared to a metric value set in the RREQ message. The factor f_{ij} is compared to the metric value. When f_{ij} is greater than metric value, f_{ij} replaces the metric value. Destination, then, determines the best path based on the metric value arrived to it by selecting the path that has minimum metric value. Although packet delivery ratio shows an improvement compared to AODV, distance calculation between two neighbour's nodes is not stated.

A scheme for mobility path selection called MPS has been proposed in [43]. The scheme is based on a proposed factor called mobility_factor. This factor is computed based on the node pause time, speed and direction. During route discovery process, mobility_factor is computed at each intermediate node. Node is selected to participate in a path between source and destination if whose mobility_factor value is equal or greater than a predetermined threshold. The analysis shows a good improvement in terms of metrics like packet delivery ratio, average end-to-end delay and routing overheads. However, network life time has not been analysed. Moreover, flexibility is a major issue in this work because of the threshold that the mobility_factor is always compared to.

A mobility prediction scheme proposed in [37] employs GPS location information obtained and used to calculate a predicted link expiration time (LET) between two adjacent nodes. The LET is used to maintain link breakage. A route, whose accumulated LET between source and destination, is greatest is chosen by the destination. The scheme is tested in the form of unicast and multicast routing protocols and shows better packet delivery ratio compared to those protocols without mobility prediction. LET is given using the following equation (4.1):

4-1)

$$LET = \frac{-(a+b)+\sqrt{(a^2+c^2)r^2-(\mathrm{ad}-\mathrm{bc})}}{a^2+c^2}$$

Where,

$a = v_i \cos\theta_i - v_j \cos\theta_j$,

$b = x_i - x_j$

$c = v_i \sin\theta_i - v_j \sin\theta_j$,

$d = y_i - y_j$

x_i , x_j *The coordinates of node i,j*

$v_i,\ v_j$ *the speeds of node i, j*

θ_i, θ_j *the moving directions of nodes i, j respectively.*

Energy and power concern is another direction of research of routing in MANETs. An algorithm that takes into account residual battery capacity, transmission power and hop count has been proposed in [44]. A mathematical model has been proposed where these three criteria been examined. The main purpose behind it is to extend the life time of the network. However, the implementation of this algorithm requires a major change to the RREQ packet and mobility has not been considered.

Extending network life time has been also the concern of another work proposed in [45]. The work is an improvement to AODV by applying energy mean value algorithm. Here, the residual energy of each node is accumulated and sent along the RREQ packets toward the destination. The later decides on the path that has maximum accumulated energy. Analysis shows improvement in network life time compared to standard AODV. However, assigning the decision to the destination increases the number of routing overhead.

In [46] another algorithm (AODV+GE) has been proposed that is an enhancement to (AODV+G). This enhancement is presented in the form of considering the remaining energy during the route discovery process. Based on a mathematical model proposed, a probability value of forwarding RREQ packet is calculated. The main problem here, the probability calculation is based on a few thresholds to number of hops, neighbours of the node and neighbours that have broadcasted.

Mobility and power aware routing algorithm based on node's location information called PMAR has been proposed in [47]. A heuristic scheme proposed to optimise the route selection based on power and mobility. Performance has been evaluated in static and mobile network in terms of network life time only.

4.3 The proposed work

4.3.1 Problem statement

Route breakage is a serious issue that routing in MANETs experiences. This issue is mainly due to node mobility or the limited residual energy of the node. The node in MANETs is completely free to move in any direction which results a topology change and link life time expiry. To illustrate link life time expiry effect, let's consider a MANET scenario presented in Figure . In this scenario, S is a source node, D is a destination. Nodes N1, N2, N3,…..,N6 are intermediate nodes between S and D. Numeric values associated with any link between two nodes represent the link life time between these nodes.

When S tries to find a route to D, a RREQ is generated by S and broadcasted. Nodes N1 and N4 receive RREQ and record S as a reverse route in their routing tables. Then RREQ is rebroadcasted by these nodes to reach N2 and N5. Again these nodes record their previous nodes N1and N4 respectively in their routing tables as reverse routes to S. RREQ is rebroadcasted further until it reaches N6. Two RREQ packets are received by N6: one from N3 and another from N5. Now N6 discards RREQ received from N3, and record N5 in its routing table as a reverse path. N6, then, rebroadcasts RREQ and D receive it successfully. At this point, D creates RREP packet and send it backward to N6. N6 forwards it back to N5. N5 forwards it to its predecessor N4. However, because of the weakness of N5-N4 link that is represented in its link life time (LLT=0.1 s), RREP may not reach S and rout discovery fails at this point. Moreover, even if RREP successfully received by source node S, and route has been established, the link N4-N5 will break shortly and that leads to route breakage.

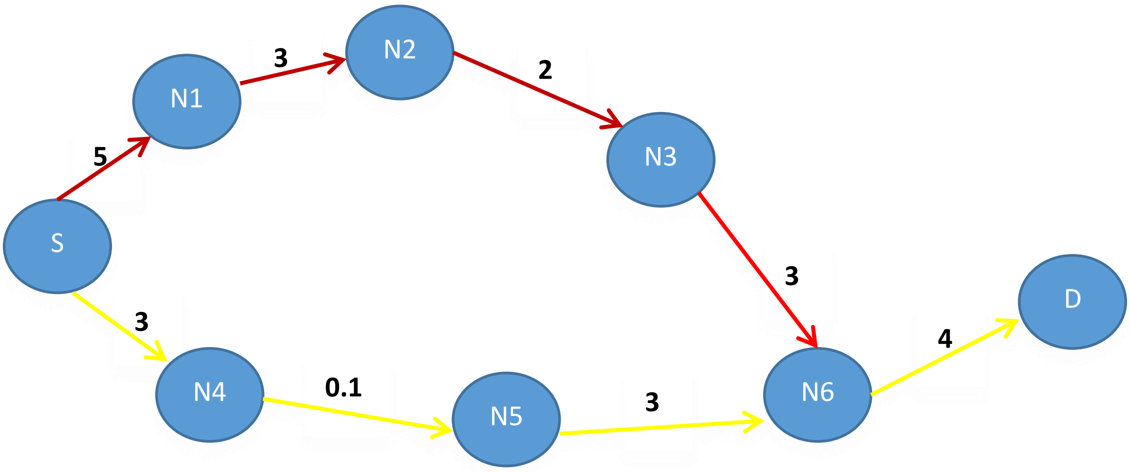


Figure 4.2 Link Life Time expiry effect

Residual energy is the other main factor that plays an important role of route stability. When the node has enough remaining energy, the node is able to stay live and active for longer which means route stability improves. To illustrate this fact, the same previous scenario is presented in Figure 4.. The difference between this figure and the previous one is that residual energy values have been added to the nodes. As the figure shows node N5 has low energy value which means if the route S, N4, N5, N6, D is chosen, the route will not be stable. In other words, either RREP is not relayed to N4, Or N5 residual energy exhausted after a few packets have been sent through this route due to N5 being died.

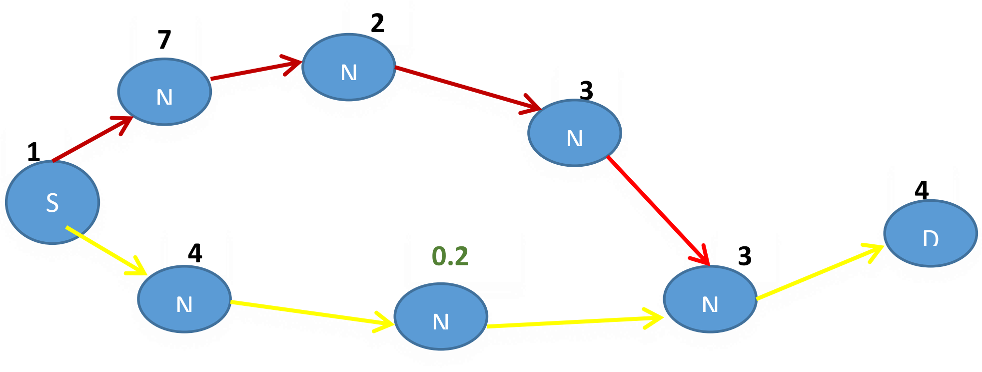


Figure 4.3 Residual Energy effect

4.3.2 Fixed and Average Link Stability and Energy Aware (F-LSEA and A-LSEA) routing protocol

Fixed Link Stability and Energy Aware (F-LSEA) [39] and Average Link Stability and Energy Aware (A-LSEA) [3] are mobility and energy aware route discovery algorithms proposed for AODV in MANETS recently. The algorithms take the above mentioned issues into consideration and work on maintaining the route stability while the route has been established. Node mobility is considered by adopting the concept of Link Life Time (LLT) [37], and node residual energy is the other factor that accompanies LLT when a route is being discovered between a source and destination.

4.3.2.1 F-LSEA:

In this work [39] [3] whenever a node receives a RREQ from a previous node, two checks are carried out: First, remaining energy of the considered node against a threshold (RE(ft)). Second, LLT between that node and the node that the RREQ received from. against a fixed threshold of LLT (LLT(ft)). If both checks are both true, then RREQ is rebroadcasted. Otherwise, RREQ is discarded.

Figure 4. shows a simplified scenario of F-LSEA' mechanism. Five nodes: S,1,2,3,D in this scenario. When source node S wants to find a route to the destination D, it broadcasts a RREQ. Intermediate nodes 1,2 and 3 receive it. Then each of these three node carries the two checks: RE and LLT against (RE(ft)) and (LLT(ft)) which they have been set to 3. Node 1 does not satisfy the first condition as it RE is less than the set threshold. Similarly, node 3 does not satisfy the second condition as it LLT is less than the set threshold. This means that only node 2 can be considered for relaying RREQ to the next hop.

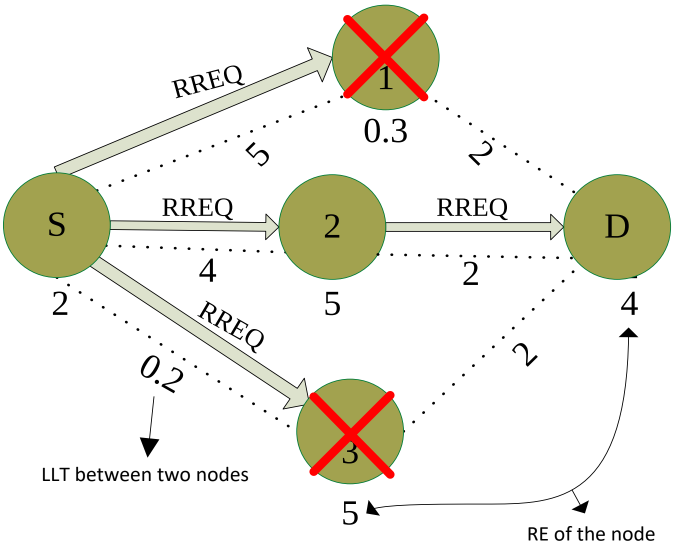


Figure 4.4 F-LSEA [5]

4.3.2.2 A-LSEA:

Average link stability and energy aware routing protocol [3] functions similarly to F-LSEA in terms of carrying out two checks: one is for remaining energy and the other is for link life time. However, the method of how to carry out these checks is different. While F-LSEA uses threshold values for RE and LLT to compare with, A-LSEA computes the average remaining energy RE_{avg} using 4-2 and average link life time LLT_{avg} using equation 4-3 for the current considered node with its neighbours then decides whether to forward the RREQ based on satisfying LLT and RE of that node are grater or equal to RE_{avg} , LLT_{avg} respectively.

$$RE_{Avg} = \sum_{i=1}^{n} \frac{RE_i}{n} \qquad 4\text{-}2)$$

$$LLT_{Avg} = \sum_{i=1}^{n} \frac{LLT_i}{n} \qquad 4\text{-}3)$$

4.3.3 Mobility and Energy aware AODV in Wireless Mobile Ad-Hoc Networks (MEA_AODV)

In this section the proposed work called Mobility and Energy aware route discovery schemes for AODV is presented. This work uses A-LSEA [3] to propose two new algorithms that not only aware of link stability in MANETs, but also is aware of the remaining energy of all active nodes that are neighbours to that relaying node. These algorithms are:

- Selective Energy_ Mobility and Energy Aware AODV (SRE_MEA_AODV)
- Selective Link Life Time_ Mobility and Energy Aware AODV (SLLT_MEA_AODV)

The main idea in the proposed work is to be selective while choosing the forwarding node during route discovery process. Similarly to A-LSEA, the node checks its mobility and energy against average value of these two parameters. However, the way how to perform the two checks is different. The computation of the average of the first parameter considers all neighbourhood nodes, and then the first stage check is performed. As for the second stage check, here, only neighbour nodes that passed the first check are taken for the computation of the average value of the second parameters; meaning, it takes only nodes that has satisfied the first condition and excluding those nodes that fail to satisfy the first condition. A combination of two conditions is checked here: link life time and remaining energy for the forwarding node checked against the average values of link life time and remaining energy respectively.

4.3.3.1 Selective Remaining Energy_Mobility and Energy Aware AODV (SRE_MEA_AODV)

In order to bring the awareness of mobility and residual energy in route selection during route discovery process in AODV [48] along with maintaining a better degree of end-to-end route stability, a new algorithm is proposed called Selective Energy AODV (SRE_MEA_AODV). SRE_MEA_AODV works as follow:

Let us consider the scenario presented in Figure 4. where N0 is an intermediate node that needs to search for a route to a destination D. N1 to N5 are other intermediate nodes. When N0 seeks to communicate with D, it starts the route discovery process by propagating a RREQ packet. N1, the next hop node, receives it and starts the SRE_MEA_AODV process. Since nodes (N2, N3, N4, N5) are neighbours to N1, it first collects the link life times with all of its neighbours

(LLT_{N10}, LLT_{N12}, LLT_{N13}, LLT_{N14} and LLT_{N15}) and computes the average link life time LLT_{avg} using equation 4-3. Having calculated the first parameter (LLT_{avg}), N1 checks (LLT_{N10}, LLT_{N12}, LLT_{N13}, LLT_{N14} and LLT_{N15}) against (LLT_{avg}). The outcome of this check is important as it determines those nodes that go into the second average computation. That is RE_{avg}. For example, in the scenario shown in Figure 4., let us assume LLT_{N14} is less than (LLT_{avg}). This means RE_4 is excluded from RE_{avg} computation. In other words, RE_{avg} is calculated as follow:

$$RE_{Avg} = \sum_{i=0}^{n} \frac{RE_i}{n} = \frac{(RE_0 + RE_1 + RE_2 + RE_3 + RE_5\ )}{5} \qquad ; n = 0,1,2,3,5 \qquad 4.4\ )$$

At this point, having obtained LLT_{avg} and RE_{avg}, N1 performs the second stage check which is a combination of two condition together (LLT_1 & RE_1) are greater or equal to (LLT_{avg} & RE_{avg}). If this combined condition is satisfied, then RREQ is rebroadcasted. Otherwise, it is discarded. Figure 4. shows a flow chart that illustrates SRE_MEA_AODV processes of receiving a RREQ at any node.

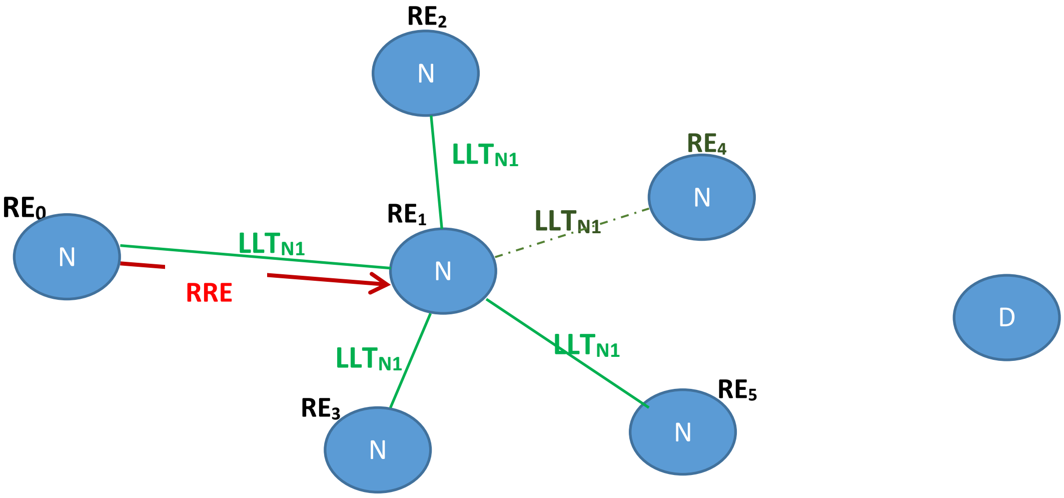


Figure 4.5 Illustration of SRE_MEA_AODV

4.3.3.2 Selective Link Life Time_ Mobility and Energy Aware AODV (SLLT_MEA_AODV)

Selective Link Life Time_ Mobility and Energy Aware AODV (SLLT_MEA_AODV) is another algorithm proposed to bring the awareness of mobility and residual energy in route selection during route discovery process in AODV along with maintaining a better degree of end-to-end route stability. This algorithm, similar to SRE_MEA_AODV, uses the same concept of being selective while deciding on the forwarding node. The node checks its reaming energy and against the average value of these two parameters. However, the way how to perform the two checks is different. The computation of the average of the remaining energy takes all neighbourhood nodes into account, and then the first check is performed. As for the second check, here, only neighbour nodes that passed the first check are taken for the

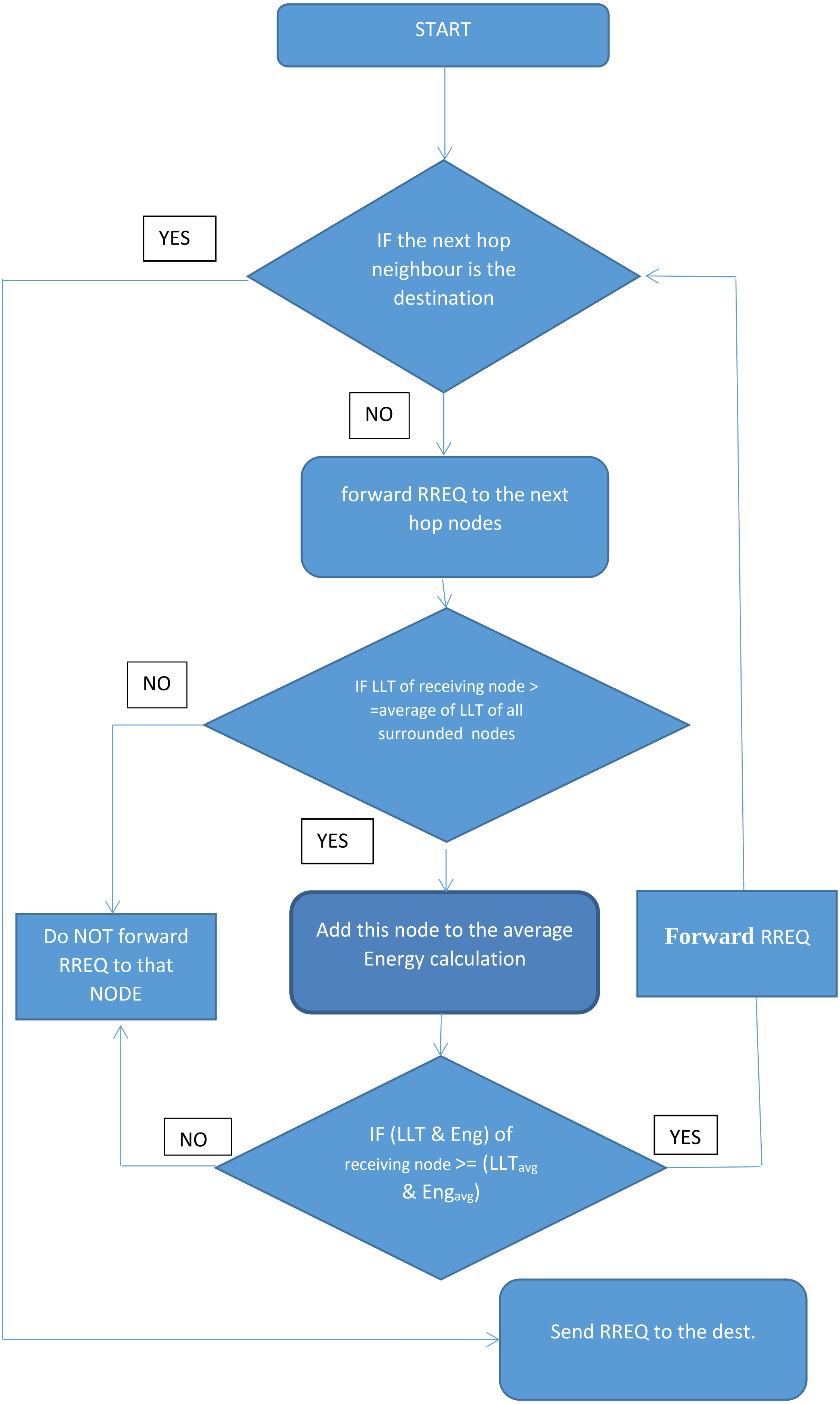


Figure 4.6 Flow Chart illustrates SRE_MEA_AODV processes of receiving a RREQ at any node.

computation of the average value of link life time; meaning, it takes only nodes that has satisfied the first condition and excluding those nodes that failed to satisfy the first condition.

In order to clarify the way it works, scenario in Figure 4. is considered again. When N0 seeks to communicate with D, it starts the route discovery process by propagating a RREQ packet. N1, the next hop node, receives it and starts the SLLT_MEA_AODV process. Since nodes (N2, N3, N4, N5) are neighbours to N1, N1 first collects the remaining energy values from all of its neighbours (RE_0, RE_1, RE_2, RE_3, RE_4 and RE_5) and computes the average remaining energy RE_{avg} using equation 4-3 as follow:

$$RE_{Avg} = \sum_{i=0}^{6} \frac{RE_i}{n} = \frac{(RE_0 + RE_1 + RE_2 + RE_3 + RE_4 + RE_5)}{6} \qquad (4.5)$$

Having calculated the first parameter (RE_{avg}), N1 checks (RE_0, RE_1, RE_2, RE_3, RE_4 and RE_5) against (RE_{avg}). The outcome of this check is important as it determines those nodes that go into the second average computation. That is LLT_{avg}. For example, in the scenario shown Figure 4., let us assume RE_4 is less than (RE_{avg}). This means LLT_{N14} is excluded from LLT_{avg} computation. In other words, LLT_{avg} is calculated as follow:

$$LLT_{Avg} = \sum_{i=1}^{n} \frac{LLT_i}{n} = \frac{(LLT_{N12} + LLT_{N13} + LLT_{N15})}{3} \quad ; n = 2,3,5 \qquad (4.6)$$

At this point, having obtained LLT_{avg} and RE_{avg}, N1 performs the second stage check which is a combination of two condition together (LLT_1 & RE_1) are greater or equal to (LLT_{avg} & RE_{avg}). If this combined condition is satisfied, then RREQ is rebroadcasted. Otherwise, it is discarded. Figure 4.5 shows a flow chart that illustrates SLLT_MEA_AODV processes of receiving a RREQ at any node.

In the next section, , the proposed mechanism is shown as promising technique to improve throughput, delivery ratio, Average delay, overheads and network life time through computer simulations.

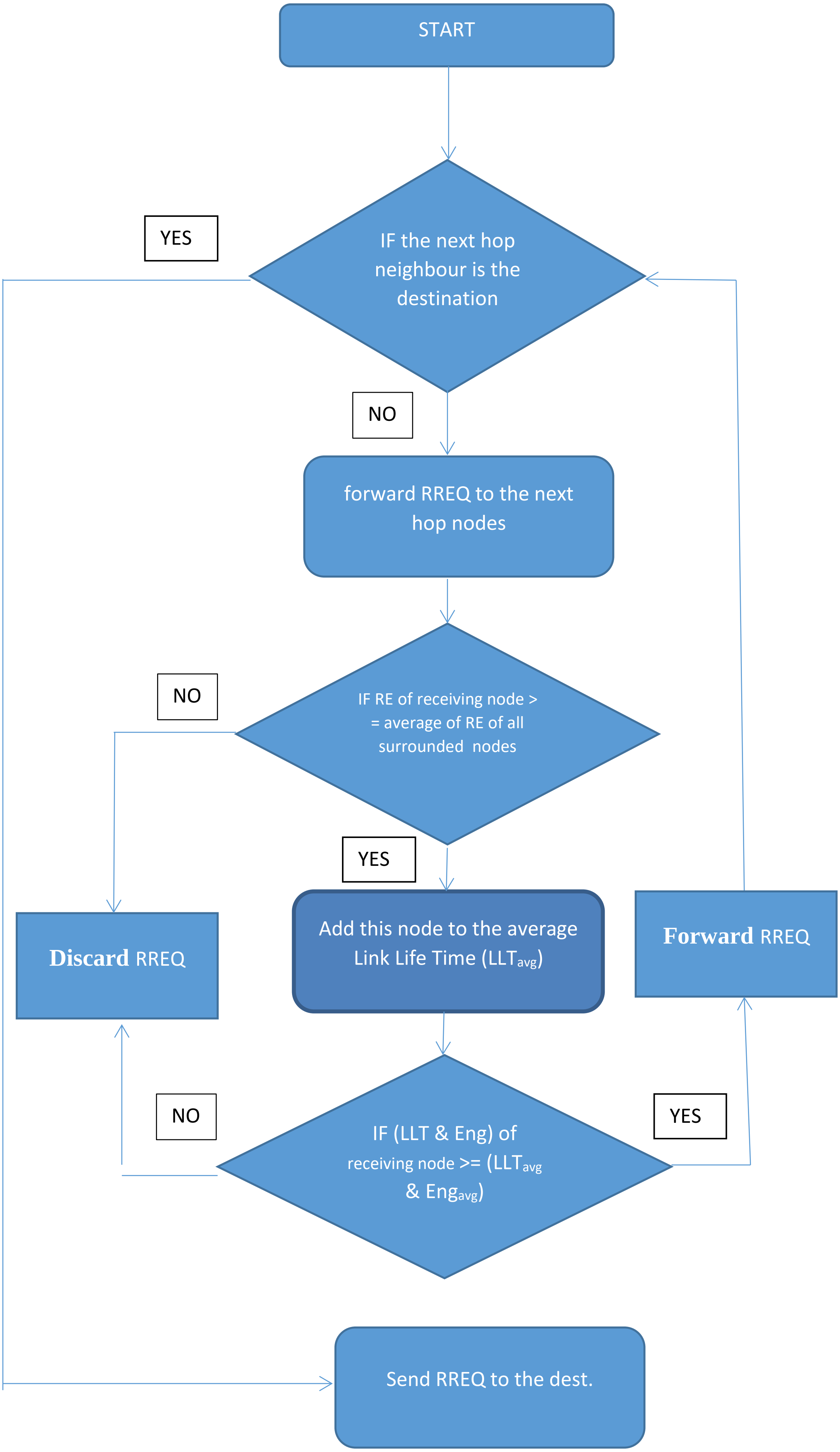


Figure 4.7 Flow Chart illustrates SLLT_MEA_AODV processes of receiving a RREQ at any node

4.3.3.3 Performance Metrics

The same metrics used in [3] have been used to evaluate the proposed algorithms:

Total Data Sent: the total amount of data sent from the sender throughout the network.

Total Data Received: the total amount of data received by the destination.

Packet Delivery Ratio: the ratio of those data packets successfully delivered to the destinations to those generated by the CBR sources.

Total Overhead: the number of control packets transmitted in the network, including the RREQ, RREP and hello messages.

Network Life Time: The aggregate times before all nodes die due to battery exhaustion. Also

Throughput: number of packets divided by the duration.

Average End-to-End Delay: the average delay of all possible delays caused by buffering during the route discovery and link recovery phases, queuing at the interface queues and retransmission delays at the MAC layer.

Average Energy Consumption: Total energy consumption divided by the number of nodes.

4.3.3.4 Numerical results and analysis from the proposed work

The proposed algorithms ((SRE_MEA_AODV) and (SLLT_MEA_AODV)) have been implemented in NS2 [49] platform for comparing MEA_AODV with AODV and A-LSEA.

A mobile topology scenario consists of 100 nodes distributed randomly in an area of 1000 m x 1000 m is implemented in NS2. The transmission range is 250 m, and the carrier sensing range is 550 m. Each link has a bandwidth of 1 Mbps. The application is CBR over udp connection. Random Waypoint model was used to simulate the nodes' mobility. In the Random Waypoint model, each node starts to move from its location to a random location with a randomly chosen speed from a minimum speed equal to 5 m/s and maximum speed equal to 30 m/s. Energy model is used. The simulation time is 1000s. Table 4-1 shows the simulation parameters for this scenario.

Table 4-1: NS2 scenario simulation parameters

Environment parameter	**Value**
Channel type	Wireless channel

Radio propagation model	Two Ray Ground
Mobility model	Random Waypoint
MAC type	802.11
Transmission range	250 m
Carrier sensing range	550 m
Interface queue type	Drop Tail/ PriQueue
Max packet in ifq	100
Application	CBR (1000 Bytes)
Type	mobile
Nodes	100
Number of Connections	20
Pause	1 s
Speed (m /s)	5, 10, 15, 20, 25,30
send rate	0.2
Coordination	1000 m x 1000 m
Simulation time	1000 s

Using energy model in ns2 simulator requires assigning values to initial energy of the network's nodes. Thus, the mobile nodes were divided into 10 groups (10 nodes each). A random distribution function (NORM(100,20)) has been used to create 10 different values of initial energy values with mean of 100 and standard deviation = 20. These values are: 118, 115, 94, 131, 95, 94, 135, 85, 62, 68. Simulation ran 5 times then average of results calculated.

4.3.3.4.1 Total data sent

Total data sent of the proposed algorithms is compared to standard AODV and A-LSEA as shown in Figure 4.. As can be seen, standard AODV is outperformed by the two proposed algorithms and A-LSEA. This is due to the end to end link stability provided by these schemes. The first proposed algorithm, SRE_MEA_AODV, outperforms the other three schemes. Here,

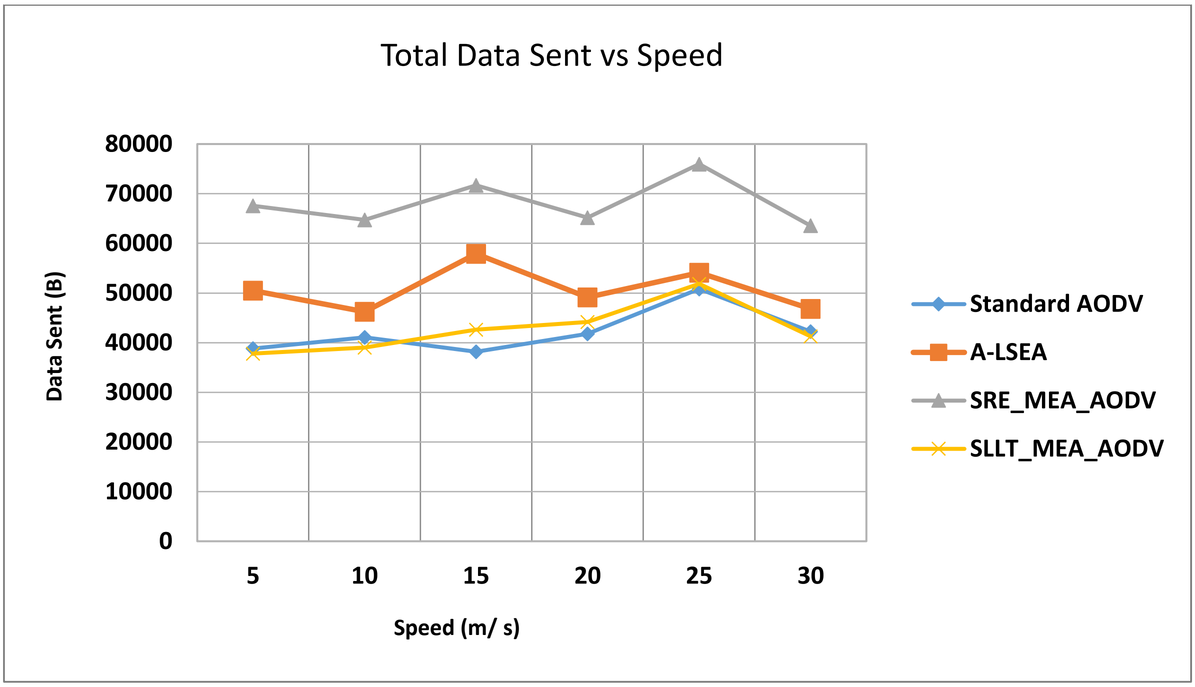


Figure 4.8 Total Data Sent vs Speed

The quality of link and remaining energy that this proposed algorithm sets leads to improved link stability with regards to link breakage and battery exhaustive.

4.3.3.4.2 Total Data Received

Total data received of the proposed algorithms is compared to standard AODV and A-LSEA as shown in Figure 4.. As shown with total data sent, standard AODV is outperformed by the two proposed algorithms and A-LSEA. While SRE_MEA_AODV outperforms the standard AODV, A-LSEA and SLLT_MEA_AODV Again, end to end link stability provided by this scheme is the main reason for this outperformance.

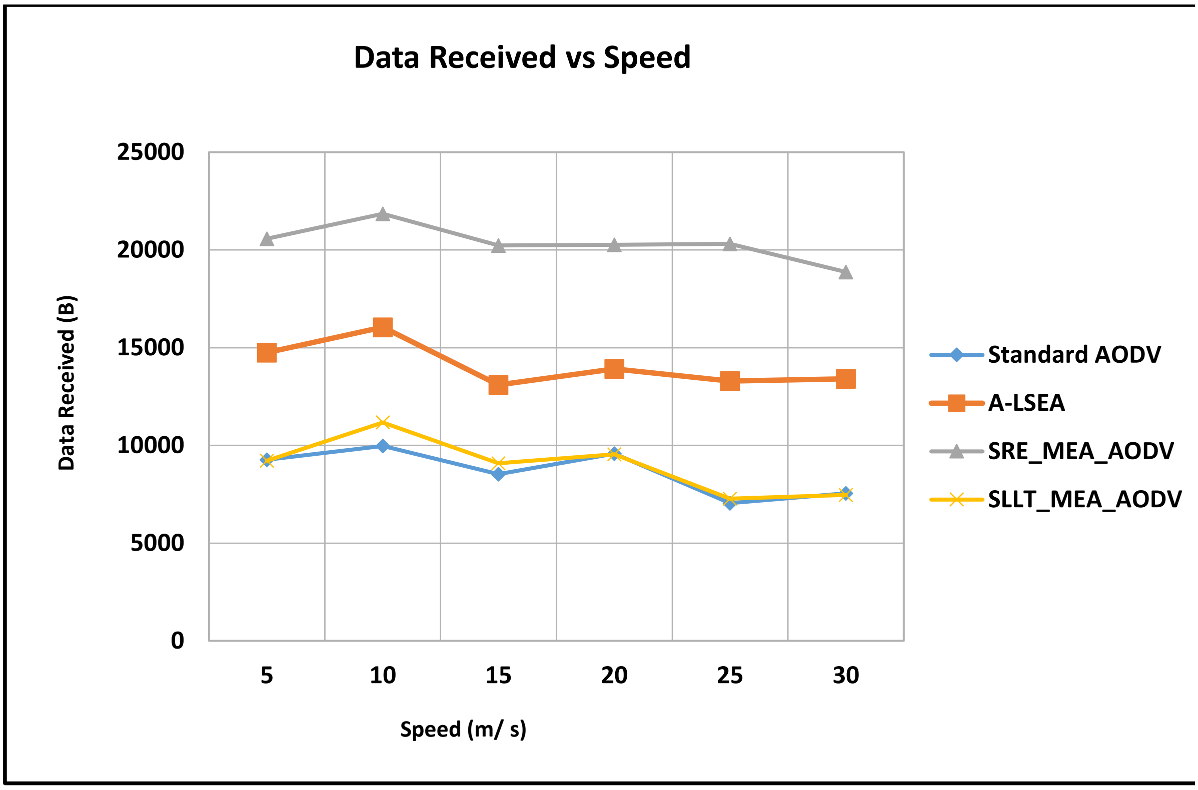


Figure 4.9 Total Data Received vs Speed

4.3.3.4.3 Packet Delivery Ratio

Figure 4. shows packet delivery ratio performance of the two proposed schemes in comparison to standard AODV and A-LSEA. Here, while SLLT_MEA_AODV does not show a real improvement in terms of packet delivery ratio when compared to standard AODV, SRE_MEA_AODV clearly has outperformed the other three schemes. As mentioned before when data sent and received discussed, the route selection criteria associated with SRE_MEA_AODV maintains a better end to end route stability. Hence, packet delivery ratio has increased.

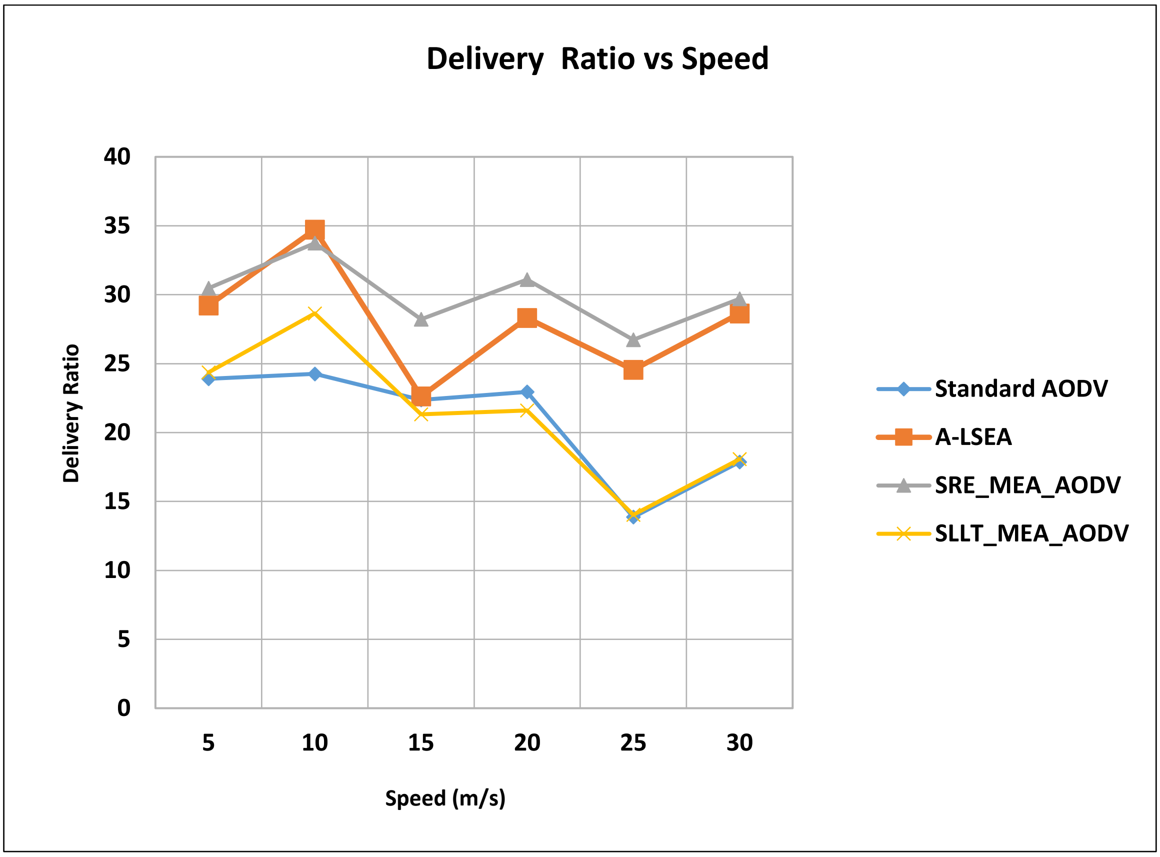


Figure 4.10 Packet Delivery Ratio vs Speed

4.3.3.4.4 Total Overhead

Total number of overhead for standard AODV, A-LSEA, SLLT_MEA_AODV and SRE_MEA_AODV has been compared and shown in Figure 4.. Due to the huge reduction in number of RREQ that is utilised in the proposed algorithms, the overhead is decreased dramatically comparing to standard AODV. A-LSEA and proposed algorithms enhance the link stability and work on selecting nodes that have better capability to handle the data. Thus, overhead, using these schemes, have been reduced by applying the route selection conditions. Also, by improving the link stability and reducing the numbers of link breakage the RREP also reduced by minimising route initiation process that happen following a link breakage. SRE_MEA_AODV, as shown in Figure 4., has outperformed standard AODV, A-LSEA and SRE_MEA_AODV because of the higher energy level that the relaying nodes been selected with. Moreover, SRE_MEA_AODV shows better stability with high mobility represented in higher speed.

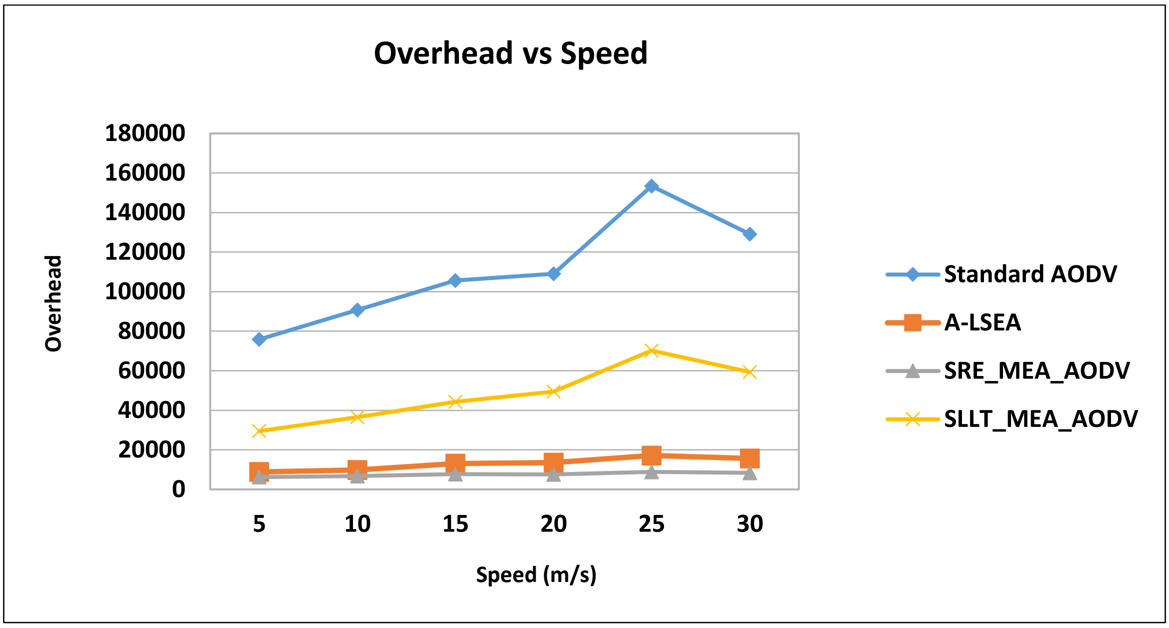


Figure 4.11 Overhead vs Speed

4.3.3.4.5 Network Life Time

Network life time is compared for the four schemes. As shown in Figure 4., SRE_MEA_AODV outperforms its peers. Its performance shows a huge improvement comparing to AODV and the other proposed work SLLT_MEA_AODV. Network life time of SRE_MEA_AODV and A-LSEA is close at lower speed. However, network life time with SRE_MEA_AODV is steady. Thus, SRE_MEA_AODV outperforms A-LSEA with higher speed as shown in the figure.

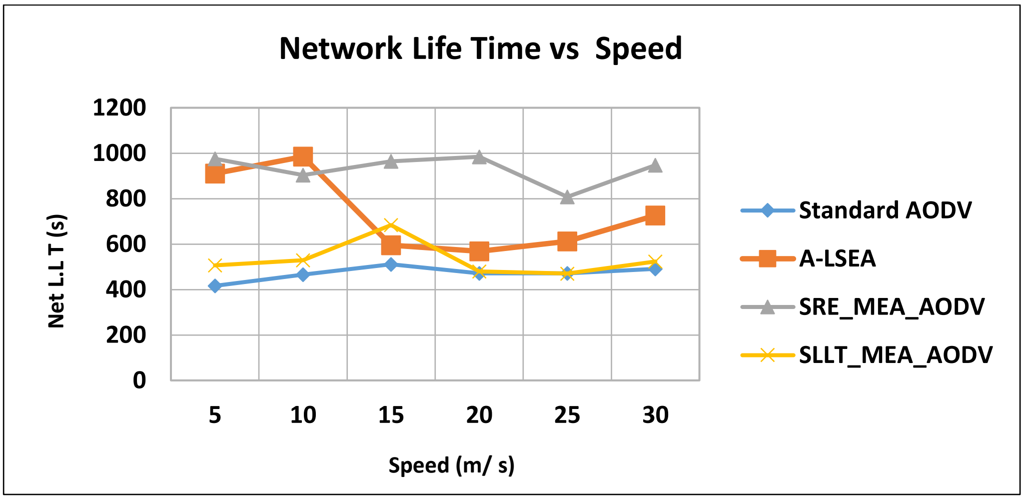


Figure 4.12 Network Life Time vs Speed

4.3.3.4.6 Throughput

Figure 4. compares the achieved throughputs by using the two proposed algorithms in comparison with Standard AODV and A-LSEA. It is clear from the results in Figure 4. that the SRE_MEA_AODV algorithm significantly outperforms the other three by a huge margin. The reason is that route stability has improved which reflected in favour of data sent and received throughout the entire network during the network life time.

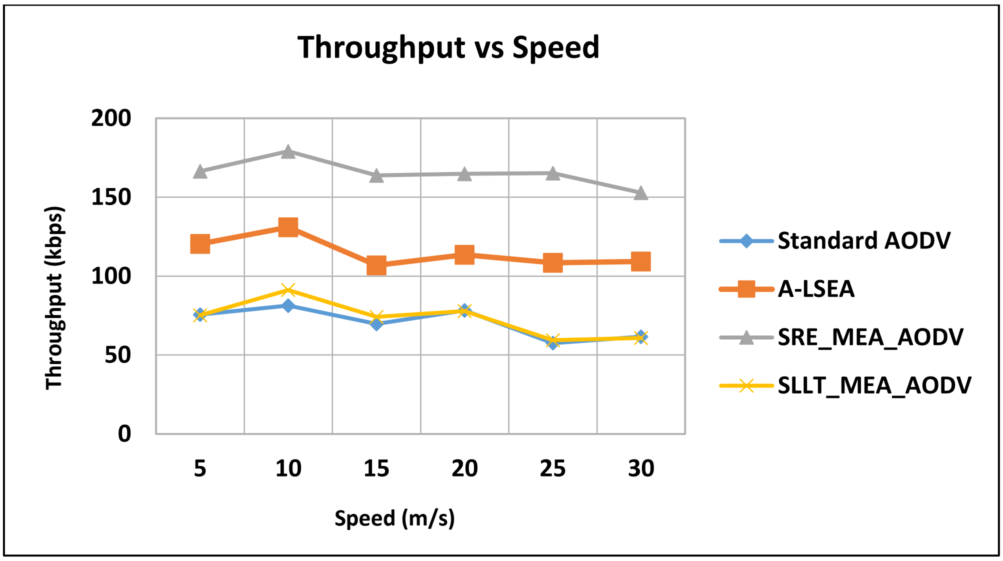


Figure 4.13 Throughput vs Speed

4.3.3.4.7 Average End-to-End Delay

Average end-to-end delay for the four schemes is presented in Figure 4.. As the figure shows, it is clear that SRE_MEA_AODV algorithm outperforms the other algorithms in terms of delay. This is due to the improved quality of end to end route that accompanies route discovery process in this proposed algorithm. On the other hand, the other proposed algorithm, SLLT_MEA_AODV performance in terms of average delay is fluctuating around the standard AODV. This is because this scheme puts more constraining on node' energy then it does take LLT into consideration. Consequently, selected route based on this scheme may be longer than the one selected by AODV which leads to more delay in some cases.

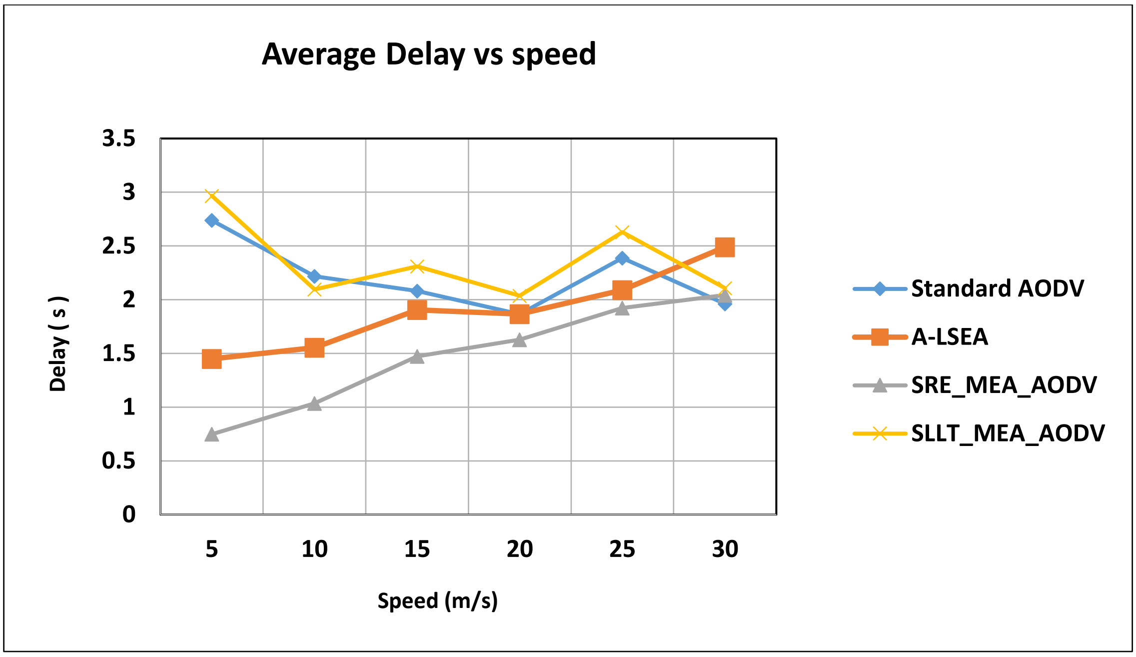


Figure 4.14 Average End-to-End Delay vs speed

4.3.3.4.8 ***Average Energy Consumption***

Average energy consumption exhibited in Figure 4.. The proposed algorithm, SRE_MEA_AODV outperforms the other three algorithms. This is because the nodes chosen by this scheme hold higher level of LLT alongside with remaining energy; RE_{avg} is calculated based on nodes with a good value of LLT that is equals or above the average LLTs. This, in turn, leads to less route breakage probability. In addition, since overhead reduced dramatically using this scheme, this also contributes to a huge energy saving throughout the network. SLLT_MEA_AODV, in contrast, does not show any saving in energy consumption when compared to the other three. This is due to the method adopted in this scheme that gives priority to energy concern before mobility. The nodes chosen by this scheme hold higher level of RE alongside with LLT; LLT_{avg} is calculated based on nodes with a good value of RE that is equals or above the average REs.

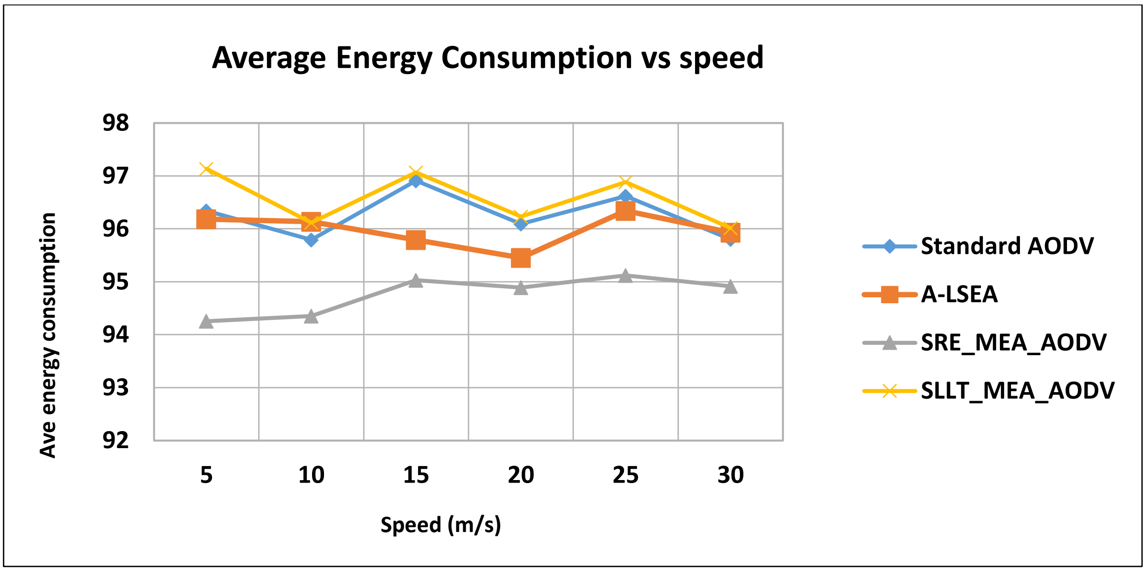


Figure 4.15 Average Energy Consumption vs speed

4.3.3.5 Performance Evaluation

In this section, Figure 4. to Figure 4. show the enhancement (%) achieved for the metrics discussed above for the two proposed algorithms SRE_MEA_AODV and SLLT_MEA_AODV compared to standard AODV (in (a)) and to A-LSEA (in (b)).

As for Packet Delivery Ratio, an enhancement range between 25% to 90% achieved with SRE_MEA_AODV comparing with standard AODV, and 5% to 25% comparing with A-LSEA. On the other hand, with SLLT_MEA_AODV, an enhancement range between -4.6% to 18 % achieved comparing with standard AODV, and -5.7% to -42.8% comparing with A-LSEA.

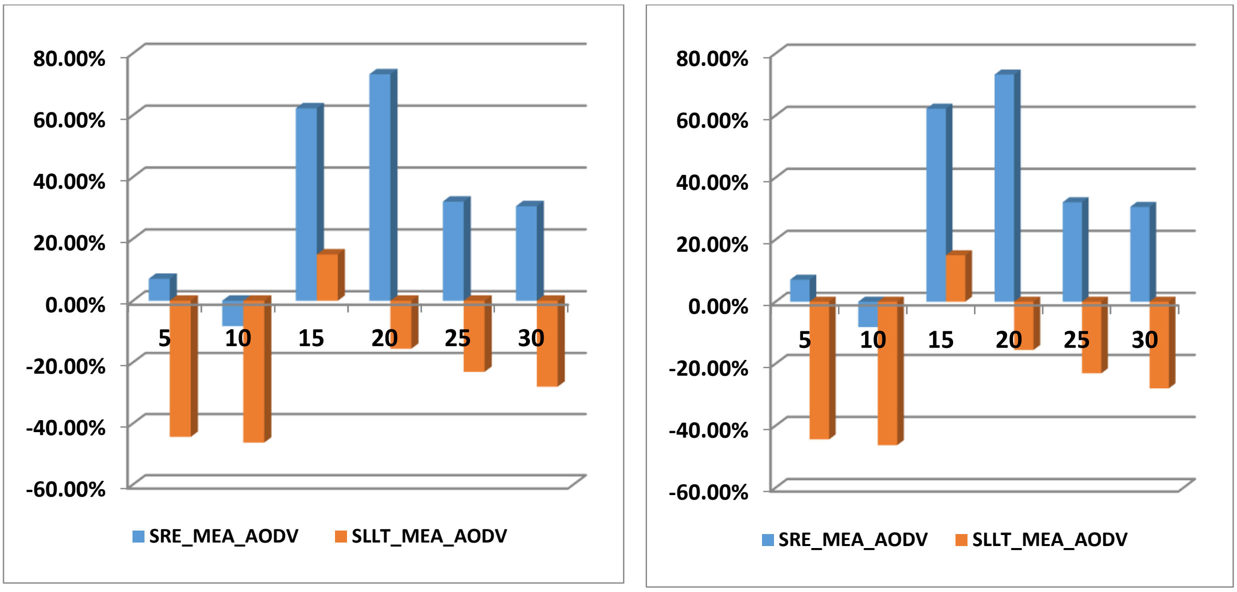
Overhead enhancement shown in Figure 4., an enhancement range between 1124% to 1632% achieved with SRE_MEA_AODV comparing with standard AODV, and 42.3% to 93.6% comparing with A-LSEA. On the other hand, with SLLT_MEA_AODV, an enhancement range between 117.5% to 157.2 % achieved comparing with standard AODV, and-70.1% to -75.5% comparing with A-LSEA.

Network Life time enhancement shown in Figure 4., an enhancement range between 71.4% to 134.4% achieved with SRE_MEA_AODV comparing with standard AODV, and -8% to 73.2% comparing with A-LSEA. On the other hand, with SLLT_MEA_AODV, an enhancement range between -0.2% to 33.8 % achieved comparing with standard AODV, and -46.3% to 14.9% comparing with A-LSEA.

Average End-to-End Delay shown in Figure 4., an enhancement range between -3.9% to 266% achieved with SRE_MEA_AODV comparing with standard AODV, and 8.7% to 93.8% comparing with A-LSEA. On the other hand, with SLLT_MEA_AODV, an enhancement range between -10 % to 5.7 % achieved comparing with standard AODV, and -51.2% to 18.2% comparing with A-LSEA.

Average Energy Consumption Enhancement shown in Figure 4., an enhancement range between 0.9% to 2.2% achieved with SRE_MEA_AODV comparing with standard AODV, and 0.6% to 2.1% comparing with A-LSEA. On the other hand, with SLLT_MEA_AODV, an enhancement range between -0.82 % to -0.15 % achieved comparing with standard AODV, and -1.31% to 0.02% comparing with A-LSEA.

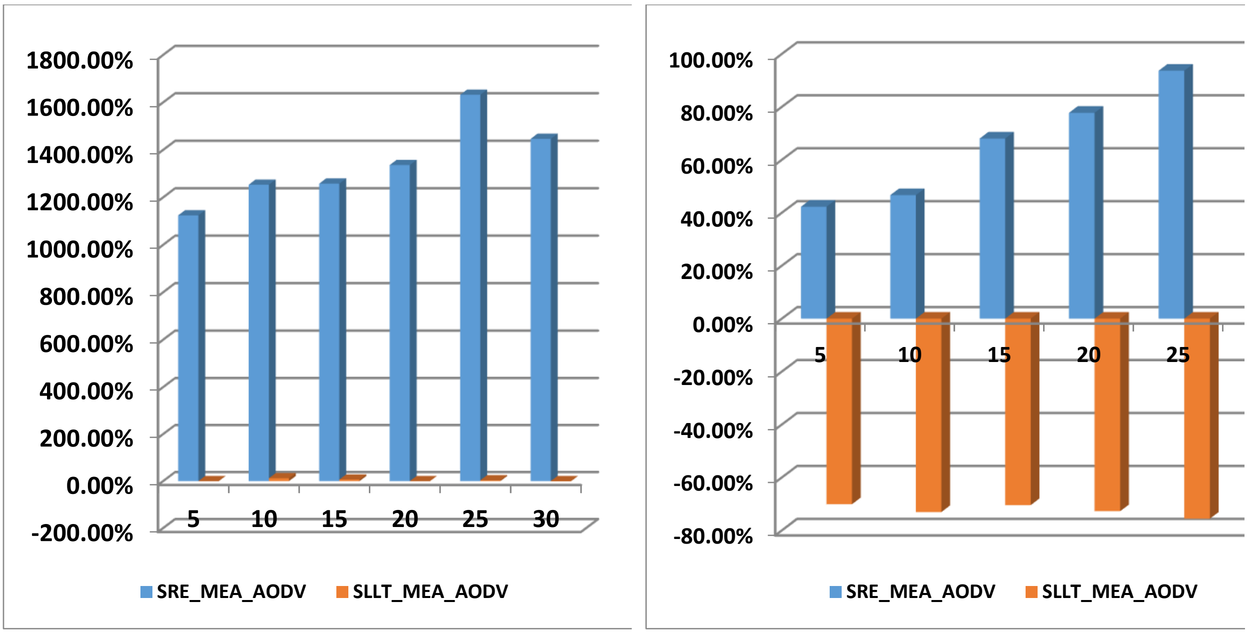
Finally, as for Throughput Enhancement (%) shown in Figure 4., an enhancement range between 110.8% to 186.9% achieved with SRE_MEA_AODV comparing with standard AODV, and 36.7% to 53.3% comparing with A-LSEA. On the other hand, with SLLT_MEA_AODV, an enhancement range between -1.1 % to 12.06 % achieved comparing with standard AODV, and -45.26% to -30.38% comparing with A-LSEA.



(a) ***Packet Delivery Ratio Enhancement (%) with proposed work vs Standard AODV***

(b) ***Packet Delivery Ratio Enhancement (%) with proposed work vs A-LSEA***

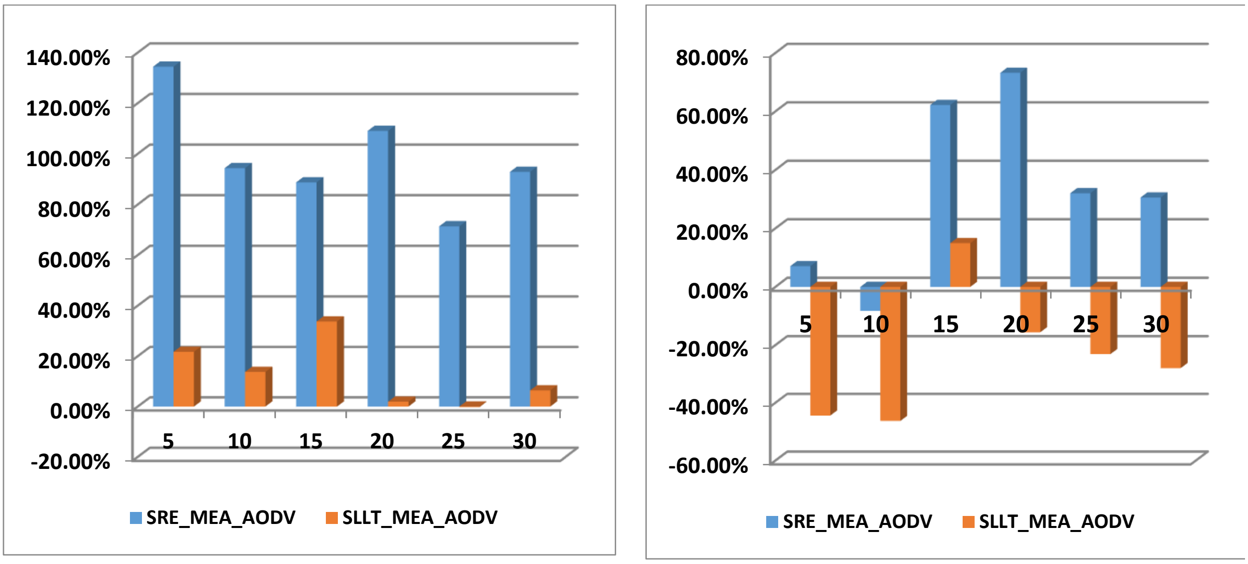
Figure 4.16 Packet Delivery Ratio Enhancement (%)



(a) ***Overhead Enhancement (%) with proposed work vs Standard AODV***

(b) ***Overhead Enhancement (%) with proposed work vss A-A-LSEA***

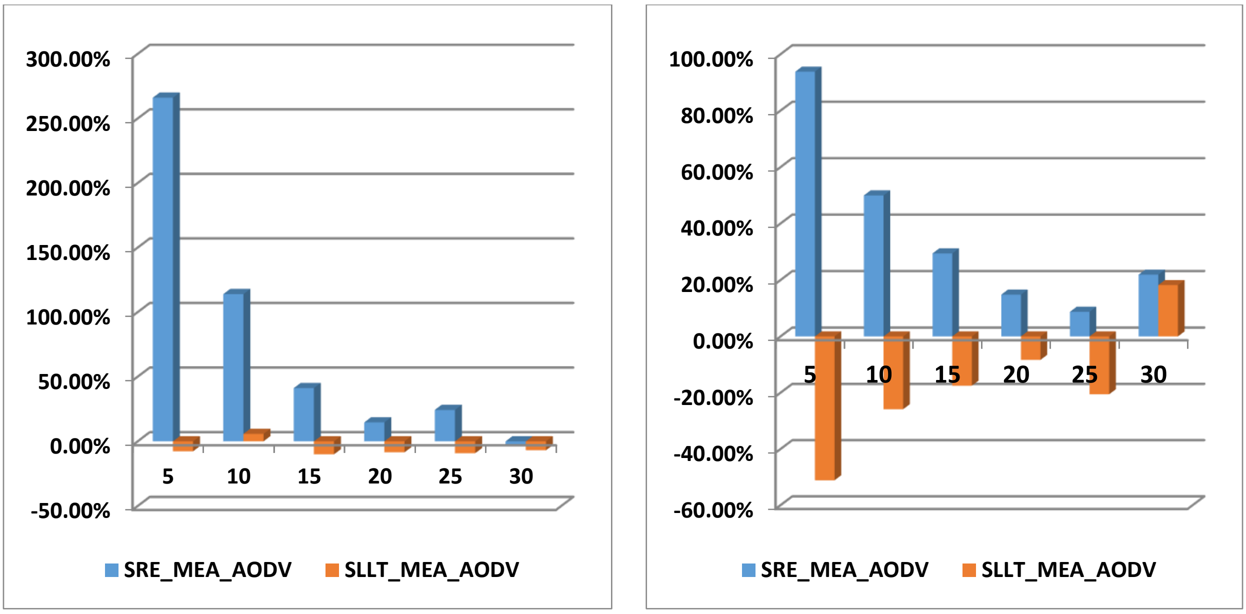
Figure 4.17 Overhead Enhancement (%)



(a) ***Network Life Time Enhancement (%) with proposed work vs Standard AODV***

(b) ***Network Life Time Enhancement (%) with proposed work vs A-LSEA***

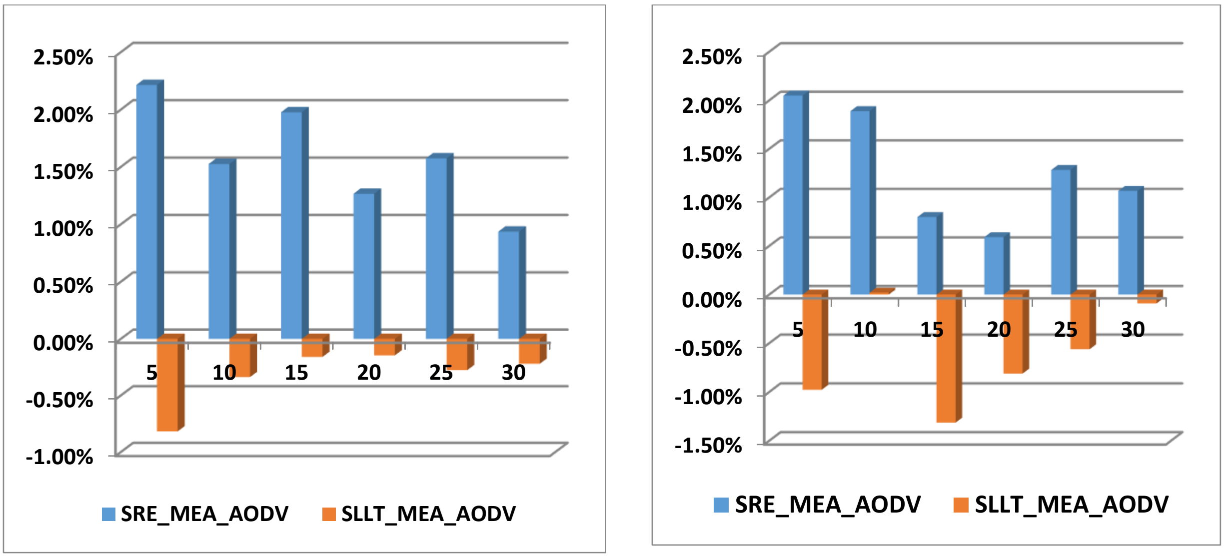
Figure 4.18 Network Life Time Enhancement (%)



(a) ***Average End-to-End Delay Enhancement (%) with proposed work vs Standard AODV***

(b) ***Average End-to-End Delay Enhancement (%) with proposed work vs A-LSEA***

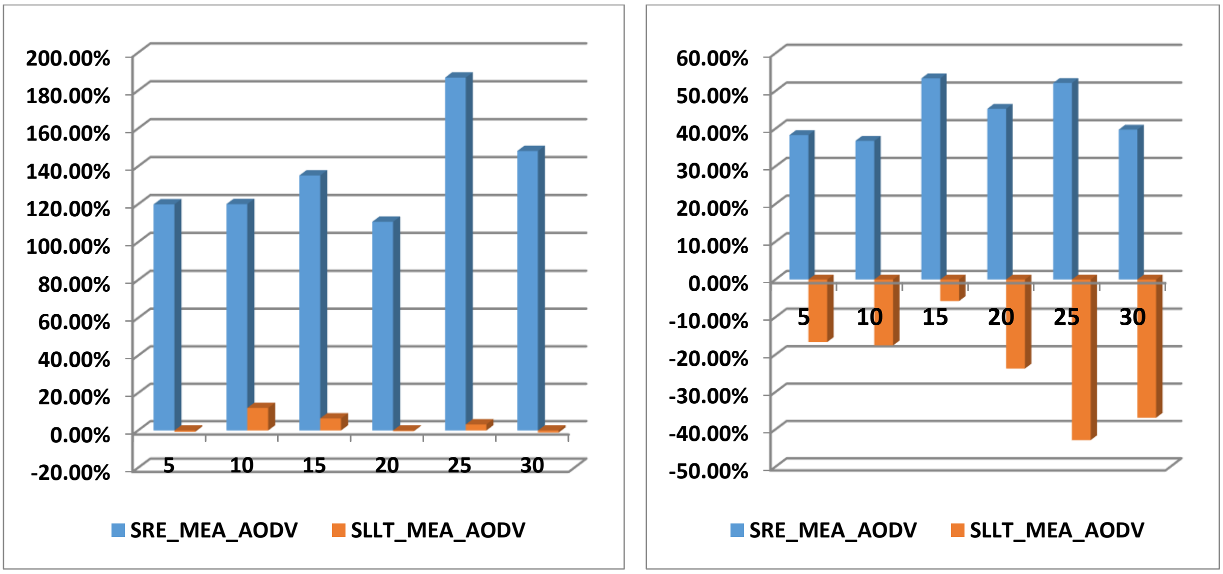
Figure 4.19 Average End-to-End Delay Enhancement (%)



(a) ***Average Energy Consumption Enhancement (%) with proposed work vs Standard AODV***

(b) ***Average Energy Consumption Enhancement (%) with proposed work vs A-LSEA***

Figure 4.20 Average Energy Consumption Enhancement (%)



(a) ***Throughput Enhancement (%) with proposed work vs Standard AODV***

(b) ***Throughput Enhancement (%) with proposed work vs A-LSEA***

Figure 4.21 Throughput Enhancement (%)

4.4 Summary

In MANETs, mobile nodes are free to move and form themselves with any mean of centralization. Any node can function as a sender, receiver or relaying node. Moreover, beside mobility, these nodes are mostly battery-based devices, which means power constrain affects the overall performance of MANETs. Hence, routing in MANETs is a challenging task. Classical routing protocols such as AODV or DSR do not consider the node' mobility or residual energy when they used to find a route between a source and a destination node. Consequently, frequent route failure, retransmission and packet dropping occur which lead to throughput and packet delivery ratio to degrade, increase of control overhead and delay, and eventually network life time is reduced.

Two novel Congestion, Mobility and Energy Aware Route-Discovery scheme for AODV in MANETs proposed, SRE_MEA_AODV and SLLT_MEA__AODV. These schemes bring the awareness of two important factors that degrade the overall network performance in MANETs: Node's mobility and remaining residual energy. Hence, route discovery process with proposed work is performed in adaptive manner. In other words, every intermediate node in the network, when participating in the route discovery process between a source and a destination, decides on it capability of handling the RREQ packet to next hop node or not based on few tests done at this node. If these tests passed, then the node rebroadcasts RREQ again. Otherwise, RREQ discarded. The schemes were tested using a mobile scenario in NS2 and promising result found. A good improvement of delivery ratio, total number of overheads, throughput, average delay, and average energy consumption has been achieved.

Chapter 5

Congestion, Mobility and Energy Aware Route-Discovery Scheme for AODV in Wireless Mobile Ad-Hoc Networks

5.1 Introduction

AODV is the dominant routing protocol widely adopted in Mobile Ad-Hoc Networks. It is a reactive protocol that has been proposed as an improvement to Destination Sequenced Distance Vector (DSDV) routing protocol [50]. The improvement aimed to overcome the huge amount of control packets that are necessary to keep the route information up to date in proactive protocols. Unlike proactive routing protocols where routing table is kept updated at every node in the network, AODV finds a route between a source and a destination only when needed. As illustrated in Figure 5.1, whenever a source node (S) seeks to communicate with a destination node (D,) it starts the route discovery process by propagating a RREQ packets to its neighbours (N1, N3, N4).

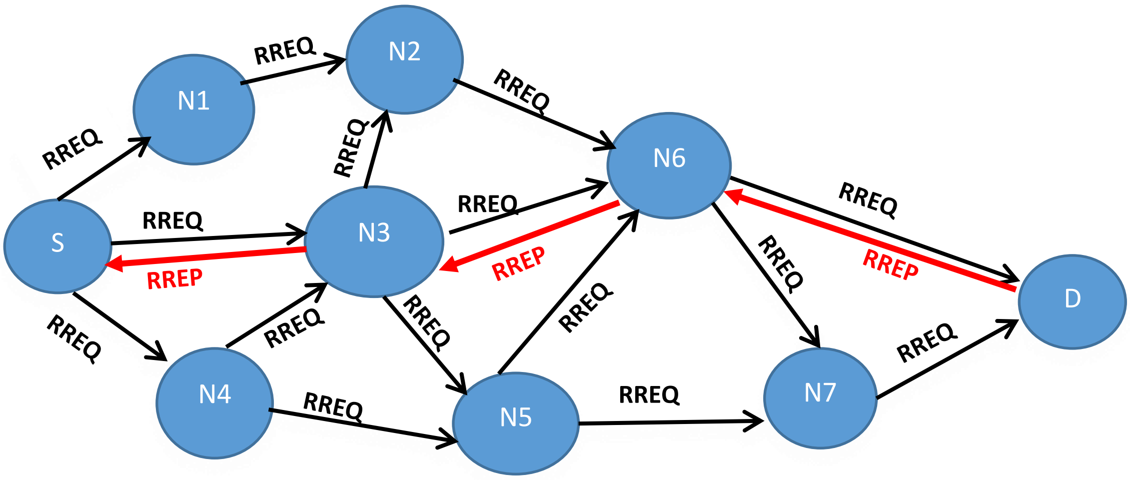


Figure 5.1 AODV route discovery process illustration

Each of these nodes consults its own table to check whether a valid route to destination exists. If it does, then a route reply is generated that states the entire route (S to D). Otherwise, these intermediate nodes keep forwarding the RREQ packet until it is received by destination (D). Here, when D receives a duplicated RREQ, it performs freshness check by checking the sequence number and hop counts. Then a route with minimum hop count (S, N3, N6, D) will be selected and a RREP will be sent back along that route [48].

Using a reactive routing protocols, such as AODV, route discovery process to a route from a source to a destination happens when needed. This saves network resources [18]. Mobility is one of the complex issues that challenge routing protocols in MANETS [37] [38]. Congestion in some parts of the network and the limited energy associated with the individual mobile nodes are other two issues. Hence, a vast amount of recent research focused on these issues in order to improve the QoS of routing in MANETs [51] [40] [41].

In this chapter, two novel congestion, mobility and energy aware route-discovery schemes for AODV in MANETs are proposed. These schemes do not only improve packet delivery ratio in MANETs, but also reduces average energy consumption, overheads and delay across the entire network.

5.2 Current research

Classical routing protocols, such as AODV, have evolved to new versions where main issue of mobility, congestion and energy constrain have been considered.

A mobility prediction scheme proposed in [37] employs GPS location information obtained and used to calculate a predicted link expiration time (LET) between two adjacent nodes. The LET is used to maintain link breakage. A route, whose accumulated LET between source and destination, is greatest is chosen by the destination. The scheme is tested in the form of unicast and multicast routing protocols and shows better packet delivery ratio compared to those protocols without mobility prediction. LET is given using the following equation:

Congestion concern is another direction of research of routing in MANETs. A dynamic congestion estimation technique was proposed in [51] that takes into account queue length capacity. The technique calculates the average queue length at each node and make use of it as a criterion to categorise the congestion status into three zones: congested, likely to be congested and safe zone. Two predetermined thresholds have been set to 35% of queue size as min and 70% as max. Then another scheme called Congestion Free Routing (CFR) is called to find a route between a source and a destination where congested zone is avoided. Compared with AODV, some improvement to packet delivery delay, control overheads and delay has been shown. However, the threshold values that serve as bases to this technique have not been examined and the value of the calculated average queue length that is utilised for zoning decision is not justified.

Discovering a path between a source and destination based on the minimum queue length has been proposed by [52]. A protocol called Queue-based Multipath Load Balancing (QMLB) has been proposed in order to overcome congestion. This protocol decides on the path that whose nodes have minimum queue length. Analysis shows improvement in packet delivery ratio and delay compared to standard AODV and another existing technique called FMLB. However, control overheads have increased twice comparing with AODV.

A round robin queue management scheme has been proposed in [53] to overcome congestion in MANETs. Packets within the buffer are managed by setting a threshold and a signal fed from MAC layer is used to manage the buffer at the node level. Having compared with FIFO, minor improvement shown in term of packet deliver ratio, throughput and energy consumption. However, the scheme assumes multi-channel transmission and it requires some changes to MAC layer.

In [54] a weighted load balancing routing scheme for MANET called WLBP has been proposed. In this scheme an aggregate weight consisting of aggregate energy, queue length and hop count for entire route between source and destination is calculated at the destination. Then route selection is determined by the destination based on highest value of this weight. The scheme has been evaluated in comparison with AODV, and minor improvement shown in terms of routing load and average end-to-end delay. However, assigning the destination route section decision increases the overall control overheads. Thus, delivery ratio and network life time would be impacted.

Mobility and power aware routing algorithm based on node's location information called PMAR has been proposed in [47]. A heuristic scheme proposed to optimise the route selection based on power and mobility. Performance has been evaluated in static and mobile network in terms of network life time only.

5.3 The proposed work

5.3.1 Problem statement

Route breakage is a serious issue that routing in MANETs experiences. This issue leads to packet dropping and poor QoS of the entire network. It is mainly due to three main reasons: Congestion, high node mobility and the limited residual energy of the node. The node in MANETs is completely free to move in any direction which results a topology change and congestion may occur. A common congestion scenario is when some intermediate node' buffers get filled. Thus, these nodes when participating in new routes, these routes are likely to break. To illustrate node's buffer effect, let's consider a MANET scenario presented in Figure 5.2. In this scenario, S is a source node, D is a destination. Nodes A, B, K, L are intermediate nodes between S and D within the transmission range. Numeric percentage values associated with each of the nodes represent the current queue length of these nodes.

When S tries to find a route to D, a RREQ is generated by S and broadcasted. Nodes A and K receive RREQ and record S as a reverse route in their routing tables. Then RREQ is rebroadcasted by these nodes to reach B and L. Again these nodes record their previous nodes A and K respectively in their routing tables as reverse routes to S. RREQ is rebroadcasted further until it reaches D. Two RREQ packets are received by D: one from B and another from L. Now D has to decide on the route whether S-A-B-D or S-K-L-D to send a RREP backward to S. If S-A-B-D is selected, and due to the buffer in B is almost full (QL in B is 93%) there are two possible scenarios. The first one is that when RREP is sent back to B the buffer is full and the Packet is dropped which results to reinitiate route discovery process. The second scenario is RREP can survive and get its way back to S, but after sending a few data packets, the buffer in B gets full. Then, packets dropped and this leads to reinitiate route discovery process.

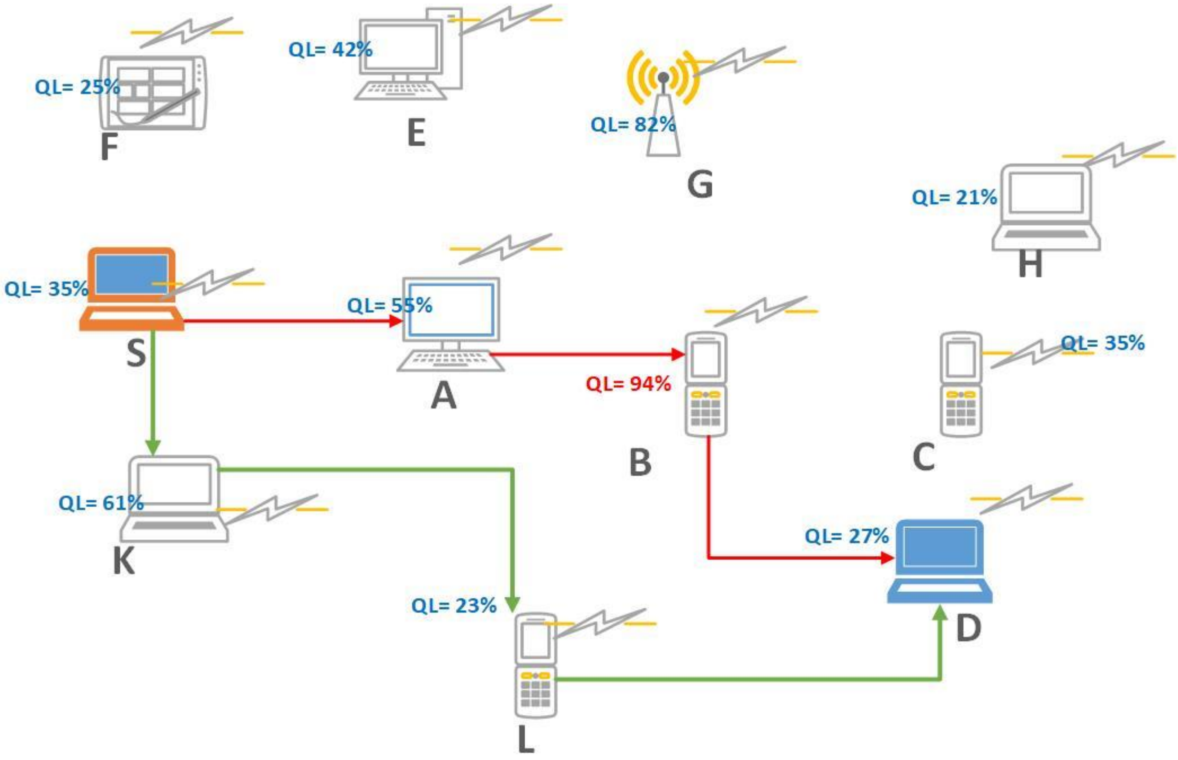


Figure 5.2 Node's buffer effect in MANET

5.3.2 Congestion, Mobility and Energy aware route discovery schemes AODV in Wireless Mobile Ad-Hoc Networks (CMEA_AODV)

In this section the proposed work called Congestion, Mobility and Energy aware route discovery schemes for AODV is presented. This work uses A-LSEA [3] to propose two new algorithms that not only aware of congestion and link stability in MANETs, but also is aware of the remaining energy of all active nodes that are neighbours to that relaying node. These algorithms are:

- Adaptive Managed Buffer_ route discovery scheme for AODV (AMB_AODV)
- Adaptive Managed Buffer and Selective Remaining Energy route discovery scheme for AODV (AMB_SRE_AODV)

The main idea in the proposed work is to adaptively selecting an intermediate node while choosing the forwarding node during route discovery process. The node checks its buffer by examining the queue length value against a predetermined threshold. If current value of QL does not exceed the threshold, node would be potentially able to carry on, and the RREQ packet is rebroadcasted. However, if buffer is full or likely to be full, then the RREQ is discarded.

5.3.2.1 Adaptive Managed Buffer route discovery scheme for AODV (AMB_AODV)

In order to bring the awareness of congestion in route selection during route discovery process in AODV [48], a new algorithm is proposed called Adaptive Managed Buffer route discovery scheme for AODV (AMB_AODV) in MANETs. This scheme works as follow:

Let us consider the scenario presented in Figure 5.3 where S is a source node that needs to search for a route to a destination D. N1 to N3 are intermediate nodes. When S seeks to communicate with D, it starts the route discovery process by propagating a RREQ packet. N1, the next hop node, receives it and starts the AMB_AODV process. It checks its current QL with Thr. Since QL1 > Thr, N1 is considered to participate in the route formation and it rebroadcasts RREQ. Nodes (N2, N3) are neighbours to N1. Upon receiving RREQ, each of N2 and N3 performs AMB_AODV check. Here, due to QL2 > Thr, N2 is considered to be congested and not suitable to participate in the route formation, and RREQ is discarded. On the other hand, N3 passes the check as it QL3 < Thr, and it rebroadcasts RREQ. Then, D receives RREQ and issues a RREP through N3-N1-S. Figure 5.4 shows a flow chart that illustrates SRE_MEA_AODV processes of receiving a RREQ at any node.

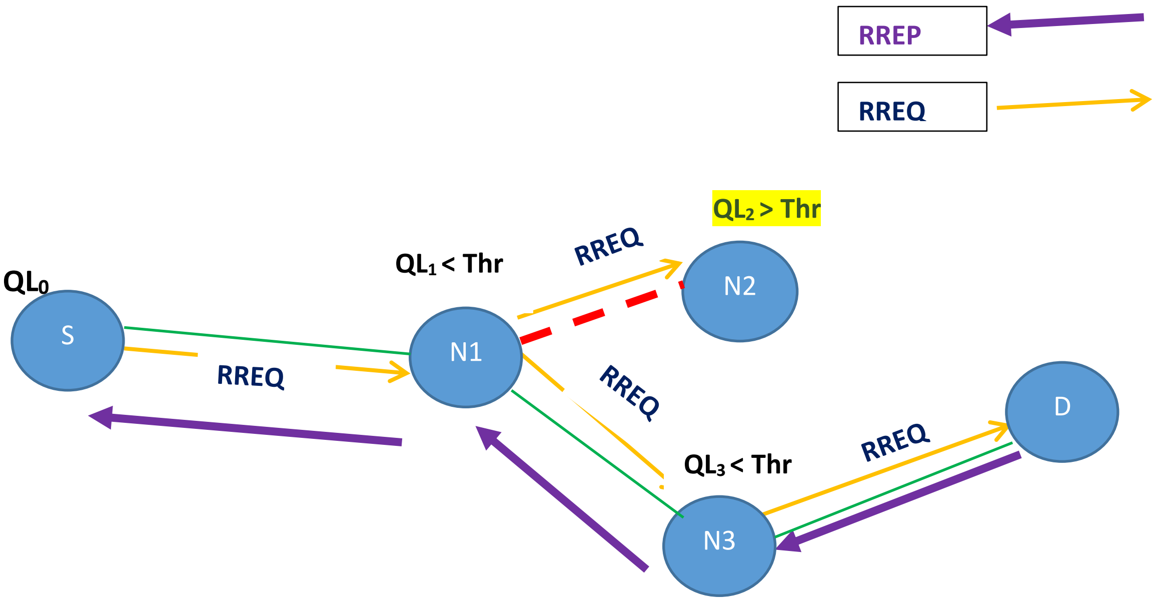


Figure 5.3 Illustration of AMB_AODV

5.3.2.2 *Adaptive Managed Buffer and Selective Remaining Energy route discovery scheme for AODV (AMB_SRE_AODV)*

Adaptive Managed Buffer and Selective Remaining Energy route discovery scheme for AODV (AMB_SRE_AODV) is another algorithm proposed in the this chapter to bring the awareness of congestion, mobility and residual energy in route selection during route discovery process in AODV along with maintaining a better degree of end-to-end route stability. This algorithm, similar to AMB_AODV, uses the same concept of deciding on a node that satisfy the buffer management condition that mentioned earlier. However, combines this scheme with the proposed scheme called SRE_MEA_AODV that has proposed in Chapter 4. Hence, AMB_SRE_AODV is selective while deciding on the forwarding node. The intermediate node, in addition of examining the buffer status, it checks its reaming energy and link life time against the average value of these two parameters. Thus, the first check of buffer status is performed first. Then, the computation of the average of the link life time takes all neighbourhood nodes into account, and then the second check is performed. As for the third check, here, only neighbour nodes that passed the first and second checks are taken for the computation of the average value of remaining energy; meaning, it takes only nodes that has satisfied the first and second conditions, excluding those nodes that fail to satisfy the first and second conditions.

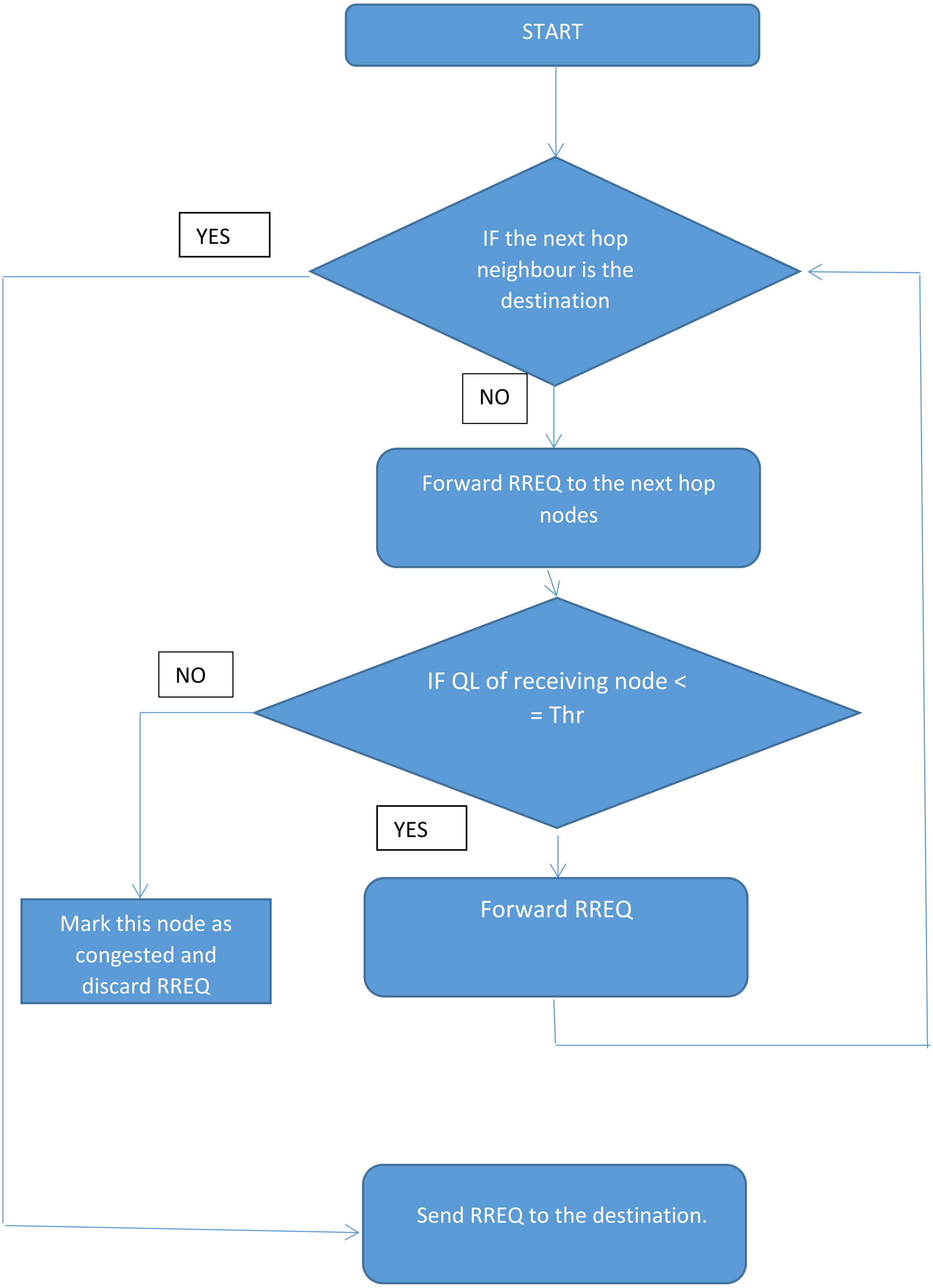


Figure 5.4 Flow Chart illustrates AMB_AODV processes of receiving a RREQ at any node.

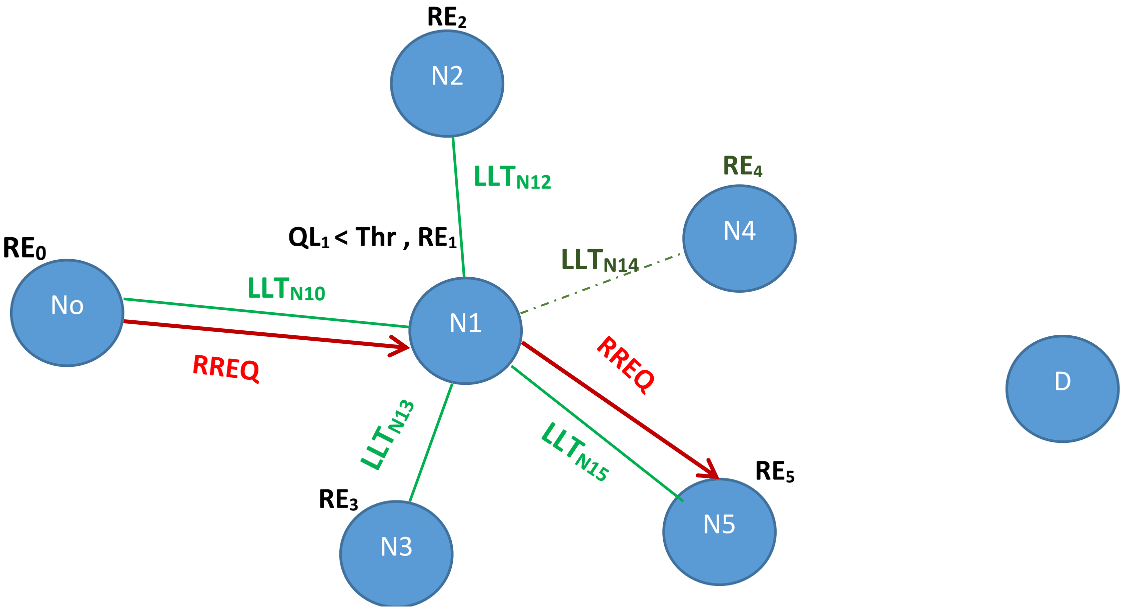


Figure 5.5 Illustration of AMB_SRE_AODV

In order to clarify the way it works, scenario in Figure 5.5 is considered. When N0 seeks to communicate with D, it starts the route discovery process by propagating a RREQ packet. N1, the next hop node, receives it and starts the AMB_SRE_AODV process. Meaning, QL1 is examined against the threshold. In the above scenario, QL1 < Thr which triggers the second check.

Since nodes (N2, N3, N4, N5) are neighbours to N1, it first collects the link life times with all of its neighbours (LLT_{N10}, LLT_{N12}, LLT_{N13}, LLT_{N14} and $LLTN_{15}$) and computes the average link life time LLT_{avg} using equation 5.1.

$$LLT_{Avg} = \sum_{i=1}^{n} \frac{LLT_i}{n} = \frac{(LLT_{N10}+LLT_{N12}+LLT_{N13}+LLT_{N14}+LLT_{N15})}{5} \quad ; n = 2,3,4,5 \quad (5.1)$$

Having calculated the first parameter (LLT_{avg}), N1 checks (LLT_{N10}, LLT_{N12}, LLT_{N13}, LLT_{N14} and LLT_{N15}) against (LLT_{avg}). The outcome of this check is important as it determines those nodes that go into the second average computation. That is RE_{avg}. For example, in the scenario shown in Figure 4., let us assume LLT_{N14} is less than (LLT_{avg}). This means RE4 is excluded from RE_{avg} computation. In other words, RE_{avg} is calculated as follow:

$$RE_{Avg} = \sum_{i=0}^{n} \frac{RE_i}{n} = \frac{(RE_0+RE_1+RE_2+RE_3+RE_5)}{5} \quad ; n = 0,1,2,3,5 \qquad (5.2)$$

At this point, having obtained LLT_{avg} and RE_{avg}, N1 performs the second stage check which is a combination of two condition together (LLT1 & RE1) are greater or equal to (LLT_{avg}

& RE_{avg}). If this combined condition is satisfied, then RREQ is rebroadcasted. Otherwise, it is discarded. Figure 5.6 shows a flow chart that illustrates SRE_MEA_AODV processes of receiving a RREQ at any node.

In the next section, , the proposed mechanism is shown as promising technique to improve throughput, delivery ratio, Average delay, overheads and network life time through computer simulations.

5.3.2.3 Performance Metrics

The following metrics have been used to evaluate the proposed algorithms:

- **Total Data Sent:** the total amount of data sent from the sender throughout the network.
- **Total Data Received:** the total amount of data received by the destination.
- **Packet Delivery Ratio:** the ratio of those data packets successfully delivered to the destinations to those generated by the CBR sources.
- **Total Overhead:** the number of control packets transmitted in the network, including the RREQ, RREP, RERR and hello messages.
- **Throughput:** number of packets divided by the duration.
- **Packet dropping Ratio:** the ratio of number of dropped packets to number of sent packets.
- **Network Life Time:** The aggregate times before all nodes die due to battery exhaustion.
- **Average End-to-End Delay:** the average delay of all possible delays caused by buffering during the route discovery and link recovery phases, queuing at the interface queues and retransmission delays at the MAC layer.
- **Average Energy Consumption:** Total energy consumption divided by the number of nodes.

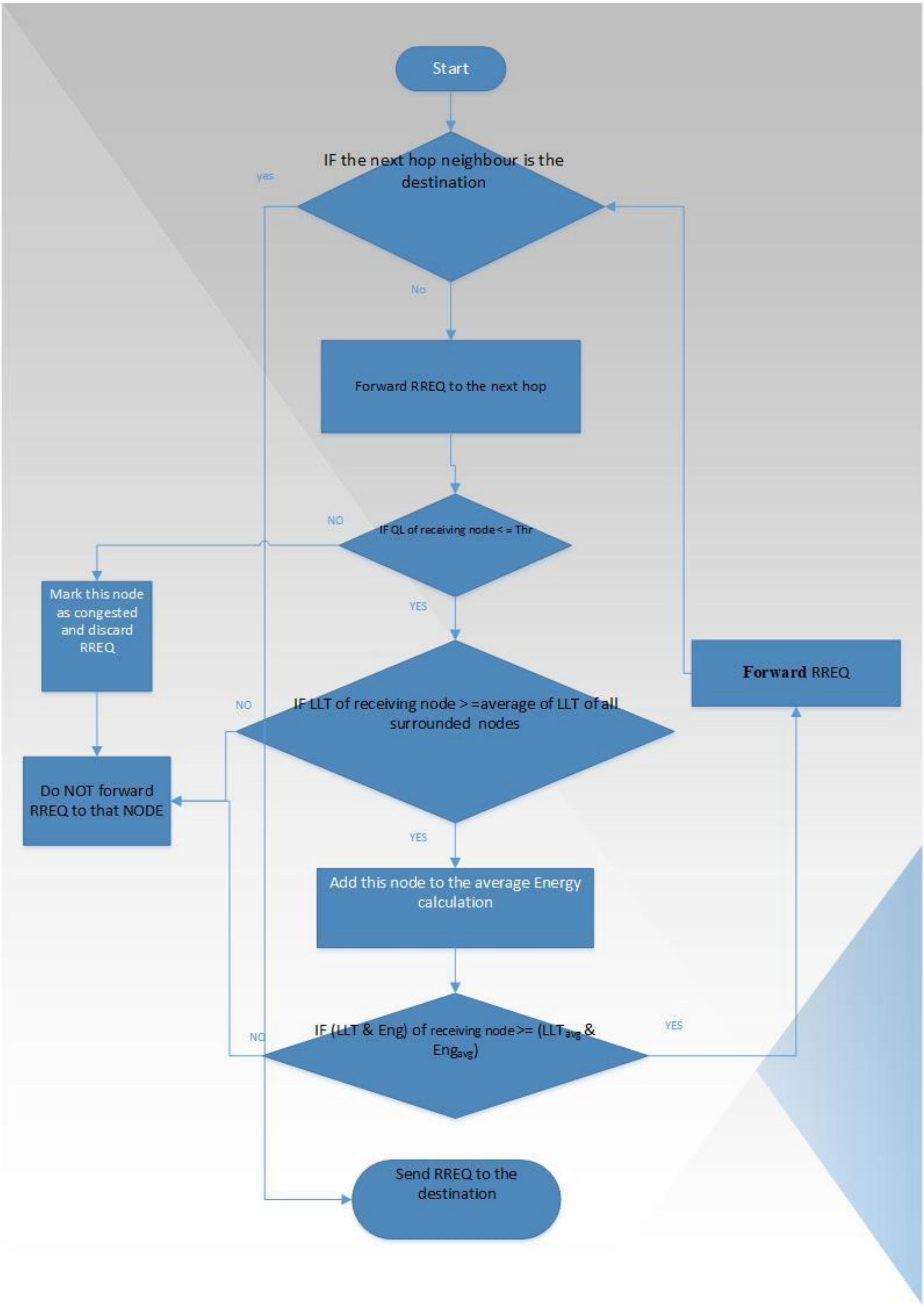


Figure 5.6 Flow Chart illustrates AMB_SRE_AODV processes of receiving a RREQ at any node

5.3.2.4 Numerical results and analysis from the proposed work

The proposed algorithms ((AMB_AODV) and (AMB_SRE_AODV)) have been implemented in ns2 [49] platform for comparing the proposed work with AODV.

A mobile topology scenario consists of 100 nodes distributed randomly in an area of 1000m x 1000m is implemented in ns2. The transmission range is 250 m, and the carrier sensing range is 550 m. Each link has a bandwidth of 1 Mbps. The application is CBR over udp connection. Random Waypoint model was used to simulate the nodes' mobility. In the Random Waypoint model, each node starts to move from its location to a random location with a randomly chosen speed from a minimum speed equal to 5 m/s and maximum speed equal to 25 m/s. Energy model is used. The simulation time is 600s. Table 4-1 shows the simulation parameters for this scenario. Simulation ran 5 times then average of results calculated.

Table 5-1: NS2 scenario simulation parameters

Environment parameter	**Value**
Channel type	Wireless channel
Radio propagation model	Two Ray Ground
Mobility model	Random Waypoint
MAC type	802.11
Transmission range	250 m
Carrier sensing range	550 m
Interface queue type	Drop Tail/ PriQueue
Max packet in ifq	100
Application	CBR (1000 Bytes)
Type	Mobile

Nodes	100
Number of Connections	20
Pause	2 s
Speed (m /s)	5, 10, 15, 20, 25
send rate	0.2
Coordination	1000 m x 1000 m
Simulation time	600 s

Using energy model in NS2 simulator requires assigning values to initial energy of the network's nodes. Thus, the mobile nodes were divided into 10 groups (10 nodes each). A random distribution function (NORM(100,20)) has been used to create 10 different values of initial energy values with mean of 100 and standard deviation = 20. These values are: 118, 115, 94, 131, 95, 94, 135, 85, 62, 68.

The proposed algorithms have been tested with six different QL Threshold values: 90%, 80%, 70%, 60%, 50% and 40%. Then the performance metrics of the proposed work has been averaged in order to evaluate the performance.

5.3.2.4.1 Total data sent

Total data sent of the proposed algorithms compared to standard AODV is shown in Figure 5.7 As can be seen, with standard AODV more data can be sent comparing to the first proposed algorithm AMB_AODV. However, AODV has been outperformed by the second proposed algorithms AMB_SRE_AODV. This is due to the end to end link stability provided by the second proposed work.

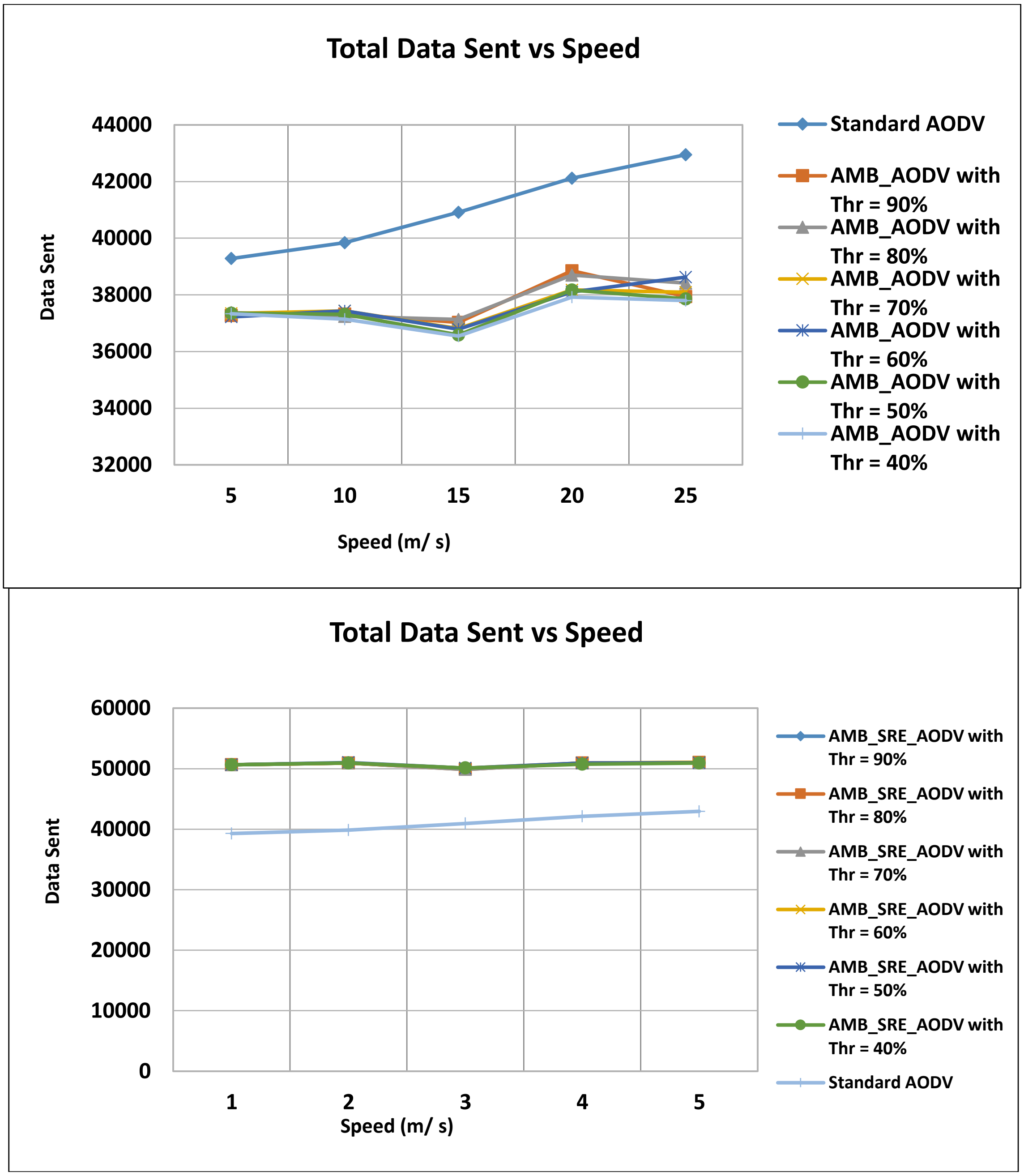


Figure 5.7 Total Data Sent vs Speed

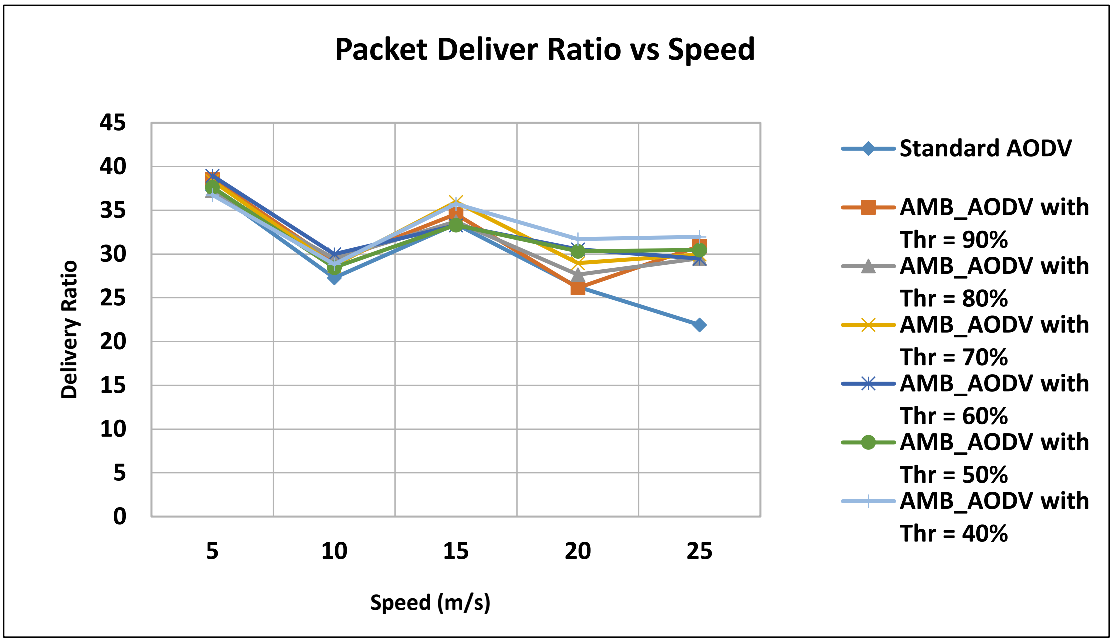
5.3.2.4.2 Total Data Received

Total data received of the proposed algorithms is compared to standard AODV as shown in Figure 5.8. As shown with total data received, standard AODV is outperformed by the two proposed algorithms. Congestion control and end to end link stability provided by this scheme is the main reason for this outperformance.

Figure 5.8 Total Data Received vs Speed

5.3.2.4.3 Packet Delivery Ratio (PDR)

Figure 5.9 shows packet delivery ratio performance of the two proposed schemes in comparison to standard AODV. Here, both schemes show a real improvement in terms of packet delivery ratio when compared to standard AODV. As with the first scheme, the packet delivery ratio varies with threshold value variation. For low Thr value (40%) highest PDR achieved.



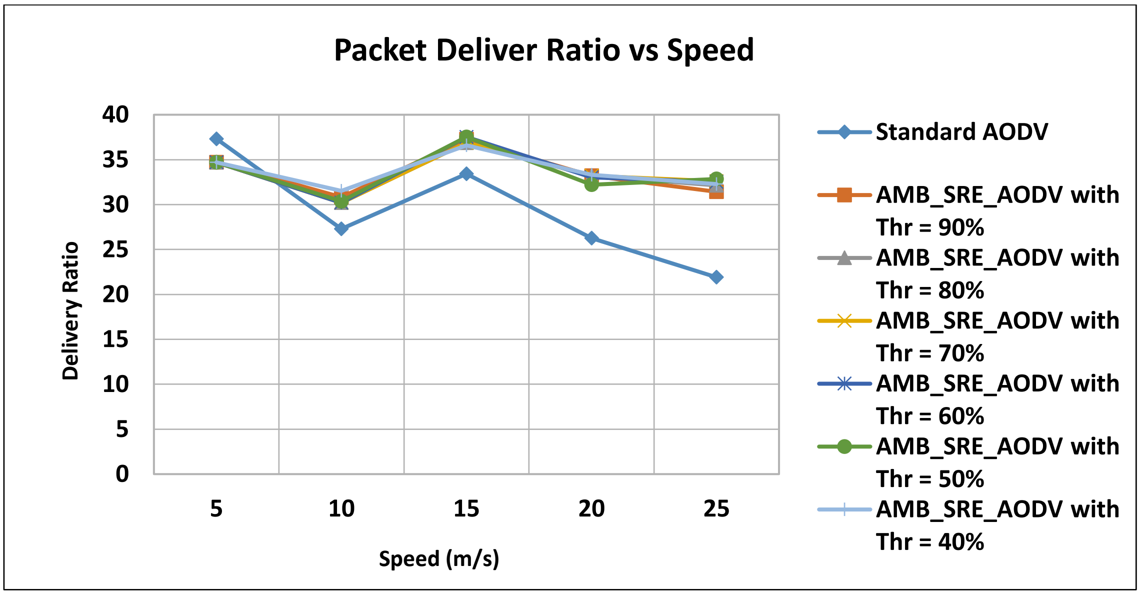
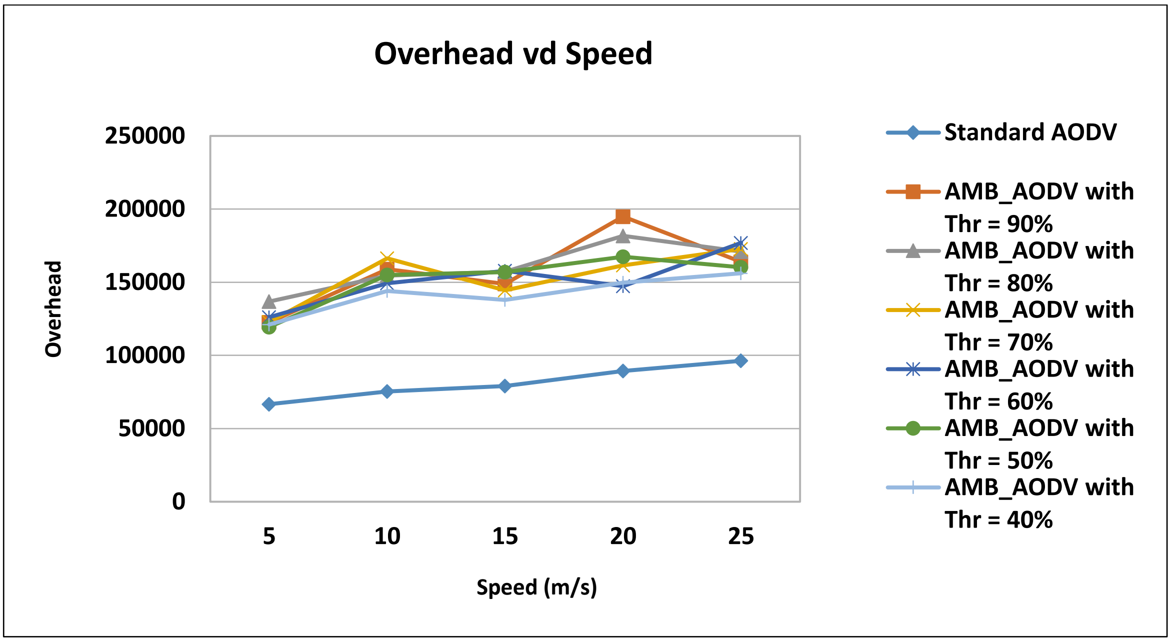


Figure 5.9 Packet Delivery Ratio vs Speed

5.3.2.4.4 Total Overhead

Total number of overhead for standard AODV, AMB_AODV and AMB_SRE_AODV has been compared and shown in Figure 5.10. with AMB_AODV overhead has increased due to the restriction on the buffer applied. In here, higher values of threshold lead to larger number of control overhead due the congestion status is more serious. However, with AMB_SRE_AODV a huge reduction in number of RREQ that is utilised in the proposed algorithms, the overhead is decreased dramatically comparing to standard AODV. This is because of the enhancement to the link stability and work on selecting nodes that have better capability to handle the data. . Moreover, AMB_SRE_AODV shows better stability with high mobility represented in higher speed.



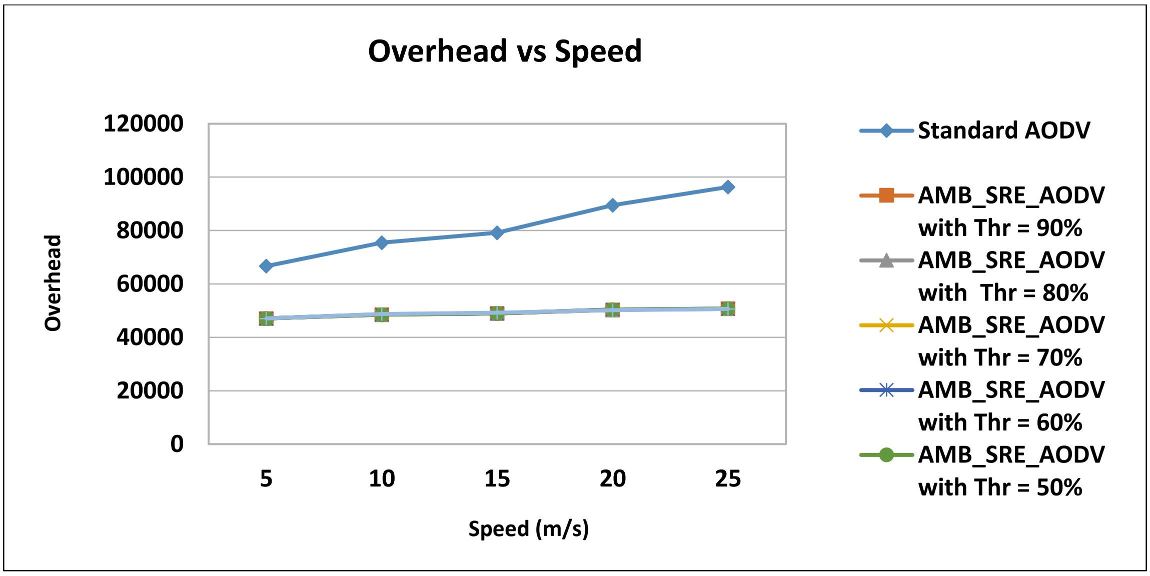


Figure 5.10 Overhead vs Speed

5.3.2.4.5 Dropping Packet Ratio

Dropping Packets Ratio is compared for the three schemes. As shown in Figure 5.11, the proposed work outperforms standard AODV due to the congestion awareness provided with this work.

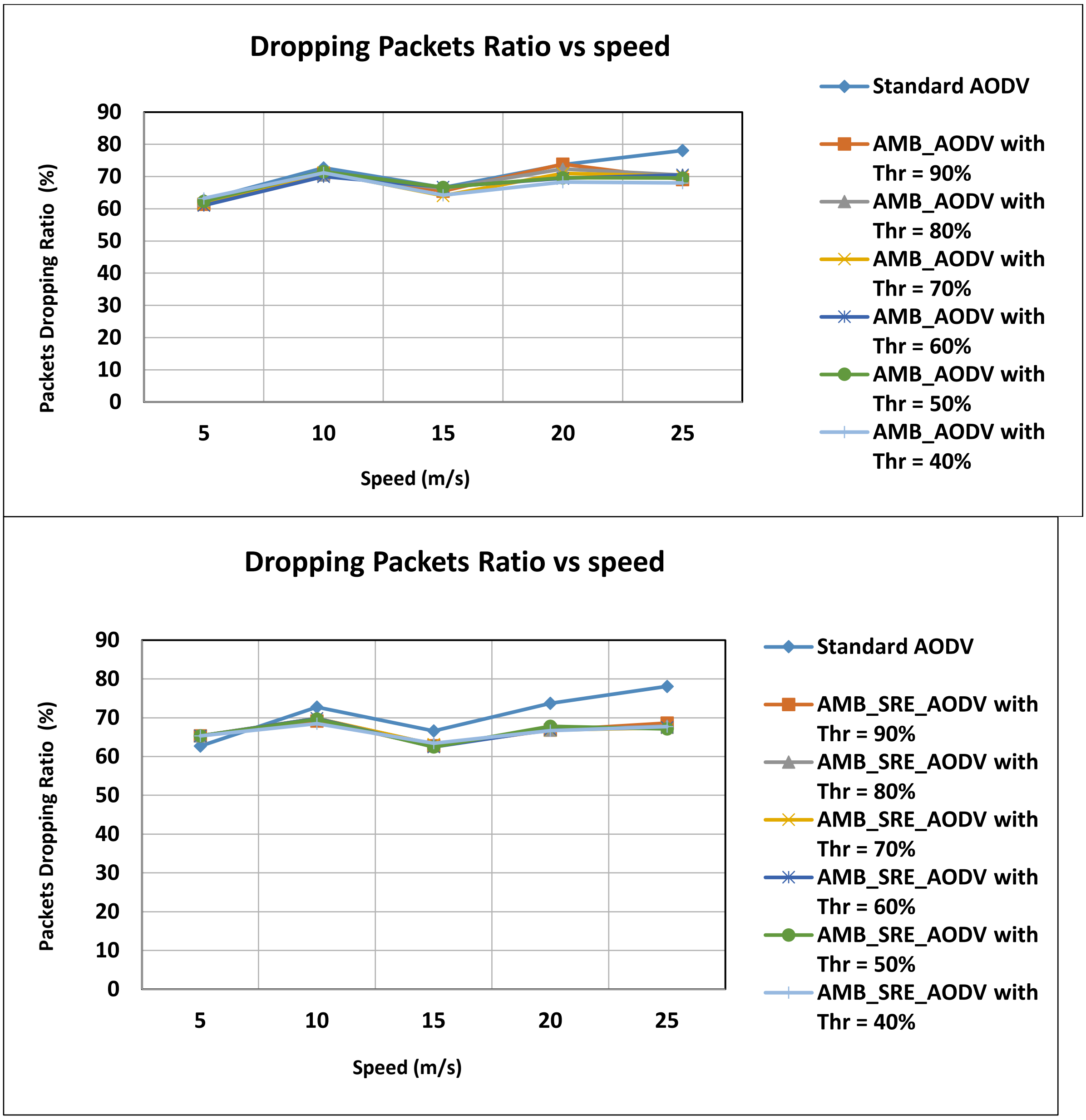


Figure 5.11 Packet Dropping Ratio vs Speed

5.3.2.4.6 Network Life Time

Network life time is compared for the three schemes. As shown in Figure 5.12, this metric does not show great improvement comparing to standard AODV. This is simply because AODV lasted nearly to the end of simulation time, leaving no rooms for the proposed work to show its performance.

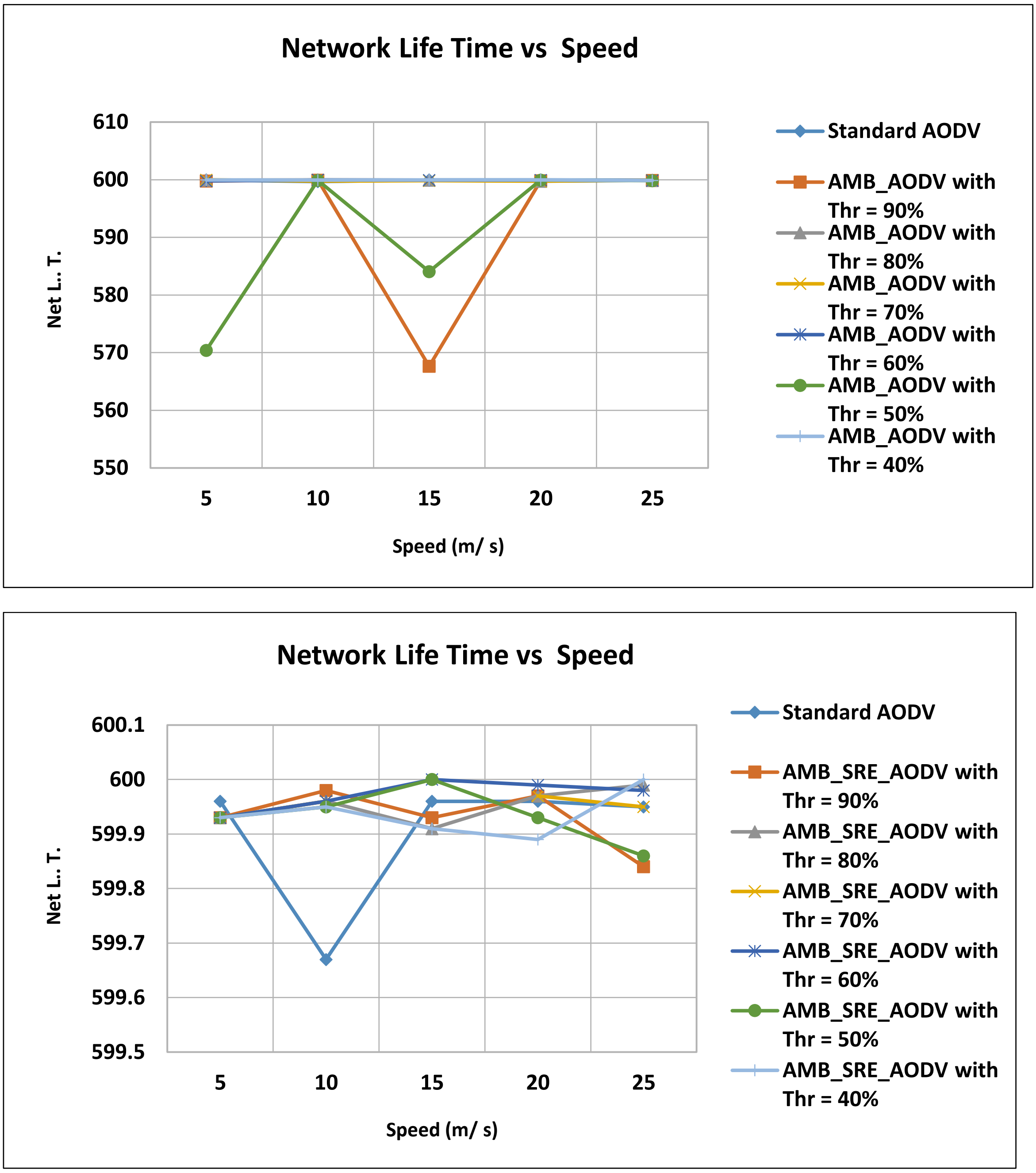


Figure 5.12 Network Life Time vs Speed

5.3.2.4.7 Throughput

Figure 4. compares the achieved throughputs by using the two proposed algorithms in comparison with Standard AODV. It is clear from the results in Figure 5.13 that the AMB_SRE_AODV algorithm significantly outperforms standard AODV. The reason is that route stability has improved which reflected in favour of data sent and received throughout the entire network during the network life time.

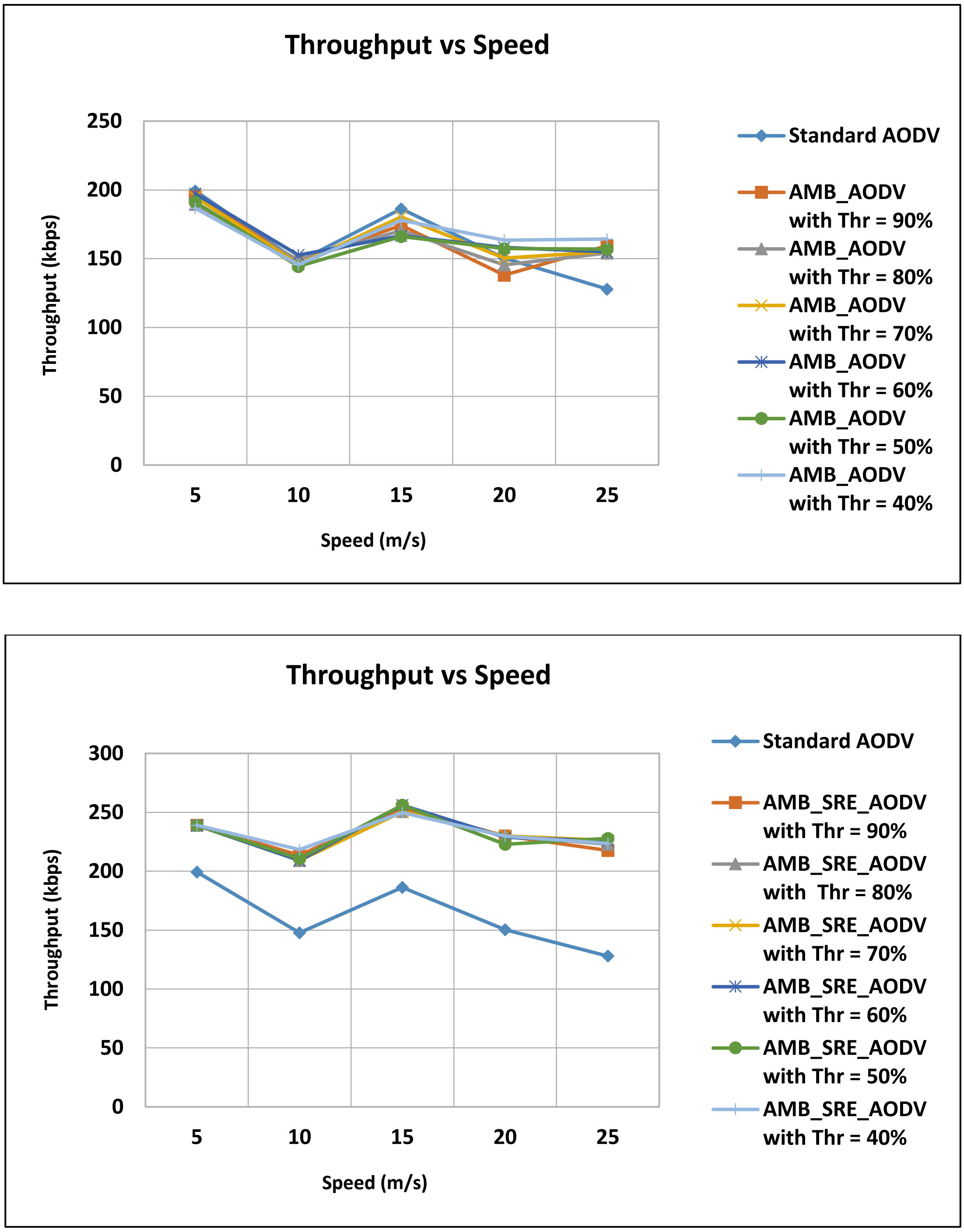


Figure 5.13 Throughput vs Speed

5.3.2.4.8 Average End-to-End Delay

Average end-to-end delay for the four the three schemes is presented in Figure Figure 5.14. As the figure shows, AMB_AODV performance fluctuates according to the QL threshold value and the speed. Thus, with lower speeds (5 – 10) AMB_AODV outperforms AODV. Moreover, as with AMB_SRE_AODV, it is clear that this algorithm outperforms the other algorithms in terms of delay. This is due to the improved quality of end to end route that accompanies route discovery process in this proposed algorithm.

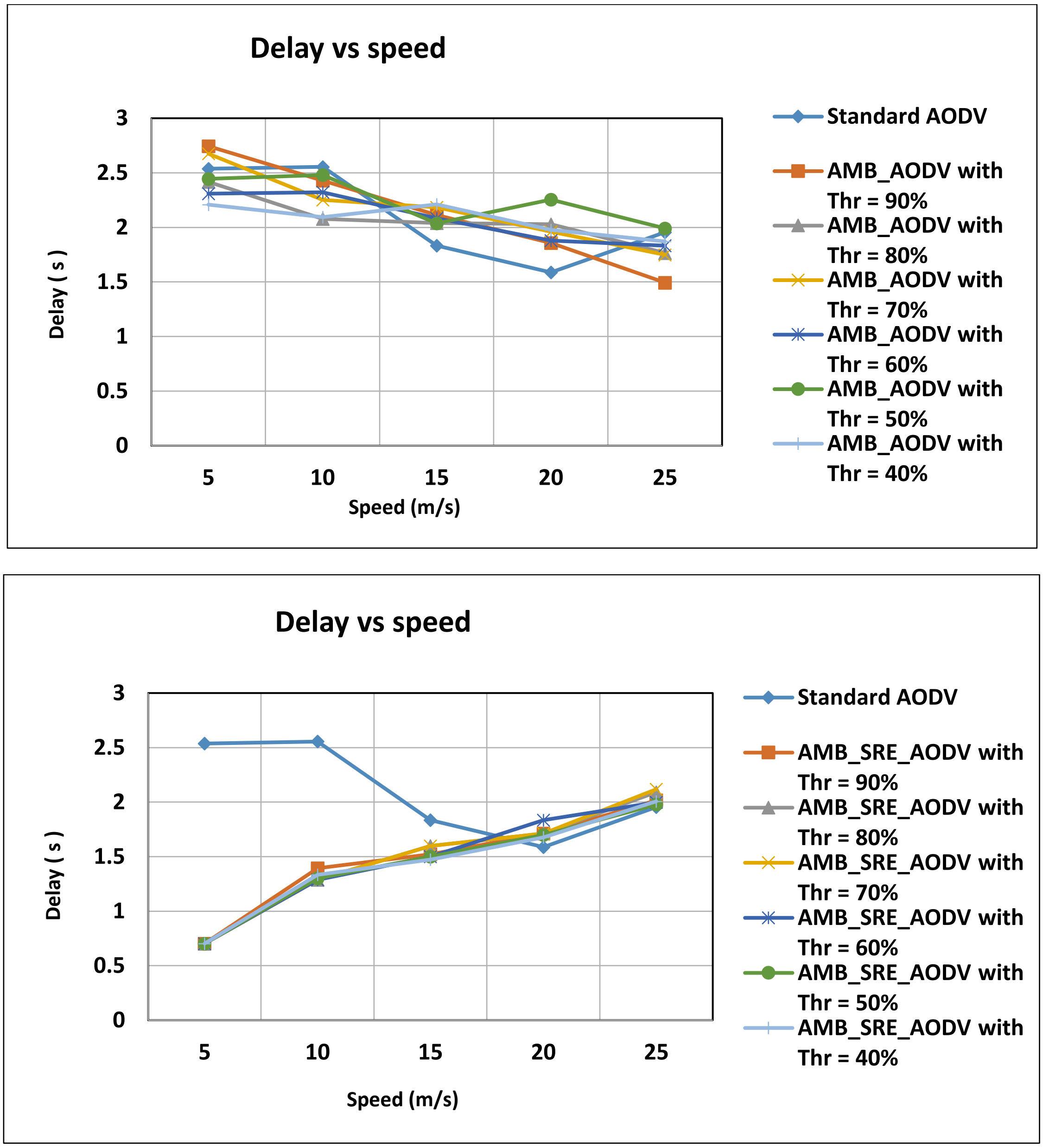
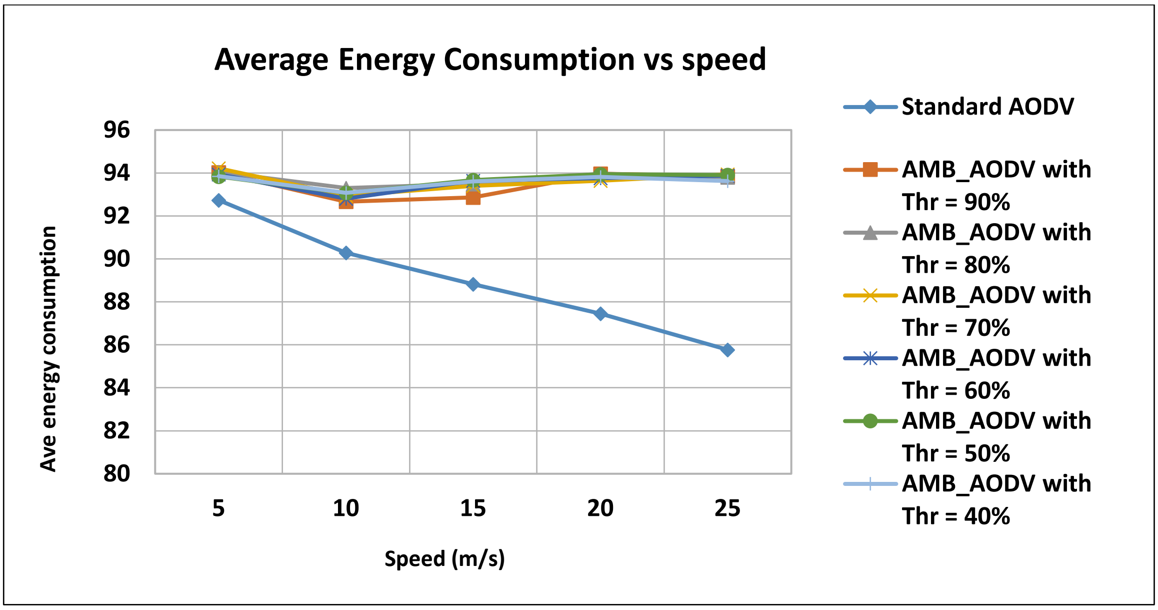


Figure 5.14 Average End-to-End Delay vs speed

5.3.2.4.9 Average Energy Consumption

Average energy consumption exhibited in Figure 5.15. This metric has not improved with the first proposed algorithm, AMB_ AODV as only congestion awareness is taking into account with this scheme. However, with the second proposed AMB_SRE_AODV average energy consumption improves dramatically compared with standard AODV. This is because the nodes chosen by this scheme hold higher level of LLT alongside with remaining energy; RE$_{avg}$ is calculated based on nodes with a good value of LLT that is equals or above the average LLTs. This, in turn, leads to less route breakage probability. In addition, since overhead reduced dramatically using this scheme, this also contributes to a huge energy saving throughout the network.



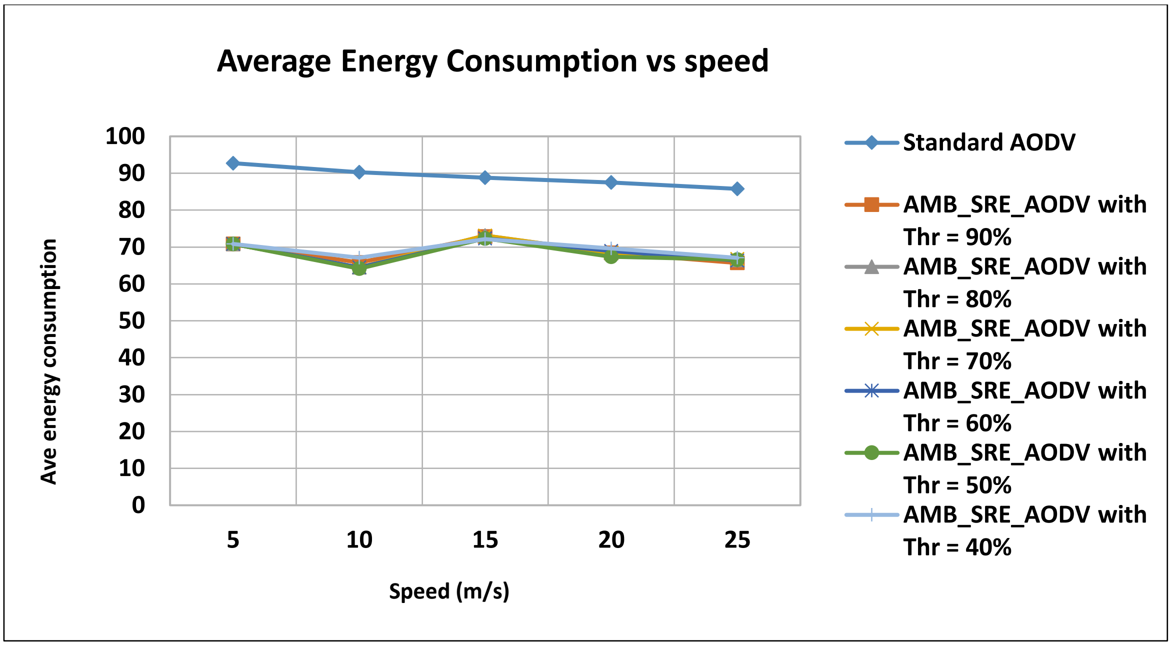


Figure 5.15 Average Energy Consumption vs speed

5.3.2.5 Performance Evaluation

In this section, Figure 4. to Figure 4.5.21 show the enhancement (%) achieved for the metrics discussed above for the two proposed algorithms AMB_AODV and AMB_SRE_AODV compared to standard AODV.

As for Packet Delivery Ratio (Figure 5.16), an enhancement range between 1.59% to 27.88% achieved with AMB_AODV comparing with standard AODV. On the other hand, with AMB_SRE_AODV, an enhancement range between -7.5% to 32.17 % achieved comparing with standard AODV.

Overhead enhancement shown in Figure 5.17, an enhancement range between -73% to -105% achieved with AMB_AODV comparing with standard AODV. On the other hand, with

AMB_SRE_AODV, an enhancement range between 29.37% to 47.34 % achieved comparing with standard AODV.

Throughput Enhancement (%) shown in Figure 5.18, an enhancement range between -7.88% to 18.73% achieved with AMB_AODV comparing with standard AODV. On the other hand, with AMB_SRE_AODV, an enhancement range between 16.62 % to 42.86 % achieved comparing with standard AODV.

Average End-to-End Delay shown in Figure 5.19, an enhancement range between –25.53% to 10.94% achieved with AMB_AODV comparing with standard AODV. On the other hand, with AMB_SRE_AODV , an enhancement range between -4.08 % to 72.30 % achieved comparing with standard AODV.

Average Energy Consumption Enhancement shown in Figure 5.20, an enhancement range between -1.35% to -9.40% achieved with AMB_AODV comparing with standard AODV. On the other hand, with AMB_SRE_AODV, an enhancement range between 18.22% to 27.92 achieved comparing with standard AODV.

Finally, as for Average Packet Dropping Ratio Enhancement shown in Figure 5.21, an enhancement range between 0.96% to 10.84% achieved with AMB_AODV comparing with standard AODV. On the other hand, with AMB_SRE_AODV, an enhancement range between -4.16% to 13.31 achieved comparing with standard AODV.

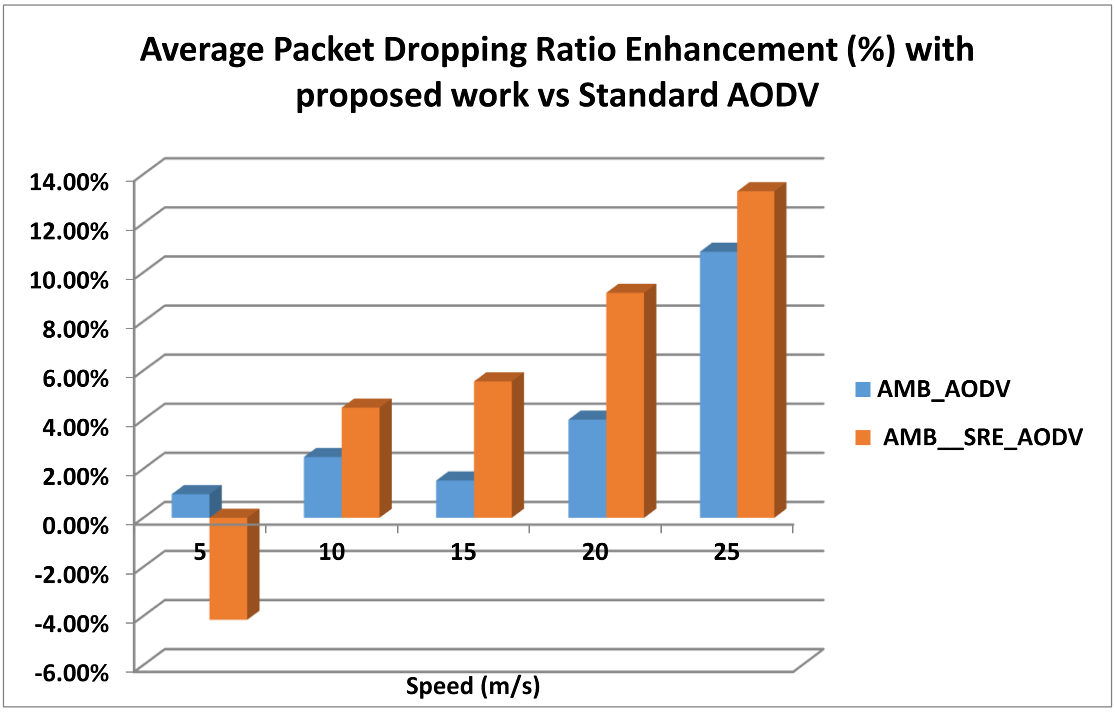


Figure 5.16 Packet Delivery Ratio Enhancement (%)

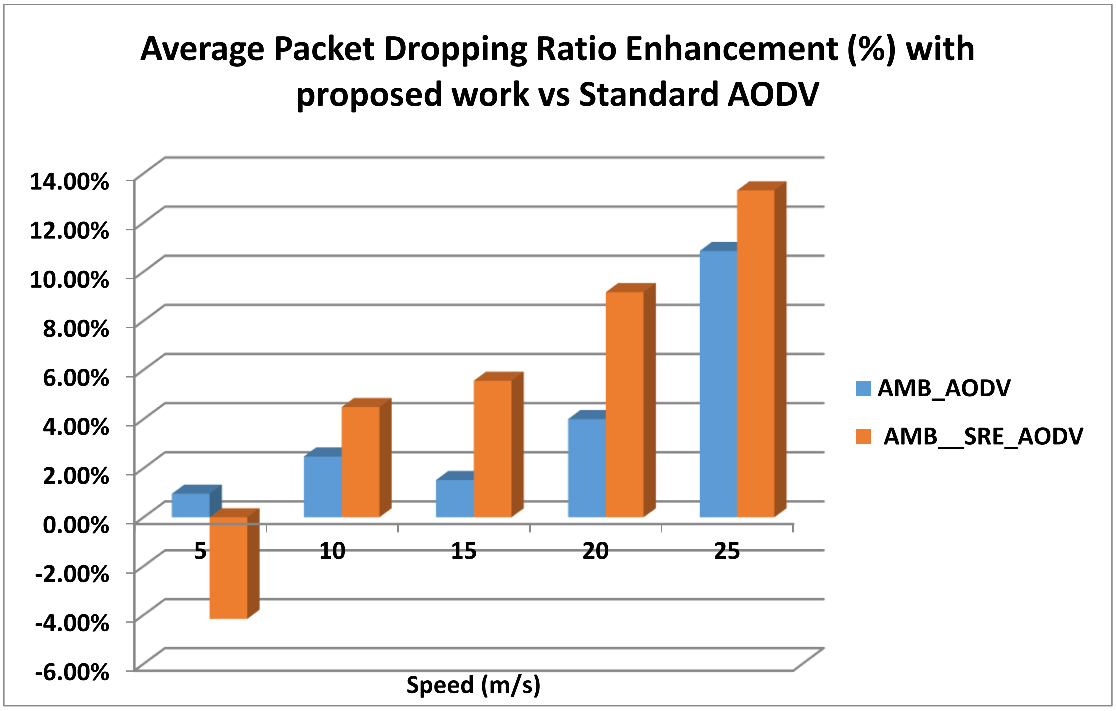


Figure 5.17 Overhead Enhancement (%)

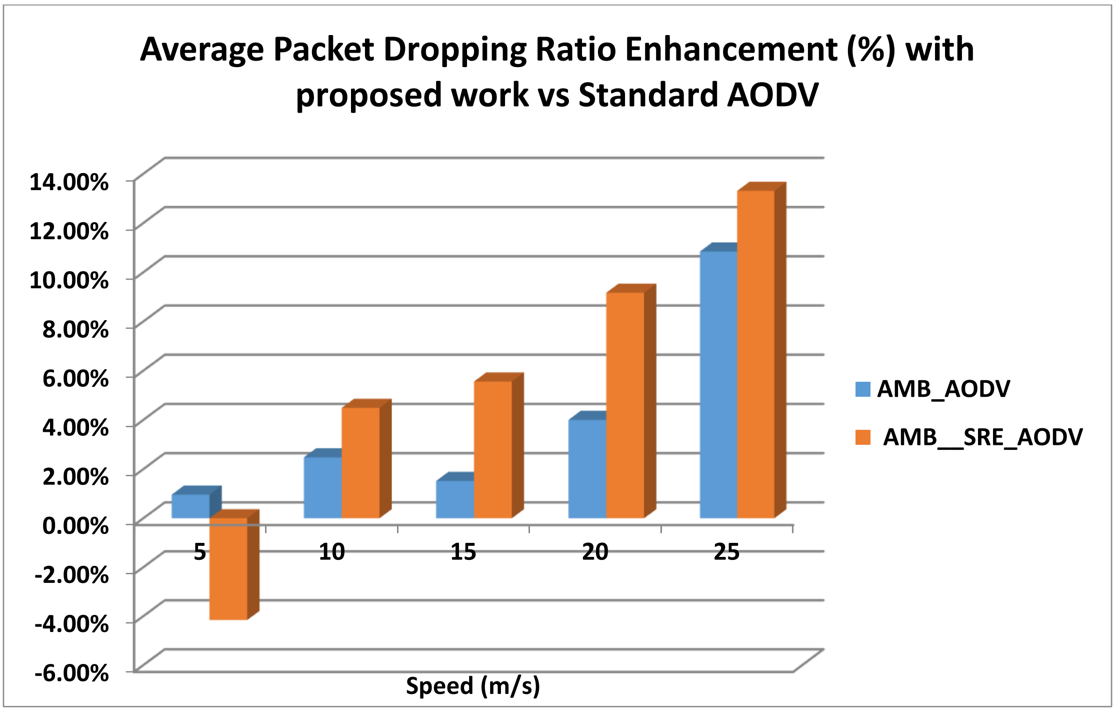


Figure 5.18 Throughput Enhancement (%)

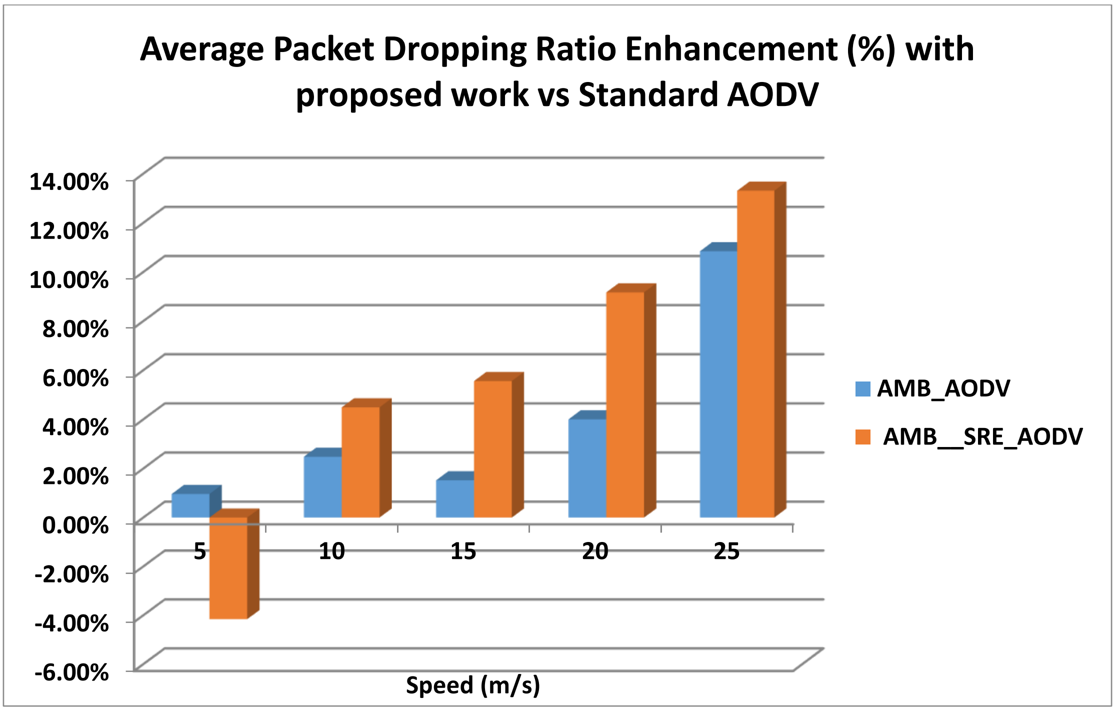


Figure 5.19 Average End-to-End Delay Enhancement (%)

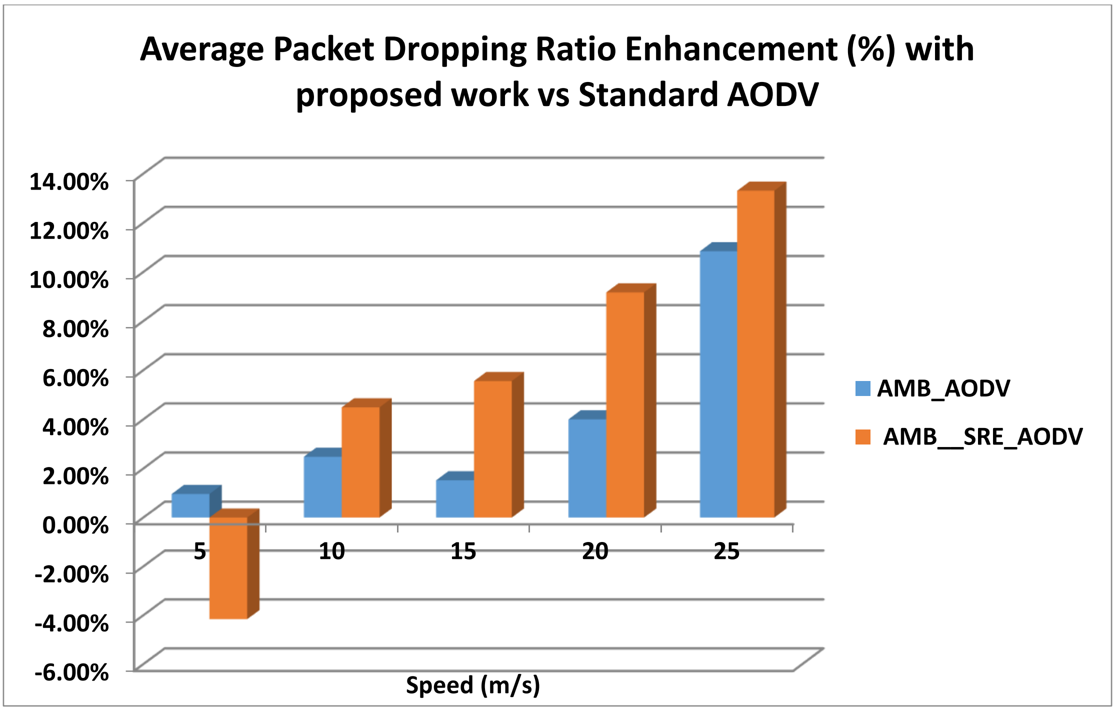


Figure 5.20 Average Energy Consumption Enhancement (%)

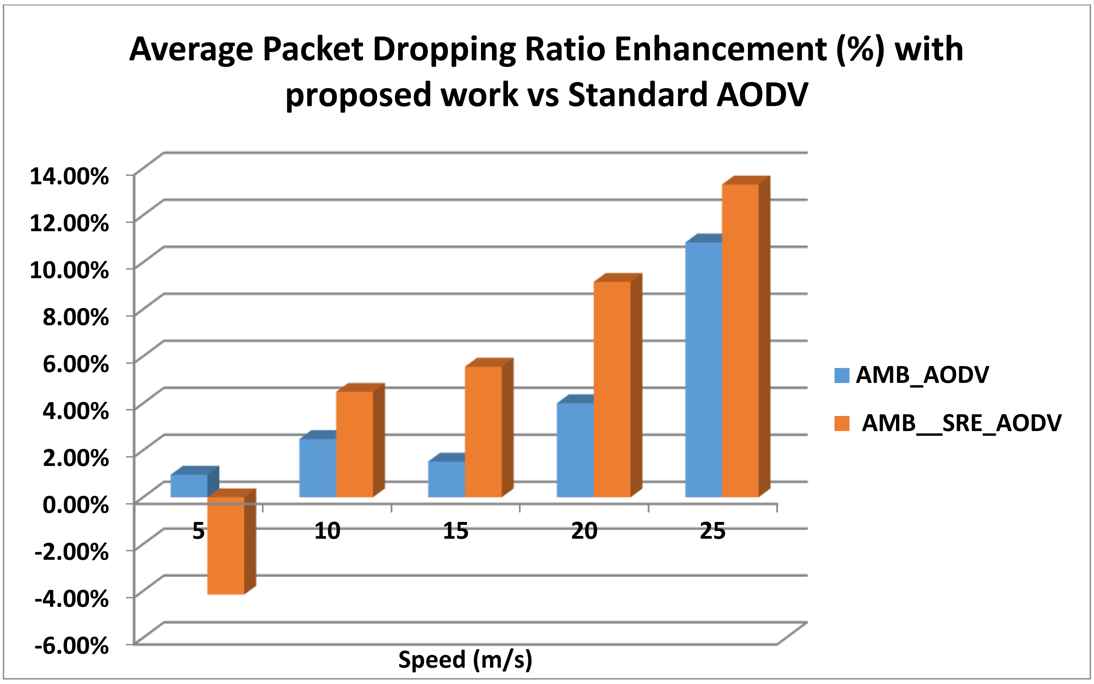


Figure 5.21 Average Packet dropping ratio Enhancement (%)

5.4 Summary

Two novel Congestion, Mobility and Energy Aware Route-Discovery scheme for AODV in MANETs proposed, AMB_AODV and AMB_SRE_AODV. These schemes bring the awareness of three important factors that degrade the overall network performance in MANETs: Node's buffer status, node's mobility and remaining residual energy. Hence, route discovery process with proposed work is performed in adaptive manner. In other words, every intermediate node in the network, when participating in the route discovery process between a source and a destination, decides on it capability of handling the RREQ packet to next hop node or not based on few tests done at this node. If these tests passed, then the node rebroadcasts RREQ again. Otherwise, RREQ discarded. The proposed schemes have been tested with six different QL Threshold values: 90%, 80%, 70%, 60%, 50% and 40%. Then the performance metrics of the proposed work has been averaged in order to evaluate the performance. The schemes were tested using a mobile scenario in NS2 and promising results found. A good improvement of delivery ratio (up to 32%), total number of overheads (up to 47%), throughput (up to 43%), average delay (up to 72%), average energy consumption (up to 28%), and packet dropping ratio (up to 13%), has been achieved. Through the performance evaluation, the value of 40% of the predetermined QL Threshold has shown the best overall performance in terms of all the aforementioned metrics. Further work can be done on optimising the threshold value of queue length.

Chapter 6

Conclusion and Future Work

This chapter summarises the major contributions of this thesis and presents the main conclusions. The future work section highlights those research areas where the findings of this research could be further investigated in new research directions.

6.1 Conclusions

This thesis has presented designated and implementation solutions to enhance the QoS in wireless mesh and mobile ad-hoc networks. These include enhancing throughput with maintaining fairness among nodes in WMNs, and designing efficient routing schemes that able to provide better QoS in terms of packet delivery ratio, delay, network life time and energy consumption.

The main challenges addressed in this thesis as well as the proposed solutions are presented in the following sections.

6.1.1 Enhanced Adaptive Delayed Acknowledgement Mechanism (EADAM)

Enhanced Adaptive Delayed Acknowledgement mechanism is proposed to enhance the throughput for all active flows in a static chain topology alongside with maintaining fairness among the flows. The proposed mechanism is an enhancement to ADAM [2]. This mechanism utilises the delayed ACK technique with factor of two and an advertised window *awnd* set to one. The proposed mechanism works on reducing the cycle T by allowing some kind of transmission parallelism among the individual flows, which leads to a significant throughput enhancement. The proposed mechanism EADAM has been implemented in NS2 [49] and validated by comparing to ADAM, throughput enhancement ratio of up to 35% has been achieved.

6.1.2 Mobility and Energy Aware AODV (MEA_AODV)

Mobility and Energy Aware AODV (MEA_AODV) is a novel route discovery scheme that is mobility and energy aware for AODV in MANETs proposed to improve QoS performance in terms of throughput, PDR, network life time, overall overhead, average delay of A-LSEA [3] which is one of the state of the art mobility and energy aware routing discovery scheme. MEA_AODV relies on two important factors: Link Life Time

(LLT) and Residual Energy (RE). It shares position based information through Hello messages, then calculates LLTs between the forwarding node and its neighbours. Then, average link lifetime LLT_{avg} is calculated. Simultaneously, the forwarding node obtains all its neighbours' residual energies through Hello messages, calculates the average energy RE_{avg}. A-LSEA performs a dual checks of the its own LLT_i and RE_i with LLTavg and RE_{avg}. If (LLT_i and RE_i) are greater than (LLT_{avg} and RE_{avg}) the RREQ packet is rebroadcasted, otherwise it is discarded.

The proposed scheme MEA_AODV utilises the same methodology of A-LSEA to find LLT_{avg} and RE_{avg} at each forwarding node in the route discovery process. However, the method of calculating these LLT_{avg} and RE_{avg} is different. The proposed scheme calculates the first average in same way that A-LSEA does. Then performs first check by comparing the node first parameter (LLT or RE) with its correspondent average. The computation of the second average excludes any node that did not pass the first check. Once the two averages calculated then the node compares its own parameters (LLT_i and RE_i) with (LLT_{avg} and RE_{avg}). Again, If (LLT_i and RE_i) are greater than or equal to (LLT_{avg} and RE_{avg}) the RREQ packet is rebroadcasted, otherwise it is discarded.

Based on the computation philosophy of MEA_AODV, Two schemes have been implemented:

- Selective Energy_ Mobility and Energy Aware AODV (SRE_MEA_AODV).
- Selective Link Life Time_ Mobility and Energy Aware AODV (SLLT_MEA_AODV).

These two schemes are called selective because they are selective when they come to the stage of calculating the second average parameter. The two proposed schemes have been evaluated in comparison with AODV and A-LSEA [3]. The evaluation shows that SRE_MEA_AODV dramatically outperforms A-LSEA and AODV.

6.1.3 Congestion, Mobility and Energy aware route discovery schemes AODV in Wireless Mobile Ad-Hoc Networks (CMEA_AODV):

A congestion aware routing scheme has been proposed to provide end-to-end guarantees in a route discovery scheme for AODV in MANETs. This scheme improves QoS by controlling the congestion that occurs as a result of unmanaged node buffer while deciding on forwarding the RREQ packet in the rout discovery process. In this work, the queue length (QL) for the forwarding node is used as a criterion to measure congestion in the node’s buffer. It is compared with a predetermined threshold (Thr). When QL exceeds (Thr) the node is considered congested and unable to participate in the route. therefore, the RREQ is discarded. Otherwise. The node forwards RREQ. The proposed scheme has been implemented in two schemes called:

- Adaptive Managed Buffer_ route discovery scheme for AODV (AMB_AODV)
- Adaptive Managed Buffer and Selective Remaining Energy route discovery scheme for AODV (AMB_SRE_AODV)

The two proposed schemes have been evaluated in comparison with standard AODV. The evaluation shows that PDR has improves to up to 27.9% and 31.2% with AMB_AODV and AMB_SRE_AODV respectively. Also, throughput enhancement of up to 18.73% and 42.7% achieved with AMB_AODV and AMB_SRE_AODV respectively comparing with standard AODV.

This research has introduced a number of diverse approaches on enhancing QoS in wireless multi-hop networks. These include EADAM for enhancing throughput with maintaining fairness among nodes in WMNs in Chapter 3. EADAM is a TCP delayed acknowledgement timeout model for a fairness throughput. It is an efficient model for achieving higher rate of equal opportunity in a static chain multi-hop topology of WMN. The proposed mechanism have a unique formulation in retaining the throughput as a primary metric with a minimum trade-off on throughput and fairness index in a multi-hop chin topology. The proposed mechanism optimises the network resources in multi-hop chain WMN that makes it a tangible model for a scalable hybrid WMN network. Additionally, this research has proposed a number of designated efficient routing schemes that able to provide better QoS in terms of packet delivery ratio, delay, network life time and energy consumption. These schemes are SRE_MEA_AODV, SLLT_MEA_AODV, AMB_AODV and AMB_SRE_AODV proposed in Chapter 4 and Chapter 5 respectively. SRE_MEA_AODV and AMB_SRE_AODV are potentially the best two schemes in terms of all performance metrics. However, SRE_MEA_AODV has outperformed AMB_SRE_AODV in terms of all performance metrics evaluated in this thesis when compared to standard AODV.

6.2 Future Work

6.2.1 Short term future research

6.2.1.1 Improving Enhanced Adaptive Delayed Acknowledgement Mechanism (EADAM)

EADAM can be further improved by extending the mechanism to include mobility as the proposed technique assumes a static chain topology. This is valid because mesh routers are fixed or have minimal mobility. Therefore, adding the mobility to EADAM will make it more realistic. Additionally, EADAM can be applied and tested to another wireless ad hoc multi-hop networks such as WSNs or VANETs.

6.2.1.2 Enhancing Mobility and Energy Aware AODV (MEA_AODV)

MEA_AODV can be tested on other reactive routing protocols such as DSR. In addition, the proposed schemes SRE_MEA_AODV and SLLT_MEA_AODV can be evaluated with various network load rather than various speeds.

6.2.1.3 Optimising the queue length threshold (CMEA_AODV):

The proposed two schemes (AMB_AODV) and (AMB_SRE_AODV) use queue length (QL) as a metric to congestion. The schemes compare the current QL of the considered node with a predetermined threshold (Thr). Various Thr_s values have been tested then an average of the performance across the simulation metrics calculated. However, the proposed schemes can be enhanced by optimising the threshold (Thr).

6.2.2 Long term future research

- EADAM is mechanism proposed to solve starvation in WMNs. However, this mechanism has a few limitations represented in global knowledge of the network such as the total number of active nodes, and the assumption of the distances between the nodes are equal. A new transport layer mechanism that considers more flexibility in terms of the participated nodes' position and distribution is a potential aspect of further research.

- MEA_AODV and CMEA_AODV are mobility and energy aware route discovery schemes designated for the routing proactive protocol AODV. The proposed schemes have shown great performance enhancement to the standard protocol and other existing scheme (A-LSEA) along with bringing the awareness of the most important challenges that degrade the performance in MANETs. However, these proposed schemes are position-based algorithms. In other words, the proposed schemes are valid for particular applications. Hence, using these schemes as a benchmark to produce more generic route discovery schemes that able to cope with a variety of applications, such as real time application, is a future research direction.
- In this thesis, all the proposed solutions were implemented and evaluated through simulation using NS2 as a validating tool. Therefore, a real test bed implementation can be explored for realistic results.

References

[1] I. F. Akyildiz, X. Wang and W. Wang , "Wireless mesh networks: a survey," *Computer Networks*, pp. 445-487, 2005.

[2] T.-C. HOU and C.-W. HSU, "Achieving Fair Throughput among TCP Flows in Multi-Hop Wireless Mesh Networks," *IEICE Transaction Communication* , Vols. E93-B, no. 4, pp. 916 - 926, 2010.

[3] S. Hamad, "Efficient Route Discovery for Reactive Routing Protocols in Wireless Ad-Hoc Networks Using Controlled Flooding," Brunel University, http://bura.brunel.ac.uk/handle/2438/7634, London, 2013.

[4] D. Rajan, "Introduction to Wireless Communications," in *Wireless Network Design : Optimization Models and Solution Procedures*, Springer , 2010, pp. 9 - 46.

[5] D. Benyamina, A. Hafid and M. Gendreau, "Wireless Mesh Networks Design — A Survey," *IEEE Communicatios Surveys & Tutorials* , vol. 14, no. 2, pp. 299 - 310, 2012.

[6] R. Bruno, M. Conti and E. Gregori, "Mesh Networks: Commodity Multihop Ad hoc Networks," *IEEE Communications Magazine*, vol. 43, no. 3, pp. 123 - 131, 2005.

[7] M. Conti and S. Giordano, "Multihop Ad Hoc Netorking: The Evolutionary Path," in *Mobile Ad Hoc Networking: Cutting Edge Directions*, y John Wiley & Sons,, 2013, pp. 3 - 33.

[8] I. Leontadis, E. Ferranti, C. Mascolo, L. McNamara, B. Pasztor, N. Trigoni and S. Waharte, "Application Scenarios," in *Mobile Ad Hoc Networking: Cutting Edge Directions*, John Wiley & Sons, Inc, 2013, pp. 77 - 105.

[9] O. Shagdar, K. Nakagawa and B. Zhang, "Achieving Per-Flow Fairness in Wireless Ad Hoc Networks," *Electronics and Communications,* vol. 89, no. 8, pp. 37-49, 2006.

[10] P. Samundiswary and S. R. Anandkumar, "Throughput Anaysis of Energy Aware REACTIVE Routing Protocol FOR Wireless Sensor Networks," *International Journal of Soft Computing and Engineering (IJSCE),* vol. 2, no. 1, pp. 497 - 501, 2012.

[11] K.-C. Leung and V. O. K. LI, "Transmission Control Protocol (TCP) in Wireless Networks: Issues, Approaches, and Challenges," *IEEE Communications Surveys & Tutorials,* vol. 8, no. 4, pp. 64 - 79, 2006.

[12] M. Allman, V. Paxson and E. Blanton, "TCP Congestion Control," Network Working Group RFC 5681, 2009.

[13] M. Taruk, E. Budiman, Haviluddin and H. J. Setyadi, "Comparison of TCP Variants in Long Term Evolution (LTE)," in *5th International Conference on Electrical, Electronics and Information Engineering (ICEEIE)* , Malang, 2017.

[14] P. Chaudhary and S. Kumar, "Comparative Study of TCP Variants for Congestion Control in Wireless Network," in *International Conference on Computing, Communication and Automation*, 2017.

[15] R. Rai and M. Shreevastava, "Performance Improvement of TCP by TCP Reno and SACK Acknowledgement," *International Journal of Advanced Computer Research,* vol. 2, no. 1, pp. 81 - 85, 2012.

[16] M. A. Smith and K. K. Ramakrishnan, "Formal specification and verification of safety and performance of TCP selective acknowledgment," *IEEE/ACM Transactions on Networking* , vol. 10, no. 2, pp. 193 - 207, 2002.

[17] J. Liu and S. Singh, "ATCP: TCP for Mobile Ad Hoc Networks," *IEEE Journal On Selected Areas In Communications,* vol. 19, no. 7, pp. 1300 - 1315, 2001.

[18] E. Alotaibi and B. Mukherjee, "A survey on routing algorithms for wireless Ad-Hoc and mesh networks," *Computer Networks,* vol. 56, no. 2, pp. 940-965, 2012.

[19] L. A. T. R. Hanzo, "A Survey of QOS Routing Solutions for Mobile Ad Hoc Networks," *IEEE Communications Surveys & Tutorials,* vol. 9, no. 2, pp. 50 - 70, 2007.

[20] B. Sadeghi, A. Yamada, A. Fujiwara and L. Yang, "A Simple and Efficient Hop-by-Hop Congestion Control Protocol for Wireless Mesh Networks," in *the 2nd Annual International Wireless Internet Conference* , 2006.

[21] R. Cheng and H. Lin, "A cross-layer design for TCP end-to-end performance improvement in multi-hop wireless networks," *Computer Communications,* vol. 31, no. 14, pp. 3145-3152, 2008.

[22] A. Majeed, S. Razak, N. Abu-Ghazaleh and K. Harras, "TCP over Multi-Hop Wireless Networks: The impact of MAC level Interactions," in *Ad-Hoc, Mobile and Wireless Networks,* Berlin / Heidelberg, Springer, 2009, pp. 1-15.

[23] K. H. A. K. C.-C. Nahm, "TCP over multihop 802.11 networks: issues and performance enhancement," in *Proceedings of the 6th ACM international symposium on Mobile ad hoc networking and computing* , New York, 2005.

[24] O. Tickoo, V. Subramanian, S. Kalyanaraman and K. Ramakrishnan, "LT-TCP: End-to-End Framework to Improve TCP Performance over Networks with Lossy Channels," in *Quality of Service – IWQoS 2005,* Berlin / Heidelberg, Springer , 2005, pp. 81-93.

[25] O. Gurewitz, V. Mancuso, J. Shi and E. Knightly, "Measurement and Modeling of the Origins of Starvation of Congestion-Controlled Flows in Wireless Mesh Networks," *IEEE/ACM Transactions on Networking,* vol. 17, no. 6, pp. 1832-1845, Dec 2009.

[26] J. W. J.-X. a. H. J.-W. Ye, "A cross-layer TCP for providing fairness in wireless mesh networks," *International Journal of Communication Systems,* vol. 24, no. 12, p. 1611–1626, Dec 2011.

[27] K. Xu, M. Gerla, L. Qi and Y. Shu, "TCP Unfairness in Ad Hoc Wireless Networks and a Neighborhood RED Solution," *Wireless Networks,* vol. 11, pp. 383-399, 2005.

[28] J. J. Galvez, P. M. Ruiz and A. F. Skarmeta, "Responsive on-line gateway load-balancing for wireless mesh networks," *Ad Hoc Networks,* vol. 10, pp. 46-61, 2011.

[29] J.-Y. Yoo and J. W. Kim, "Impact of TCP ACK Losses on TCP Fairness in Wireless Mesh Networks," in *Global Telecommunications conference,* 2009.

[30] S. Floyd and V. Jacobson, "Random Early Detection Gateways for Congestion Avoidance," *IEEE Transactions on Systems,* vol. 40, no. 1, pp. 66 - 76, 1993.

[31] N. Chilamkurti and S. A. Prakasam, "Enhanced Active Queue Management for Multi-hop Networks," *Mobile Networks and Applications* , vol. 16, no. 6, pp. 771-781, 2010.

[32] K. Jamshaid, P. A. Ward and M. Karsten, "Mechanisms for centralized flow rate control in 802.11-based wireless mesh networks," *Computer Networks,* vol. 56, no. 2, pp. 884-901, 2011.

[33] X. Guo and J. Liu, "Path Diversified Retransmission for TCP over Wireless Mesh Networks," in *18th International Workshop on Quality of Service (IWQoS),* Beijing, 2010.

[34] Y. Ling, Z. Xiao-fan and L. Yu-shan, "Analyzing and improving the TCP flow fairness in 802.11 based ad hoc networks," in *International Conference on Wireless Communications and Signal Processing*, Nanjing, 2009.

[35] J. B. Ernst and M. K. Denko, "The design and evaluation of fair scheduling in wireless mesh networks," *Journal of Computer and System Sciences*, vol. 77, no. 4, pp. 652-664, 2011.

[36] P. T. Giang and K. Nakagawa, "Achieving Fairness over 802.11 Multihop Wireless Ad Hoc Networks," *IEICE Transaction Communications*, Vols. E92-B, no. 8, pp. 2628-2637, 2009.

[37] W. Su, S.-J. Lee and M. Gerla, "Mobility prediction in wireless networks," in *MILCOM 2000 Proceedings. 21st Century Military Communications. Architectures and Technologies for Information Superiority*, 2000.

[38] Y. Khamayseh, O. M. Darwish and S. A. Wedian, "MA-AODV: Mobility Aware Routing Protocols for Mobile Ad hoc Networks," in *Forth International Conference on Systems and Networks Communications*, Porto, 2009.

[39] S. Hamad, H. Noureddine and H. Al-Raweshidy, "LSEA: Link Stability and Energy Aware for efficient routing in Mobile Ad Hoc Network," in *The 14th International Symposium on Wireless Personal Multimedia Communications (WPMC)*, 2011.

[40] R. Asokan and A. M. Natarajan, "Performance Evaluation of Energy and Delay Aware Quality of Serfice (QoS) Routing Protocols in Mobile Adhoc Networks," *International Journal of Business Data Communications and Networking*, vol. 4, no. 2, pp. 52 - 63, 2008.

[41] P. Samundiswary and S. R. A Nandkumar, "Throughput Analysis of Energy Aware Reactive Routing Protocol for Wireless Sensor Networks," *International Journal of Soft Computing and Engineering (IJSCE)*, vol. 2, no. 1, pp. 497 - 500, 2012.

[42] B. Ahmed, Z. Ouadoudi, R. Mohamed and O. Mohamed, "A mobility aware Modified AODV for heterogeneous mobile ad hoc networks," in *2012 International Conference onMultimedia Computing and Systems (ICMCS)*, Tangier, Morocco, 2012.

[43] S. Sarkar and R. Datta, "Mobility-aware route selection technique for mobile ad hoc networks," *IET Wireless Sensor Systems*, vol. 7, no. 3, pp. 55 - 64, 2017.

[44] G. Varaprasad, "Efficient power aware routing algorithm for mobile ad hoc networks," *Wireless Communication and Mobile Computing*, vol. 12, no. 1, pp. 1 - 6, 2009.

[45] J. M. Kim and J. W. Jang, "AODV based Energy Efficient Routing Protocol for Maximum Lifetime in MANET," in *Advanced International Conference on*

Telecommunications and International Conference on Internet and Web Applications and Services, French Caribbean, 2006.

[46] T. C. Huang, S. C. Chen and L. Tang, "Energy-Aware Gossip Routing for Mobile Ad Hoc Networks," in *International Conference on High Performance Computing and Communications*, Banff, 2011.

[47] W. C. W. Tan, S. K. Bose and T. H. Cheng, "Power and mobility aware routing in wireless ad hoc networks," *IET Communications* , vol. 6, no. 11, pp. 1425 - 1437, 2012.

[48] C. Perkins, "Ad hoc On-Demand Vector (AODV) Routing," University of California, Santa Barbara, July 2003.

[49] "The Network Simulator: Building Ns," [Online]. Available: https://www.isi.edu/nsnam/ns/ns-build.html. [Accessed 2017].

[50] A. Boukerche, B. Turgut, N. Aydin, M. Z. Ahmad, L. Bölöni and D. Turgut, "Routing protocols in ad hoc networks: A survey," *Computer Networks,* vol. 55, pp. 3032-3080, 2011.

[51] S. Kumaran and V. Sankaranarayanan, "Congestion Free Routing in Adhoc Networks," *Journal of Computer Science,* vol. 8, no. 6, pp. 971-977, 2012.

[52] M. Naseem and C. Kumar, "Queue-based multiple path load balancing routing protocol for MANETs," *International Journal of Communication Systems,* vol. 30, no. 6, 2016.

[53] Niharika and P. Tanwar, "A Novel Method for Better Queue Management in MANETS," *International Journal of Engineering Research and General Science,* vol. 3, no. 3, pp. 1472 - 1478, 2015.

[54] A. Rani and M. Dave , "Weighted Load Balanced Routing Protocol for MANET," in *2008 16th IEEE International Conference on Networks* , New Delhi, 2008.