DESIGN AND ANALYSIS OF A FUZZY PRIORITY CO-ORDINATOR (FPC) FOR USE IN IMPROVING QUALITY OF SERVICE (QOS) IN MOBILE AD HOC NETWORKS (MANETS) ROUTING.

ERAC OMBATI MOMANYI

MASTER OF SCIENCE

(Electrical Engineering - Telecommunication option)

PAN AFRICAN UNIVERSITY

INSTITUTE FOR BASIC SCIENCES TECHNOLOGY AND INNOVATION

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ERAC OMBATI MOMANYI

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2014

DECLARATION

This thesis is my original work and has not been submitted to any other university for examination.

Signature:.. Date:...

ERAC OMBATI MOMANYI

This thesis report has been submitted for examination with our approval as University supervisors.

Signature:..   Date:...

Prof. VITALICE. K. ODUOL (University of Nairobi)

Signature:.. Date:...

Prof. STEPHEN. MUSYOKI (Technical University of Kenya)

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DEDICATION

I dedicate this thesis to my parents John and Susan for making me who am, my wife Selpha and daughters Susan and Genna for their support all the way and my mentors Mr. Shem Osinde and Dr. Joash Migosi.

ABSTRACT

This thesis explores the design and use of a fuzzy priority coordinator (FPC) in Mobile Ad Hoc Networks (MANETS) for the purpose of improving Quality of Service (QoS).

A MANET is an independent system of mobile nodes utilizing wireless links. The major challenge in MANETS is adapting multicast communication to environments in which mobility is unlimited and failures are frequent. Such problems increase delay and decrease overall network throughput leading to poor QoS. To improve QoS, priority packet scheduling can be carried out. Its on this basis that the thesis is exploring the design and the analysis of the FPC. The FPC is designed in MATLAB with the help of the fuzzy tool. It has got four inputs which results to 81 rules. This rules guide in the determination of the priority index of a packet to be transmitted. A C++ programme is then developed so as to enable a co-simulation in OPNET for the purpose of analysis.

The coordinator is evaluated under a low load and high load network conditions. The deployed applications include VoIP, Video conferencing and file transfer. The FPC is analyzed in graphical comparisons between itself, FIFO and Type of Service (ToS) priority. The parameters under consideration include Mean Opinion Score (MOS), Jitter, packet end to end delay, packet delay variation, download response time and upload response time.

The coordinator is found to outperform the other two existing scheduling mechanisms in a wide range of results obtained. It is thus advisable that the FPC can be used in packet coordination in MANETS to improve QoS.

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LIST OF ABBREVIATIONS

AAQR	……………….…......	Application Aware QoS Routing
AI	……………….…......	Artificial Intelligence
AODV	……………….…......	Ad hoc On Demand Distance Vector Routing protocol
CAAODV	……………….…......	Contention Aware Ad hoc ODV
CACP	……………….…......	Contention Aware Admission Control Protocol
CDMA	……………….…......	Collision Detection Multiple Access
DCF	……………….…......	Distributed Coordination Function
DS	....	Differentiated service
DSR	……………….…......	Dynamic Source Routing Protocol
FDMA	……………….…......	Frequency Division Multiple Access
GAMAN	……………….…......	Genetic Algorithm based Routing for MANETS
GSM	……………….…......	Global System for Mobile Communications
HARP	……………….…......	Hybrid Ad hoc Routing Protocol
IEEE	……………….…......	Institute of Electrical and Electronics Engineers

MAC ……………….…...... Medium Access Control

MANETS ……………….…...... Mobile Ad hoc NETworks

MISO ……………….…...... Multiple Input Single Output

MRT ……………….…...... Maximum Required Throughput

MTD ……………….…...... Maximum Tolerable Delay

PARSEC ……………….…...... Parallel Simulation Environment for Complex Systems

PCF ……………….…...... Point Coordination Function

PHB .... Per Hope Behavior

QoS ……………….…...... Quality of Service

TCP .... Transmission Control Protocol

TTL ……………….…...... Time To Leave

UDP .... User Datagram Protocol

CHAPTER 1

1 INTRODUCTION

1.1 BACKGROUND

1.1.1 REVIEW OF WIRELESS NETWORKS AND EVOLUTION

The wireless communication landscape has been changing dramatically, driven by the rapid advances in wireless technologies and the greater selection of new wireless services and applications. The emerging third-generation cellular networks have greatly improved data transmission speed, which enables a variety of higher-speed mobile data services. Meanwhile, new standards for short-range radio such as Bluetooth, Hiperlan, and infrared transmission are helping to create a wide range of new applications for enterprise and home networking, enabling wireless broadband multimedia and data communication in the office and home. Radio antennas couple electromagnetic energy from space to another guided medium (for example: wire, coaxial cable, or waveguide) or vice versa [1]. Wireless networking refers to the use of infrared or radio frequency signals to share information and resources between devices. Many types of wireless devices are available today; for example, mobile terminals, pocket size PCs, hand-held PCs, laptops, cellular phone, PDAs, wireless sensors, and satellite receivers. Due to the differences found in the physical layer of these systems, wireless devices and networks show distinct characteristics from their wire line counterparts, specifically,

- *Higher interference results in lower reliability.*

Infrared signals suffer interference from sunlight and heat sources, and can be shielded/absorbed by various objects and materials. Radio signals usually are less prone to being blocked, however, they can be interfered with by other electrical devices. The broadcast nature of transmission means all devices are potentially interfering with each other. There is also self-interference due to multipath.

- *Low bandwidth availability and much lower transmission rates.*

Typically much slower-speed compared to wire line networks, causing degraded quality of service, including higher jitter, delays, and longer connection setup times.

- *Highly variable network conditions:*

Higher data loss rates due to interference, user movement causes frequent disconnection, channel changes as users move around, received power diminishes with distance

- *Limited computing and energy resources.*

Limited computing power, memory, and disk size due to limited battery capacity, as well as limitation on device size, weight and cost.

- *Limited service coverage.*

Due to device, distance, and network condition limitations, service implementation for wireless devices and networks faces many constraints and is more challenging compared to wired networks and elements.

- *Limited transmission resources.*

Sharing the medium of transmission, limited availability of frequencies with restrictive regulations and spectrum scarce and expensive are some of the challenges faced by wireless networks

- *Device size limitation*

This leads to problems in portability resulting in limited user interfaces and displays.

- *Weaker security:*

Because the radio interface is accessible to everyone, network security is more difficult to implement, as attackers can interface more easily.

Wireless networks are classified using different criteria [2] which include:

1. By network formation and Architecture which includes; Infrastructure based network and Infrastructureless (Ad hoc) networks.
2. By communication coverage area which includes; Wireless WANs, Wireless MANs, Wireless LANs, Wireless PANs.
3. By Access technology which includes; GSM, TDMA, CDMA, Satellite, Wi-Fi (802.11), Hiperlan2, Bluetooth and Infrared.
4. By network applications which includes; Enterprise, Home, Tactical, Sensor, Pervasive, Wearable computing and Automated Vehicle networks.

Many forces are behind the growth of wireless technology. One can argue that the commercial history of wireless started with first generation in the 1980s, which supported the analog cell phones using FDMA and was generally unsophisticated.

1.1.2 MOBILE AD HOC NETWORKS.

Non-infrastructure-based mobile ad hoc networks (MANETS) are expected to become an important part of the 4G architecture. A mobile ad hoc network is a transient network formed dynamically by a collection of arbitrarily located wireless mobile nodes without the use of existing network infrastructure or centralized administration. Mobile ad hoc networks are gaining momentum because they help realize network services for mobile users in areas with no pre-existing communications infrastructure [2]. Ad hoc Networking enables independent wireless nodes, each limited in transmission and processing power, to be “chained” together to provide wider networking coverage and processing capabilities. The nodes can also be connected to a fixed-backbone network through a dedicated gateway device, enabling IP networking services in areas where Internet services are not available due to lack of preinstalled infrastructure. All these advantages make ad hoc networking an attractive option in the future wireless networks arena.

As shown in Figure 1.1 below, an ad hoc network might consist of several home-computing devices, including notebooks and handheld PCs. Each node will be able to communicate directly with other nodes that reside within its transmission range. For communicating with nodes that reside beyond this range, the node needs to use intermediate nodes to relay messages hop by hop. This is clearly shown in Figure 1.1 [2].

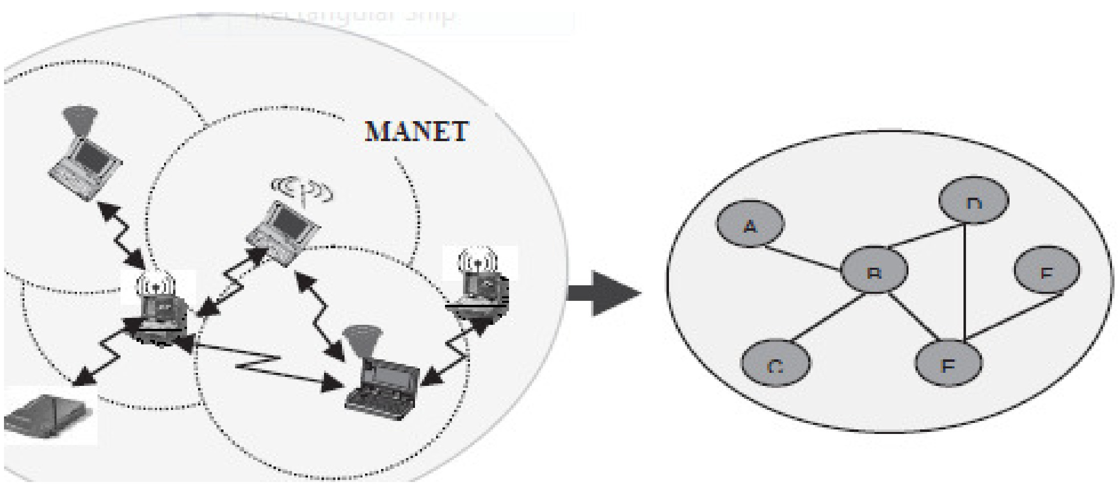

Figure 1.1: Mobile ad hoc Network

MANETS inherit common characteristics found in wireless networks in general, and add characteristics specific to ad hoc networking which add up to make their advantages:

- *Wireless.* Nodes communicate wirelessly and share the same media (radio, infrared, etc.).
- *Ad-hoc-based.* A mobile ad hoc network is a temporary network formed dynamically in an arbitrary manner by a collection of nodes as need arises.

- *Autonomous and infrastructureless.* MANET does not depend on any established infrastructure or centralized administration. Each node operates in distributed peer-to-peer mode, acts as an independent router, and generates independent data.
- *Multihop routing.* No dedicated routers are necessary; every node acts as a router and forwards each others' packets to enable information sharing between mobile hosts.
- *Mobility.* Each node is free to move about while communicating with other nodes. The topology of such an ad hoc network is dynamic in nature due to constant movement of the participating nodes, causing the intercommunication patterns among nodes to change continuously.

In general, ad hoc wireless networks eliminate the constraints of infrastructure and enable devices to create and join networks on the fly—anytime, anywhere—for virtually any application.

The table 1.1 below [2] summarises the applications of MANETS

Table 1.1: Mobile Ad hoc Networks Applications

Application	**Description**
Tactical networks	Military communication, operations Automated Battlefields
Sensor networks [3]	Collection of embedded sensor devices used to collect real-time data to automate everyday functions. Data highly correlated in time and space, e.g., remote sensors for weather, earth activities; sensors for manufacturing equipment.
Emergency services	Search-and-rescue operations as well as disaster recovery; e.g., early retrieval and transmission of patient data (record, status, diagnosis)

	from/to the hospital
Commercial environments [4]	E-Commerce, e.g., electronic payments from anywhere (e.g. in a taxi). Business: dynamic access to customer files stored in a central location on the fly provide consistent databases for all agents mobile office Vehicular Services: transmission of news, road conditions, weather, music local ad hoc network with nearby vehicles for road/accident guidance
Home networking	Home/office wireless networking (WLAN), e.g., shared whiteboard application, use PDA to print anywhere, trade shows. Personal area network (PAN)
Educational applications	Set up virtual classrooms or conference rooms Set up ad hoc communication during conferences, meetings, or lectures
Entertainment	Multiuser games, robotic pets, Outdoor internet services
Location-aware services	Follow-on services e.g. Automatic call forwarding. Information services: Push: Advertise specific location of a service e.g petrol station, Pull: Location depended travel guide

1.1.3 DESIGN ISSUES AND CONSTRAINTS

As described in the previous section, the ad hoc architecture has many benefits, such as self-reconfiguration and ease of deployment. However, this flexibility and convenience come at a price. Ad hoc wireless networks inherit the traditional problems of wireless communications, such as bandwidth optimization, power control, and transmission quality enhancement [2], while, in addition, their mobility, multihop nature, and the lack of fixed infrastructure create a number of complexities and design constraints that are new to mobile ad hoc networks. The challenges include:

- They are infrastructureless hence lots of design issues and hard network management issues.
- Their topologies dynamically keep changing.
- The radio interface at each node uses broadcasting for transmitting traffic and usually a limited range leading to issues such as hidden terminal problems.
- Limited link bandwidth.
- Poor Quality of links.
- Variation of link and node capabilities.
- Energy issues [3].
- Robustness and unreliability.
- Poor network security.
- Scalability issues [5].
- Quality of Service (QoS).

A quality of service (QoS) guarantee is essential for successful delivery of multimedia network traffic. QoS requirements typically refer to a wide set of metrics including throughput, packet loss, delay, jitter and error rate [6]. Wireless and mobile ad hoc specific network characteristics and constraints described above, such as dynamically changing network topologies, limited link bandwidth and quality, variation in link and node capabilities, pose extra difficulty in achieving the required QoS guarantee in a mobile ad hoc network. [2]

1.1.4 USE OF FUZZY LOGIC IN ROUTING IN MOBILE AD HOC NETWOKS

In an attempt to counter the aforementioned challenges in MANETS, routing algorithms which make use of Artificial Intelligence (AI) and fuzzy logic are an ongoing area of research. Artificial Intelligence generally involves the design of intelligent systems; intelligent in that they are environmentally sensitive and take actions that maximize chances of success [7], [8].

The QoS problem [9] in MANETS renders itself as a good candidate for Fuzzy and AI based solutions especially in the routing process as prominence of MANETS and number of users increases. In this proposed research, the main concern is the design and use of fuzzy priority coordinator in improving QoS in MANETS. The fuzzy logic implements human experience and preference by using membership functions and fuzzy logic rules [10] [11] [12] hence leading to improved QoS in MANETS.

1.2 PROBLEM STATEMENT

In mobile ad hoc networks, the presence of additional bandwidth, link and medium constraints, as well as the constant change in network topology, make supporting Quality of Service more difficult than in fixed wired line networks [2], which only need to deal with static constraints such as bandwidth, memory, or processing power. Due to the lack of sufficiently accurate knowledge of the network states, both instantaneous and predictive, even statistical QoS guarantees may be impossible if the nodes are highly mobile. Consequently, many existing QoS solutions developed for Internet are not suitable for MANET environments and need to be adapted.

In general, Quality of Service is not related to any dedicated network layer, but, rather, requires coordinated efforts from all layers. Important QoS components in the MANET domain include QoS models, QoS Medium Access Control (MAC), QoS routing and resource reservation signaling, and so on [13]. A QoS model outlines the overall QoS goals and architecture for implementing a given application or service. These objectives may include link capacity, latency, link utilization percentage, throughput, bandwidth and energy consumption, and so on. QoS routing refers to the discovery and maintenance of routes that can satisfy QoS objectives under given the resource constraints, whereas QoS signaling is responsible for actual admission control, and scheduling, as well as resource reservation along the route determined by QoS routing or other routing protocols. Both QoS routing and QoS signaling coordinate with the QoS MAC protocol to deliver the QoS service required [14].

Improving QoS in MANETS through human intelligence means, especially with the ever exponentially increasing users is critical. A fuzzy coordinator is a promising solution to the QoS problem in MANETS. It is an important addition of knowledge in a sector where many scholars are still struggling to find a lasting solution.

1.3 JUSTIFICATION

Quality of Service support is inherently difficult in an ad hoc environment. In order to support real-time multimedia applications, effort must be made to control network QoS factors such as end-to-end delay, packet loss, and jitter. It has been recognized that hard QoS guarantees will be difficult to achieve in a dynamic environment. Consequently, there is a trend toward an adaptive QoS approach instead of the “plain’’ resource reservation method with hard QoS guarantees. Since end-to-end QoS guarantee requires coordinated effort from all layers, more research effort is needed to come up with coherent mechanisms that present an “all layer QoS” solution instead of individual optimization within each layer. The Fuzzy Priority Coordinator (FPC) will be part of this effort.

1.4 OBJECTIVES

1.4.1 MAIN OBJECTIVE

The main objective of this thesis is to design and analyze a fuzzy logic based packet scheduling coordinator (FPC) for use in improving QoS in MANETS routing.

1.4.2 SPECIFIC OBJECTIVES

1. Review of factors influencing Quality of Service in MANETS.
2. Designing a fuzzy logic based packet scheduling coordinator (FPC) system for use in MANETS.
3. Analyze the effectiveness of the use of designed system over other existing packet scheduling schemes.

1.5 THESIS ORGANIZATION

Chapter 1

This chapter lays down an overview of the work concerned in the thesis. The rest of the thesis is divided as follows

Chapter 2

This chapter lays down the literature review of various works done by other researchers on Mobile Ad hoc Networks, their architecture, protocols and techniques in routing, problems facing the routing in MANETS, Models for MANETS and summary of QoS routing protocols. It also covers the prospects and use of fuzzy logic in improving QoS in MANETS.

Chapter 3

This chapter presents an analysis on the viability and use of fuzzy based priority coordinator (FPC) in MANETS routing to improve QoS. It elaborates the design procedure in MATLAB giving fuzzy inference rules, the membership functions of various inputs and the output of the designed FPC. It then gives the surface view of the relations of at least three inputs of the FPC

Chapter 4

This chapter presents an analysis on the viability of the use of the FPC in improving QoS in MANETS routing. The simulations are done in OPNET. A C++ programme is developed to enable the linking/calling of the MATLAB model to the OPNET simulator. Several applications are deployed during the simulation. The basics of OPNET co simulation mechanism are discussed. The simulation results are shown graphically. A performance comparison of the FPC in both low load and high load conditions for each of the applications is done. The comparison is also done on an increased number of nodes in the MANETS set up.

Chapter 5

This chapter gives the summary, conclusion and various recommendations from the thesis work.

CHAPTER 2

2 LITERATURE REVIEW

2.1 INTRODUCTION

This chapter presents the various well known and common Quality of Service approaches in Mobile Ad hoc NETworks.

2.2 MOBILE AD HOC NETWORKS (MANETS)

A Mobile Ad hoc Network (MANET) is an autonomous system of mobile nodes connected by wireless links. Each node operates as an end system and a router for all other nodes in the network. A MANET is a self configuring network of mobile routers connected by wireless links –the union of which forms an arbitrary topology. An Ad hoc network is often defined as an "infrastructure-less" network, as shown in Figure 2.1 and Figure 2.2. It is a network without the usual routing infrastructure, link fixed routers and routing backbones [1]. A MANET is a distributed network that does not require centralized control, and every host works not only as a source and a sink but also as a router [15]. This type of dynamic network is especially useful for military communications or emergency search and rescue operations, where an infrastructure cannot be supported. The nodes that make up a network at any given time communicate with and through each other. In this way every node can establish a connection to every other node that is included in the MANET. Examples of nodes can be personal devices like, mobile phones, Laptops and Personal Data Assistants (PDA's). Smaller and simpler devices also use wireless ad-hoc networking, like wireless headsets and hands [2].

The challenges of supporting QoS in ad hoc networks are in reserving bandwidth and guaranteeing the specified delay for real-time application data flows. For wireless transmissions, the channel is shared among neighbours. Therefore, the available bandwidth depends on the neighbouring traffic status, as does the delay. Due to this characteristic, supporting QoS cannot be done by the host itself, but cooperation from the hosts within a node's interference range is needed. This requires an innovative design to coordinate the communication among the neighbours in order to support QoS in MANETS. Furthermore, the distributed organization of MANETS brings additional challenges to collaboration for supporting QoS.

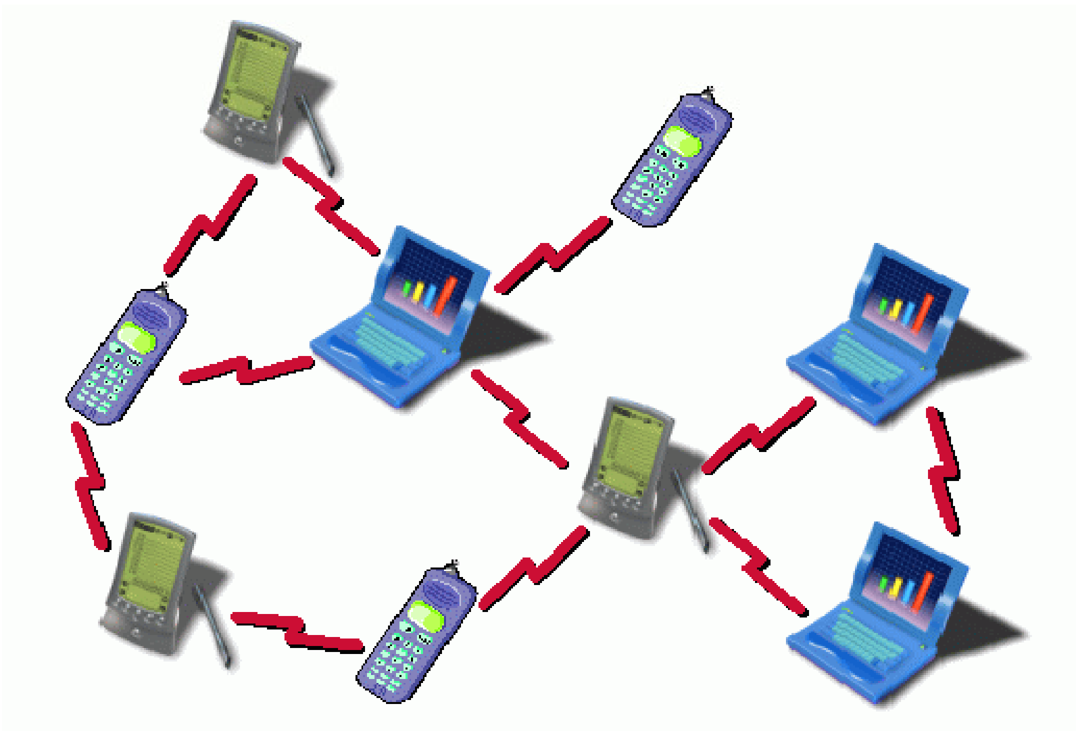

Figure 2.1: Mobile Ad hoc devices

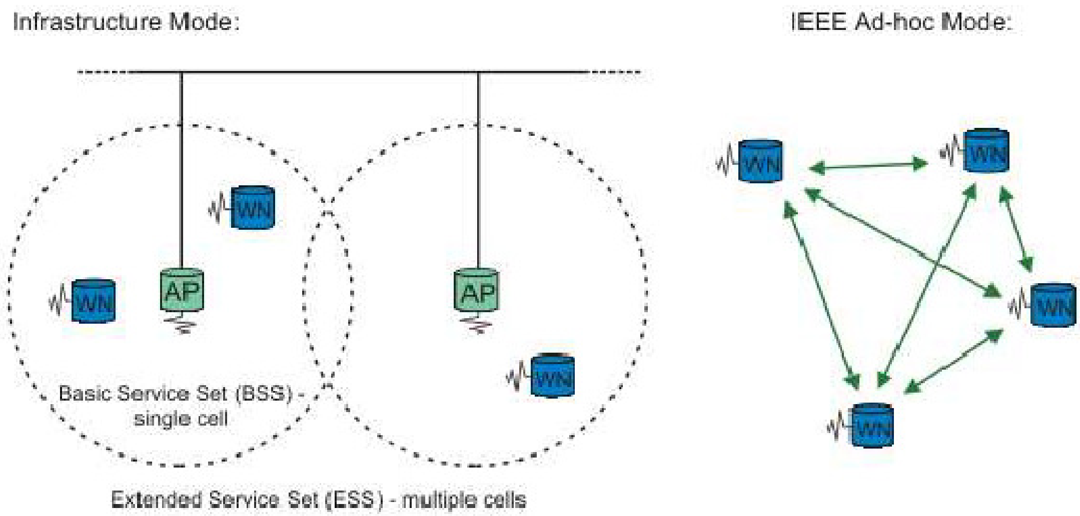

Figure 2.2: Infrastructure and Ad hoc Mode of WLANs configuration

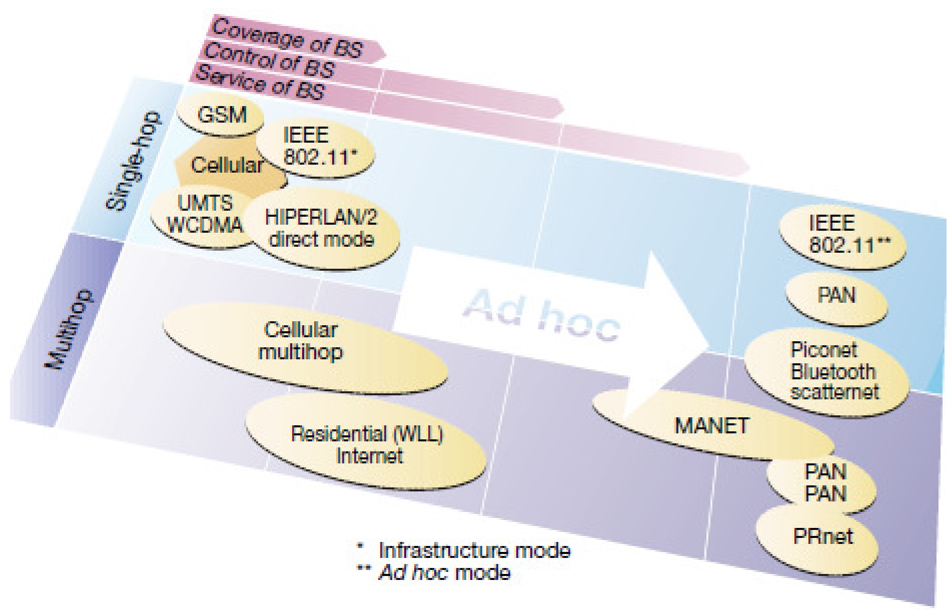

Figure 2.3: Position of MANETS among the Wireless networks and topology

2.3 EEE802.11 ARCHITECTURE AND PROTOCOLS

2.3.1 IEE802.11 ARCHITECTURE

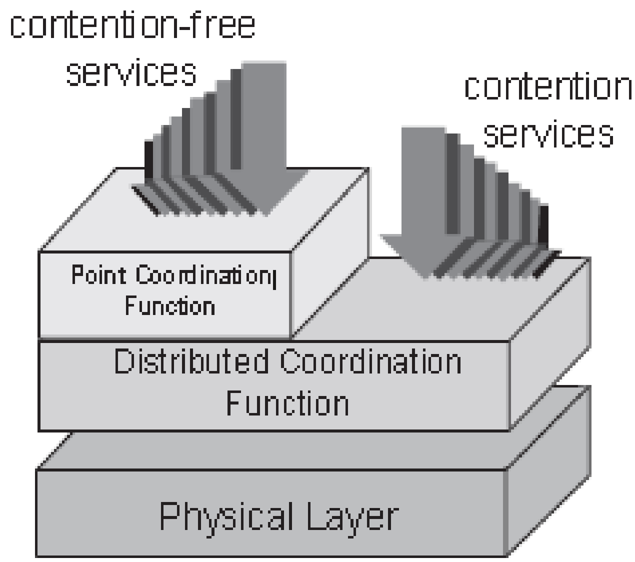

Figure 2.4: IEEE802.11 architecture

Figure 2.4 [2] shows the IEEE 802.11 architecture. IEEE 802.11 is a set of medium access control (MAC) and physical layer (PHY) specifications for implementing wireless local area network (WLAN) computer communication in the 2.4, 3.6, 5 and 60 GHz frequency bands. They are created and maintained by the IEEE LAN/MAN Standards Committee (IEEE 802) [1]. The base version of the standard was released in 1997 and has had subsequent amendments. The standard and amendments provide the basis for wireless network products using the Wi-Fi brand. While each amendment is officially revoked when it is incorporated in the latest version of the standard, the corporate world tends to market to the revisions because they concisely denote capabilities of their products. As a result, in the market place, each revision tends to become its own standard [16].

The IEEE 802.11 standard specifies both the MAC layer and the Physical Layer (Figure2.4) [2]. The MAC layer offers two different types of service: a contention-free service provided by the

Distributed Coordination Function (DCF), and a contention-free service implemented by the Point Coordination Function (PCF). These service types are made available on top of a variety of physical layers. Specifically, three different technologies have been specified in the standard: Infrared (IF), Frequency Hopping Spread Spectrum (FHSS), and Direct Sequence Spread Spectrum (DSSS).

The DCF provides the basic access method of the 802.11 MAC protocol and is based on a Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) scheme. The PCF is implemented on top of the DCF and is based on a polling scheme. It uses a Point Coordinator that cyclically polls stations, giving them the opportunity to transmit [2].

2.3.2 IEEE802.11 PROTOCOL TECHNIQUES IN MANETS

Portable devices have limited capacity (battery power, available memory, and computing power) that further complicates the protocol design. Several protocols for ad hoc networks have been developed. The protocols can perform well under certain situations that they are designed to solve, but they fail completely in other situations that can occur in the network[2]. The routing protocols for ad hoc networks have been classified as given below.

2.3.2.1 Proactive/ Table driven

In proactive routing, each node has one or more tables that contain the latest information of the routes to any node in the network. Various table-driven protocols differ in the way the information about change in topology is propagated through all nodes in the network. The two kinds of table updating in proactive protocols are the periodic update and the triggered update. Proactive routing tends to waste bandwidth and power in the network because of the need to broadcast the routing tables/updates. Furthermore, as the number of nodes in the MANET increases, the size of the table will increase; this can become a problem in and of itself. e.g. Destination Sequenced Distance Vector (DSDV), Optimized Link State Routing(OLSR) [17].

2.3.2.2 Reactive /On demand

They do not maintain or constantly update their route tables with the latest route topology. Instead, when a source node wants to transmit a message, it floods a query into the network to discover the route to the destination. The discovered route is maintained until the destination node becomes inaccessible or until the route is no longer desired. The protocols in this class differ in handling cache routes and in the way route discoveries and route replies are handled. Reactive protocols are generally considered efficient when the route discovery is employed rather infrequently in comparison to the data transfer. Although the network topology changes dynamically, the network traffic caused by the route discovery step is low compared to the total communication bandwidth. e.g. Dynamic Source Routing Protocol (DSR) [11], Ad hoc On-Demand Distance Vector routing protocol (AODV) [18] , Temporally Ordered Routing Algorithm (TORA) [1].

2.3.2.3 Hybrid

Both the proactive and reactive protocols work well for networks with a small number of nodes. As the number of nodes increases, hybrid reactive/proactive protocols are used to achieve higher performance. Hybrid protocols attempt to assimilate the advantages of purely proactive and reactive protocols. The key idea is to use a reactive routing procedure at the global network level while employing a proactive routing procedure in a node's local neighbourhood. e.g. Zone Routing Protocol (ZRP), Hybrid Ad hoc Routing Protocol (HARP) [19].

2.4 PROBLEMS FACING THE PROVISION OF QoS IN MANETS

The following is a summary of the major challenges to providing QoS guarantees in MANETS. [1]

2.4.1 Unreliable Wireless Channel

The wireless channel is prone to bit errors due to interference from other transmissions, thermal noise, shadowing, and multipath fading effects. This makes it impossible to provide hard packet delivery ratio or link longevity guarantees.

2.4.2 Node Mobility

The nodes in a MANET may move completely independently and randomly as far as the communications protocols are concerned. This means that topology information has a limited lifetime and must be updated frequently to allow data packets to be routed to their destinations. Again, this invalidates any hard packet delivery ratio or link stability guarantees. Furthermore, a QoS state which is link- or node position dependent must be updated with a frequency that increases with node mobility. An important general assumption must also be stated here: for any routing protocol to be able to function properly, the rate of topology change must not be greater than the rate of state information propagation. Otherwise, the routing information will always be stale and routing will be inefficient or could even fail completely. This applies equally to QoS state and QoS route information. A network that satisfies this condition is said to be combinatorially stable [2]

2.4.3 Lack of Centralized Control

The major advantage of an ad hoc network is that it may be set up spontaneously, without planning, and its members can change dynamically. This makes it difficult to provide any form of centralized control. As such, communications protocols which utilize only locally available state and operate in a completely distributed manner are preferred [20]. This generally increases an algorithm’s overhead and complexity, as QoS state information must be disseminated efficiently.

2.4.4 Channel Contention

In order to discover network topology, nodes in a MANET must communicate on a common channel. However, this introduces the problems of interference and channel contention. For peer-to-peer data communications these can be avoided in various ways. One way is to attempt global clock synchronization and use a TDMA-based system where each node may transmit at a predefined time. This is difficult to achieve due to the lack of a central controller, node mobility and the complexity and overhead involved [9]. Other ways are to use a different frequency band or spreading code (as in CDMA) for each transmitter. This requires a distributed channel selection mechanism as well as the dissemination of channel information. However data communications take place, without a central controller, some setup, new neighbor discovery and control operations must take place on a common contended channel. Indeed, avoiding the aforementioned complications, much MANET research, as well as the currently most popular wireless ad hoc networking technology (802.11x) is based on fully-contended access to a common channel, that is, with Carrier-Sense Multiple Access with Collision Avoidance (CSMA/CA). However, CSMA/CA greatly complicates the calculation of potential throughput and packet delay, compared to TDMA based approaches. This is because nodes must also take into account the traffic at all nodes within their carrier sensing range. Furthermore, the possibility of collisions also arises. Collisions waste channel capacity, as well as node battery energy, increase delay, and can degrade the packet delivery ratio. Finally, the well understood hidden node and exposed node problems are a further consequence of channel contention. These problems are even more pronounced when we consider that nodes may interfere with transmissions outside of their transmission range [21], since receivers are able to detect a signal at a much greater distance than that at which they can decode its information.

2.4.5 Limited Device Resources

To some extent this is an historical limitation, since mobile devices are becoming increasingly powerful and capable. However, it still holds true that such devices generally have less computational power, less memory, and a limited (battery) power supply, compared to devices such as desktop computers typically employed in wired networks. This factor has a major impact on the provision of QoS assurances, since low memory capacity limits the amount of QoS state that can be stored, necessitating more frequent updates, which incur greater overhead. Additionally, QoS routing generally incurs a greater overhead than best-effort routing in the first place, due to the extra information being disseminated. These factors lead to a higher drain on mobile nodes' limited battery power supply. Finally, within the pool of QoS routing problems, many are incomplete [22], and thus complicated heuristics are required for solving them, which may place an undue strain on mobile nodes' less-powerful processors.

2.5 REVIEW OF QoS MODELS FOR MANETS

QoS models specify the architecture in which certain services could be provided in the network. In this section, QoS models for the Internet, such as lntServ [23]and DiffServ [24], are first introduced, before discussing QoS models proposed for MANETS.

2.5.1 INTEGRATED SERVICES (IntServ)

The Integrated Services (IntServ) model was the first standardized model for the Internet developed by IETF (RFC 1633) . The model offers two kinds of services: Guaranteed QoS and Controlled Load QoS. Guaranteed QoS ensures the requested bandwidth and delay bounds for the duration of the connection, while Controlled Load QoS is a better than best effort service for applications that can tolerate some amount of delay, but is sensitive to congestion in the network. RFC 2212 provides specification of guaranteed quality of service, while RFC 2211 defines specifications of the controlled load network element service. In implementing Guaranteed QoS service, IntServ provides hard guarantees to the flows by performing admission control and making reservations along the nodes before the flow commences. The framework includes four components: packet scheduler, admission control routine, classifier and reservation setup protocol. Several issues hinder the direct applicability of the IntServ framework to MANETS [17].

2.5.2 DIFFERENTIATED SERVICES (DiffServ)

The Differentiated Services (DiffServ) model [9] was designed to overcome the inherent demerits of the IntServ model. Many RFCs have been developed to standardize various aspects of the model such as definition of per hop behavior identification codes (RFC 3140) and behavior of the nodes to different classes of traffic (RFC 2597 , RFC 3246). DiffServ appears as a potential model for a MANET environment, because of its merits such as low per node complexity, low control overhead due to the absence of an external signaling mechanism and no per flow reservation requirement. However, the model as defined for wired networks cannot be directly applied to a MANET. There are several issues that need to be resolved, such as distinction between the edge and the core nodes. Intuitively, the source nodes play the role of edge routers and the relaying nodes act as core nodes. Then, each node must have the capability to act as an edge node and a core node, resulting in an increased complexity at each node. Also, the concept of a Service Level Agreement (SLA) does not exist in a MANET. Each node itself must be responsible for not overwhelming the network with traffic.

2.5.3 Flexible QoS Model for MANET (FQMM)

A Flexible QoS Model for MANET (FQMM) has been proposed which considers the characteristics of MANETS and tries to take advantage of both the per-flow service granularity in IntServ and the service differentiation in DiffServ. FQMM is the first attempt at proposing a QoS model for MANETS [25]. However, some problems still need to be solved. First, how many sessions could be served by per-flow granularity? Without an explicit control on the number of services with per-flow granularity, the scalability problem still exists. Secondly, just as in DiffServ, the interior nodes forward packets according to a certain PHB in the DS field. It is arguable that it is difficult to code the PHB in the DS field if the PHB includes per-flow granularity, considering that the DS field is at most 8 bits without extension. Finally, making a dynamically negotiated traffic profile is very difficult.

2.5.4 Service Differentiation in Wireless Ad hoc Networks (SWAN)

The SWAN model was developed by the Comet team at Columbia University [17] . The model differentiates traffic into real time UDP traffic and best effort TCP traffic. It is a stateless and fully distributed model that provides soft QoS assurances to real-time traffic. It uses admission control for real-time traffic, rate control of TCP traffic and ECN congestion control mechanisms to ensure that real-time packets meet QoS bounds. Each node comprises an admission controller that maintains information about the status of the outgoing link in terms of the available bandwidth and amount of congestion. It does this by promiscuously listening to all packet transmissions within its range. The admitted real-time traffic bypasses the rate controller and has a scheduling priority over best-effort traffic. The admitted real-time flows only have soft QoS assurances, so that some of the flows may be dropped or downgraded to best effort if network traffic conditions change due to rerouting of traffic [26].

2.6 REVIEW OF OTHER WORK ON THE QoS OF MANETS

Several different approaches can be suggested in an effort to improve QoS provision in MANETS. Some of the works are reviewed next.

2.6.1 METRICS USED TO SPECIFY QoS REQUIREMENTS.

Various sample metrics commonly used by applications to specify QoS requirements to the routing protocol are;

- Minimum Required Throughput (MRT) or Capacity in which the desired application data throughput [27].
- Maximum Tolerable Delay (MTD) usually defined as the maximum tolerable end-to-end (source to destination) delay for data packets [28]. This incorporates the queuing delay at each node
- Maximum Tolerable Delay for which widely accepted definition, is the difference between the upper bound on end-to-end delay and the absolute minimum delay [25]. This is determined by the propagation delay and the transmission time of a packet
- The transmission time between two nodes in bits/ channel capacity [29], also expressed as delay variance, Maximum Tolerable Packet Loss Ratio (PLR)
- End to end delay defined as the delay incurred by a packet to travel from the source to the application layer of the destination.
- Average throughput which is defined as the average number of data packetsreceived by a destination node per second.
- Jitter which indicates the rise and fall of delay from one packet to the next
- Latency
- Link Reliability/frame delivery ratio
- Signal to interference ratio (SIR)
- Bit error rates (BER)
- Node cost [30]

2.6.2 QoS ROUTING PROTOCOLS BASED ON THE MAC LAYER.

MAC layer QoS routing protocols are classified into three groups;

- *Routing protocols that rely on accurately quantified resource (commonly channel capacity) availability and resource reservation.* The protocols require a contention-free MAC solution such as TDMA. Such protocols are able to provide what is termed as pseudo-hard QoS. Hard QoS guarantees can only be provided in a wired network, where there are no unpredictable channel conditions and node movements. In the solutions that employ a contention-free MAC, the QoS guarantees provided are essentially hard, except for when channel fluctuations or node failures or movements occur, and hence the term "pseudo-hard." Due to these unpredictable conditions, a MANET is not a suitable environment for providing truly hard QoS guarantees [1].
- *Routing protocols that rely only on a contended MAC protocol*. Such protocols rely only on the available resources or achievable performance to be statistically estimated. The protocols typically use these estimations to provide statistical or soft guarantees. Implicit resource reservation may still be performed, by not admitting data sessions which are likely to degrade the QoS of previously admitted ones. However, all guarantees are based on contended and unpredictable channel access or are given only with a certain probability and are thus inherently soft.
- *Routing protocols that do not require any MAC layer interaction at all and are thus independent from the MAC protocol.* Such protocols cannot offer any type of QoS guarantees that rely on a certain level of channel access. They typically estimate node or link states and attempt to route using those nodes and links for which more favourable conditions exist. However, the achievable level of performance is usually not quantified

or is only relative and therefore no promises can be made to applications. The aim of such protocols is typically to foster a better average QoS for all packets according to one or more metrics. This comes often at the cost of trade-offs with other aspects of performance which includes increased complexity, extra message overhead, or limited applicability.

2.6.3 SUMMARY OF QoS ROUTING PROTOCOLS.

Classification and summary of different QoS protocols published in quality literature in the period stated above is given in the table below. This enables the highlighting of the variety of approaches investigated, as well as to observation of the trends in the field of QoS especially in the MANETS.

Table 2.1: Different QoS Routing Protocols.

No.	PROTOCOL	NETWORK/NODE INFORMATION UTILIZED	MAC PROTOCOL FUNCTIONALITY	QoS ASSURANCES
1	AAQR — Application Aware QoS Routing [32]	Packet transmission delays; session throughput requirements	None	Bounded delay and jitter; assured throughput
2	CAAODV — Contention-Aware Ad hoc On-Demand Distance Vector routing [33]	Channel idle time ratio	802.11 DCF; channel idle time estimation	Assured throughput
3	CACP — Contention-aware Admission Control Protocol [33]	Channel idle time ratio	802.11 DCF; channel idle time estimation	Assured throughput

4	SIRCCR — SIR and Channel Capacity-Based Routing [35]	Time slot schedule; transmission power; path los	Time slot schedule; transmission power; path loss	Assured throughput; bounded BER
5	GAMAN — Genetic Algorithm based routing for Mobile Ad hoc Networks [35]	Node traversal delay; packet transmission success ratio	None	Bounded delay and packet dropping rate
6	QGUM — QoS-GPSR (Greedy Perimeter Stateless Routing) for Ultra-Wideband (UWB) MANETS [36]	Bounded delay and packet dropping rate	Idle time estimation; PLR measurement; multi-rate transmission	Assured throughput; bounded PLR; bounded delay
7	TBR — Ticket-Based Routing [15]	Available channel capacity; delay estimates	Soft reservations	Assured throughput or bounded delay
8	ODCR-On-Demand Delay-Constrained Routing .	End-to-end path delay	Resource reservation	bounded delay
9	CLMCQR — Cross Layer Multi-Constraint QoS Routing.	MAC delay; channel idle time ratio; link reliability	Statistical estimation of the utilized information	Assured throughput, bounded delay and packet dropping rate
10	MRPC — Maximum Residual Packet Capacity routing	Node residual battery charge; link packet dropping ratio	None	Improved route lifetime; reduced energy consumption; reduced packet dropping rate

2.6.4 ARTIFICIAL INTELLIGENCE BASED ADAPTIVE QoS METHODS

In [37], a system based on fuzzy neural networks (FNNs) is proposed for solving the load balancing problem. Mobile Ad hoc Networks are facing continuous changes in the network. The proposed (FNN) is located at each point in the network to make load balancing for nodes. This is done by using two fuzzy neural networks. FNN1is based on two measurements. First is queue length, which permit queue size to classify queue state (Underfull to Overfull). Secondly, FNN2 used queue state that represented output of the FNN1, while the other is throughput for node and the output is load for this node. The Gaussian membership function is used with back propagation algorithm for training the NN. A Hopfield neural network beam former yields better results

In [38] The researcher presents a fuzzy logic based decision algorithm that weighs individual links as a path to the necessary destination. If this link is deemed suitable by the fuzzy logic system it is added to the path and route construction continues. The fuzzy controller is used to make decisions and to optimize route selection as only good quality links are recorded in source destination paths. A route discovery attempt can possibly result in several paths being uncovered for a single destination. As nodes often have a finite capacity path cache, it may not be possible to store all paths. So as to influence productive caching decisions a fuzzy logic system is applied to the route discovery technique to curb non-optimal network floods. This action causes a cessation in the generation of low quality routes as only paths with good routing metrics are selected for the rebroadcast of route discovery packets. Consequently, route query packets arriving at the necessary destination node, or at some intermediate node with knowledge of the destination node, generate high quality route replies hence improved QoS.

2.6.5 SCHEDULING ALGORITHMS IN MANETS

There are several scheduling policies for different network scenarios. Different routing protocols use different methods of scheduling. The drop-tail policy is used as a queue management algorithm in all scheduling algorithms for buffer management. For the scheduling algorithms that give high priority to control packets, different drop policies are used for data and control packets when the buffer is full. When the incoming packet is a data packet, the data packet is dropped. When the incoming packet is a control packet, the last queued data packet is dropped. If queued packets are control packets, the incoming control packet is dropped. Except for the no-priority scheduling algorithm, all the other scheduling algorithms give higher priority to control packets than to data packets. The differences in the algorithms are in assigning priority between data packets. In no-priority scheduling, both control and data packets are served in FIFO order. In the priority scheduling, control and data packets are maintained in separate queues in FIFO order and high priority is assigned to control packets.

Weighted-hop scheduling gives higher weight to data packets that have fewer remaining hops to traverse. If the packet has fewer remaining hops, then it has to reach the destination quickly. The data packets can be stored in round-robin fashion. The remaining hops to traverse can be obtained from packet headers.

Weighted-distance scheduling gives higher weight to data packets which have shorter geographic distances. The remaining distance is the distance between a chosen next hop and a destination.

Round-robin scheduling maintains per-flow queues. The flow can be identified by a source and destination pair. Here each flow queue is allowed to send one packet at a time in a round-robin fashion.

In the greedy scheduling scheme, each node sends its own data packets before forwarding those of other nodes [8]. The data packets of other nodes are serviced in FIFO order. In earliest deadline first (EDF), a packet arriving at time t and having delay bound d has a deadline $t + d$. The packets will be scheduled based on this deadline. In virtual clock (VC), a packet with size L of a flow, with rate r, has a priority index L/r plus the maximum of current time t and priority index of the flow's previous packet.

In these scheduling algorithms, the parameters used to find the priority of data packets are remaining hops to traverse, distance, per-flow queues, greediness of nodes, delay bound, and flow.

2.7 THE USE OF FUZZY LOGIC TO IMPROVE QoS

2.7.1 FUZZY LOGIC

Fuzzy logic is a form of multi-valued logic; it deals with reasoning that is approximate rather than fixed and exact. Compared to traditional binary sets (where variables may take on true or false values) fuzzy logic variables may have a truth value that ranges in degree between 0 and 1. Fuzzy logic has been extended to handle the concept of partial truth, where the truth value may range between completely true and completely false.[1] Furthermore, when linguistic variables are used, their degrees may be managed by specific functions. The term "fuzzy logic" was introduced with the 1965 proposal of fuzzy set theory by Lotfi A. Zadeh [39]. It is advantageous to use the fuzzy logic in the target system because it is flexible and capable of operating with imprecise data. Basically the fuzzy system consists of four blocks, namely, the fuzziffication block, rule evaluation block, the aggregation block and the defuzzification block which produces the output. The block diagram of a fuzzy logic system is shown in Figure 2.5.

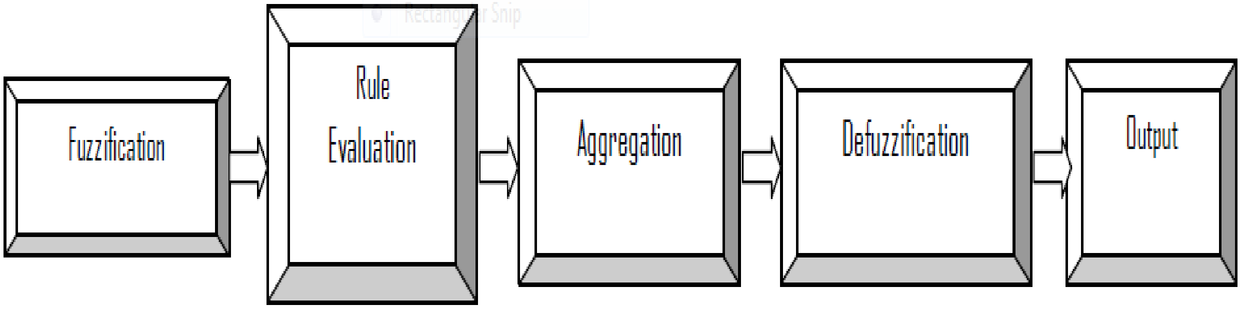

Figure 2.5: Stages in the Fuzzy Inference System.

2.7.1.1 Fuzzification of inputs and outputs

The first step in fuzzy logic system is to take the inputs and determine the degree to which they belong to a specific appropriate fuzzy set. This is done via the membership functions. The inputs are always numerical values limited to the universe of discourse and the output is always a fuzzy degree of membership in the qualifying linguistic set (always the interval between 0 and 1. A fuzzy set A in the universe of discourse U is a set of ordered pairs $\{(x_1, \mu A(x_1)), (x_2, \mu A(x_2)), \ldots,$ $(x_n, \mu_A(x_n))\}$, where $\mu_A : U \rightarrow [0, 1]$is the membership function of the fuzzy set A and $\mu_A(x_i)$ indicates the membership degree of x_i in the fuzzy set A [10].

2.7.1.2 Fuzzy inference process

If a fuzzy system has n inputs and a single output, its fuzzy rules R_j can be of the following general format;

(R_j): IF X_1 is A_{1j}, X_2 is A_{2j}, X_3 is A_{3j}, . . ., and X_m is A_{mj}, THEN Y is B_j .

The variables $X_i\{i = 1, 2,3, \ldots, m\}$ appearing in the antecedent part of the fuzzy rules R_j are called the input linguistic variables. The variable Y in the consequent part of the fuzzy rules R_j is called the output linguistic variable. The fuzzy sets A_{ij} are called the input fuzzy sets of the input linguistic variable X_i and the fuzzy sets B_j are called the output fuzzy sets of the output linguistic variable Y of the fuzzy rules R_j .

2.7.1.3 The implication method

Before applying the implication method, the rule's weight must be taken care of. Every rule has a weight (a number between 0 and 1), which is applied to the number given by the antecedent. Once proper weighting has been assigned to each rule, the implication method is implemented. A consequent is a fuzzy set represented by a membership function, which weighs appropriately the linguistic characteristics that are attributed to it. The consequent is reshaped using a function associated with the antecedent (a single number). The input for the implication process is a single number given by the antecedent, and the output is a membership function, implemented for each rule.

2.7.1.4 Aggregation of all outputs

Since decisions are based on the testing of all of the rules, the rules must be combined in some manner in order to make a decision. Aggregation is the process by which the fuzzy sets that represent the outputs of each rule are combined into a single fuzzy set. Aggregation occurs only once, for each output variable, just prior to the final step of deffuzzification. The input of the aggregation process is the list of truncated output functions returned by the implication process for each rule. The output of the aggregation process is one fuzzy set for each output variable.

2.7.1.5 Deffuzzification

The final desired output for each variable is generally a single number. However the aggregate of a fuzzy set encompasses a range of output values and so it must be deffuzzified in order to resolve a single output value from the set. Centroid method [10] can be used to deffuzzify. It returns the centre of area under the curve.

2.7.2 FUZZY PRIORITY COORDINATOR

In improving the performance and the QoS of MANETS, a Fuzzy Priority Coordinator is proposed. This coordinator evaluates which packet among the ones in the queue is given priority to propagate from a given node. Currently, techniques like drop tail are used to drop the packets whenever congestion occurs. In the case of FIFO scheduling (also called no priority in this case), both the control and data packets are processed in the first in first out basis.

In the proposed FPC method, higher priority is given to control packets and then Data packets. An intermediary node may receive packets from more than one node and may not be able to determine which packets to give priority, hence might end up forwarding packets which have no urgency. The proposed FPC calculates the priority index of the packets based on parameters such as Expiry Time, Data rate, Queue length and Packet type. The packets with a high priority index will be given the earliest opportunity to propagate. This will improve the throughput and hence the QoS of a MANET system.

CHAPTER 3

3 FUZZY LOGIC BASED PRIORITY SCHEDULER

The four proposed inputs are source data rate, packet type of service, queue length and packet expiry time. The output of the FPC is a priority index value in the range 0-1. A low priority index value is indicative of a packet that must be scheduled with high priority. A high priority index value is indicative of a packet that is to be scheduled with low priority. The linguistic terms associated with the input variables are Low (L), Medium (M), and High (H). The linguistic terms associated with the output variable are Very Very Low (VVL), Very Low (VL), Low (L), Medium (M), High (H), Very High (VH) and Very Very High (VVH). Gaussian membership functions are used for representing these variables. The resultant fuzzy inference system is as illustrated by Figure 3.1.

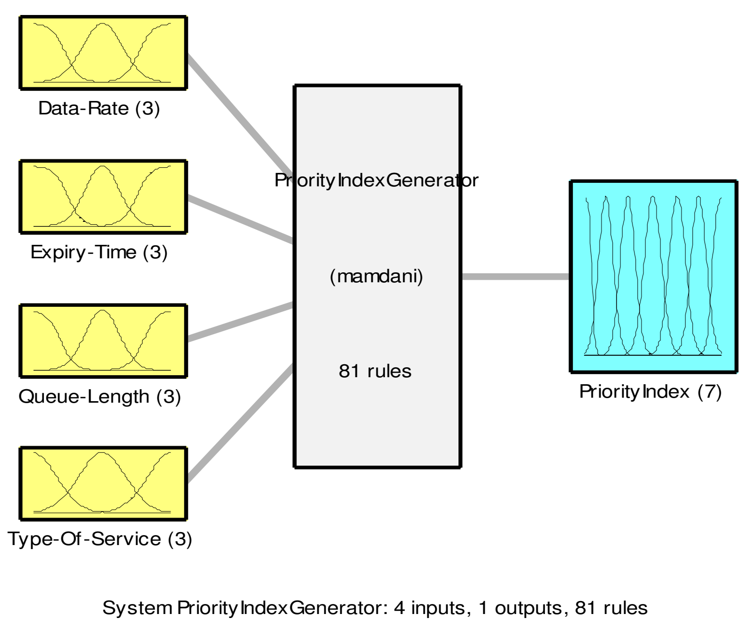

Figure 3.1: Fuzzy inference system.

The corresponding rule table is shown in Table 3.1.

Table 3.1: Implemented fuzzy inference system rules.

	Queue length	Low	Medium	High
Data rate				
		Low Expiry Time		
		Low urgency type of service		
Low		M	M	L
Medium		L	L	L
High		M	L	L
		Medium urgency type of service		
Low		L	L	VL
Medium		VL	VL	VL
High		L	VL	VL
		High urgency type of service		
Low		VL	VL	VVL
Medium		VVL	VVL	VVL
High		VL	VVL	VVL
		Medium Expiry Time		
		Low urgency type of service		
Low		H	H	M
Medium		H	H	M
High		H	H	H
		Medium urgency type of service		
Low		M	M	L
Medium		M	M	L
High		M	M	M
		High urgency type of service		
Low		L	L	VL
Medium		L	L	VL
High		L	L	L
		High Expiry Time		
		Low urgency type of service		
Low		VVH	VVH	VH
Medium		VH	H	H
High		VH	VH	H
		Medium urgency type of service		
Low		VH	VH	H
Medium		H	M	M
High		H	H	M
		High urgency type of service		
Low		H	H	M
Medium		M	L	L
High		M	M	L

The input membership functions are as shown in Figures 3.2 to 3.6. Gaussian membership functions are used in this case. The Gaussian membership functions have advantage in that they are smooth and continuously differentiable hyper surfaces of a fuzzy model. Furthermore, they facilitate theoretical analysis of fuzzy systems as they have derivatives of any grade.

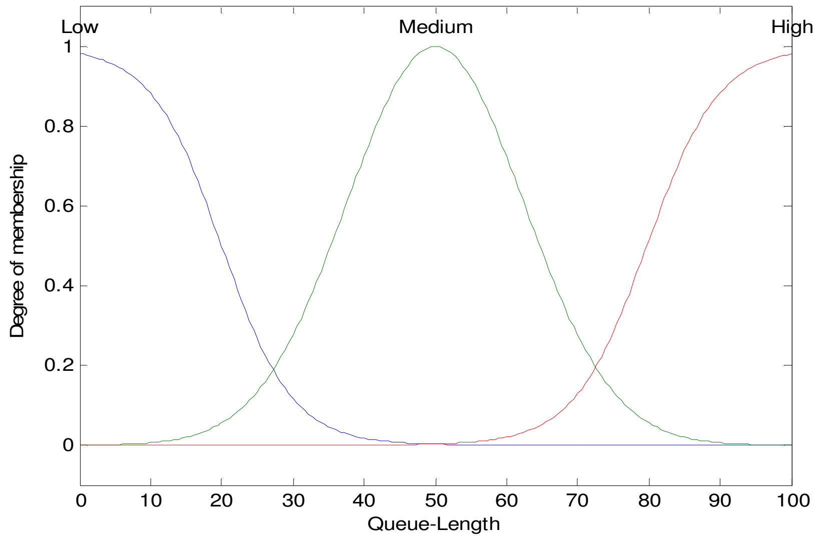

Figure 3.2: Queue length membership function.

The queue length input variable is resolved into Low, Medium and High membership functions as in Figure 3.2. A packet in a queue whose length is high is to be given higher priority.

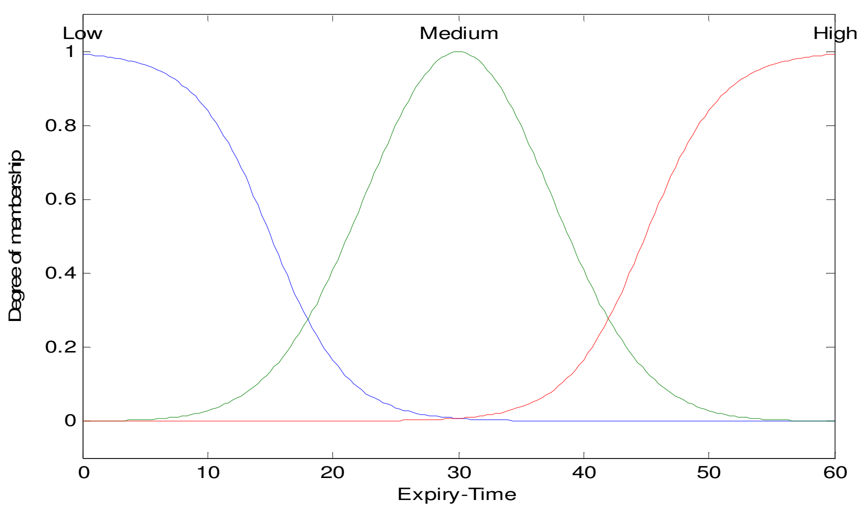

Figure 3.3: Expiry time membership function.

The expiry time input variable is resolved into Low, Medium and High membership functions as shown in Figure 3.3 . A packet with very low Time To Leave (TTL) is to be given higher transmission priority.

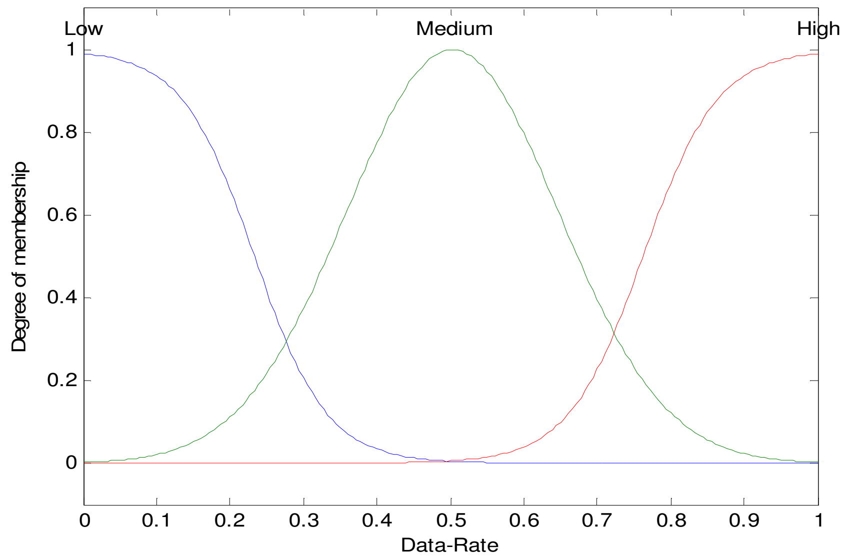

Figure 3.4: Data rate membership function.

The normalized transmission data rate input variable is resolved into Low, Medium and High membership functions as shown in Figure 3.4.

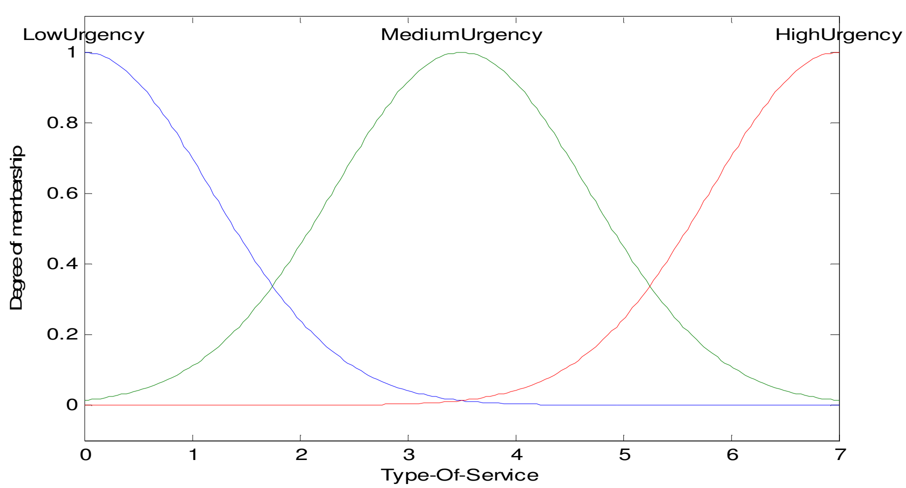

Figure 3.5: Type of service membership function.

The type of service input variable is resolved into Low, Medium and High membership functions as shown in Figure 3.5. Applications such as VoIP requiring fast transmission are accorded higher priority. Data packets are given least priority.

The output membership functions are resolved as shown in Figure 3.6

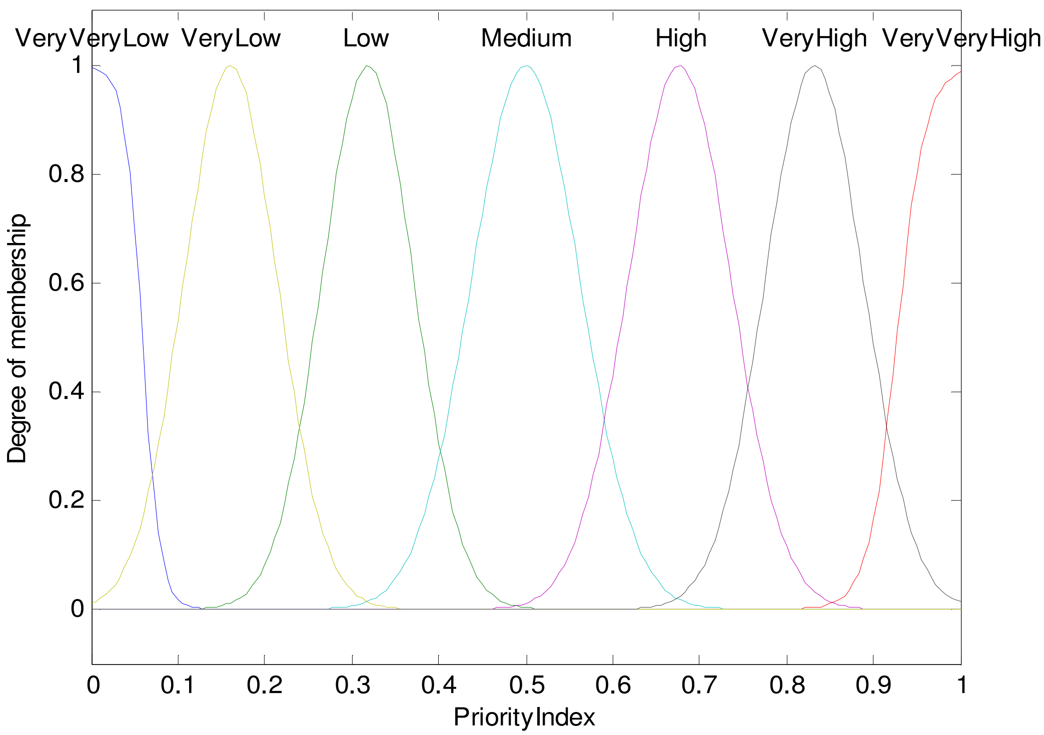

Figure 3.6: Priority index membership function.

Typical surface views are as shown in Figures 3.7 - 3.10.

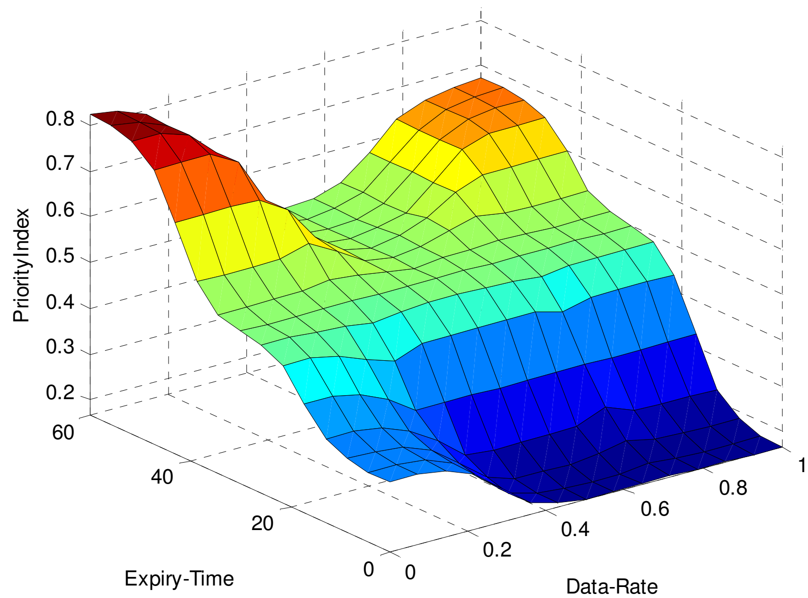

Figure 3.7: Expiry time/data rate surface view.

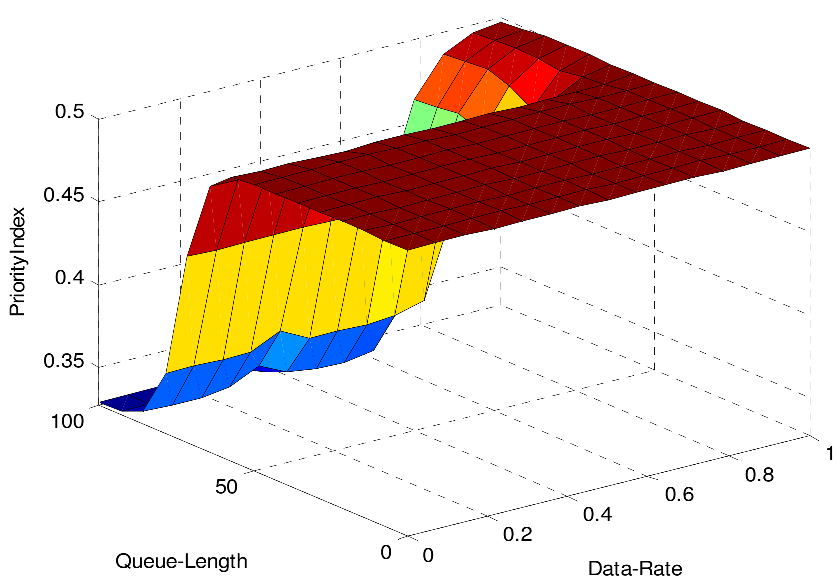

Figure 3.8: Queue length/data rate surface view.

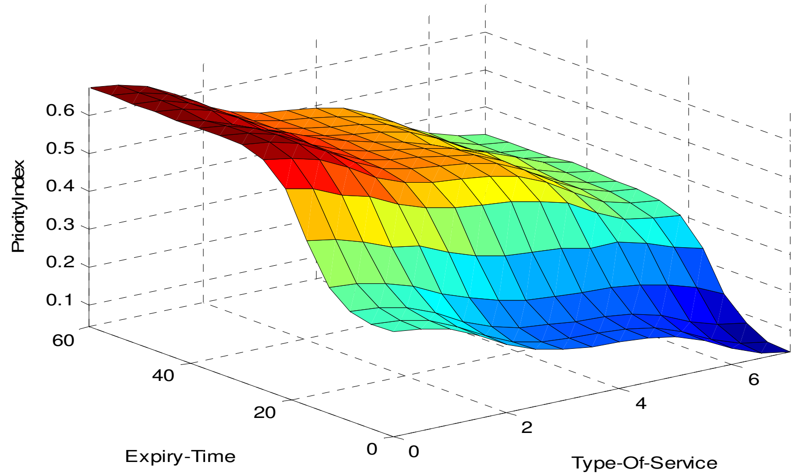

Figure 3.9: Expiry time/type of service surface view.

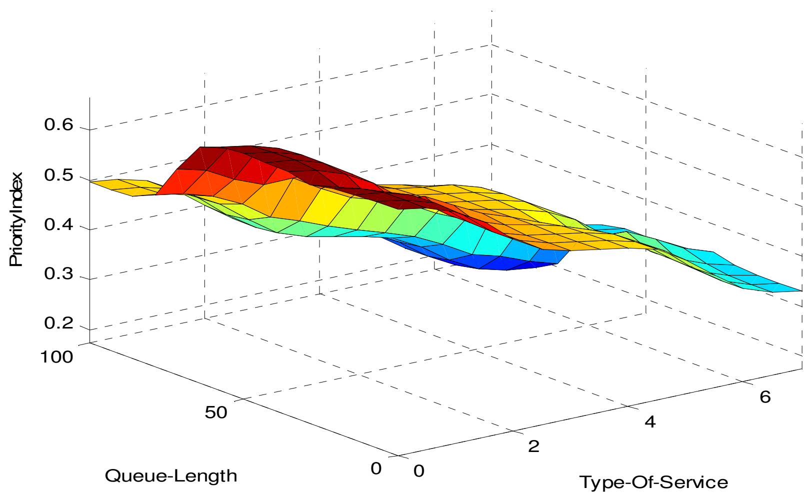

Figure 3.10: Queue length/type of service surface view.

The developed fuzzy inference system is invoked to generate priority index values from the OPNET simulation platform. Centroid defuzzification method is used. The corresponding MATLAB – OPNET link is described in the next Chapter.

CHAPTER 4

4 SIMULATION SET-UP AND RESULTS

4.1 OVERALL SIMULATION SETUP

Simulations carried out are basically aimed at establishing the viability of the developed fuzzy logic based packet scheduler. This is done in comparison to FIFO and Type of Service based packet scheduling mechanisms. The two scheduling types are chosen because they are the most commonly. Variations in network load are simulated. Nodes are configured to move in a random fashion. The simulation area is 500m by 500m square. Six nodes are configured using attribute configuration, profile configuration and the application definition. Each node is configured to move randomly at a speed of 5m/s within the confinements of the area. A data rate of 2Mbps is set. Transmit power threshold is set at 0.005Watts. Further increase in the threshold power may increase interference. Packet reception Power Threshold is -95dB. Figure 4.1 gives the general set up in OPNET.

Dynamic Source Routing (DSR) is used for routing the packets. DSR suits MANETS because of their mobility. Routing tables at the nodes keep changing as the nodes move. This calls for a reactive routing protocol also called on demand routing protocol. In this protocol, if a node wants to send a packet to another node, DSR searches for the route in an on demand manner and establishes a connection. The route discovery occurs by flooding the route request packets throughout the network. The discovered route is not kept in the routing table since the nodes keep moving from time to time.

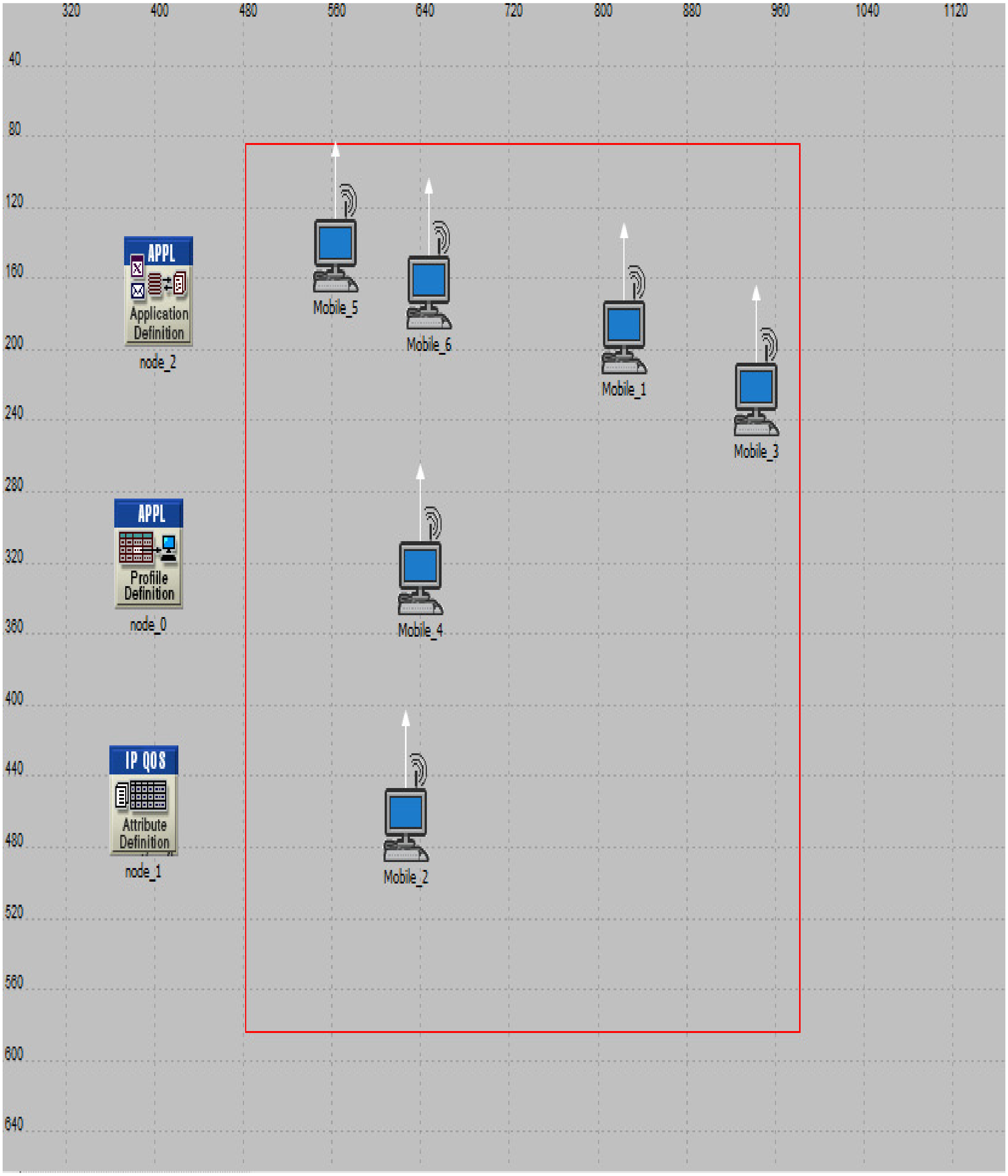

Figure 4.1: Simulation network setup

4.1.1 Deployed applications

4.1.1.1 Voice over Internet Protocol application

A VoIP application is deployed between MANET nodes 1 and 2. The nature of the VoIP application is as shown in table 4.1.

Table 4.1: VoIP application setup

Attribute	**Value**	
Silence Length (seconds)	Incoming Silence Length (seconds)	exponential (0.65)
	Outgoing Silence Length (seconds)	exponential (0.65)
Talk Spurt Length (seconds)	Incoming Talk Spurt Length (seconds)	exponential (0.352)
	Outgoing Talk Spurt Length (seconds)	exponential (0.352)
Symbolic Destination Name	Voice Destination	
Encoder Scheme	G.711 (silence)	
Voice Frames per Packet	1	
Type of Service	Interactive Voice (6)	
RSVP Parameters	None	
Traffic Mix (%)	All Discrete	
Signaling	None	
Compression Delay (seconds)	0.02	
Decompression Delay (seconds)	0.02	

4.1.1.2 Video conferencing application

A video conferencing application is deployed between MANET nodes 3 and 4. The nature of the video conferencing application is as shown in table 4.2.

Table 4.2: Video conferencing application setup

Attribute	**Value**
Frame Inter-arrival Time Information	15 frames/sec
Frame Size Information (bytes)	128X240 pixels
Symbolic Destination Name	Video Destination
Type of Service	Excellent Effort (3)
RSVP Parameters	None
Traffic Mix (%)	All Discrete

4.1.1.3 File transfer application

A file transfer application is deployed between MANET nodes 5 and 6. The nature of the file transfer application is as shown in table 4.3.

Table 4.3: File transfer application setup

Attribute	**Value**
Command Mix (Get/Total)	50%
Inter-Request Time (seconds)	exponential (360)
File Size (bytes)	constant (50000)
Symbolic Server Name	FTP Server
Type of Service	Best Effort (0)
RSVP Parameters	None
Back-End Custom Application	Not Used

4.2 OPNET SIMULATOR/ MATLAB LINK

OPNET Modeler co-simulation interface allows the modeler to interact with external systems during simulation. The MATLAB engine library also contains routines that allow one to invoke MATLAB commands from external systems. The procedure involved in creating an OPNET-MATLAB link is explained below.

4.2.1 Basic mechanism

The OPNET co-simulation mechanism involves the following concepts:

- External System Definition (ESD) model: The ESD model defines a set of interfaces that allow process models in OPNET modeler to communicate with external programs. These interfaces can be read or written by both OPNET process models and external programs.
- Esys (External System) module: The Esys module allows a developed simulation model to link with external systems.
- Simulator description file: The simulation description file is a plain-text file containing statements that specify how to build the co-simulation program.

- Esys API package: The Esys API package contains functions that can read and write interfaces' values defined in the ESD model from process models during co-simulation.
- External Simulation Access (ESA) API package: The ESA API package contains functions that can read and write interfaces' values defined in the ESD model from external code during co-simulation. This package also contains functions that are able to control the simulation flow process, read/write text, and issue debugging commands from external code.

4.2.2 Co-simulation with MATLAB

The MATLAB engine library contains routines that allow one to invoke MATLAB commands from C or C++ programs.

4.2.2.1 Setup of environment variables

The relevant MATLAB engine library paths should be added to the environment variable table. The variables include;

- ***libmat.lib and libmex.lib:*** Enables one to use the Matilab C or C++ library.
- ***libeng.lib**:* Enables the use of MATLAB engine (Run MATLAB process in the background) to make it do computation and receive results seamlessly.
- ***libmx.lib**:* Created mex (MATLAB) functions in C or C++ programming language.

4.2.2.2 Calling MATLAB from OPNET

The MATLAB engine is started in OPNET by using the inbuilt function "engOpen". This provides the OPNET simulation with a pointer to a memory location that can be used to pass MATLAB commands to the MATLAB engine. The engine pointer is easily shared among different processes by declaring the engine pointer in a header file common to all process models. Variables can be exchanged between OPNET and MATLAB using functions "engPutArray" and "engGetArray".

Information sent to MATLAB are fuzzy inference system inputs and information retrieved from MATLAB is a priority index value.

4.3 SIMULATION RESULTS

4.3.1 LOW LOAD CONDITION

4.3.1.1 VOIP APPLICATION

4.3.1.1.1 MEAN OPINION SCORE (MOS)

Figure 4.2: Mean Opinion Score

Figure 4.2 shows the resultant MOS upon using three different packet scheduling mechanisms (FIFO, Type of Service priority and fuzzy scheduler priority). The fuzzy scheduler priority scheduling yields the best MOS performance compared to the other scheduling mechanisms. FPC MOS averages 3.5, that of ToS priority averages at 2.5 while the MOS value when using FIFO averages at 1.

4.3.1.1.2 JITTER

Figure 4.3 shows the resultant jitter upon using three different packet scheduling mechanisms (FIFO, Type of Service priority and fuzzy scheduler priority). The fuzzy scheduler priority scheduling yields the best performance giving a jitter value of 0 compared to the other scheduling mechanisms. FIFO gives the highest jitter of average value 0.05.

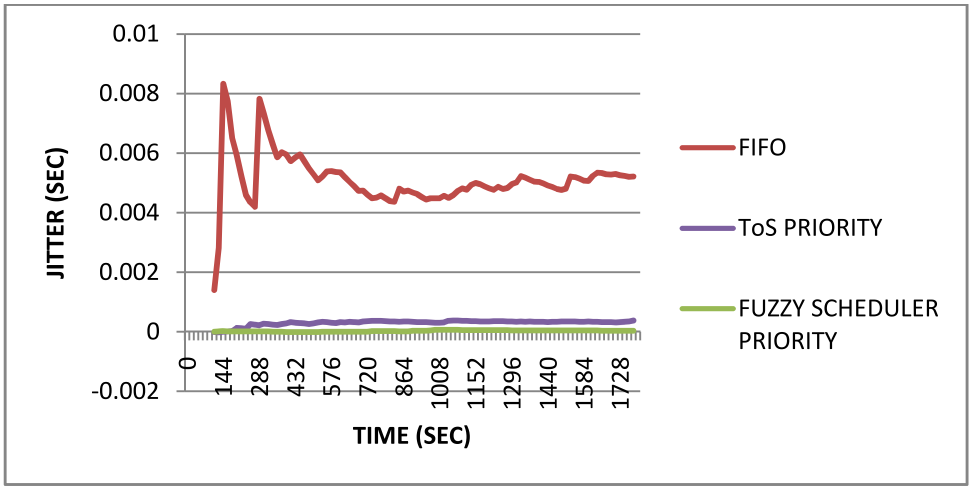

Figure 4.3: Jitter

4.3.1.1.3 PACKET END TO END DELAY

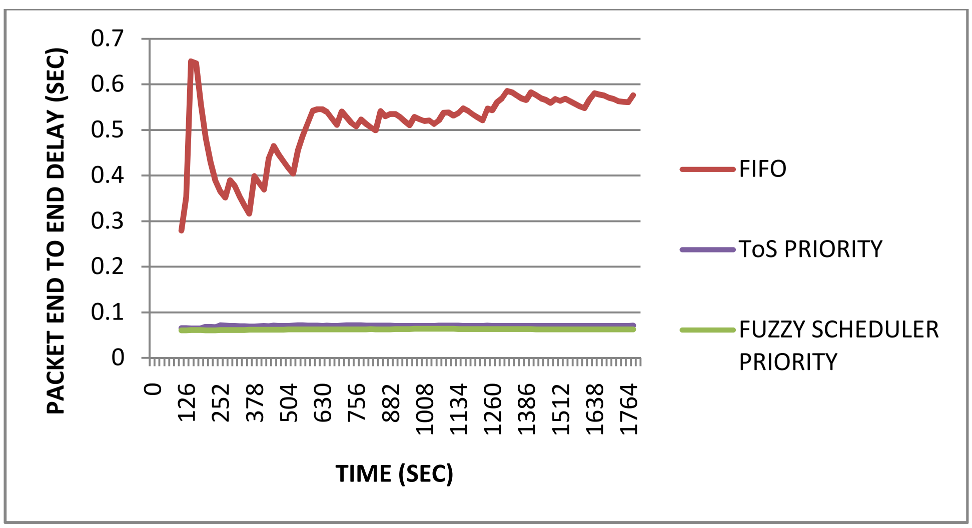

Figure 4.4 (a): Packet end to end delay

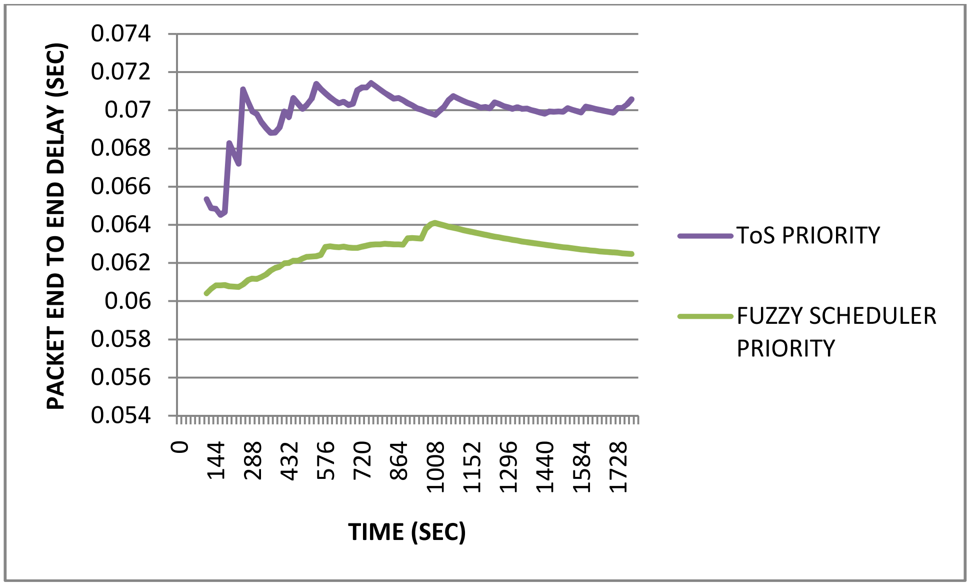

Figure 4.4 (b): Packet end to end delay (ToS priority/ fuzzy scheduler)

Figure 4.4 shows the resultant packet end to end delay upon using three different packet scheduling mechanisms (FIFO, Type of Service priority and fuzzy scheduler priority). The fuzzy scheduler priority scheduling yields packet end to end delay mean of 0.062seconds. This is the best performance compared to the other scheduling mechanisms which have an average of 0.07seconds and 0.5 seconds for ToS and FIFO respectively.

4.3.1.2 VIDEO TRANSFER APPLICATION

4.3.1.2.1 PACKET DELAY VARIATION

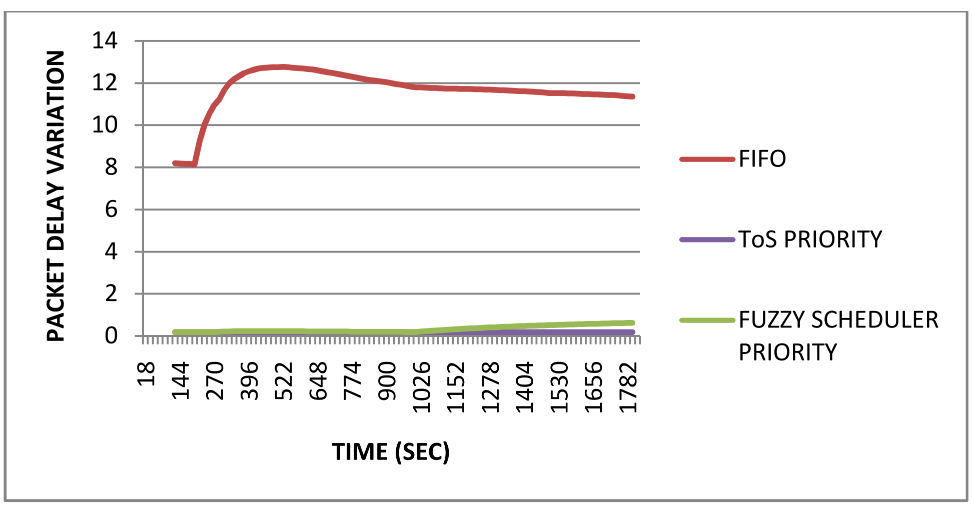

Figure 4.5 (a): Packet delay variation

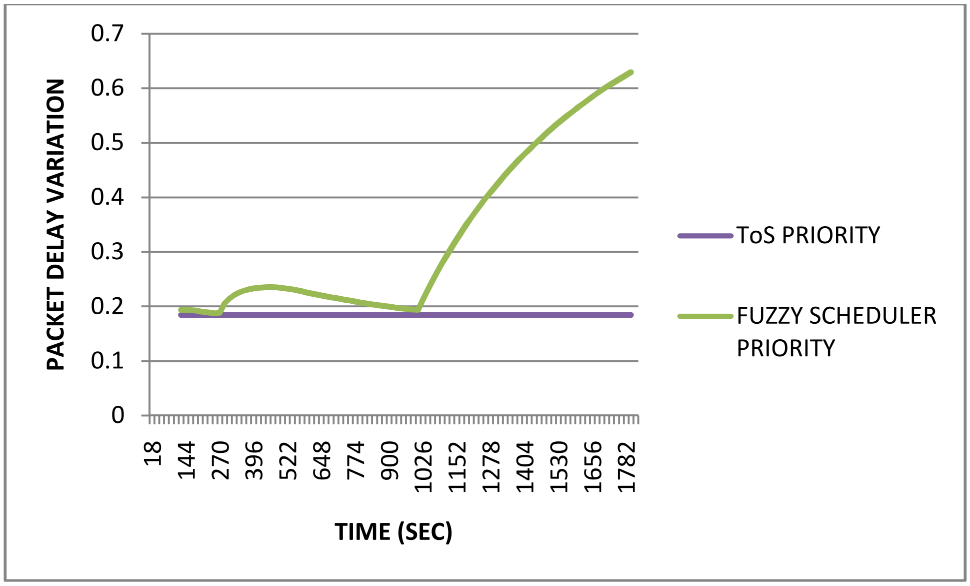

Figure 4.6 (b): Packet delay variation (ToS priority/ fuzzy scheduler)

Figure 4.5 shows the resultant packet delay variation upon using three different packet scheduling mechanisms (FIFO, Type of Service priority and fuzzy scheduler priority). The fuzzy scheduler priority scheduling yields a poorer performance of average 0.2 seconds compared to that of Type of Service priority scheduling mechanism which gives an average delay variation of 0.19 seconds.. This is because the FPC does not consider only the ToS as a scheduling criteria but takes into consideration all the factors in the four inputs.

4.3.1.2.2 PACKET END TO END DELAY

Figure 4.6 shows the resultant packet end to end delay upon using three different packet scheduling mechanisms (FIFO, Type of Service priority and fuzzy scheduler priority). The fuzzy scheduler priority scheduling yields performance comparable to that of Type of Service priority of average packet end to end delay of 1second. FIFO scheduling gives the worst performance of average end to end delay of 9 seconds.

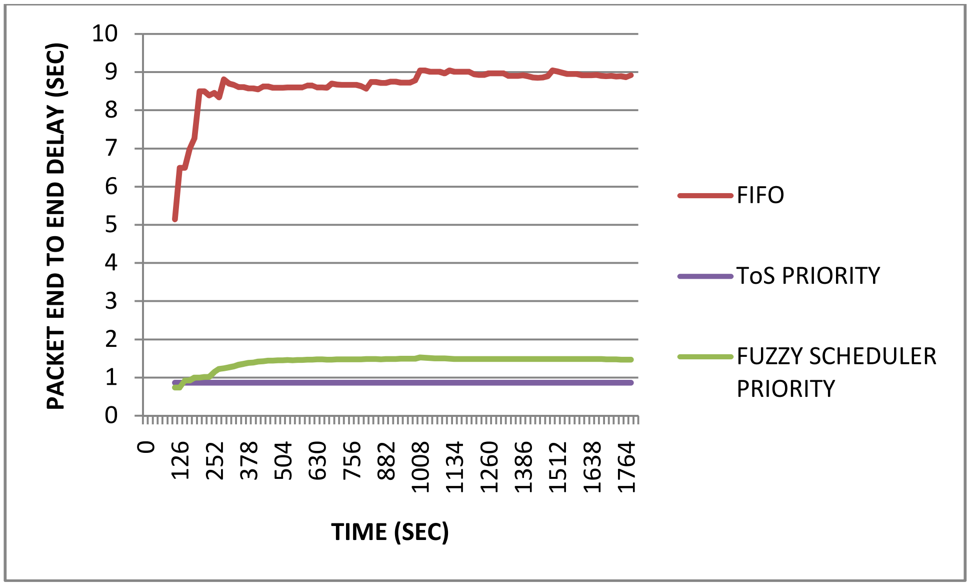

Figure 4.7: Packet end to end delay

4.3.1.3 FILE TRANSFER APPLICATION

4.3.1.3.1 DOWNLOAD RESPONSE TIME

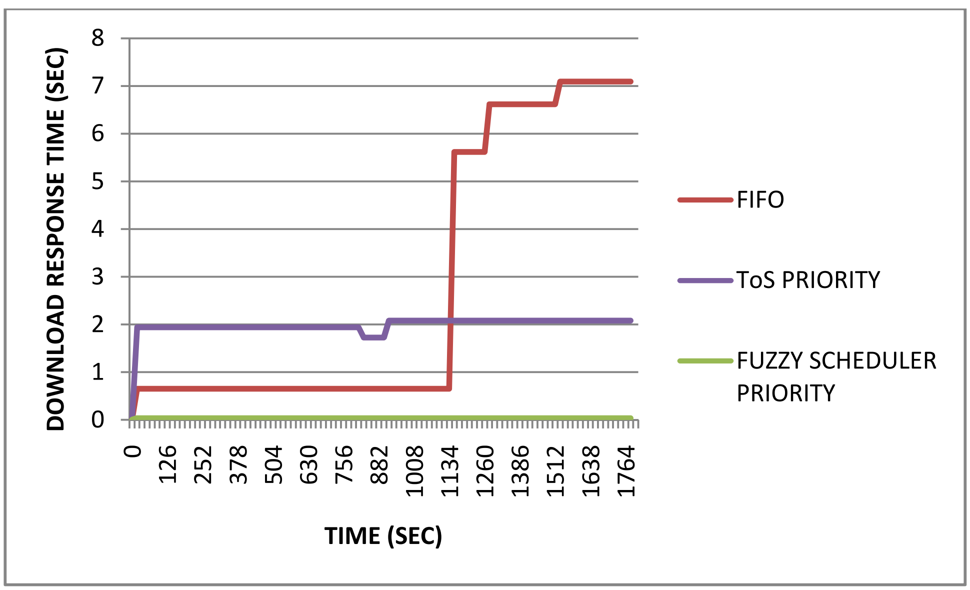

Figure 4.8: Download response time

Figure 4.7 shows the resultant download response time upon using three different packet scheduling mechanisms (FIFO, Type of Service priority and fuzzy scheduler priority). The fuzzy scheduler priority scheduling yields the best performance compared to the other scheduling mechanisms. Its download response time is almost 0 as compared to ToS whose download response time is 2seconds and that of FIFO which rises from 2 seconds to average at 7 seconds.

4.3.1.3.2 UPLOAD RESPONSE TIME

Figure 4.8 shows the resultant upload response time upon using three different packet scheduling mechanisms (FIFO, Type of Service priority and fuzzy scheduler priority). The fuzzy scheduler priority scheduling yields the best performance compared to the other scheduling mechanisms. Its upload response time is 0.01seconds. Those of FIFO and ToS are 1.6seconds and 0.5seconds respectively.

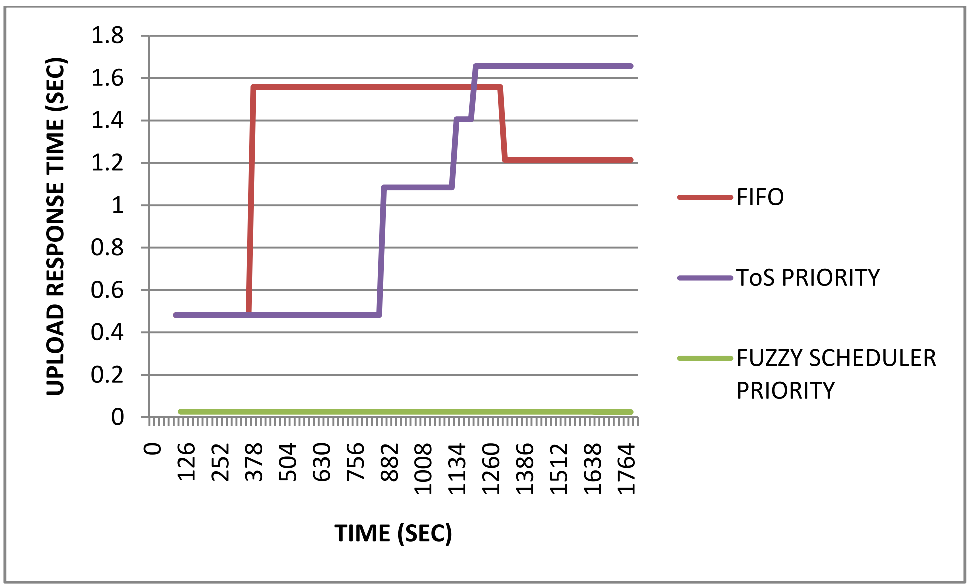

Figure 4.9: Upload response time

4.3.2 HIGH LOAD CONDITION

4.3.2.1 VOIP APPLICATION

Figure 4.9 shows the resultant MOS upon using three different packet scheduling mechanisms (FIFO, Type of Service priority and fuzzy scheduler priority). The fuzzy scheduler priority scheduling yields the best MOS performance compared to the other scheduling mechanisms. Its MOS value averages at 3 while that of ToS averages at 1.8 and that of FIFO averages at 1.

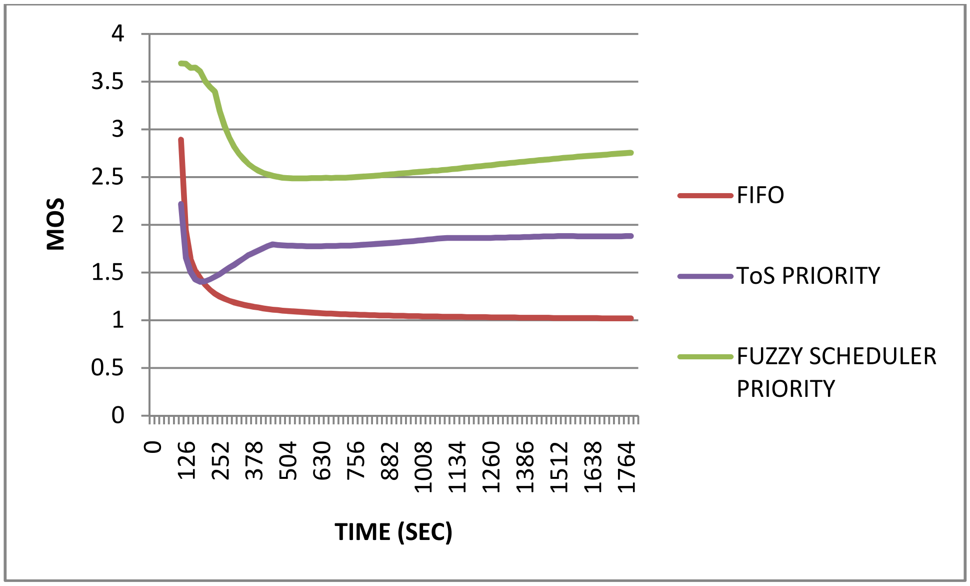

Figure 4.10: Mean opinion score

4.3.2.1.1 JITTER

Figure 4.10 shows the resultant jitter upon using three different packet scheduling mechanisms (FIFO, Type of Service priority and fuzzy scheduler priority). The fuzzy scheduler priority scheduling yields Jitter value of almost 0 seconds, ToS averages 0.001 seconds and FIFO averages 0.007 seconds.

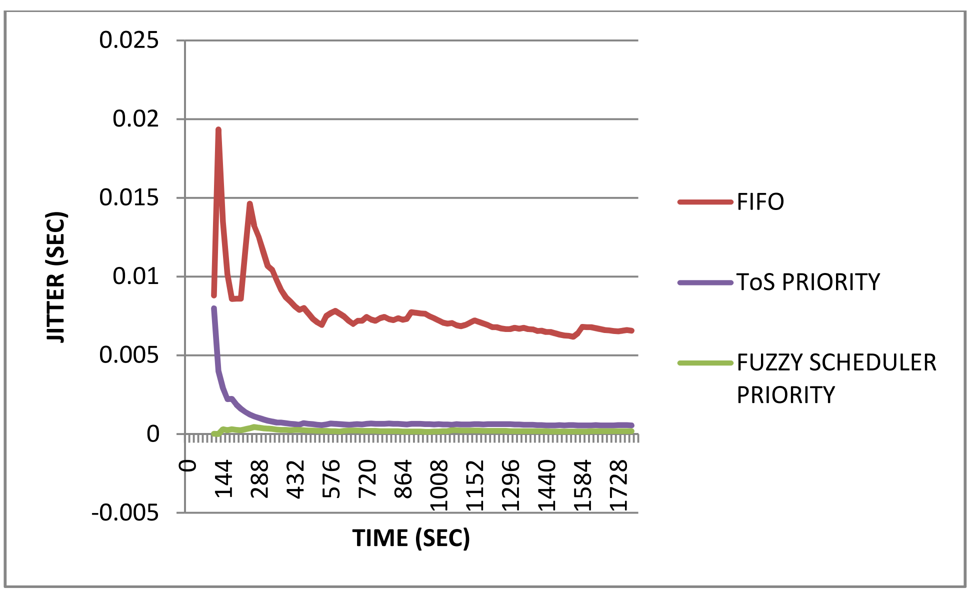

Figure 4.11: Jitter

4.3.2.1.2 PACKET END TO END DELAY

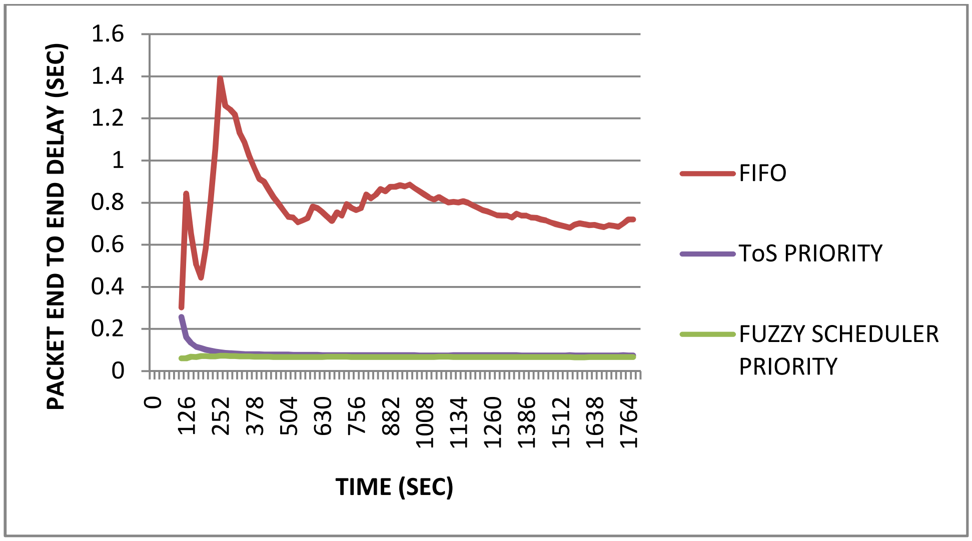

Figure 4.12 (a): Packet end to end delay

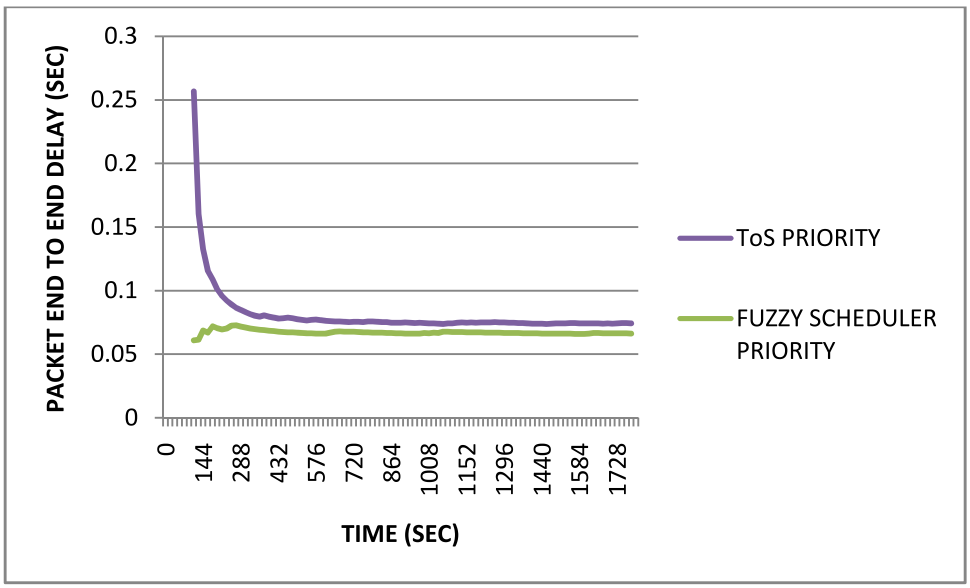

Figure 4.13 (b): Packet end to end delay (ToS priority/ fuzzy scheduler)

Figure 4.11a and 4.11b shows the resultant packet end to end delay upon using three different packet scheduling mechanisms (FIFO, Type of Service priority and fuzzy scheduler priority). The fuzzy scheduler priority scheduling yields the least packet end to end delay of 0.06 seconds as opposed to TOS (0.05 seconds) and FIFO (0.8 seconds).

4.3.2.2 VIDEO TRANSFER APPLICATION

4.3.2.2.1 PACKET DELAY VARIATION

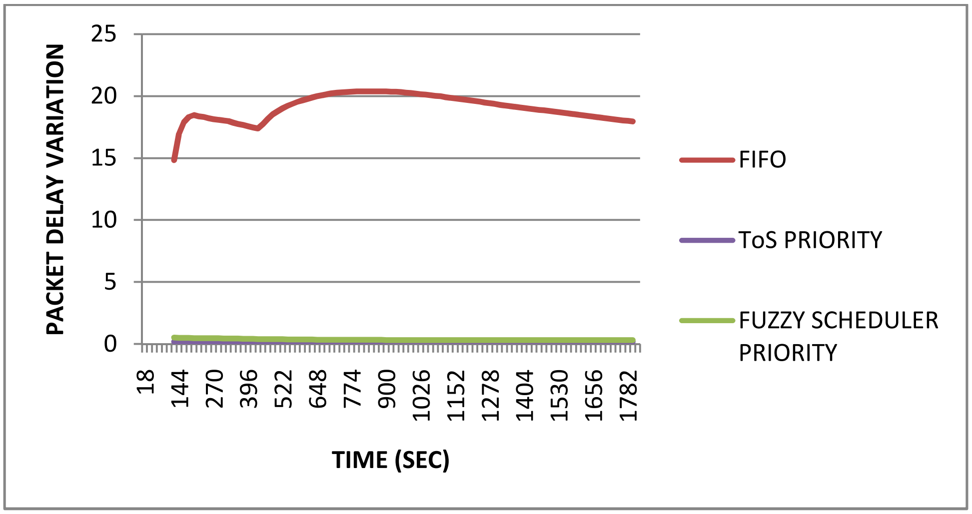

Figure 4.14 (a): Packet delay variation

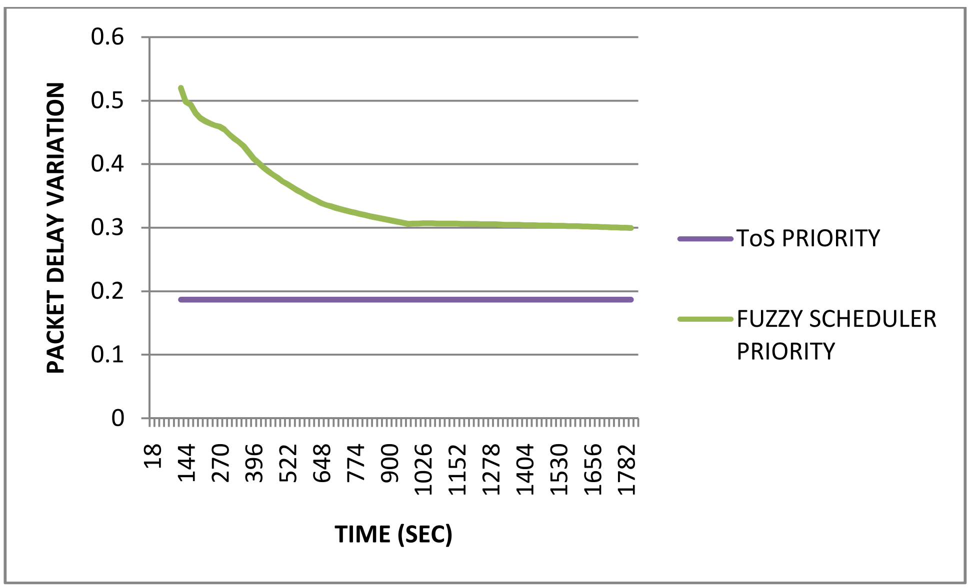

Figure 4.15 (b): Packet delay variation (ToS priority/ fuzzy scheduler)

Figure 4.12 shows the resultant packet delay variation upon using three different packet scheduling mechanisms (FIFO, Type of Service priority and fuzzy scheduler priority). The fuzzy scheduler priority scheduling yields performance comparable to that of Type of Service priority scheduling mechanism.

4.3.2.2.2 PACKET END TO END DELAY

Figure 4.13 below shows the resultant packet end to end delay upon using three different packet scheduling mechanisms (FIFO, Type of Service priority and fuzzy scheduler priority). The fuzzy scheduler priority scheduler gives a packet end to end delay of 2 seconds. The best prformance is that of ToS whic gives a packet end to end delay of 1 second. This can be explained since ToS gives priority to some packets without taking time to calculate their individual priority.

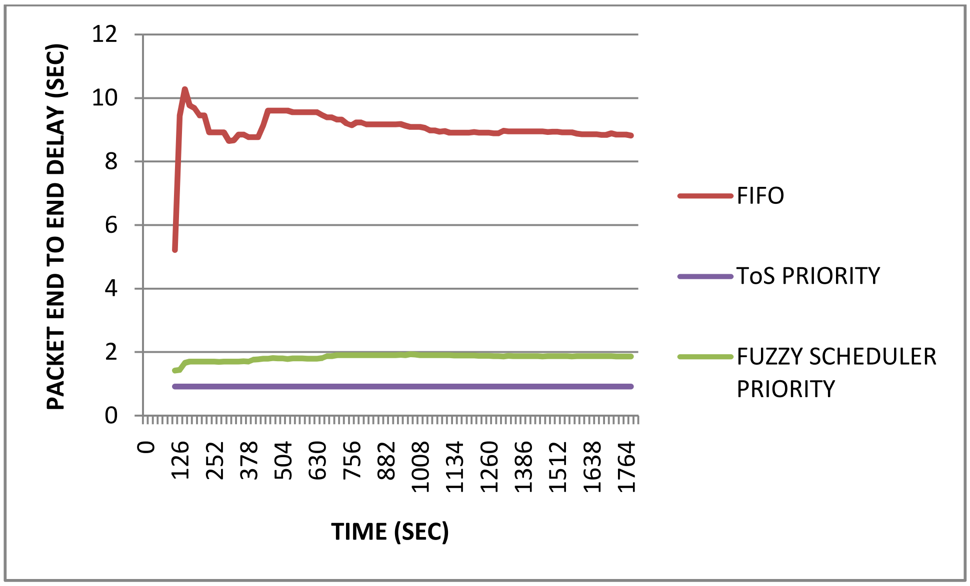

Figure 4.16: Packet end to end delay

4.3.2.3 FILE TRANSFER APPLICATION

4.3.2.3.1 DOWNLOAD RESPONSE TIME

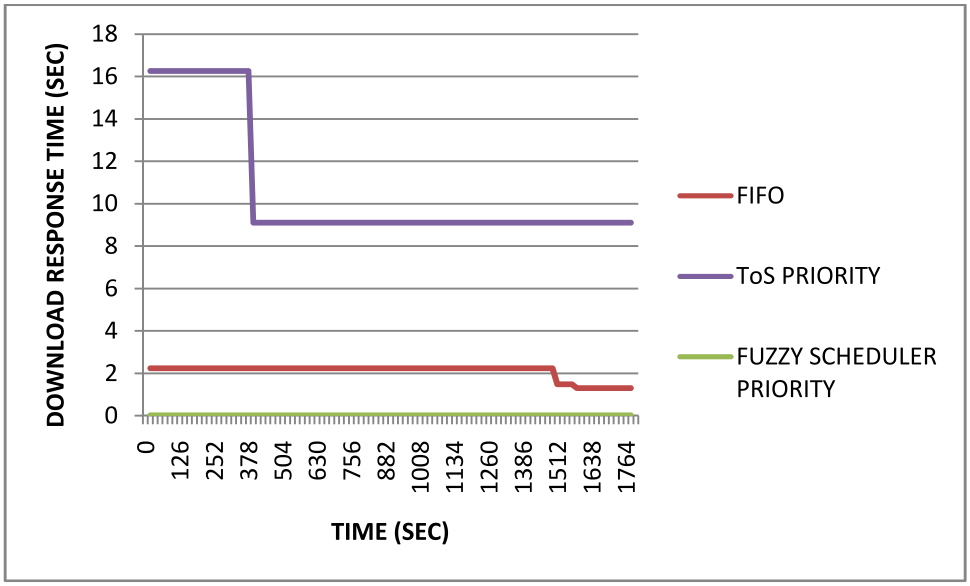

Figure 4.17: Download response time

Figure 4.14 shows the resultant download response time upon using three different packet scheduling mechanisms (FIFO, Type of Service priority and fuzzy scheduler priority). The fuzzy scheduler priority scheduling yields the best performance compared to the other scheduling mechanisms. It requires 0 seconds to start download while FIFO takes 2 seconds to start downloading.

4.3.2.3.2 UPLOAD RESPONSE TIME

Figure 4.15 below shows the resultant upload response time upon using three different packet scheduling mechanisms (FIFO, Type of Service priority and fuzzy scheduler priority). The fuzzy scheduler priority scheduling yields the best performance compared to the other scheduling mechanisms.

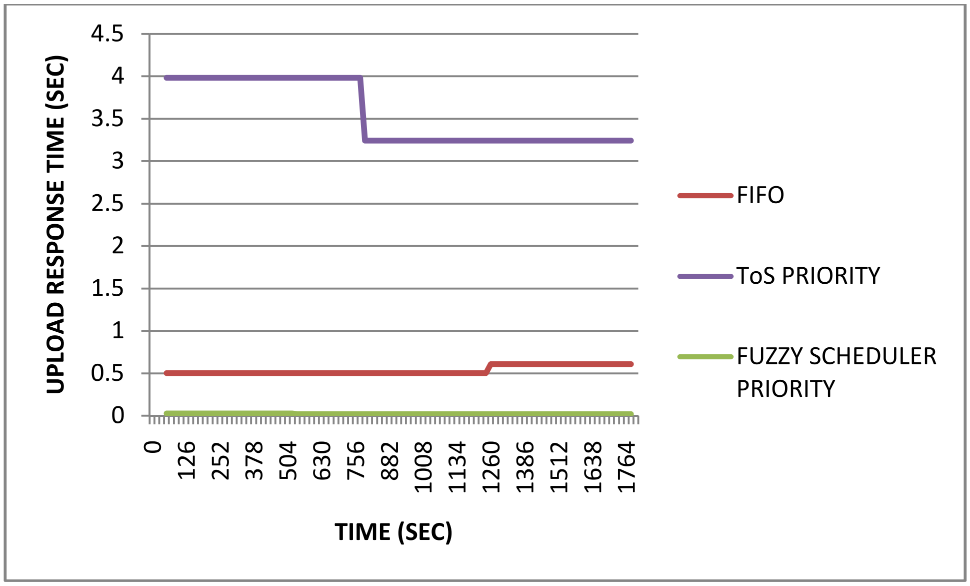

Figure 4.18: Upload response time

4.3.3 PERFORMANCE INVOLVING AN INCREASE IN NUMBER OF NODES

Performance comparison on the basis of an increased number of nodes is hereby studied. The network setup involves a scenario featuring 20 nodes (Figure 4.16). Applications deployed are the same as highlighted in section 4.1.1.

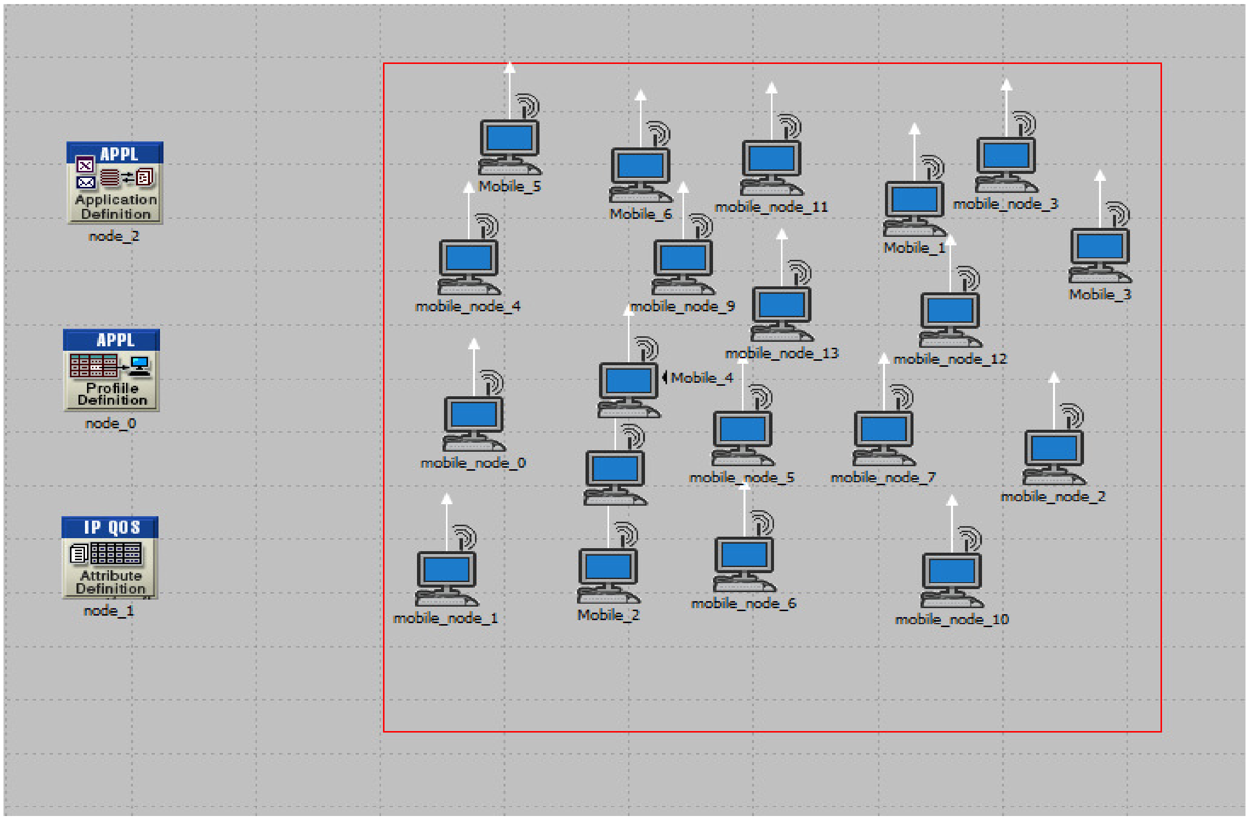

Figure 4.19: Simulation network (20 nodes) setup

4.3.3.1 VOIP APPLICATION

4.3.3.1.1 Mean Opinion Score (MOS)

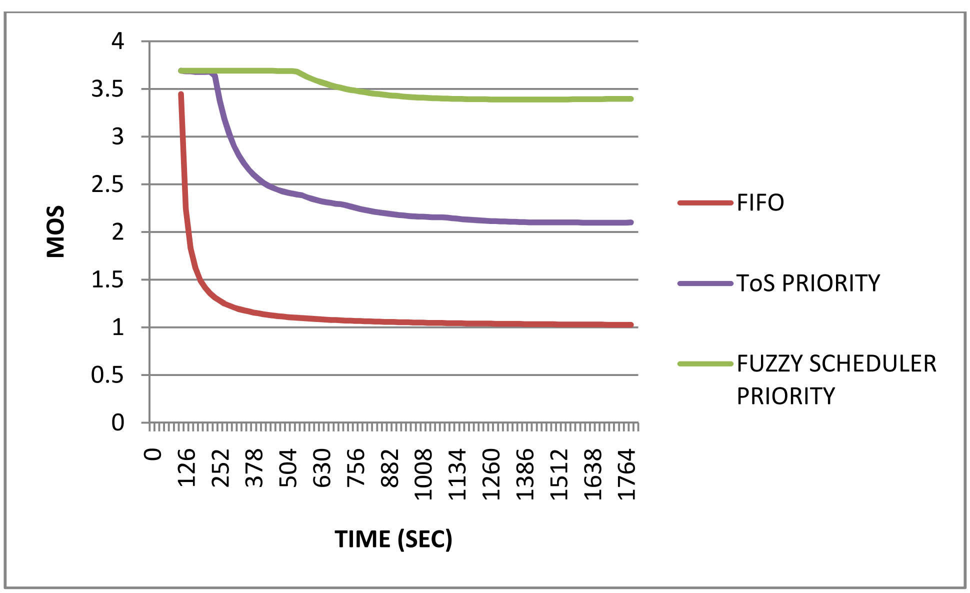

Figure 4.20: Mean Opinion Score

Figure 4.17 shows the resultant MOS upon using three different packet scheduling mechanisms (FIFO, Type of Service priority and fuzzy scheduler priority). The fuzzy scheduler priority scheduling yields the best MOS performance of 3.5 compared to the other scheduling mechanisms which yield 2 and 1 respectively for ToS and FIFO respectively. Increasing the number of nodes to 20 maintains priority queuing as the better queuing mechanism.

4.3.3.1.2 JITTER

Figures 4.18 and 4.19 illustrate the resultant jitter upon using three different packet scheduling mechanisms (FIFO, Type of Service priority and fuzzy scheduler priority). The fuzzy scheduler priority scheduling yields the best performance compared to the other scheduling mechanisms.

It is important to note that the negative jitter as seen in Figure 4.22 may be attributed to sudden uncontrolled burst which might have occurred in the network. When this happens, the first packet experiences high delays on the queue. As the burst clears, the second packet experiences less delay. This may lead to negative jitter.

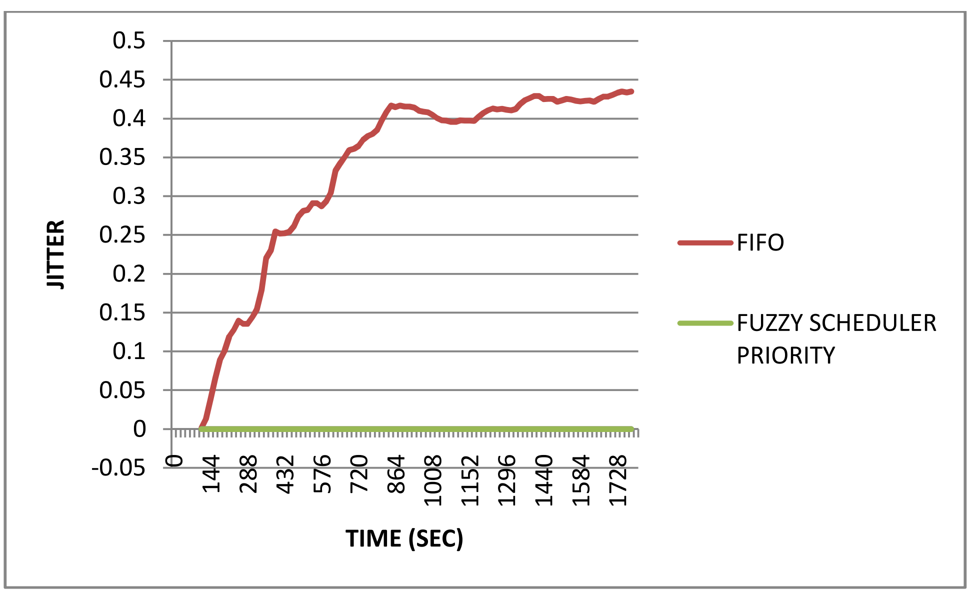

Figure 4.21: Jitter

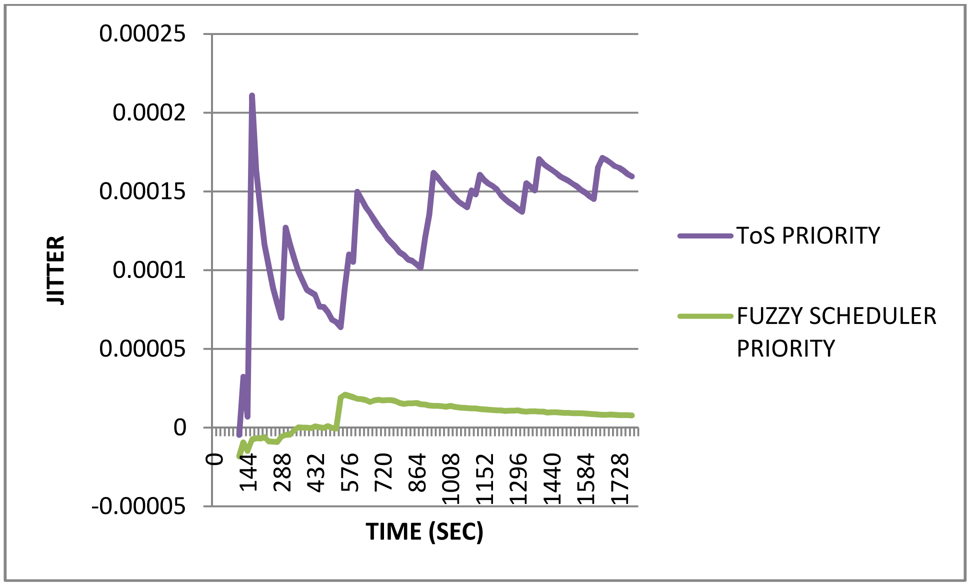

Figure 4.22: Jitter (ToS priority/ fuzzy scheduler)

4.3.3.1.3 PACKET END TO END DELAY

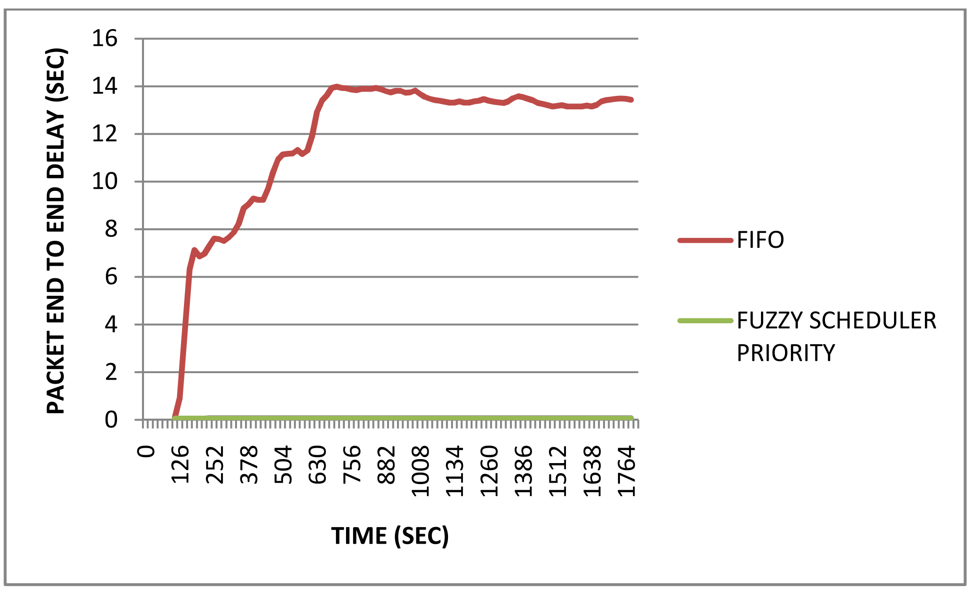

Figure 4.23: Packet end to end delay

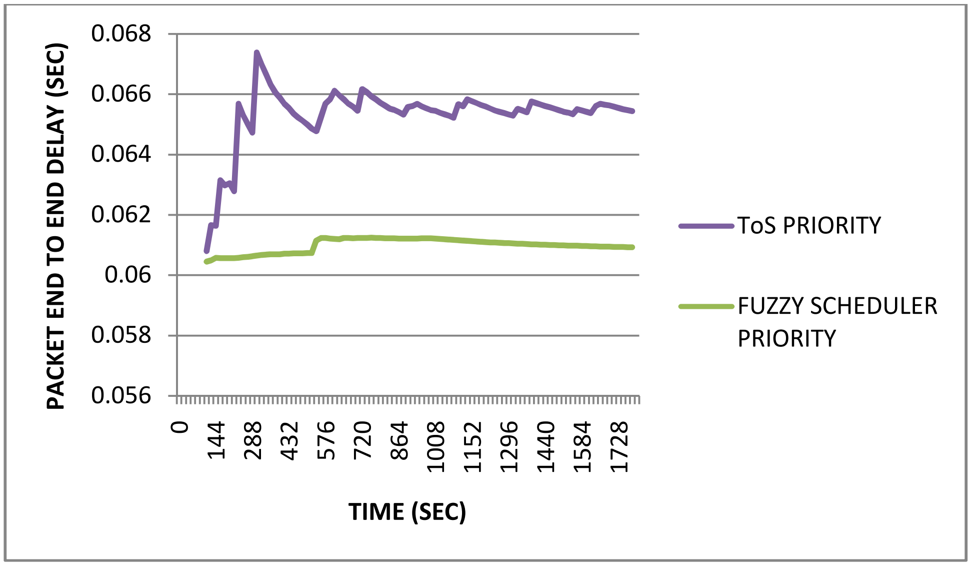

Figure 4.24: Packet end to end delay (ToS priority/ fuzzy scheduler)

Figures 4.20 and 4.21 shows the resultant packet end to end delay upon using three different packet scheduling mechanisms (FIFO, Type of Service priority and fuzzy scheduler priority). The fuzzy scheduler priority scheduling yields the best performance compared to the other scheduling mechanisms.

4.3.3.2 VIDEO TRANSFER APPLICATION

4.3.3.2.1 PACKET DELAY VARIATION

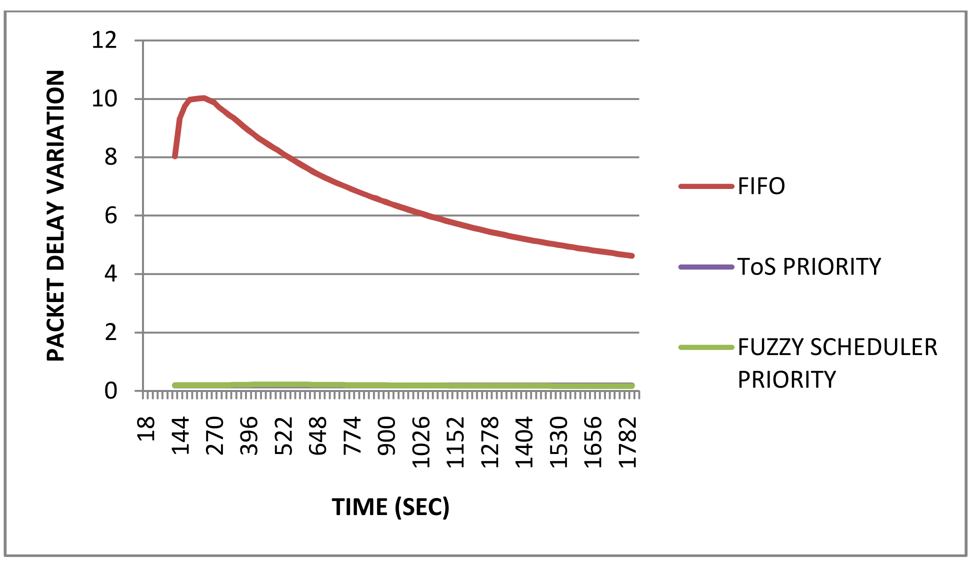

Figure 4.25: Packet delay variation

Figure 4.22 above shows the resultant packet delay variation upon using three different packet scheduling mechanisms (FIFO, Type of Service priority and fuzzy scheduler priority). The fuzzy scheduler priority scheduling yields performance comparable to that of Type of Service priority scheduling mechanism.

4.3.3.2.2 PACKET END TO END DELAY

Figure 4.23 shows the resultant packet end to end delay upon using three different packet scheduling mechanisms (FIFO, Type of Service priority and fuzzy scheduler priority). The fuzzy scheduler priority scheduling yields performance comparable to that of Type of Service priority scheduling mechanism. FIFO scheduling gives the worst performance.

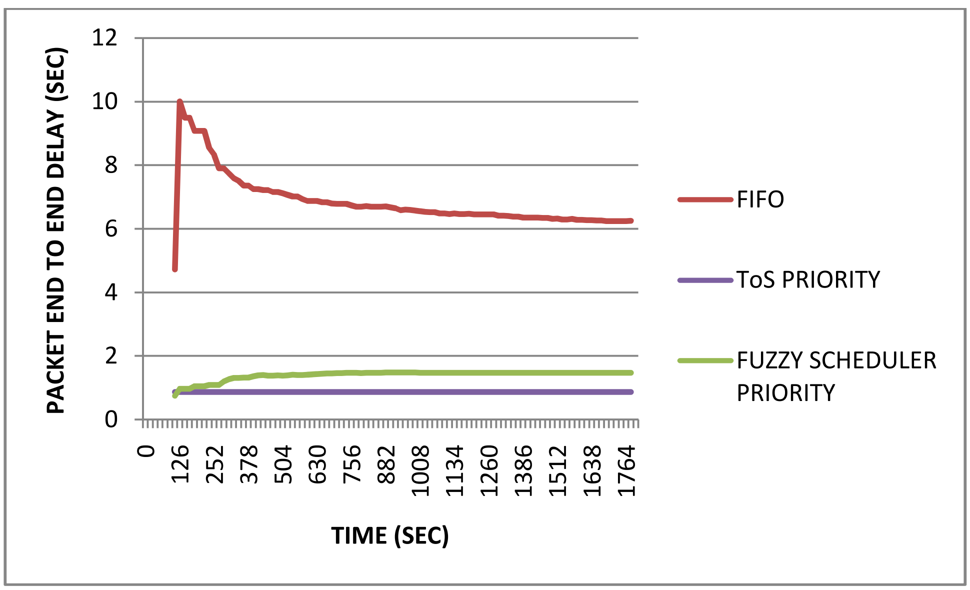

Figure 4.26: Packet end to end delay

CHAPTER 5

5 OVERALL CONCLUSION AND RECOMMENDATIONS

5.1 CONCLUSION

A worthwhile contribution of this work above existing published work has been an in depth analysis of various factors which affect QoS in MANETS above designing and analyzing the performance of the proposed fuzzy priority coordinator in an effort to improve the QoS in MANET routing.

The use of this FPC in the coordination of routing in MANETS has been found to be providing a better QoS in both the high load and low load scenarios. This has been established via the OPNET simulations. It is found out that using the FPC on a VoIP application results to best MOS, least jitter and least packet end to end delay as compared to MANETS using FIFO and Type of Service Priority.

On Video transfer application, ToS priority gives the least packet delay variation and packet end to end delay. This is followed very closely with the FPC. The developed FPC requires the least upload and download response times in file transfer applications.

The same result is found when using high load and increased nodes in a given simulation environment.

It is therefore advisable that fuzzy logic coordinator be used in packet scheduling in MANETS in an effort to improve QoS.

5.2 RECOMMENDATIONS

The proposed FPC is an attractive candidate for use in MANETS routing to improve on Quality of Service. As such, it is recommended that the following scenarios be studied further to establish full potential of the proposed FPC:

- It is advisable to do a practical analysis of the developed fuzzy packet scheduling mechanism to wholly establish the capability of the fuzzy scheduler. This may involve setting up of physical test beds.
- The area of coverage of the MANETS was 250000 square meters. It is therefore important that a study be done to show the effect of increasing the area of coverage of the MANETS.
- Rather than in this thesis where the simulations have involved only MANETS in the study, further research needs to be done on the effectiveness of the FPC on the scenario with mixed nodes such as static wireless routers and MANETS.

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APPENDIX

APPENDIX 1: OPNET – MATLAB LINK

```
/*    C++ program calling MATLAB fuzzy inference system to evaluate fuzzy
Priority index value*/


#include<stdlib.h>

#include<stdio.h>

#include<string.h>

#include"engine.h"

#define  BUFSIZE 256


int main()


{

      Engine *ep;

      mxArray *T = NULL, *result = NULL, *PriorityIndex = NULL,
*FuzzyInputOne = NULL ;

      char buffer[BUFSIZE+1];

      double FuzzyInputVariables[4] = { 1, 1, 1, 1 }; /*default fuzzy
inputs*/


      /*

       * Call engOpen with a NULL string. This starts a MATLAB process

     * on the current host using the command "MATLAB".

       */

      if (!(ep = engOpen(""))) {
```

```
            fprintf(stderr, "\nCan't start MATLAB engine\n");
            return EXIT_FAILURE;
      }



      T = mxCreateDoubleMatrix(1, 4, mxREAL);
      /*memcpy((void *)mxGetPr(T), (void *)time, sizeof(time));*/
      memcpy((void *)mxGetPr(T), (void *)FuzzyInputVariables,
sizeof(FuzzyInputVariables));
      /*
       * Place the variable T into the MATLAB workspace
       */
      engPutVariable(ep, "T", T);

      /* Evaluate priority index     */
            engEvalString(ep, "double out;");
      engEvalString(ep,"fismat=
readfis('F:\ombatiFuzzy\PriorityIndexGenerator');"); /*location of FIS*/
      engEvalString(ep, "out = evalfis(T,fismat);");



      PriorityIndex = engGetVariable(ep, "out");
      /*printf("Priority Index is %d\t\n", (unsigned int)*((double
*)mxGetData(PriorityIndex)));*/
      printf("Priority Index is %f\t\n", ((float)*((double
*)mxGetPr(PriorityIndex))));
      printf("Priority Index is class %s\t\n",
mxGetClassName(PriorityIndex));
```

```
	/*Plot the result  */

	engEvalString(ep,
"figure(1);plotfis(fismat);figure(2);plotmf(fismat,'input',1);figure(3);plotm
f(fismat,'input',2);figure(4);plotmf(fismat,'input',3);figure(5);plotmf(fisma
t,'input',4);figure(6);plotmf(fismat,'output',1);figure(7);gensurf(fismat);")
;

	/*Closing MATLAB   */
	printf("Done.\n");
	mxDestroyArray(T);
	engEvalString(ep, "clear;");
	engEvalString(ep, "close;");


	engClose(ep);

	return EXIT_SUCCESS;
}
```

APPENDIX 2: FUZZY INFERENCE SYSTEM

```
[System]
Name='PriorityIndexGenerator'
Type='mamdani'
Version=2.0
NumInputs=4
NumOutputs=1
NumRules=81
```

```
AndMethod='min'
OrMethod='max'
ImpMethod='min'
AggMethod='max'
DefuzzMethod='centroid'

[Input1]
Name='DataRate'
Range=[0 1]
NumMFs=3
MF1='Low':'dsigmf',[10000 -0.2 20.2 0.233477789815818]
MF2='Medium':'gaussmf',[0.144680082319703 0.503]
MF3='High':'dsigmf',[19.7 0.762188515709642 13.7 10000]

[Input2]
Name='ExpiryTime'
Range=[0 60]
NumMFs=3
MF1='Low':'dsigmf',[167 -12 0.329 15.0487540628386]
MF2='Medium':'gaussmf',[7.482 30]
MF3='High':'dsigmf',[0.328 44.9147562296858 0.228 599997.07475623]

[Input3]
Name='QueueLength'
Range=[0 100]
NumMFs=3
MF1='Low':'dsigmf',[100 -20 0.2021 20]
MF2='Medium':'gaussmf',[12.47 50]
MF3='High':'dsigmf',[0.197 79.7 0.137 1000000]
```

```
[Input4]
Name='TypeOfService'
Range=[0 7]
NumMFs=3
MF1='LowUrgency':'gaussmf',[1.189 5.551e-17]
MF2='MediumUrgency':'gaussmf',[1.189 3.5]
MF3='HighUrgency':'gaussmf',[1.189 7]

[Output1]
Name='PriorityIndex'
Range=[0 1]
NumMFs=7
MF1='VeryVeryLow':'psigmf',[30000 -10000 -96.7714026283023 0.059]
MF2='Low':'gaussmf',[0.053 0.318422535211268]
MF3='VeryVeryHigh':'psigmf',[60.3 0.9269 -0.0055 50000]
MF4='Medium':'gaussmf',[0.0625719202812409 0.5]
MF5='High':'gaussmf',[0.0592 0.677082340195016]
MF6='VeryLow':'gaussmf',[0.0537 0.160500541711809]
MF7='VeryHigh':'gaussmf',[0.0566 0.83210292524377]

[Rules]
1 1 1 1, 4 (1) : 1
1 1 2 1, 4 (1) : 1
1 1 3 1, 2 (1) : 1
2 1 1 1, 2 (1) : 1
2 1 2 1, 2 (1) : 1
2 1 3 1, 2 (1) : 1
3 1 1 1, 4 (1) : 1
```

3 1 2 1, 2 (1) : 1

3 1 3 1, 2 (1) : 1

1 1 1 2, 2 (1) : 1

1 1 2 2, 2 (1) : 1

1 1 3 2, 6 (1) : 1

2 1 1 2, 6 (1) : 1

2 1 2 2, 6 (1) : 1

2 1 3 2, 6 (1) : 1

3 1 1 2, 2 (1) : 1

3 1 2 2, 6 (1) : 1

3 1 3 2, 6 (1) : 1

1 1 1 3, 6 (1) : 1

1 1 2 3, 6 (1) : 1

1 1 3 3, 1 (1) : 1

2 1 1 3, 1 (1) : 1

2 1 2 3, 1 (1) : 1

2 1 3 3, 1 (1) : 1

3 1 1 3, 6 (1) : 1

3 1 2 3, 1 (1) : 1

3 1 3 3, 1 (1) : 1

1 2 1 1, 5 (1) : 1

1 2 2 1, 5 (1) : 1

1 2 3 1, 4 (1) : 1

2 2 1 1, 5 (1) : 1

2 2 2 1, 5 (1) : 1

2 2 3 1, 4 (1) : 1

3 2 1 1, 5 (1) : 1

3 2 2 1, 5 (1) : 1

3 2 3 1, 5 (1) : 1

1 2 1 2, 4 (1) : 1

1 2 2 2, 4 (1) : 1

1 2 3 2, 2 (1) : 1

2 2 1 2, 4 (1) : 1

2 2 2 2, 4 (1) : 1

2 2 3 2, 2 (1) : 1

3 2 1 2, 4 (1) : 1

3 2 2 2, 4 (1) : 1

3 2 3 2, 4 (1) : 1

1 2 1 3, 2 (1) : 1

1 2 2 3, 2 (1) : 1

1 2 3 3, 6 (1) : 1

2 2 1 3, 2 (1) : 1

2 2 2 3, 2 (1) : 1

2 2 3 3, 6 (1) : 1

3 2 1 3, 2 (1) : 1

3 2 2 3, 2 (1) : 1

3 2 3 3, 2 (1) : 1

1 3 1 1, 3 (1) : 1

1 3 2 1, 3 (1) : 1

1 3 3 1, 7 (1) : 1

2 3 1 1, 7 (1) : 1

2 3 2 1, 5 (1) : 1

2 3 3 1, 5 (1) : 1

3 3 1 1, 7 (1) : 1

3 3 2 1, 7 (1) : 1

3 3 3 1, 5 (1) : 1

1 3 1 2, 7 (1) : 1

1 3 2 2, 7 (1) : 1

```
1 3 3 2, 5 (1) : 1
2 3 1 2, 5 (1) : 1
2 3 2 2, 4 (1) : 1
3 3 1 2, 5 (1) : 1
3 3 2 2, 5 (1) : 1
3 3 3 2, 4 (1) : 1
2 3 3 2, 4 (1) : 1
1 3 1 3, 5 (1) : 1
1 3 2 3, 5 (1) : 1
1 3 3 3, 4 (1) : 1
2 3 1 3, 4 (1) : 1
2 3 2 3, 2 (1) : 1
2 3 3 3, 2 (1) : 1
3 3 1 3, 4 (1) : 1
3 3 2 3, 4 (1) : 1
3 3 3 3, 2 (1) : 1
```

APPENDIX 3: PUBLISHED WORK

The following papers arising from the research work have been published:

1. Erac Ombati Momanyi, V. K. Oduol, S. Musyoki: *Performance analysis of FIFO and priority packet queuing mechanisms in MANETS*.(Proceedings of 2014 international conference on Sustainable Research and Innovation volume 5, JKUAT. pages 267-271): In this paper, a comparison is made between use of FIFO and PQ mechanisms in a mixed traffic scenario (file transfer and VoIP applications). PQ is implemented on the basis of packet Type of Service (ToS) with VoIP data packets being given the upper hand. It will be shown that PQ gives a better

Quality of Service (QoS) as opposed to FIFO. This can be observed via the results of the simulations. OPNET simulator is utilized in this paper.

2. Erac Ombati Momanyi, V. K. Oduol, S. Musyoki: *An analysis of Priority Queuing, Weighted Fair Queuing and FIFO mechanisms in Mobile Ad hoc Networks (MANETS)* (The 4th Annual International Research Conference, 15th - 18th July 2014, Kabarak University - Not yet printed): In this paper, a comparison is made between use of FIFO, WFQ and PQ mechanisms in a mixed traffic scenario (HTTP and FTP and VoIP applications). PQ is implemented on the basis of packet Type of Service (ToS), with VoIP data packets being given the upper hand. OPNET simulator is utilized in this paper. The study has been carried out on some issues like: Traffic dropped Traffic Received and packet end to end delay and the simulation results shows that WFQ technique has a better-quality than the other techniques.

3. Erac Ombati Momanyi, V. K. Oduol, S. Musyoki: *Comparative Analysis of First InFirst Out and Priority Queuing scheduling in MANETS based on Type of Service (ToS) under different load conditions*. (Journal of Information Engineering and Applications, 31st July 2014- ISSN (Paper) 2224-5782, ISSN (Online) 2225-0506. Pages 22-36): In this research paper, a comparison is made between FIFO and PQ mechanisms in a mixed traffic scenario (HTTP, FTP and VoIP applications). PQ is implemented on the basis of packet Type of Service, with VoIP data packets being given the upper hand. OPNET simulator is utilized in this research. The study has been carried out on some issues like: Traffic dropped Traffic Received and packet end to end delay and the simulation results shows that Priority Queuing technique results to a better-quality of service than the other techniques