A DISTRIBUTED MAC SCHEDULER FOR PROVIDING DIFFERENTIAL SERVICES FOR MOBILE MULTICAST APPLICATIONS

by

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A Thesis Presented in Partial Fulfillment
of the Requirements for the Degree
Master of Science

ARIZONA STATE UNIVERSITY

May 2003

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ABSTRACT

A Mobile Ad-hoc NETwork (MANET) is mainly constrained by the bandwidth. Multicasting optimizes the bandwidth by reducing the amount of information to be sent across the network. However, data packets for multimedia-based and real-time applications cannot be delivered using the best-effort services and, hence, providing Quality of Service (QoS) support is important. The key component required to support QoS is the QoS MAC protocol, which provides medium access and reliable data transfer and is capable of performing bandwidth reservation. In MANETs, bandwidth is shared by all the nodes in the transmission range. The basic IEEE 802.11 does not provide any resource reservation or QoS guarantees.

In this research work, a distributed packet scheduler has been developed to provide service differentiation among multiple multicast senders, and this scheduler exploits the broadcast nature of the wireless medium to construct a prioritized schedule. This prioritized schedule is used to control bandwidth-sharing. The scheduler does not use any additional control messages to reserve the resources (bandwidth). The comparative study of this scheduler is done with frameworks that use best-effort and unicast mechanisms to achieve group communication. The parameters used for comparison were the rate of mobility, the speed of the node and the variation of the number of nodes in a multicast session. The distributed scheduler correctly allocates the bandwidth to different flows based on the priorities and provides higher throughput and lower delays to the high-priority sources. The scheduler also adapts to the varying mobility and error conditions.

Dedicated To My Parents

ACKNOWLEDGMENTS

I thank Dr. Sandeep Gupta for his continued guidance, suggestions and providing the lab facilities to conduct the research work. His willingness to meet me on a regular basis and the advice provided by him during those fruitful discussions helped me overcome many technical problems.

I am thankful to Dr Arunabha Sen and Dr Martin Reiselein for their valuable time and suggestions. I would also like to thank Sriram, Yashwanth Prakash, Vijay Subramanian and Suresh Lalwani for helping me with the NS problems. I wish to thank my friends for proof-reading the report and providing me with valuable feedback.

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CHAPTER 1

INTRODUCTION

This chapter reviews the Fundamentals of Mobile Ad Networks (MANET), Multicasting ans Quality of Service (QoS). The Chapter also discusses the advantages of using Multicasting in MANET's and the need to provide QoS to Mobile multicast applications.

1. Mobile Ad hoc NETwork (MANET)

A Mobile Ad hoc NETwork (MANET) is formed by a set of mobile hosts without the aid of any administrative aid or existing infrastructure. It is essentially a special form of distributed system with the features like no fixed topology, no fixed connectivity, varying link capacity, without any central control and are constrained by the lack of resources. The nodes in the network can communicate and forward the packets within the radio transmission range of each other. Since the network is created without any centralized administration and the network comes into existence due to the interaction between the nodes, the network is highly flexible and **fault-tolerant** compared to the fixed topology.

Mobile Ad hoc networks are based on the wireless links and are constrained by low bandwidth, low power and frequent changes in the topology. Each mobile node is equipped with the transceivers capable of transmitting and receiving the data. All the nodes posses the full functionality to route and forward the data through the network. Since there is no central administration such as Access Point (AP), Base Station, all the functionality of the network is completely distributed to each node in the network. A mobile node in MANET acts as both router and a host machine. The main characteristics of the MANET's are summarized as follows [26]

- The topology of network changes dynamically and frequently depending on the mobility of the nodes
- Wireless links are error-prone and are constrained by low bandwidth(link capacity)
- Mobile devices operate on battery and have limited power supply and limited memory for storage
- Mobile networks offer limited security and are affected by higher packet loss and higher delays.

The practical benefits of the mobile ad hoc networks make them an obvious choice for military applications, rescue operations and wireless local area networks. The ad hoc networks are also expected to play an important role in the commercial application like conferences, virtual classrooms, and sensor networks in hospitals and super markets. The reason for increasing popularity of MANET's are, it provides a unique way of forming a network without any administrative interference, two or more nodes can form a network if they are in the same transmission range of each other. The network can be deployed rapidly and the nodes are capable of reconfiguring dynamically without any manual configuration at the routing layer. Ad hoc networks are increasingly becoming popular due to the recent technological advances in the 802.11 MAC technologies, which enables the nodes to deliver the packets at a very high rate, providing an attractive medium to deliver multimedia content and reaching the speeds of the conventional networks.

2. Multicasting

Multicasting is a transmission mechanism used to support group communication. In a multicasting service, a packet is delivered to one or more receivers that are identified by a single multicast group address. The advantage of using the multicasting, as opposed to multiple unicasts to implement the group service is that, multcasting optimizes the bandwidth usage by reducing the number of packet replications at the source node. The packets are replicated at the multicast router only if the router has more than one downstream node in the multicast tree.

Majority of applications in Mobile ad hoc networks are in the areas where rapid deployment and dynamic re-configurations are necessary [26]. These applications typically involve group of people involved in a collaborative task and requires dynamic sharing of information among multiple recipients. These applications can be implemented efficiently using multicasting services. Since MANET's are constrained by bandwidth, multicasting services helps the applications to conserve the bandwidth. The objective of the multicast routing protocol is to construct a multicast tree, connecting all the receivers to the source node which satisfies all the constraints. The constraints could be bandwidth constraints, delay constraints or reliability constraints. Before the source node can transmit the packet, multicast protocol constructs the tree, after the tree is constructed, source node sends a single copy of data packet as opposed to the multiple unicast packets. The intermediate nodes forward the data packets to the downstream nodes. In wired networks the packets are replicated at the multicast routers, if there are multiple downstream nodes. However in wireless networks there are two ways the data forward operation can be performed [20].

1. Simple broadcast to all the neighbor nodes

2. Forward to all the neighbors that are part of the multicast tree and have not already received the packet.

In order to improve the multicast gain(ratio of unicast bandwidth cost to multicast bandwidth cost) a simple broadcast to all the next hop nodes is more efficient and should be exploited. Traditionally the research in multicasting is focused on scalability, reliability and efficiency. The emergence of high speed mobile devices opens a new area of research, which is to provide a QoS or differential services to different nodes which have diverse application requirements.

3. Quality Of Service

Quality Of Service(QoS) is defined as "The capability of a mechanism to differentiate between one or more classes of traffic so that packets belonging to higher priority class receives preferential treatment compared to the lower priority packet" [7]. The QoS characteristics for an application depends on the application requirements and includes timeliness, bandwidth and reliability. The networking applications have diverse application requirements and QoS has been proposed to capture these diverse requirements. For instance, some applications are sensitive to latency and packet loss, while some are tolerant to fair amount of delay. When a QoS model is defined in the network, it specifies the system goal, and captures the notion of contract between service provider and customer. An user application specifies QoS requirements, these requirements are set of constraints which include bandwidth guarantee and end-to-end delay guarantees. Currently the Internet provides only a single class of service that is **best-effort** service, where all the traffic is treated equal. With best-effort service it is not possible to provide the services promised to the customer and hence we need a mechanism to differentiate the traffic and allocate the resources to the traffic based on the user requirements and contractual obligations.

The QoS mechanisms provides us with a set of mechanisms to differentiate the traffic based on customer needs, which helps the network to provide wide variety of services to the customers and develop a new economic model to generate additional revenues. The QoS mechanism is also applicable in corporate and academic environment, where a policy can be set to give a preferential treatment to research labs, professors and CEO's.

4. Motivation

Multimedia applications such as audio and video combine real-time traffic and bursty traffic. The application requires time-bounded service and bandwidth guarantees. The packets belonging to this class cannot be delivered using the best-effort service and hence providing QoS support is important. It is hard to provide guaranteed QoS in mobile ad hoc networks due to the broadcast and dynamic nature of the network. In order to provide QoS support in MANET, network should provide some kind of **resource provisioning (reservation)** scheme, to allocate the resources to individual flows or classes to meet the QoS requirements of the applications. The process of resource reservation includes installing and removing the reservation states at all the nodes along the path from source to destination. This process is lot different compared to the wired networks, since the topology of the network changes dynamically and the reservation algorithm should be light-weight and adaptable to the changes in the network. A quality of Service framework includes **QoS Model, QoS MAC protocol, QoS Routing protocol and Resource reservation**

or signaling protocol. The key component required to support QoS is the QoS MAC protocol, which provides medium access, reliable data transfer and is capable of performing bandwidth reservation.

In Mobile ad hoc networks, bandwidth is shared by all the nodes in the transmission range. The basic IEEE 802.11 does not provide any resource reservation or QoS guarantees. The medium access is controlled by means of random-access timer without any knowledge of the priority of the packet. In order to provide differential services in the network, the medium access mechanism must be a function of the priorities of the Head-Of-Line (HOL) packets at the other nodes. In other words all the nodes in the same transmission range must exchange the priorities before accessing the channel. MACA/PR [14] and Distributed Multi-Hop Algorithm [11] are proposed to provide Quality of Service Support in Mobile ad hoc networks. The protocols were designed primarily for unicast communications and uses RTS-CTS and positive ACK packets to install and renew reservation states at all the neighbor nodes in the same transmission range. IEEE 802.11 [1] MAC protocol specifications states that the RTS/CTS and ACK(Indirect detection of collisions) mechanisms cannot be applied to packets with broadcast and multicast address because there are multiple destinations for the RTS and thus potentially multiple concurrent senders of the CTS and ACK in response.

The focus of this research work has been to develop a distributed packet scheduler for mobile multicast services. The emphasis of the research work was to develop a scheduler which can provide a differential services and be adaptable to the mobility of the nodes. Key contributions of the thesis are

- A Mechanism to provide differential services in the network. The research work proposes three algorithms to achieve this.

1. To classify the traffic at the network interface queue based on the priorities of the packet.
2. To construct a local schedule table which consists of priorities of all the neighboring nodes without using any additional control messages.
3. A new modified medium access scheme. The Medium access scheme is defined as the function of local schedule table.

- The scheduler is adaptable to the link errors and mobility of the nodes.
- The scheduler algorithm exploits the broadcast nature of the wireless medium to construct a prioritized schedule. The research work also demonstrates the bandwidth gain when a multicast forward operation is implemented as a simple broadcast as opposed to the sending it to all the downstream nodes one by one at the multicast router.

In order to provide a QoS for multimedia group applications, the framework need appropriate support from all the layers. The research focuses on designing a QoS packet scheduler and communicating the application requirements to all the nodes in the network and does not focus on QoS Routing aspects.

5. Thesis Overview

Majority of applications in Mobile ad hoc networks are in the areas where rapid deployment and dynamic re-configurations are necessary. These applications(Virtual Conference Room, Class Rooms ..etc) typically involve group of people collaborating for a task requiring dynamic sharing of information among multiple recipients. The applications also requires time-bounded service and bandwidth guarantees. The packets belonging to these applications cannot be delivered using the best-effort service and hence require QoS scheduling to work correctly. The need for QoS Support for multicast applications and the benefits of multicast in MANET's are discussed in this chapter.

Chapter 2 discusses the QoS models, QoS signaling requirements for wireless networks and QoS MAC protocol proposed in the literature for unicast communications. The protocols proposed in the literature are broadly divided into two groups. The Distributed fair scheduling algorithms [24, 25] are aimed at achieving fairness and QoS MAC protocols like MACA/PR and Distributed Multi-Hop Algorithm [11] are proposed to provide QoS support in mobile ad hoc networks. The algorithms can not be used for multicast or broadcast communications. This chapter concludes with the discussion of the protocols proposed in the literature and the need for a distributed priority based scheduler.

Chapter 3 describes the design of a dynamic distributed scheduler. This chapter describes all the different components that are used to achieve the desired QoS. The chapter describes the QoS Marking module, Classifier and QoS Packet scheduler. The state diagram for the mobile node is described in this chapter. An Example scenario is given, which explains the mechanism used in the research work to provide differential services.

The comparative study of this framework is done with frameworks that use best-effort and unicast mechanism to achieve the same. The experimental details and simulator validations are described in Chapter 4. Chapter 5 provides the conclusion and future work.

CHAPTER 2

RELATED WORK

This chapter reviews the prior related work done on supporting Quality of Service in MANET's and Mobile Ad hoc distance vector [20] routing multicast protocols for group communication. The chapter reviews various QoS models, QoS Medium Access protocols and resource reservation techniques proposed in the literature and discusses the suitability of these approaches to the mobile environment for multicast group communications.

1. QoS Model

QoS Model defines a framework for resource allocation that supports resource assurance, service differentiation and provides a new service model in addition to the existing best-effort service. The QoS model defines the system goal. The QoS routing, QoS MAC and resource reservation protocols co-ordinate with each other to achieve this goal. This section describes the existing QoS models developed for the Internet which includes Integrated Services [4] architecture and Differential Services [3] Architecture and the newly proposed Flexible QoS Model for MANET's.

1.1. Integrated Services. The Integrated Services(IntServ)[4]framework was designed to provide a mechanism for applications to choose between multiple levels of delivery services for its traffic. The framework suggests that the existing Internet architecture need not be modified but extensions can be added to provide different levels of services to the application, so that applications can receive better than best-effort quality of service.

The IntServ architecture provides a set of mechanisms and protocols for making explicit resource reservation and the reservation is performed for every flow. In order to receive the desired quality of service, an application must first set up a flow which satisfies the QoS requirements. In the IntServ architecture sender starts the setup of flow by specifying the application QoS requirements and flow characteristics. The network performs admission control on all the hops along the path and accepts the connection only if there are sufficient resources to satisfy the flow requirements. Once the flow is established sender can start the transmission of the data.

The IntServ model can be logically divided in to two parts [26]

- Control Plane :- The control plane consists of resource reservation and admission control modules that are responsible for resource management and installing the reservation state for a flow in the network.

- Data Plane :- The data plane consists of packet classifier and scheduler and performs the data forward operations based on the reservation state.

The Integrated Service architecture separates the routing from resource reservation process. The architecture uses Resource Reservation Protocol(RSVP)[6] to perform resource reservations. The reservation protocol installs the reservation state on all the hops along the path. The reservation protocol maintains the reservation in the soft-state to deal with the route changes and varying topological changes in the network. In order to guarantee the assured service to the flows, incoming flows should be subjected to admission control. The purpose of the admission control is to determine if a new reservation can be accepted for the incoming flow or not, the decision is made based on the pre-defined policies of the network. The Packet classifier examines every incoming packet and compares the packet identifier with the reservation table to retrieve the reservation state and forward the packet to the scheduler along with the reservation state. The Packet scheduler is the most important component responsible for enforcing the resource allocation. The scheduler selects the packet from the interface queue for transmission when the outgoing transmission link is idle, the selection of the packet determines the per-hop delay for a packet.

Integrates Services architecture is not suitable for MANET's for the following reasons

1. IntServ architecture focuses primarily on long-lasting and delay-sensitive applications. Most of the applications are short-lived and the overheads for setting up a reservation for each session are simply too high.

2. The MANET's are mainly constrained by the bandwidth and the resource reservation signaling protocol contends for the channel with data packets, severely affecting the system throughput.

3. IntServ requires very high computing power and the overhead involved in maintaining per-flow information is very high.

1.2. Differential Services. The Differential Services (DiffServ) [3] was developed to overcome the scalability and complex implementation difficulties of Integrated Services in the Internet routers. In the DiffServ architecture, traffic is divided into small number of aggregate flows or forwarding classes. In the DiffServ network, the nodes at the boundary of the network are called edge routers and are responsible for packet classification and traffic conditioning. The responsibilities of edge routers includes mapping the incoming traffic to the forwarding classes, checking whether the traffic flows meet the service agreement and dropping the non-conforming packets. The interior routers are called core routers and these nodes forward the packets based on the Per-Hop Behavior (PHB) [3].

Diffserv does not require resource reservation set up before it can begin transmission. The resource assurance is provided through provisioning combined with prioritization [26]. When a sender application wants to transmit a packet, it forwards the packet to the boundary router, the boundary router performs the marking of the packet based on the Service Level Agreement (SLA) [3] and also performs traffic policing and traffic shaping to drop the non-conforming packets or to remark the packet with a different forwarding class. The DiffServ architecture uses 6-bit Differential Services Code Point (DSCP) to represent the PHB group. The PHB defines a forwarding treatment that a packet receives in the interior routers. IETF has standardized 3 forwarding groups [26]

- Default (BE) PHB:-Defined mainly for backward compatibility with existing best-effort traffic. All Diffserv router must implement this code-point.

- Assured Forwarding (AF) group:- This group can be used to provide simple services based on the drop priority.

- Expedited Forwarding (EF)group:-This group can be used to create low delay, low loss and end-to-end bandwidth assurance services.

Differential Services architecture is considered attractive to MANET's because it is scalable, relatively easier to implement, computationally more efficient and does not use out-of-band signaling protocol to perform resource reservation. However implementing

DiffServ in Ad-hoc Networks is not straight forward since it is designed originally for a wired-networks. The following are some of the problems in implementing the DiffServ router in the MANET.

1. In MANET we do not have static boundary routers or core-routers. This is relatively a simple problem to solve if the source and destination are assigned as the boundary routers and the intermediate hops as core-routers. In MANET's because of the mobility of the nodes, every node is a potential core-router and hence should implement the functionalities of a core-router.

2. In order to receive differential services every node or a customer must have some kind of Service Level Agreement with the network. In MANET we do not have a centralized point and is not clear how a node can negotiate SLA dynamically when it joins the network.

3. The model clearly violates the Service Level Agreement by consuming more resources that it is allocated when it is used for multicast applications. The DiffServ model is designed by assuming that a packet entering the network leaves the network as a single packet. In multicast applications a packet entering the core router may replicate into several packets and hence consuming more packets than it is allocated [23].

1.3. A Flexible QoS Model for MANET (FQMM). A Flexible QoS Model for MANET (FQMM) [29] was the first attempt to propose a QoS model for MANET's. It considers the dynamic characteristics(varying link conditions and mobility) of the MANET and proposes a hybrid provisioning scheme that combines per-flow granularity of the IntServ [4] and per-class granularity of the DiffServ [3]. FQMM defines three kinds of nodes in a network, Ingress node is a mobile node that sends data, egress node is a destination node and interior nodes are intermediate hops along the path. The role of the node changes dynamically based on the position and functionality(sender/receiver) of the node in the network. The provisioning scheme in FQMM combines both per-flow granularity of the IntServ [4] and per-class granularity of the DiffServ [3]. The higher priority traffic in the network is given per-flow provisioning, while other priority classes are given per-class priority provisioning. An adaptive traffic conditioner is placed at the ingress node. The conditioner polices the traffic based on relative and adaptive differentiation traffic profile. The conditioner is also responsible for marking, dropping and monitoring the traffic at the ingress node.

The following are some of the problems with FQMM

1. The per-class provisioning requires a node to have some kind of Service Level Agreement with the network. FQMM does not specify how the SLA is negotiated in the network dynamically.

2. The model is applicable where traffic is generated by a single sender and terminates at a egress node. In multicast applications there are potentially more than one receiver and some receivers act as forwarding node. Hence the model can not be used for multicast applications.

2. QoS Signaling Requirements

Usually the application knows best about its desired quality of service requirements. However, once the packet is delivered to the network, the QOS information is lost. There are two different ways for an application to communicate the QOS requirements to the network. In-Band signaling where the control information is carried along with the data packet [12, 13]. In out-of-band signaling explicit control messages are used to install the reservation state on all the hops along the path. The purpose of the QoS Signaling is to reserve the resources for a flow in a network. This section describes the existing QoS Signaling techniques developed for the MANET which includes dynamic RSVP [18] and INSIGNIA [12, 13].

2.1. Dynamic RSVP. Dynamic RSVP (dRSVP) [18] is an out-of-band signaling protocol. The protocol extends the functionalities of RSVP [6] to capture the dynamic characteristics of the network. The main motivation for the design of the protocol is to provide feedback to all the nodes in the path to learn about reservation states on the upstream and downstream nodes and adapt accordingly.

In the reservation set up phase, an adaptive application provides the range at which the data is generated. The information is carried with the PATH message. On receiving the PATH message, receiver requests reservation of resources and sends RESV message to the sender using the reverse route. The RESV message is extended to include Traffic Spec(tspec) and Measurement Spec(mspec). The tspec is used to describe the ranges of traffic flows and mspec is used to measure the traffic conditions to learn about the downstream nodes. RecvNotify message is used to allow the nodes to communicate the sender measurement specifications and is used to learn about the up-stream nodes. The dRSVP algorithm takes upstream and downstream bottlenecks into account before performing reservations. The algorithm divides the available bandwidth among all the flows and allocates the minimum requested bandwidth plus a fraction of the requested bandwidth range.

The protocol adapts to the varying conditions of the network and link variations and divides the network bandwidth equally among all flows. The protocol requires the applications to be adaptable to the varying conditions. The protocol also includes aggregation of PATH and RESV message for multicast flows. However the protocol is very complex and decreases the system throughput since the reservation is performed using the explicit control messages and the additional messages are used to perform resource adaptation in the network. The protocol is designed for MANET's and considers the dynamic changes in topology due to mobility and varying link conditions. However, the protocol suffers from all the problems of the deployment of RSVP for MANET's(It is heavy-weight protocol and is is uses out-of-band signaling protocol to perform resource reservation).

2.2. INSIGNIA. INSIGNIA [12, 13]is an IP-based QoS Framework based on in-band signaling and soft-state resource management approach that supports adaptive services in mobile ad-hoc networks. The INSIGNIA QoS framework allows an application to specify the required bandwidth range and uses it to perform resource allocations and adaptation. Like RSVP, provisioning scheme in INSIGNIA is based on the per-flow granularity. Each flow-state information is kept in a soft-state and is restored, adapted and removed in response to the mobility of the nodes or the topological changes in the netwrok.

Figure 1 [12, 13] shows the architectural components of INSIGNIA framework.

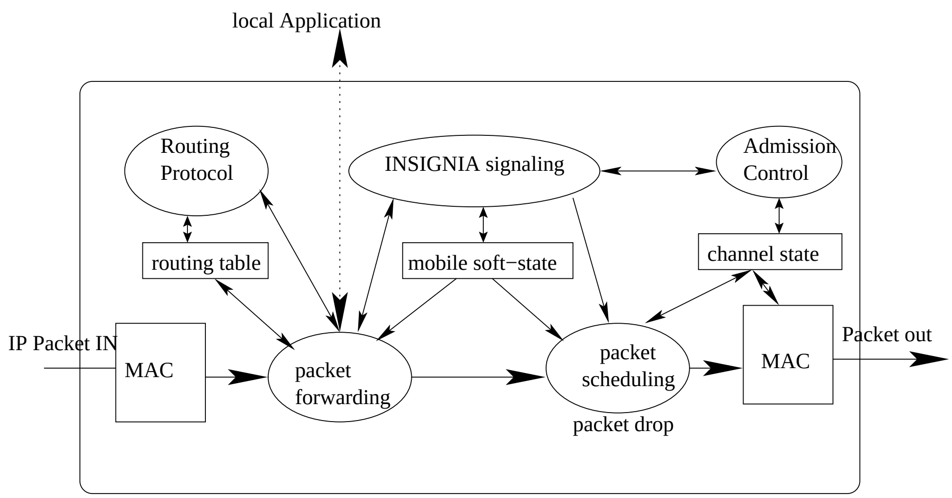

Figure 1. INSIGNIA Quality Of Service Framework

The INSIGNIA signaling module is responsible for establishing, adapting, restoring and removing the end-to-end reservation between source and destination pairs. Signaling messages received by the node is processed by this module and is delivered to the local application or to the next hop provided by the routing module. Admission control module actively monitors the bandwidth utilization and its testing is based on the channel utilization in the transmission range and the requested bandwidth of the flow. The framework proposes a clean separation between routing, signaling and forwarding. The ĨNSIGNIA framework does not propose any new QoS routing protocol, QoS MAC protocol or a distributed scheduler, rather it defines components where variety of algorithms can be plugged in to realize the ideal QoS schedule.

In INSIGNIA framework protocol commands are encoded using the IP option field and it includes payload type, service mode, bandwidth indicator(Min or Max) and the bandwidth range. When the source node initiates the flow, INSIGNIA module encodes the reservation request in the data packet and forwards the packet toward the destination node. Reservation packets execute admission control algorithm at all the nodes(hops) along the path to install the reservation state. The reservation packets are sent by the source node until it receives a QoS REPORT message from the destination node, informing the reservation state. The destination node actively monitors the ongoing flows and collect status information such as packet loss, delay and throughput. The QoS REPORTS are also used for resource adaptation purposes. The destination node compares the flow-reception quality to the application specific adaptation policy and actions are taken to adapt to the observed conditions. The QoS REPORT defines three commands: Scale-Up, to request a source to initiate the reservation for its enhanced or base service quality. Scale-Down, to request the source to send its enhanced QoS packets as best-effort packets and Drop command to drop the existing flow or to indicate the source to stop transmitting the packets.

INSIGNIA is a light-weight signaling protocol suitable for mobile ad hoc networks. The framework is well suited for supporting mobile and end-to-end quality of service in a highly dynamic environment. The framework does not support the aggregation of the Resource Reservation and Reporting messages, which is quintessential for supporting multicast applications. The proposed thesis borrows the framework components from INSIGNIA and implements the distributed packet scheduler to provide differential services to different multicast sources.

3. QoS MAC Protocols

In the Infrastructure based networks and cellular networks, the access-point (AP) and Base station (BS) acts as a centralization point. In these networks most of the network functionality lies within the access point. If the access point alone controls the medium access, no collisions are possible and AP can act as a centralized point for arbitration of

QOS demands. However in MANET there is no central point which can perform resource reservation. A QoS framework relies on MAC protocol for providing medium access, reliable data transfer and supporting bandwidth reservation for a flow. Several MAC protocols are proposed in the literature, most of them focus in solving the hidden/exposed terminal problem and many of them do not provide a resource reservation mechanism.

In this section, we review IEEE 802.11 MAC protocol [1], and discuss few distributed scheduler algorithms [11, 24, 25, 14] proposed in the literature to discuss the applicability of these algorithms to the QoS framework.

3.1. IEEE 802.11 Medium Access Control Layer. The basic IEEE 802.11 [1] MAC layer provides three basic access mechanisms. These access mechanisms are grouped into two methods. Distributed co-ordination function, supports mandatory access mechanism based on CSMA/CA and an optional method to avoid hidden/exposed terminal problem. Point-co-ordination function is used to provide contention free polling method for time-bounded services used only in infrastructure based networks.

The mandatory access mechanism of IEEE 802.11 is based on carrier sense multiple access and collision avoidance (CSMA/CA), which allows multiple users contending for the channel before accessing it at a random back-off time following distributed inter frame spacing (DIFS) period. The Access mechanism in 802.11 uses two timers, random back off timer avoid collision and a residual back-off timer to provide some degree of fairness to the lone-waiting stations.

Following figure explains the basic access mechanism to transmit broadcast frames using IEEE 802.11 MAC scheme.

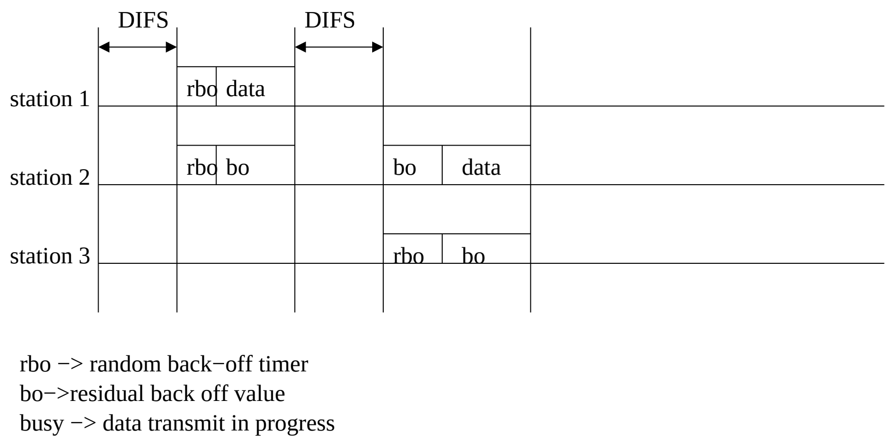

Figure 2. IEEE 802.11 basic access mechanism

Station 1 and 2 start the transmission of packet. Since the channel is idle both nodes start the back off timer within the contention window and start counting the value backward. Station 1 captures the channel, because it has a lower back off value, Station 2 stops the back off timer value. At the next interval station2 and new node Station 3 attempts to capture the channel, In the contention window station 3 chooses a new timer value and station 2 resumes the old timer. Since the new node has to choose the back-off timer value from the whole contention window , statistically it will have higher value compared to the old station [22].

IEEE 802.11 specifications states that the RTS/CTS and ACK(Indirect detection of collisions) mechanisms cannot be applied to packets with broadcast and multicast address because there are multiple destinations for the RTS and thus potentially multiple concurrent senders of the CTS and ACK in response.

The basic IEEE 802.11 does not provide any resource reservation or QoS guarantees. the medium access is controlled by means of random-access timer without any knowledge of the priority of the packet. In mobile ad hoc networks, bandwidth is shared by all the nodes in the transmission range. In order to provide differential services in the network, priorities of the Head-Of-Line(HOL) packets at each node must be exchanged and the medium access mechanism must be updated to examine the neighborhood packet priorities to realize the ideal schedule which satisfies the system goal.

3.2. Multiple Access Collision Avoidance with Piggyback Reservation (MACA/PR). Multiple Access Collision Avoidance with Piggyback Reservation (MACA/PR) [14] is an extension of IEEE 802.11 and FAMA [8] designed to provide real-time traffic support. This scheme combines the asynchronous operations of wireless LAN and QoS support of the centralized TDMA based networks.

To transmit the datagram(non-real-time)packets, the protocol is basically same as IEEE 802.11 and includes non-persistent CSMA to improve the performance at heavy load. For a station with a packet to send must wait for a free window in the reservation table and then waits for an additional random delay before sensing the channel. If the channel is idle, it proceeds with RTS-CTS-DATA-ACK sequence to complete the packet transmission. If the channel is busy it repeats the above process.

The mechanism to transmit the real-time packets is slightly different. The scheduling information of the real-time packets is carried in the DATA and ACK packets. This information is maintained in the reservation table on all the nodes in the same transmission range. The protocol does not always use RTS-CTS mechanism before transmitting the DATA packet. The hidden terminal problem is avoided by propagating the reservation table among all the neighbors. The protocol uses RTS-CTS only to set up the flow, subsequent packets uses only DATA and ACK packets. The sender node transmits the DATA packet with the priority of the next Head-Of-Line(HOL) packet. The receiver on receiving the packet, makes an entry in the reservation table and sends an ACK to the sender with the received priority of the next packet, all the nodes in the transmission range makes an entry in the reservation table. The ACK packets serves the purpose of renewing the reservations. The protocol requires every node to have a reservation table, which keeps track of transmit and received reserved windows. The protocol does not retransmit the lost packets after collision.

3.3. Distributed Multi-Hop Scheduling and Medium Access with Delay and Throughput Constraints. Distributed Multi-Hop Scheduling and Medium Access with Delay and Throughput Constraints [11] is a MAC protocol designed to support Quality Of Service communications in multi-hop mobile networks. The protocol exploits the broadcast nature of the wireless medium and proposes two mechanisms to achieve the desired QoS. First mechanism is a distributed priority scheduler to exchange the priorities of the Head-Of-Line(HOL) packets with the neighbors and use this information to approximate the back-off timer to realize the ideal schedule. Secondly the protocol proposes a multi-hop co-ordination function so that downstream nodes can increase the packet's priority to make up for any delays it experienced in the up-stream nodes due to link errors.

In order to exchange the current and HOL packet priority information with the neighbors, protocol proposes piggybacking the priority information of current packet in the RTS/CTS packet and HOL packet information in the DATA/ACK packets. The exchange mechanism is very similar to the one proposed in the MACA/PR [14] except that this protocol uses RTS-CTS-DATA-ACK sequence for every packet. The protocol provides a mechanism to map the partial information present in the local schedule table to a back-off scheme. The back-off policy uses both contention reduction and collision resolution. The contention reduction is achieved by reducing the number of nodes in the contention window by deferring the transmission beyond distributed inter frame spacing (DIFS) period for some nodes. In a network if all the nodes have the same schedule information, then the node with the higher priority packet will capture the channel.

A packet can experience delays due to the random access nature of the medium, link error and the mobility of the nodes. In order to make up for delays experienced in some of the upstream nodes , protocol provides a multi-hop co-ordination function to increase the priority of the flow. This gives an opportunity to the downstream nodes to satisfy the end-to-end Quality of Service requirements.

3.4. Distributed Fair Scheduling in Wireless LAN. Distributed Fair Scheduling in a Wireless LAN [24] is a fully distributed fair scheduling algorithm, which allocates bandwidth proportional to the weights of the packet flows sharing the channel. The protocol uses IEEE 802.11 Distributed Co-Ordination Function (DCF) and implements a new back-off mechanism based on the finish times of the packets to achieve better fairness.

The proposed protocol is fully distributed, with each node makes the decision on channel access using only the local knowledge. The protocol does not require any node to have information on the weights of the flows at different nodes. The protocol uses the Self-Clocked Fair Queuing (SCFQ) idea of transmitting the packet with the smallest finish tag and the SCFQ's mechanism of updating the virtual clocks. The IEEE 802.11 MAC back-off interval mechanism is modified to choose a back-off interval proportional to the finish tag of the packet to be transmitted.

Each node maintains a virtual clock, which is updated every time a node transmits or receives a packet. Node calculates a start time and a finish time for every packet based on virtual clock and size of the packet. The back-off time for a node is calculated as a function of the finish time of the packet. The objective is to choose a small back-off interval for a packet with smaller finish time. The protocol provides fairness for several competing flows sharing the broadcast medium.

3.5. Fair Scheduling in Broadcast Environments. The proposed protocol is very similar to the Distributed Fair scheduling algorithm [24] except that the protocol uses Start-Time Fair Queuing(SFQ) algorithm. The protocol uses IEEE 802.11 Distributed Co-Ordination Function (DCF) and implements a new back-off mechanism based on the SFQ's idea of choosing the packet with the smallest start times to achieve better fairness.

The proposed protocol is fully distributed, with each node makes the decision on channel access using only the local knowledge. The protocol does not require any node to have information on the weights of the flows at different nodes. Protocol borrows the SFQ's idea of transmitting the packets with the smallest start time. Each node maintains a virtually clock, the process of updating the virtual clock is fully distributed. A node updates the virtual clock when it hears a packet with the start tag, the new value for virtual clock is calculated as a function of the start tag of the packet. When a MAC layer receives a new packet for transmission from the network interface queue, it calculates the start tag and finish tag for the packet. The back-off timer for a packet is calculated as a function of start time as opposed to finish time that is used in SCFQ's mechanism. In order to eliminate unfairness, which will result when the packets collide, protocol transmits a resolution burst for one time slot after IFS time slots signaling that collision resolution is about to take place. Any node that has not experienced the collision would them back off giving an other chance to collided nodes to contend for the channel.

3.6. Discussion. In contrast to Distributed fair scheduling algorithms [24, 25], which are aimed at achieving fairness, MACA/PR and Distributed Multi-Hop Algorithm [11] are proposed to provide Quality of Service Support in Mobile ad hoc networks. The protocols were designed primarily for unicast communications and uses RTS-CTS and positive ACK packets to install and renew reservation states at all the neighbor nodes in the same transmission range. The algorithms can not be used for multicast or broadcast communications since there are potentially more than one receiver for every packet since both the protocols rely CTS and positive ACK from the receiver to make the bandwidth reservations, which would result in CTS or ACK collisions. The IEEE 802.11 MAC protocol provides only the best-effort service and the packets for multimedia and real-time traffic cannot be delivered using the best effort service. Hence we need a MAC mechanism which supports resource reservation and distributed priority based scheduler which is capable for providing the differential services to the multicast flows based on the flow priorities.
Next chapter discusses the framework design to support Quality of Support for multicast applications in mobile ad hoc networks. The chapter focuses on the design of distributed priority based scheduler to achieve the differential services.

3.7. Multicast Ad hoc On-Demand Distance Vector Routing. Multicasting is an effective mechanism by which group communication can be achieved. There are well-established multicast protocols exist which provides efficient multicast services in wired networks. However for MANET's multicast protocol designed should be adaptable to the frequent changes in the topology, low power and interference of wireless signals. In this section we review Multicast Ad hoc On-Demand Distance Vector Routing(MAODV) [20] designed to support multicast operation in MANET. The protocol is used in the experiments to evaluate the performance of the framework.

MAODV protocol uses **Route Request(RREQ)**, **Route Reply(RREP)** and **Multicast Activation(MACT)** messages to discover and activate the route. When a node wishes to join a multicast group or wants to find a route to a multicast group, node broadcast RREQ message. For Join RREQ messages only the multicast member nodes can respond however for route discovery message any node which has a valid route can respond. Each node when it receives the RREQ message either responds or forwards the request to the next hop. When a message reaches a node which has a valid route, it reverses the source route and unicasts a RREP message to the sender. The source node waits for a period of RREP_WAIT_TIME and collects all the route responses. After the expiry of the discovery period it selects the best route and activates the route by sending a MACT message along the selected path. MAODV uses sequence numbers to ensure that routes found to multicast groups are always current one. A node responds to a RREQ message only when the sequence number of a route table entry is at least as great as that contained in RREQ message.

The protocol uses **Group Hello(GRPH)** message to communicate the group sequence number to the group members. The first member of the group becomes the leader of the group and is responsible for maintaining and communicating the number to the group. The protocol supports the dynamic membership to the group and a member can leave the group any time by sending a MACT message with a 'P' flag. The node however can leave the tree only if it is a leaf node. Links in the tree are monitored to detect the broken links. When a broken link is detected, the node that is further from the leader node attempts to repair the link.

CHAPTER 3

FRAMEWORK DESIGN AND IMPLEMENTATION

Given the multicast group members, a multicast protocol constructs a multicast tree, which covers all the group members. The protocol constructs a shared-tree and allows multiple senders in the same group to act as multicast senders. Mobile Ad hoc Networks are primarily constrained by bandwidth and all the nodes in the same transmission range, share the bandwidth. In order to support QoS in MANET's, a network should take active role in allocating the bandwidth among all the competing nodes. Quality of Service enabled networks differentiate between users based on their QoS requirements, so that users with different QoS requirements will receive different treatments. This chapter presents the design of the QoS framework for providing differential services. This framework uses Mobile Ad hoc On Demand Distance Vector(MAODV) [20] multicast routing protocol. The research does not focus on designing the QoS multicast routing protocol, as it is out of scope of this work. However the focus is on the design of the distributed differential scheduler to allocate the bandwidth to the competing multicast sources, in order to provide differential services for multicast applications.

Figure 3 shows the various modules involved in providing differential serevices in MANET's. QoS Layer is resposible for mapping the packets to one of the pre-defined classes. The details of the mapping mechanism is explained in section QoS Marking Module

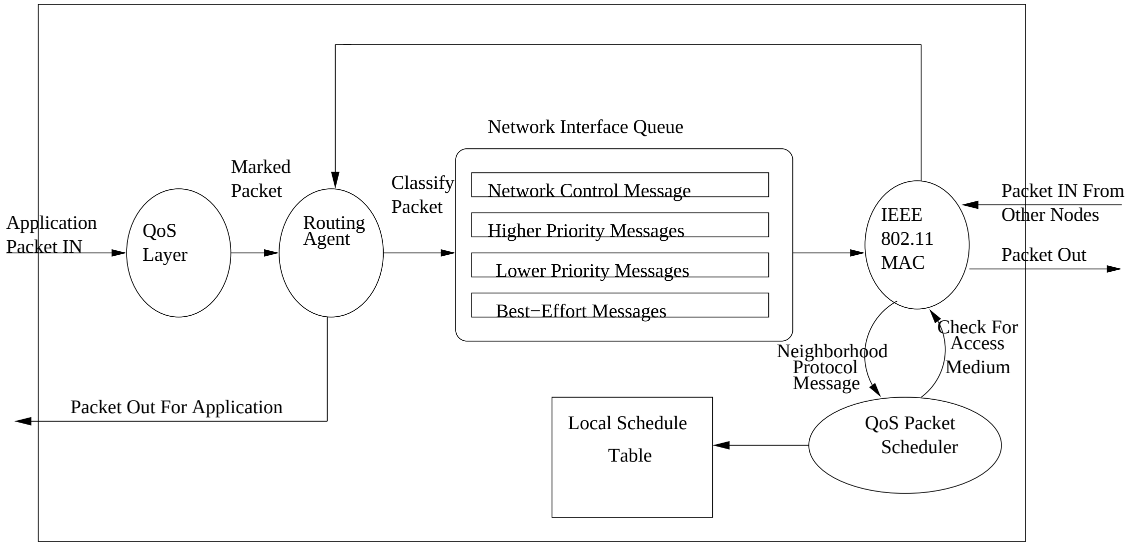

Figure 3. Framework for providing differential services for mobile multicast applications

1. Network Interface queue is used to store the packets before transmitting to the next hop. The Interface queue is used to classify the packets based on the priorities. Section Classifier 2 describes the detailed mechanism of classifying the traffic. QoS Packet scheduler and Local schedle table are the core components of the system. The MAC protocol interacts with these cmponents to achive the differential services in the network.

1. QoS Marking Module

Usually the application or the source node knows best about its desired quality of service requirements. However, once the packet is delivered to the network, the QoS information is lost. There are two different ways for an application to communicate the QoS requirements to the network [5].

- **Header-based (In-Band Signaling mechanism)**: In this method, a node requests QoS by using indicators such as ip-address, port number or protocol number (FTP, TELNET, CBR.. Etc). Additional indicators like desired bandwidth, end-to-end delay-target for the packet can also be added to the data packet. In the in-band signaling mechanism, the QoS information is carried in the data packet. It is usually lightweight, consumes less bandwidth and will not contend for the channel with data packets. This mechanism is already used in the design of INSIGNIA [12] [13] and is proved to be very efficient compared to the out-of-band signaling.

- **Protocol-based (out-of-band Signaling Mechanism)**: The Out of band signaling mechanism used in the IntServ [4] architecture. It requires an application to set up a reservation before it can transmit traffic. This requires a new protocol for setting up resource reservation in the network. The advantage of this mechanism is that complex reservation mechanisms can be implemented. This can not be implemented with absolute in-band signaling. However, the mechanism consumes lot of bandwidth and computing resources compared to the In-band signaling mechanism.

In this research work, Header-based signaling mechanism is used to communicate the QoS requirements to the network. In the Header-based mechanism, the QoS information is carried along with the data packet. This mechanism is highly suitable in highly dynamic environment such as mobile ad hoc networks.

The QoS guarantees can be attained only with appropriate resource reservation techniques. Since the mobile ad hoc networks are mainly constrained by the bandwidth and computing resources, the signaling overhead required for flow management must be kept to the minimum. The QoS options indicates the desired quaility of service requirements for an application or a source. The option usually include desired bandwith, end-to-end delay target. The research work introduces the following QoS options (See Figure 4) that are carried along with the data packet. The reason for including the QoS options with the data packet is to provide a way for an application to communicate the QoS requirements to the network.

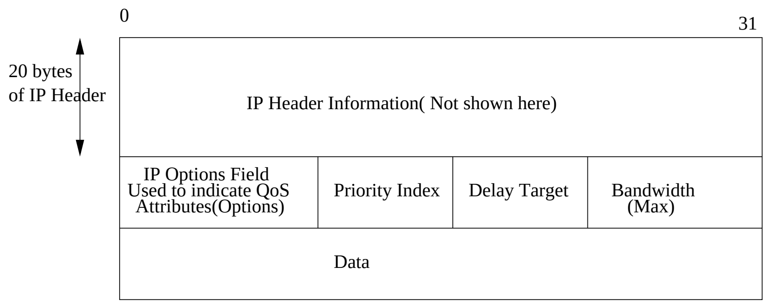

Figure 4. Framework QoS options

- Priority Index: The Priority Index request allows a source to specify the desired priority class for the application. This field specifies the packet priority and is used by the classifier or a forwarding module to differentiate the incoming packets into one of the pre-defined classes. This attribute is used to determine the role of the node (Higher Priority or Lower Priority) and determines the subset nodes in the same transmission range, which can contend for the channel. The lower priority nodes can contend for the channel only when there are no higher priority nodes in the same transmission range.

- Max bandwidth: The bandwidth request allows a source to specify the desired bandwidth requirement for an application. This field can be used to perform bandwidth reservation and admission control. Currently in the research work, admission control is not implemented(See Chapter 5 on future work and conclusiosns).

- Delay-target: The delay-target request allows a source to specify the desired delay-target for the packet. Every application will have different delay targets; framework uses this field to communicate the requirements to the network. Every forwarding node in the path updates this field, to reflect the remaining lifetime of the packet. The packet with the lowest delay-target is scheduled first in every node to ensure the ideal schedule of the packet.

The source node performs the mapping of application requirements into the QoS requirements based on the pre-defined policies and initializes the QoS attributes in the packet. The QoS module in addition to performing the mapping also updates the hop-to-hop delay of the packet. The main objectives considered while designing the QoS module were, no additional control packets to perform reservation, the reservation is for per packet and flow information is not maintained. The main objective of this module is to provide the information to the forwarding module and scheduler to realize the ideal schedule, which provides a differential service to the application.

2. Forwarding Module (Traffic Classifier)

A classifier classifies an incoming packet into multiple groups based on the pre-defined rules. In this research work, a multi-level priority queue is used to classify the traffic (See fig 5). The queuing mechanism classifies the traffic based on the priority index set by the application. In order to provide traffic differentiation among the competing users, a controlled sharing of bandwidth is required. In wireless networks bandwidth is shared by all the nodes in the same transmission range and it is necessary to allocate bandwidth to these applications based on the priority of the head-of-line packets. The traffic classifier only performs the classification of incoming traffic into one of the pre-defined class of application, it is up to the scheduler to select the packet and acquire the transmission channel.

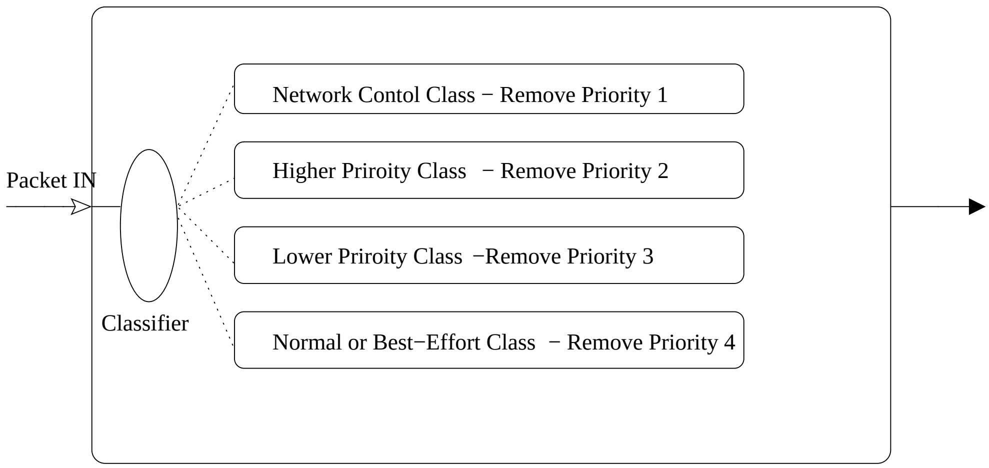

Figure 5. Multi-Level Priority Based Network Interface Queue used in the Framework

Queuing Mechanism

The algorithm for Remove and Insert functions are given in Appendix A and the mechanisms are explained briefly here.

- Insert: The insert mechanism examines the priority-index of the packet and classifies the incoming packet into one of the 4 pre-defined classes.

- Remove: This function is invoked when the previous packet is transmitted or it is the first packet to be transmitted. The function uses the policy file to determine the order in which the packets need to be removed. Since the topology of the network changes rapidly the control messages should be given a higher priority compared to the data packets and hence are queued in the first queue. These messages are scheduled first irrespective of the delay target of the data packets.

The advantage of using the priority queue is several levels of priorities can be defined (LOW, HIGH,..etc) and also the granularity in identifying traffic to be classified into each queue is quite flexible. For example, in this work, we use the priority index, network control messages to prioritize the traffic. Network control messages are queued before higher priority packets, higher priority packets are queued before low priority packets, and lower priority packets are queued before best-effort packets. The approach is quite simple and flexible to define different levels of differential services. The advantage of this queuing is we can define the preference by which each of the queues will be serviced.

The classifier in addition to classifying the packets also provides following services to the lower layer.

1. Updates the queuing delays for the other packets in the queue.

2. Provides a next head-of-line packet priority in queue to be piggybacked in the outgoing data packet.

3. Packet Scheduler

The Packet scheduler is responsible for enforcing bandwidth allocation to individual flows or packets. When the network resources cannot accommodate all traffic flows, queues will start to build up at all the nodes. In wireless networks, all the nodes that are in the same transmission range share the bandwidth. If all the nodes have the Head-of-Line (HOL) packets ready for transmission, then, the purpose of the scheduler is to decide which node should get the channel for transmission.

The QoS is defined as a capability of a mechanism to differentiate the traffic so that network can treat one or more classes of traffic differently than the other types. This is a major feature of the modern networks; the quality received by the user depends on the user or application requirements. The design goal of the differential scheduler should be such that if two users have different QoS requirements they should receive different treatment else they should receive the same treatment based on the application requirements.

Scheduler Design

In order to provide differential services, the scheduler should meet the following basic requirements in the design.

- Bandwidth Allocation: In order to meet the assured quality of service requirements of certain nodes or flows, the scheduler should allocate the bandwidth to the application based on the priority of a node (HOL packet in the node determines the priority of the node). In wireless environment the bandwidth is shared by all the nodes that are present in the same trasmission range and the scheduler should allow only the node with the highest priority to capture the channel.

- Delay Bounds: The scheduling algorithms are required to support delay bounds. The distributed scheduling algorithm should allow the node with the lowest deadline value to capture the channel.

In this research work, it is important that some class of traffic be given preferential treatment over other traffic. To achieve this, the framework defines four classes of traffic.

1. Network control Messages: These include Routing messages, Neighborhood discovery control messages and any other network related messages.

2. Higher priority Messages: These include packets from the application, which has higher priority index set. Note that the differentiation is done by examining the priority-index and not by the node address or port information.

3. Lower priority Messages: These include packets from the applications, which has lower priority set by the applications.

4. Default or best-effort messages: These include all other messages including the messages that are not marked. They have the lowest priority compared to all other classes of traffic.

As stated before the purpose of the distributed scheduler is to select the node, which has a higher priority packet ready for transmission compared to all other nodes in the same transmission range. The scheduler maintains a local schedule table, by sniffing all the packets in the broadcast region. The schedule table contains the list of all the neighbor nodes and the corresponding HOL packet priorities. Pseudo-code for the Scheduler is shown below.

Algorithm 1: Packet Classifier Algorithm

Data : Pointer to Packet Header
Result : Return $TRUE$ for transmit packet and $FALSE$ to back-off initialization

```
while No More Packets in the Queue do
    read the current packet priority
    if Network Control Message then
        Contend for the channel
    else
        if High Priority Data Message then
            contend only if no Control message entry is in local schedule table
        else
            if Lower Priority Data Message then
                contend only if there are no Control and higher priority mes-
                sages entry is in local schedule table
            else
                contend only if there are no entries in the table for marked
                packets
            end
        end
    end
end
```

The scheduler uses a simple priority scheme where the higher priority always has precedence over lower priority. When the outgoing link becomes available for transmission, scheduler contends for the channel only if it has any packets in the higher priority class or if the higher priority class is empty.

4. Construction Of Local Schedule Table

In the Infrastructure based networks and cellular networks, the access-point (AP) and Base station (BS) act as a centralization point. In these networks most of the network functionality lies within the access point. If only the access point controls the medium access, no collisions are possible and AP can act as a centralized point for arbitration of QoS demands. However, the infrastructure-based nodes loose some of the flexibility that wireless networks can offer i.e. it is not distributed and hence not fault tolerant and this is not suitable for dynamic environment where nodes keep moving from one transmission area to another.

To distribute the information about the Head-Of-Line (HOL) packets at the other nodes, this research propose to piggyback HOL packet information in the DATA packet and if the data rate is slower, additional protocol messages are sent to all the neighbor nodes with the priority of the HOL packet. The piggybacked information includes the priority of the packet with the source node (See figure 6). The obvious shortcoming of the problem is lower priority node may be hidden from the higher priority node and the tables may still be inconsistent or these two nodes may still not know about the priority of each other. As stated before, the proposed scheme assumes the reliable MAC multicast protocol and assumes that there are no hidden terminals with respect to the source.

Mobile Ad hoc networks are based on the wireless links, which are prone to errors and frequent changes in the topology. Due to this the scheduler could go into an invalid state. It is a state in which, the nodes have an invalid reservation entry, that prevents them from accessing the channel. The two scenarios, which could cause the scheduler to go into the invalid state are,

1. A node moves out of the transmission range after making a reservation for the next packet.

2. Packet is lost due to link error or collision.

To recover from the invalid state, a soft-state timer is implemented, which invalidates the reservations after the time-out value (See section 5). The source node is also required to invalidate the reservation entry for a packet after moving out of the transmission range. When a source node moves out to a new transmission range after making a reservation for the next packet, the node carries the reservation it made in the previous transmission range. This reservation is not valid in the current transmission range and hence must be invalidated. To invalidate the reservation, the QoS scheduler interacts with routing protocol to determine, if route has changed as a result of the mobility. If the route has changed, then the QoS scheduler invalidates the reservation for the packet and performs a new reservation.

Each node maintains the multiple queues and updates the QoS attributes, such as priority index and delay target for the packet. The node performs following steps to construct the table and to access the medium. For the sake of simplicity, following algorithm is split into three sub sections namely, construction of schedule table, priority based medium access mechanism and Mobility & Collision handling mechanism.

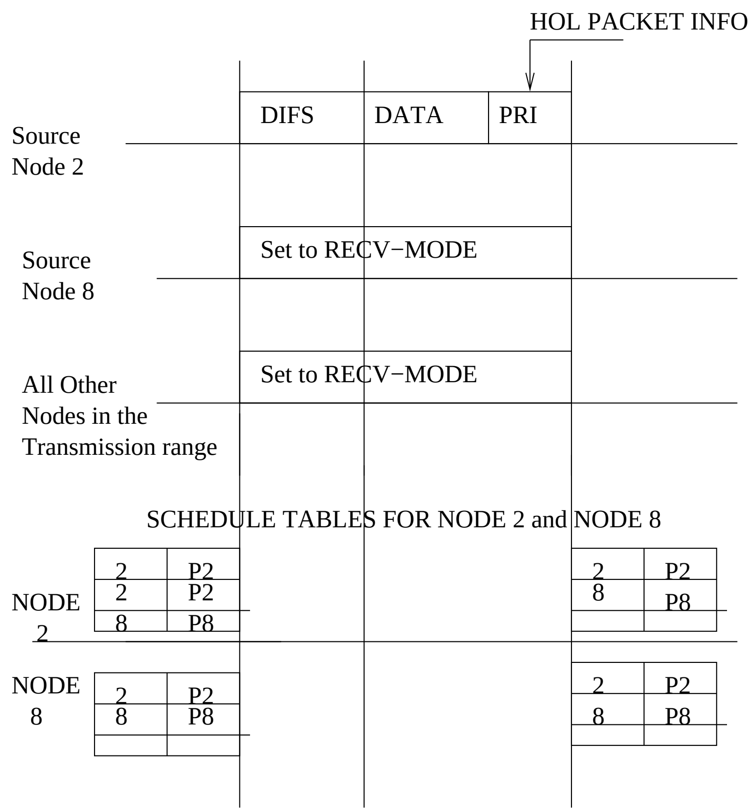

Figure 6. Priority Exchange Mechanism

4.1. Protocol Description. The Following definitions are used in describing the protocol.

- *Distributed Inter-Frame Spacing (DIFS)*: The DIFS is same as descibed in the IEEE 802.11 [1] specification.
- $CURRENT\_PKT\_PRI$: Indicates the priroity of the packet that is to be transmitted.
- TOP_PRI: Indicates the priroity of the top most entry in the schedule table.
- PRI_NEXT: Indicates the priority of the next packet in the network interface queue.

The protocol is designed as an extension to IEEE 802.11 MAC protocol for supporting Quality Of Service in mobile multicast applications. The protocol exploits the broadcast nature of the wireless medium and proposes a dynamic distributed scheduler to achieve the desired QoS. The distributed priority scheduler described here is a mechanism to exchange the priorities of the Head-Of-Line (HOL) packets with the neighbors and use this information to determine the back-off timer to realize the ideal schedule. The protocol achieves this without using any additional control messages. On the sender side, when a node wants to send any data (State S1 of Figure 7), it sends the data packet to the MAC layer. MAC Layer calculates the priority of this data packet and verifies the reservation state for the packet. If a reservation state for this packet is not present in the schedule table, node constructs a protocol priority message with the priority of the current packet and sends out the priority message to all the neighbors (States $S1 \rightarrow S2 \rightarrow S3 \rightarrow S5$). If a reservation state is already present, then the node senses the channel for a period of DIFS, if the channel is still free when the backoff timer expires, the node executes the modified medium access algorithm (See Section 4.3). In the modified medium access algorithm, the current packet priority is compared with all other nodes HOL packet priority. If the current packet's priority is higher than all other nodes then the channel is acquired (State S7) and the packet is transmitted to all the downstream nodes (States $S1 \rightarrow S2 \rightarrow S3 \rightarrow S6 \rightarrow S7$), otherwise the node goes through the channel access process all over again.

On the receiver side, when a node receives a packet, it extracts the priority information from the packet (priority is 0 if it is not set by the source node). If the received packet contains a valid priority information, then the reservation for the packet is entered in the table (State R2 of Figure 8). The packet is further examined for the address type. If the destination address is not a multicast address,or not destined for this node or if it a protocol priority message, then the packet is dropped. If the address is a multicast address, then the packet is sent to the upper layer for further processing and the reservation state for the received packet is removed from the schedule table (State $R2 \rightarrow R5 \rightarrow R1$).

In case of unicast packets the modified medium access mechanism is not executed (State S4 (Figure 7), R4 (Figure 8)). The mechanism to construct the schedule table by **spoofing** the broadcast packets and working of the Modified medium access mechanisms are explained in the following sections (See Section 4.2 and 4.3).

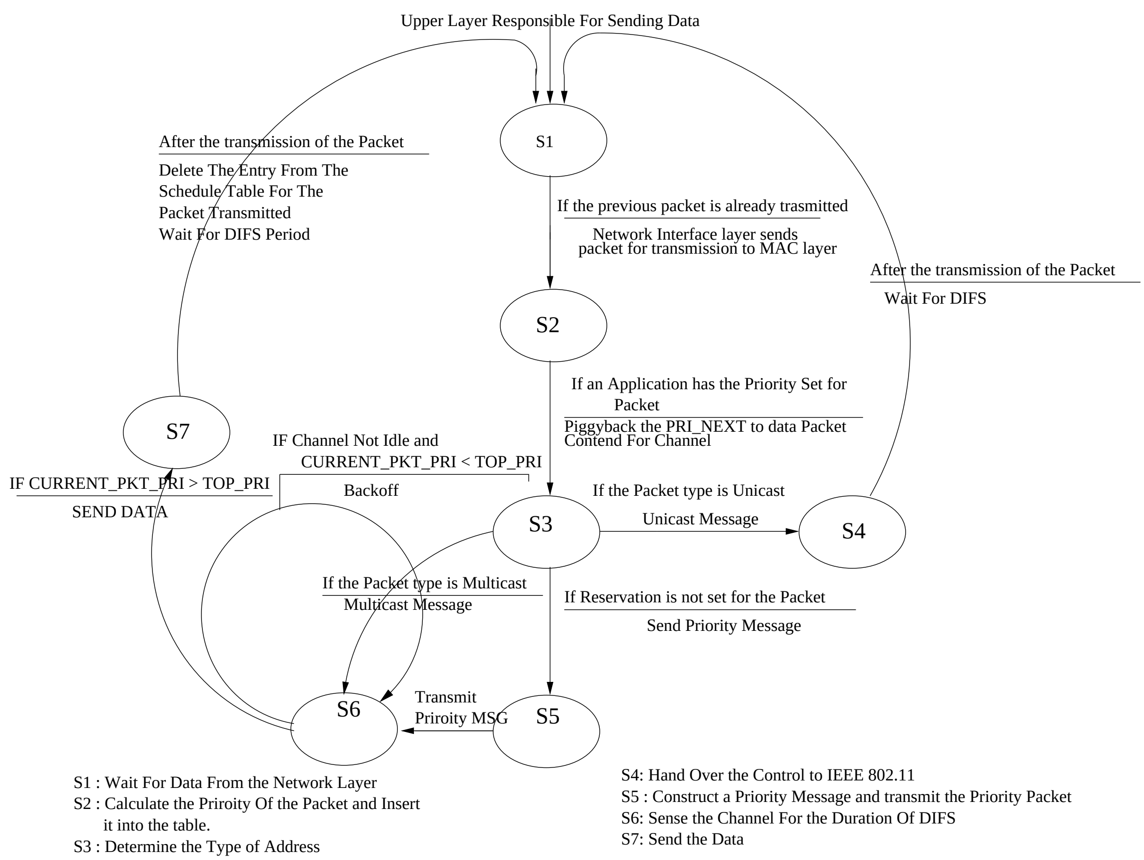

Figure 7. State diagram for a node(source/hop), which has a packet to transmit.

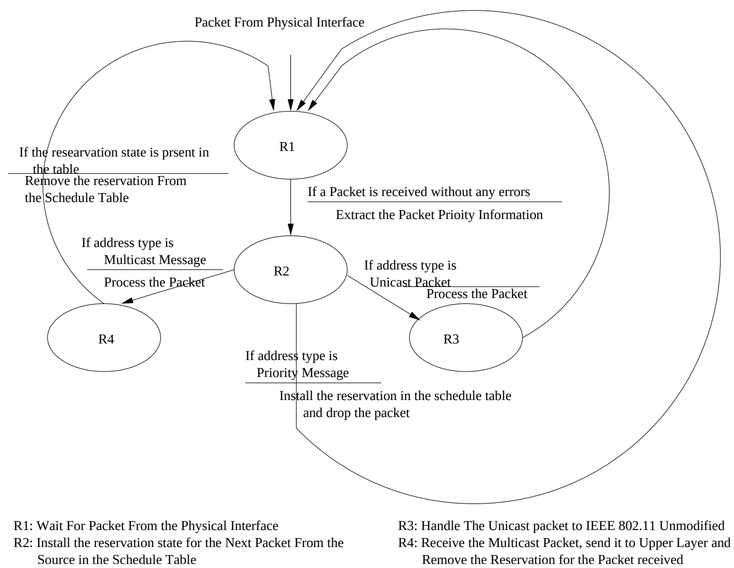

Figure 8. State diagram for a downstream node, which is ready to receive a packet.

Following symbols are used to describe the mechanism to exchange the relative priority of the head-of-line packets with the neighbors.

- Node-id: MAC identifier of the node
- Priority (Node-id): gives the priority of the packet to be transmitted by the node
- Priority-Recv: is the priority of the HOL packet in the node that just transmitted the packet.

4.2. Construction Of Table.

1. Network Interface layer sends a packet for transmission to MAC layer, when the previous packet is already transmitted or if it is the first packet to be transmitted. Mac layer calculates the priority of the packet that it receives from the interface queue.
2. Node inserts <Node-id, Priority (Node-id)> entry into the schedule table.

3. Node calculates the priority of the next packet in the interface queue and appends the information into the data packet;

4. Node executes the modified Medium Access Protocol (See section 4.3)

5. All the neighboring nodes that receive the packet, access the priority of the next packet. They examine the Priority-recv in the packet and perform following two steps.

   (a) Insert the $< sourcenode - id, priority - recv >$ entry into the schedule table

   (b) Remove the old entry of the source-node from the schedule table

It is possible that when a node executes step 3, the network interface queue may not have any data packet queued in it's network queue, hence the neighboring nodes will not add any entry for the next packet in the schedule table. In order to communicate the priority index of the next packet in the queue to all the neighbors, a periodic priority message is used to send the priority information of the next packet to be scheduled in the node. The periodic priority messages are essential, if the data output rate of the queue is very slow. However, if the data rate in a node is high, then the data packets are sufficient to carry the priority information and hence is not necessary to send the priority messages periodically. Hence, the protocol maintains the time-stamp for the last packet sent. It sends out a priority message with the priority of HOL packet, if and only if the difference between the time when last packet was sent and the current time is greater than packet generation rate of the application and also if there is a packet to be transmitted in the queue.

4.3. Modified Medium Access Mechanism. When a node receives a request from higher layer to send a packet, it performs following steps.

1. Node senses the channel for the duration of DIFS, if the medium is idle for the duration of DIFS, perform step 2 and 3 otherwise perform step 4

2. Compare the priority (Node-id) with the top entry in the schedule table. If the priority of the packet in a node is greater than all its neighbors, then it captures the medium and transmit the packet, otherwise perform step 4, so that the higher priority node in the same transmission range will be able to capture the medium and send the packet.

3. After the packet transmission the old entry is deleted from the schedule table.

4. Wait for the duration of DIFS and enter the contention phase after-wards.

5. Mobility And Collision Handling Through Soft State

The bandwidth (resource) reservation or access is controlled by means of random back-off, that is if a node 'i' has a reservation for node j, the reservation will not be removed from the schedule table of node 'i' until it hears the packet from node j. This kind of reservation is known as a soft-state reservation since, it does not associate the bandwidth with a specific static path through the network. However in wireless networks due to the mobility and collision the scheduler could go into an invalid state. The invalid state is defined as, a state where the nodes have an invalid reservation entry, which is preventing them from accessing the channel. Two scenarios, which could cause the scheduler to go into the invalid state, are

1. Node moves out of transmission range after making the reservation for the next packet.

2. Packet is lost due to link error or collision.

To recover from the invalid state, a soft-state timer is implemented, which invalidates the reservations after the time-out value. The value of the timeout value is a function of the multicast routing protocol's refresh message rate. In this work we are taking it as twice the MAODV [20] refresh message rate.

6. Example

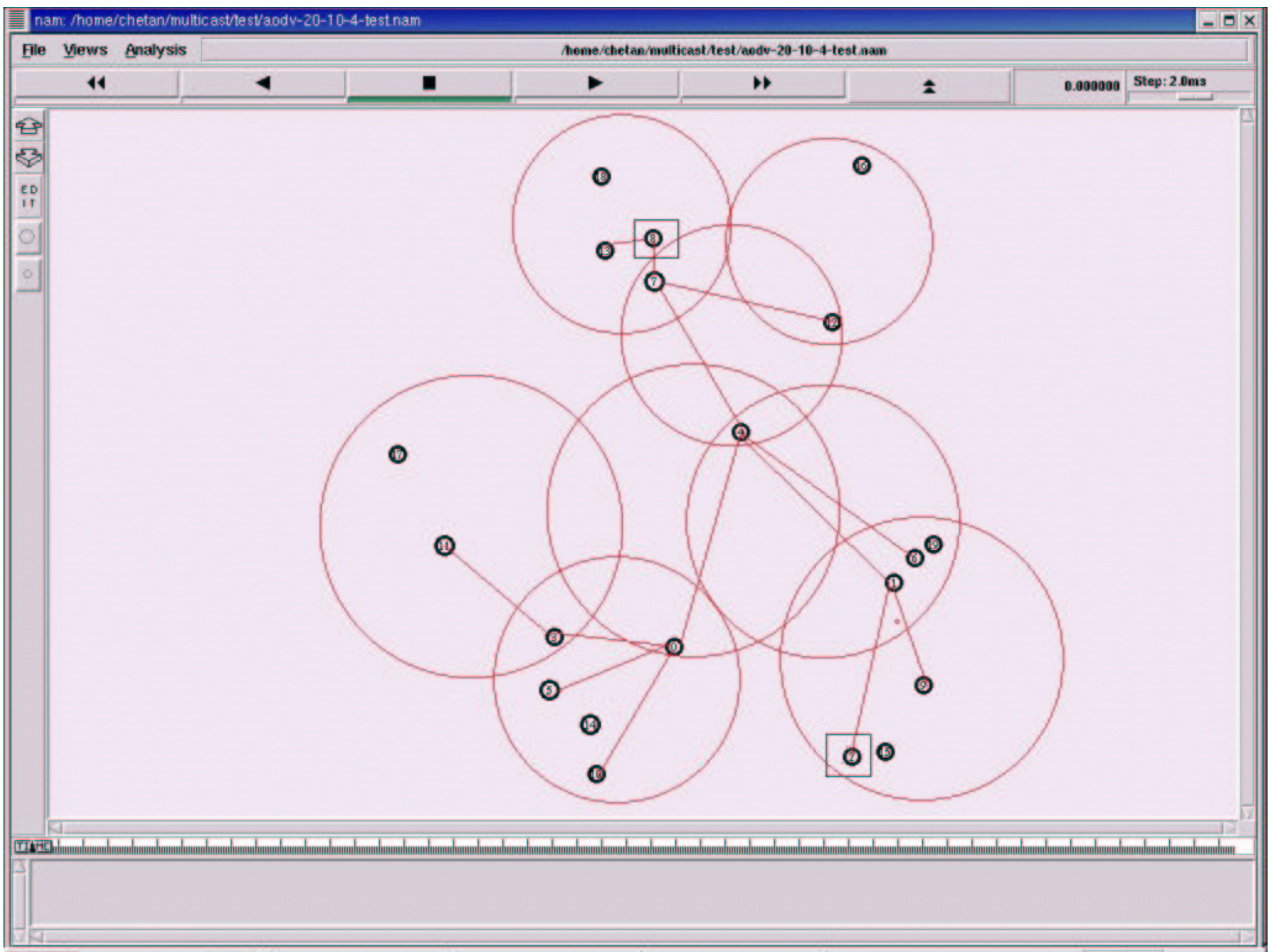

Figure 9. Example Scenario with 20 nodes and two sources node 2 and node 8

Node ID	Priority
8	P8

Table 1. Schedule table at node 13, 18 and 7 after processing the first protocol priority message from node 8.

Node ID	Priority
2	P2

Table 2. Schedule table at node 15, 9, 1, 6 and 19 after processing the first priority message node 2.

Figure 9 shows one of the example scenario used in simulation.In this example 20 mobile nodes are form a mobile network. MAODV multicast routing protocol[20] creates a shared multicast tree for this scenario, with two source nodes (Node number 2 and Node number 8). For this example node 2 is running an application, which has higher QoS requirements, while node 8 is running a lower priority application. When node 8 wants to transmit the first packet, it sends out a priority message with the priority of the packet (defined by the application), let this value be P8. Nodes 13, 7 and 18, which are in the same transmission range receives the priority message and updates the local schedule table. The Schedule tables for node 13, 18 and 7 after processing the priority message will have the entries for node 8's HOL packet (See Table 1).

Node 2 also sends out a priority message in its transmission range when it receives a packet from the network interface queue. The schedule table for nodes 15, 9, 1, 6 and 19 after processing the priority message will have the entries for node 2's HOL packet (See Table 6).

Node 8 sends the packet to all its downstream nodes. The data packet also contains the priority information of the next packet to be transmitted. When the data packet is received by all the neighbors, the reservation is removed for the old packet and a new reservation is added into the table. Since node 7 has 2 downstream nodes, it attempts

Node ID	Priority
8	P8

Table 3. Schedule table at node 4 and 12 after processing the first priority message from node 7.

Node ID	Priority
2	P2
8	P8

Table 4. Schedule table at node 4 after processing the priority messages from both node 2 and node 8.

to forward the packet by performing the reservation and transmission. After the initial reservation set up for the first packet, the schedule table at nodes 4 and 12 will contain the entries for node 8 (See Table 6).

Node 2 sends the packet to all its downstream nodes. The nodes 15, 9, 1, 6 and 19 receive the packet and update the schedule table. Node 1 also acts as a forwarding node and hence will be forwarding the data packet to its downstream nodes. Since this is first packet, it sends out a priority message to its neighboring nodes 6, 19 and 4. The schedule table at node 4 after the priority message received will have the entries for both node 8 and 2 (See Table 6).

At node 4, since the packet from node 2 contains a higher priority compared to the other packet received from node 8. The higher priority packet will be transmitted. Subsequent packets from the source node do not require priority messages, since the priority information will be piggybacked to the data packet. The source node 7 will not attempt to access the channel, since the schedule table contains a higher priority entry compared to the current packet under transmission. If node 4 moves out of transmission range after making the reservation and before transmitting the packet, then node 7 should get the access to the channel. Since node 7 contains an entry for node 4, we need a mechanism to invalidate this entry. The invalidation is achieved by maintaining the reservation in soft-state and removing the reservation after the time-out (See Section 5).

CHAPTER 4

PERFORMANCE EVALUATION AND SIMULATION RESULTS

This chapter describes the experiments conducted to study the performance of the proposed "Quality Of Service Framework" and the best-effort service. This research work uses Network Simulator [19] to measure the performance of the Framework.

This thesis uses two metrics to study the performance of the framework.

1. Throughput: It is measured for every flow in a group with different Quality Of Service requirements. This metric is useful to study the bandwidth service differentiation.

2. Average End-To-End Delay: It is defined as the average of all delays experienced by all the members of the multicast group over all packets.

The objective is to show that when two users have different QOS requirements they should receive different treatment; otherwise they should receive the same treatments, based on the application requirements. Experiments were conducted with varying mobility, varying number of multicast nodes and varying the number of multicast sources.

1. Throughput Analysis

This section analyzes the throughput service differentiation for mobile hosts with different priorities. The basic IEEE 802.11 [1] MAC access mechanism, distributed coordination function (DCF), supports mandatory access mechanism based on CSMA/CA and an optional method to avoid hidden/exposed terminal problem. In this research work, the DCF function is modified to provide differential services. It is also important that some class of traffic be given preferential treatment over other traffic. To achieve this, the framework defines four classes of traffic. For the throughput analysis, we consider the following classes: Higher Priority Class, Lower Priority Class and Best-Effort Class. Let n_h, n_l and n_b represent the number for nodes that have an active session in each of the classes of traffic. Let p_h denotes the probability that a higher priority mobile host has a packet for transmission and the MAC is not idle. The p_l and p_b are similarly defined for lower-priority and best-effort hosts. Since the higher priority classes are given preferential treatment and usually the application specifies end-to-end delay target and desired bandwidth, the probability that a higher priority host has a packet for transmission can expressed in terms of end-to-end delay target and the throughput requirements.

Consider a transmission range with n number of nodes with all the nodes having the packets for transmission, then the probability that a station transmits in a randomly chosen time slot is given by [2],

$$\tau = \frac{2(1-2p)}{(1-2p)(1+W) + pW(1-(2p)^m)} \tag{4.1}$$

W is the initial backoff window, p is the conditional collision probability for a mobile host and m is the maximum backoff stage. The conditional collision probabilities for each class can be represented as follows

$$cp_h = 1 - (1 - p_h\tau_h)^{n_h - 1}(1 - p_l\tau_l)^{n_l}(1 - p_b\tau_b)^{n_b} \tag{4.2}$$

$$cp_l = 1 - (1 - p_h\tau_h)^{n_h}(1 - p_l\tau_l)^{n_l - 1}(1 - p_b\tau_b)^{n_b} \tag{4.3}$$

$$cp_b = 1 - (1 - p_h\tau_h)^{n_h}(1 - p_l\tau_l)^{n_l}(1 - p_b\tau_b)^{n_b - 1} \tag{4.4}$$

With known values of n_h, n_l, n_b, p_h, p_l and p_b the equations are jointly solved to obtain the values for $\tau_h, \tau_l, \tau_b, cp_h, cp_l$ and cp_b. For a basic IEEE 802.11 MAC access mechanism, the transmission probability is expressed as [2][**?**],

$$P_{tr} = 1 - (1 - \tau)^n \tag{4.5}$$

Since we have defined three classes of traffic with different data rates and QoS requirements, the above equation is written as

$$P_{tr} = 1 - (1 - p_h\tau_h)^{n_h}(1 - p_l\tau_l)^{n_l}(1 - p_b\tau_b)^{n_b} \tag{4.6}$$

The probability of successful transmission, i.e at least one station transmits a packet successfully is,

$$\begin{aligned} P_s = {} & n_h p_h \tau_h (1 - p_h\tau_h)^{n_h - 1}(1 - p_l\tau_l)^{n_l}(1 - p_b\tau_b)^{n_b} \\ & + n_l p_l \tau_l (1 - p_h\tau_h)^{n_h}(1 - p_l\tau_l)^{n_l - 1}(1 - p_b\tau_b)^{n_b} \\ & + n_b p_b \tau_b (1 - p_h\tau_h)^{n_h - 1}(1 - p_l\tau_l)^{n_l}(1 - p_b\tau_b)^{n_b} \end{aligned} \tag{4.7}$$

The normalized throughput S (the fraction of channel holding time) is defined as [2]

$$S = \frac{P_s P_{tr} E[p]}{(1 - P_{tr})\sigma + P_{tr} P_s T_s + P_{tr}(1 - P_s) T_c} \tag{4.8}$$

$E[p]$ is the average packet payload size, σ is the length of an empty time slot, T_s and T_c are the average time the channel is sensed busy due to successful transmission and collision

Parameters	Value
Nodes	20
E[p]	512 bytes
SIFS Duration	10μs
DIFS Duration	50μs
Propagation Delay	5μs
Length of an empty time slot (σ)	50μs
Simulation time	200 sec
T_s	86.96μs
T_c	5.04μs

Table 5. Simulation parameters used in the experiments.

Number of nodes	Analysis	Simulation
20	3110	3104
30	4583	5358
40	4613	5788
50	5084	5443
60	3376	3155

Table 6. Comparison of analysis and simulation results.

respectively. The value of T_s and T_c are expressed as

$$T_s = RTS + SIFS + \delta + H + E[p] + \delta + DIFS \tag{4.9}$$

$$T_c = 2 * R_t + RTS + \delta + DIFS \tag{4.10}$$

R_t is the refresh time to invalidate the request.

Let us assume that the value for p_h is 0.8, p_l 0.2 and p_b 0. After substituting the values from Table 5, the values obtained for throughput differentiation between two sources using analysis and simulation are tabulated in Table 6.

2. Network Simulator

The Network Simulator(NS) [19] is a discrete event simulator and provides support for transport, routing and multicast protocol over wired and wireless networks. A scenario file, connection file and node-configuration(that specifies the routing, MAC protocol and other properties of the node) are fed to simulator which produces a trace file. A scenario file describes the initial node placement and node mobility for every node throughout the simulation. A connection pattern file specifies various application agents and how the data transfers to be performed. All the nodes in the simulation are assumed to be running the same routing and MAC protocols.

The architecture of NS with the QoS components are shown in fig 4.1. Each node runs the network stack organized as Transport Layer, Routing Layer, Link Layer and Physical Layer.

In this research work, Constant-Bit-Rate(CBR) agent is used to generate the traffic at the multicast sources. UDP null agents are set up at all the multicast receiver nodes. At the routing layer Mobile Ad hoc Distance vector (MAODV) routing protocol is used to create a multicast tree. The detailed operations and implementations are explained in the MAODV Internet draft [20]. QoS Marker is added to the NS simulator to intercept all the outgoing messages and to initialize the QoS header. The Marker module reads the policy file and initializes the priority index and bandwidth requirements in the packet header. This module is the key to communicate the QoS requirements to the network.

The Link Layer is split up into four subparts. MAC Module, ARP module, Multi-Level Network Interface Queue and a QoS scheduler. The MAC module is an implementation of IEEE 802.11 with the modifications to medium access mechanism. The multi-level network queue is a drop-tail FIFO queue holding the packets to be transmitted. The Interface queue is divided into four sub-queues with different priority levels. The sub-queues are indexed based on the priority levels. Network control messages(Routing) are stored in sub-queue 0 and is given highest priority compared to all other classes of traffic. sub-queue 1 is given

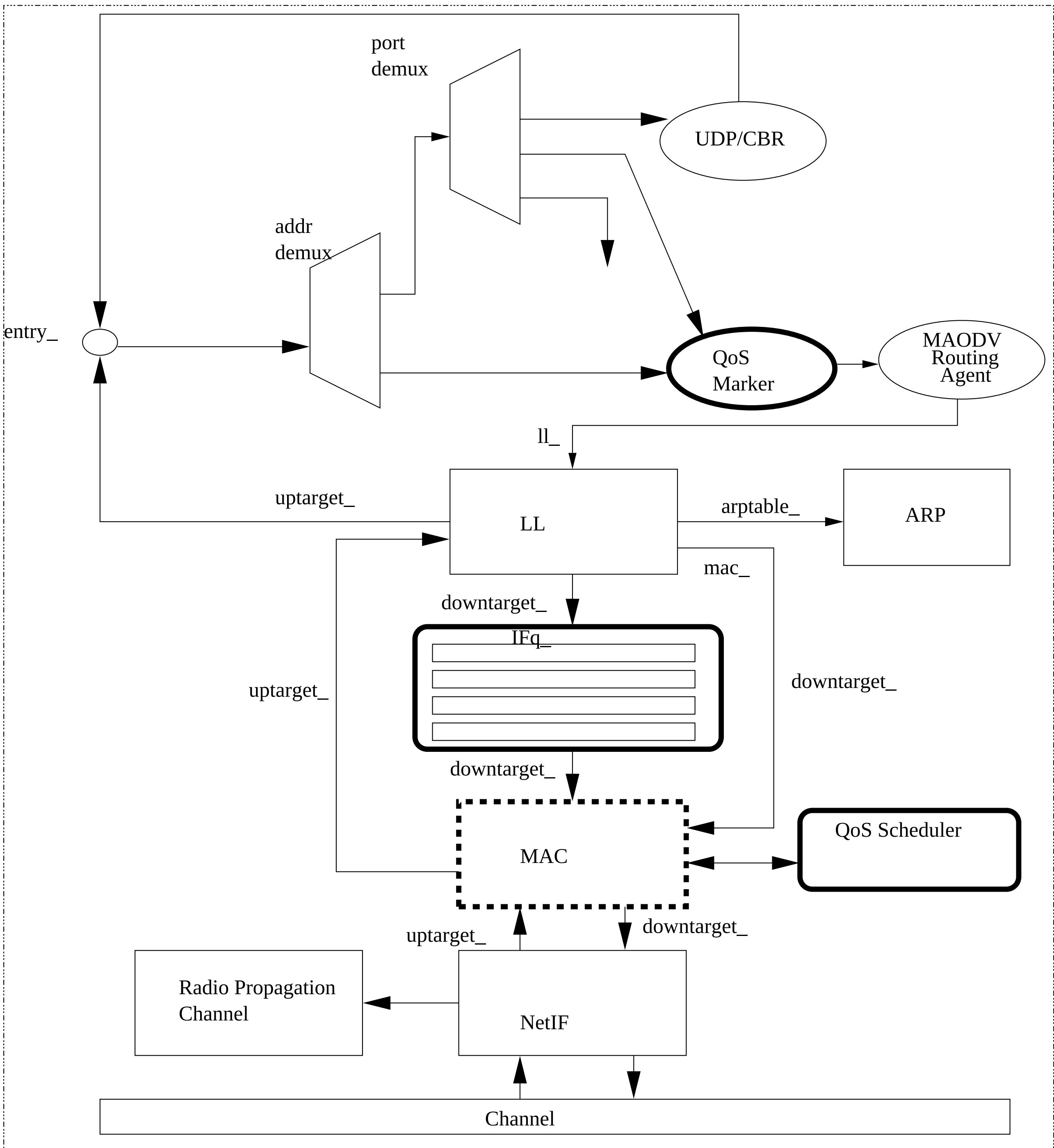

Figure 10. Network Simulator with QoS Components added (QoS Scheduler, QoS Marker and Classifier). The MAC protocol is also changed to provide differential services.

next highest priority and is used to hold the packets belonging to the higher priority traffic. sub-queue 2 holds the packets belonging to the lower-priority class and sub-queue 3 is used to hold the best-effort traffic(unmarked packets). The interface queue implements the insertion and deletion operations on the queue and both Routing and Link layer have full access to these queue operations. The interface queue also provides a helper routine which returns the next highest priority index of the packet to be transmitted by the node. This routine is used by the MAC layer to piggyback the information with the current packet. The QoS scheduler is responsible for sniffing all the messages before it is filtered by the MAC module. The priority information is retrieved from the sniffed packet at all the neighbor nodes to construct the local schedule table. The table is examined by the MAC module before accessing the medium and the entry in the schedule table acts as reservation state for the neighbor nodes in the local node.

3. Experimental Input and Output

The Simulator takes three inputs; a scenario file, a connection pattern and a node configuration file, which specifies the choice of physical, MAC, Routing layer attributes for every node. Four sets of experiments were conducted by varying the mobility, pause time, number of nodes and the number of flows in a network. The scenario files are generated using the "*setdest*" program [19]. The program takes the number of nodes, simulation time, dimensions of network(topology), speed of the nodes and the pause time as inputs and generate the scenario file that specify how the nodes move about. Each node is associated with the position and moves with the specified speed until it reaches the destination. The scenario file also contains the random node movement instructions for all the nodes used in the simulation.

The connection pattern file contains the various applications agents and initiates the data transfer at the specified time. The file also initiates multicast "*join*" and "*leave*" operations for the nodes.

The output of the simulator is a trace file. The trace file contains all the information for a packet at every layer. The trace file identifies each packet by a unique sequence number and is interpreted by another program to get the performance metrics of interest.

4. Evaluation

In this section we evaluate the performance of the QoS framework through simulations. The objectives of the simulations are:

- To show the correctness of the simulator. To ensure the correctness of the simulator, the framework was tested with small a topology of three nodes with little mobility. Extensive logging is used to verify the behavior of the system with the theoretical behavior.
- To show that if two users have different Quality Of Service requirements they should receive different treatment otherwise they should receive the same treatment.
- To show that the framework is suitable for the multicast flows in mobile ad hoc networks. The experiments were conducted with varying number of multicast nodes and varying mobility, to demonstrate that the framework handles mobility and collision correctly.

The performance of the framework is compared against that of a best-effort service and the framework which uses unicast at every hop instead of simple broadcast at the intermediate nodes to forward the packets.

4.1. Simulation Environment. The simulator uses a mobile node which has a transmission range of 250 m, bandwidth of 2 Mbps and has a Shared-Media interface with parameters to make it work like the 914MHz Lucent WaveLAN DSSS radio interface. Experiments 1-3 use 20 mobile nodes whereas experiment 4 uses mobile nodes varying from 20 to 70 nodes. The mobility model is based on random movements of the nodes.

4.2. Experiment 1. The objective of this experiment is to show the throughput service differentiation and the average delay a packet experiences for two senders with different priorities. This experiment uses 20 mobile nodes, with 12 multicast group members and two source nodes.

In this experiment X-axis represents pause time. Pause time controls the rate of mobility [19]. The node starts at the initial position specified by the node, pauses for the specified amount of time, randomly choses a new position and travel towards the new destination at a speed of 1 m/s. Figure 11 shows average delay for the packets using the QoS framework originating from higher priority source and lower priority source. Figure 12 shows the average delay for the packets using the best-effort framework and Figure 13 shows the average delay for the packets using the multicast protocols which uses multiple unicasts at the router. The scenario files were created by using the following steps.

- Fix a Pause time P
- Generate 20 scenario files for a given P. The scenario files are generated for the same speed but the positions of the nodes are varied.

The two sources were randomly selected to generate CBR traffic. From Figure 11 and 13 it is clear that packets of higher priority experiences lower delays compared to the lower priority source while in best-effort service, both nodes experience random delays and in some cases for instance at pause time 5-14 and 39-40 higher priority source experience higher delays compared to the lower priority source.Note that the delay is measured as $\frac{\sum_{j=1}^{j=m} \frac{\sum_{i=1}^{i=n} d_{ij}}{N}}{m}$, average of delays for all the packet for all receivers by number of successful transmissions. Note that the delays are measured only for the packets that are successfully transmitted. In the case of best-effort service, the throughput and the multicast reliability ratio, which is defined as the number of multicast nodes that received the packet to the actual number of receivers are significantly low compared to the proposed framework.

In this experiments, it is clear from the graphs that the proposed framework with a simple broadcast performed better than the framework with multiple unicasts and best-effort service. The graphs also shows the correctness of the implementation in allocating the bandwidth to the competing flows based on the pre-defined priorities. The average throughput for a higher priority source in the proposed framework (Figure 14) is twice the average thought the higher priority source experiences with the best-effort service (Figure 15). The average throughput gain for a higher priority source is not significantly when compared to the framework with multiple unicasts (Figure 16), this is mostly because of the lower load and limited mobility.

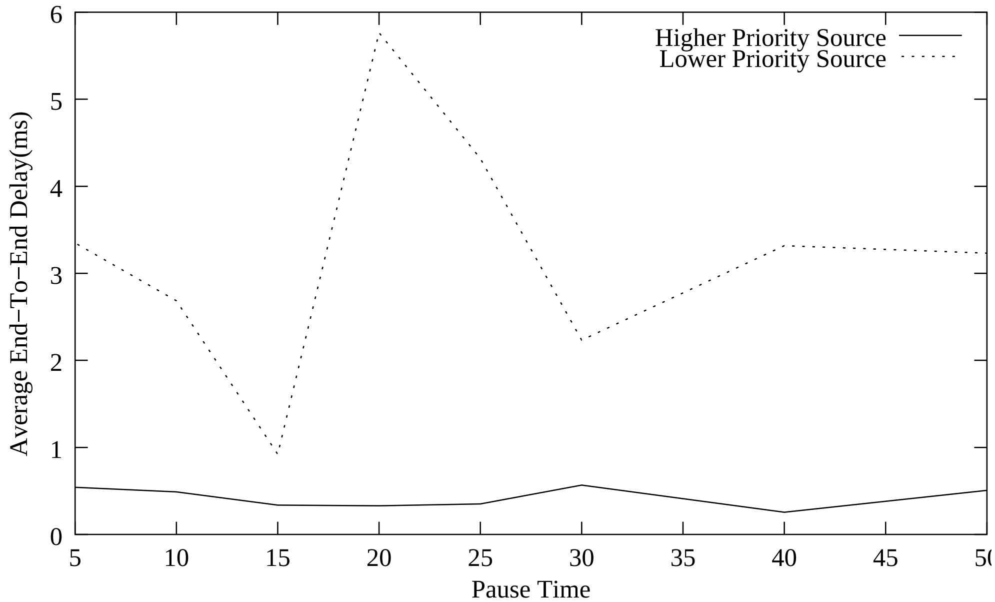

Figure 11. Average Delay For Two sources- QoS Framework

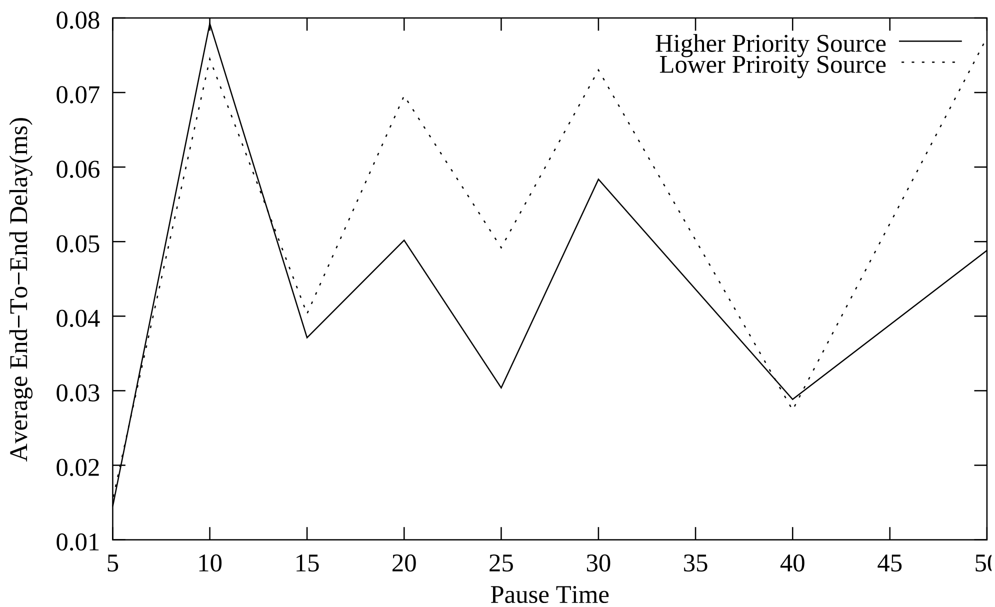

Figure 12. Average Delay For Two sources - Best-Effort Service

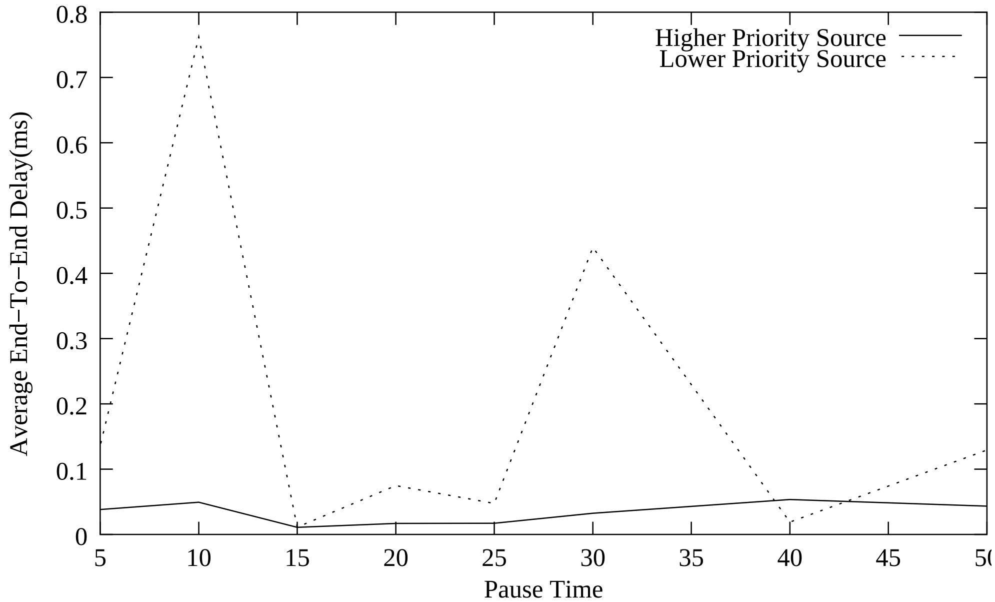

Figure 13. Average Delay For Two sources -QoS Framework (Unicast

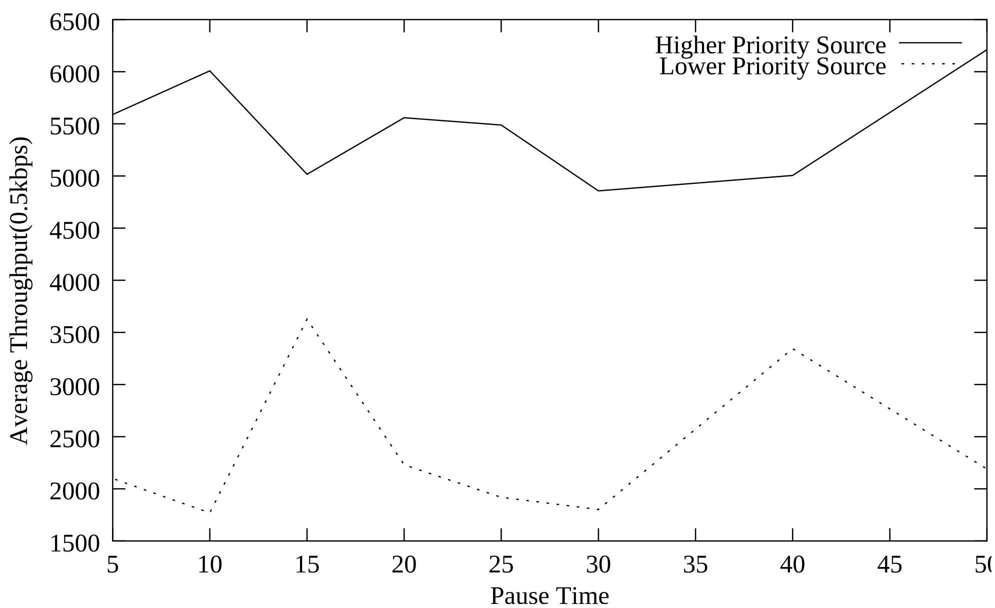

Figure 14. Throughput For Two sources -QoS

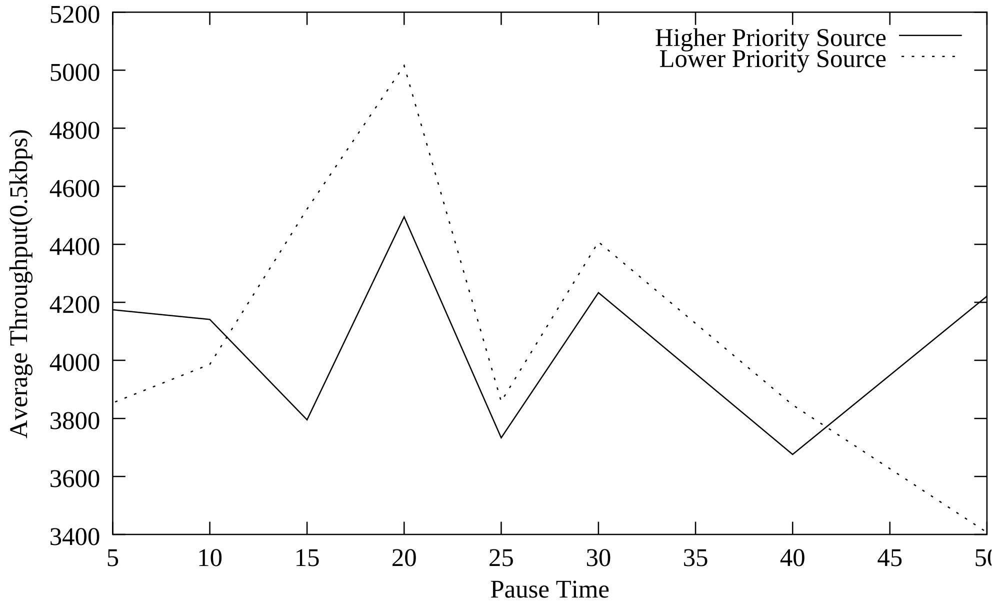

Figure 15. Throughput For Two sources -Best-Effort

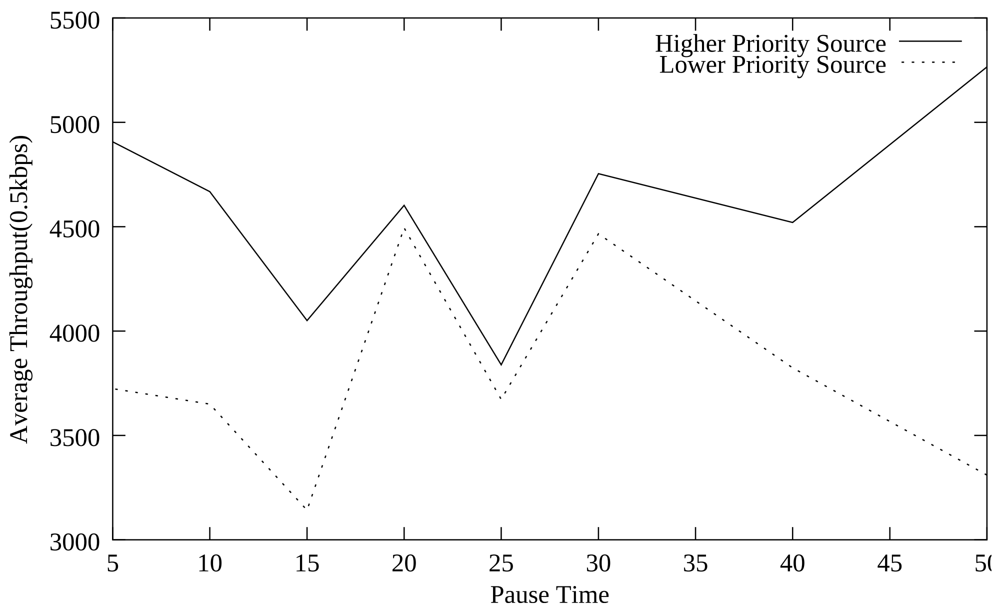

Figure 16. Throughput For Three sources -QoS (Unicast)

4.3. Experiment 2. The objective of this experiment is to show that if two users have similar Quality Of Service requirements they should receive the same treatment and to demonstrate that the proposed framework performs a better in terms of efficient utilization of bandwidth compared to the framework with multiple unicast. One of the main motivation for the research work is to demonstrate the effective use of simple broadcast medium to increase the multicast bandwidth gain. This experiment demonstrates the throughput gain obtained by the framework and is compared with the multicast protocol which uses multiple unicasts to achieve the same. The throughput service differentiation and the average delay a packet experiences for two senders with similar QoS requirements and another source is randomly selected with a lower priority. This experiment uses same scenario files and connection files that are used in the experiment 1, except another high priority CBR traffic agent is added to the connection file.

The difference in the implementation of the proposed framework and the framework which uses multiple unicasts are

- The multicast protocol performs replication of the packet at the network layer, if there are more than one downstream node.
- The MAC Layer doesn't use RTS/CTS mechanism and ACK mechanism and the MAC layer performs an additional check on the IP address and for a mul;ticast address packet, it simply broadcasts the packet.

Figure 17 shows average delay for the packets using the QoS framework originating from two higher priority sources and a lower priority source. Figure 18 shows the average delay for the packets using the best-effort framework and Figure 19 shows the average delay for the packets using the multicast protocols which uses multiple unicasts at the router. From Figure 17 and 19, it can be seen that higher priority packets experiences lower delays compared to the lower priority source. Keep in mind the delays are drawn with respect to the multicast reliability ratio and throughput. Figures 20, 21 and 22 show the throughput for the flows originating from all three sources. The proposed framework performs better than best-effort and also provides higher bandwidth utilization compared to the multiple unicast framework. This shows that a simple broadcast at every intermediate hop is better than multiple unicasts at a hop. From the graph it is also evident that the bandwidth is allocated to the lower priority source only when there is no transmissions are pending for higher priority source. From the figure 20 it can be seen that the packets originating from the higher priority sources receives the same treatment. While the lower priority source receives a degraded service.

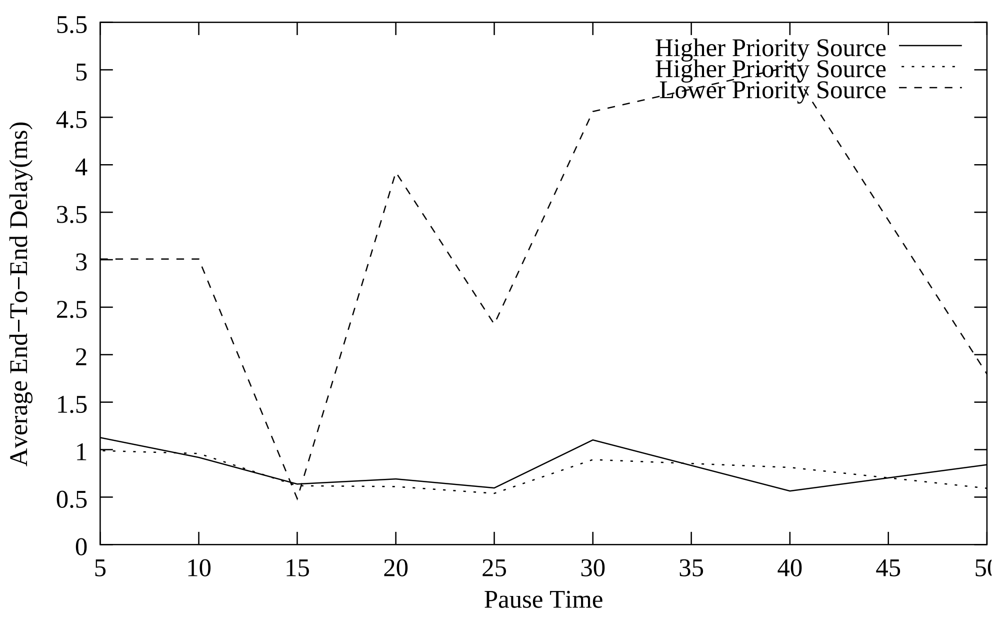

Figure 17. Average Delay For Three sources- QoS Framework

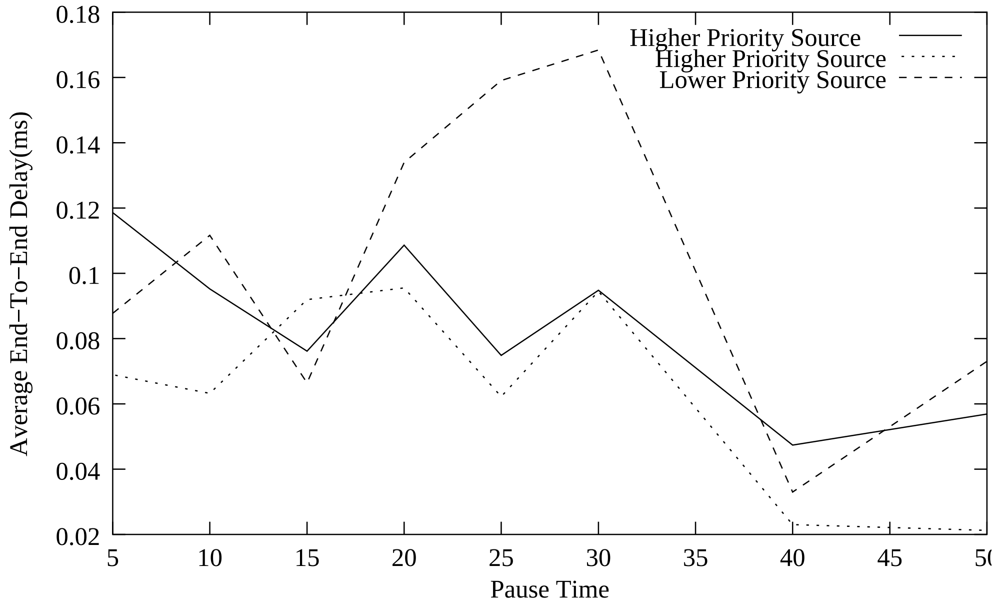

Figure 18. Average Delay For Three sources - Best-Effort Framework

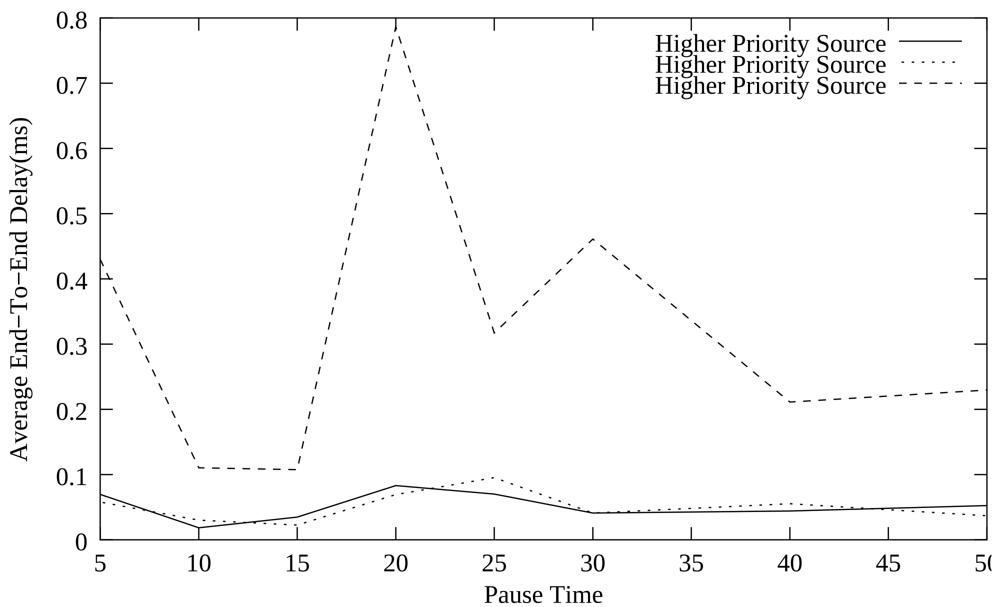

Figure 19. Average Delay For Three sources -QoS Framework (Unicast)

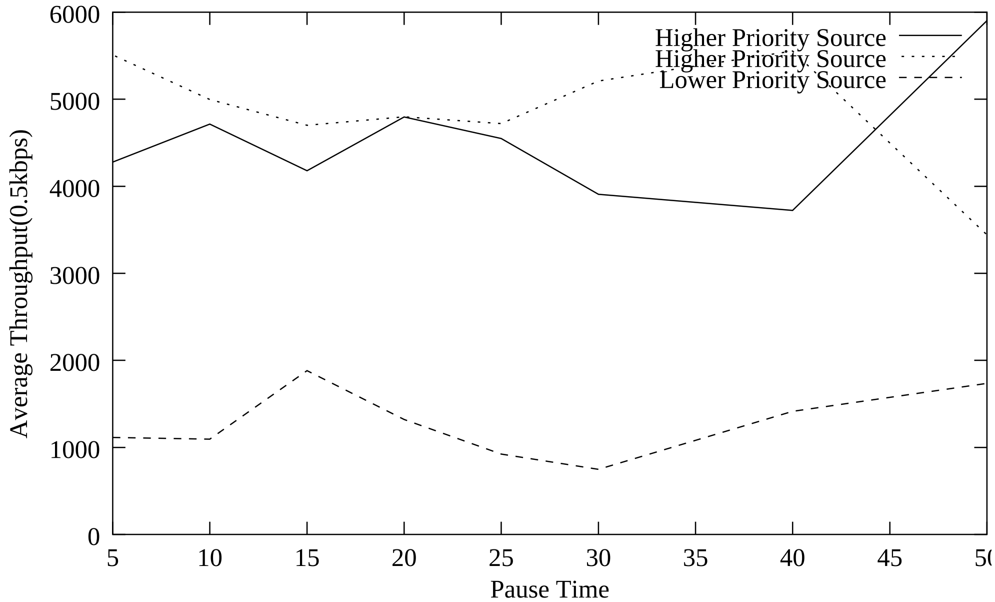

Figure 20. Throughput For Three sources -QoS

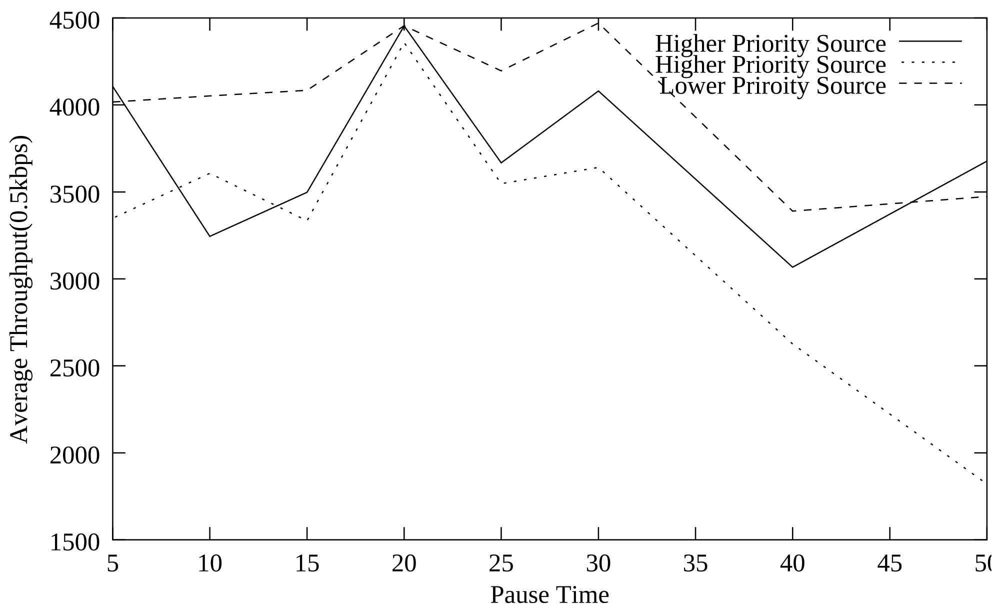

Figure 21. Throughput For Three sources - Best-Effort

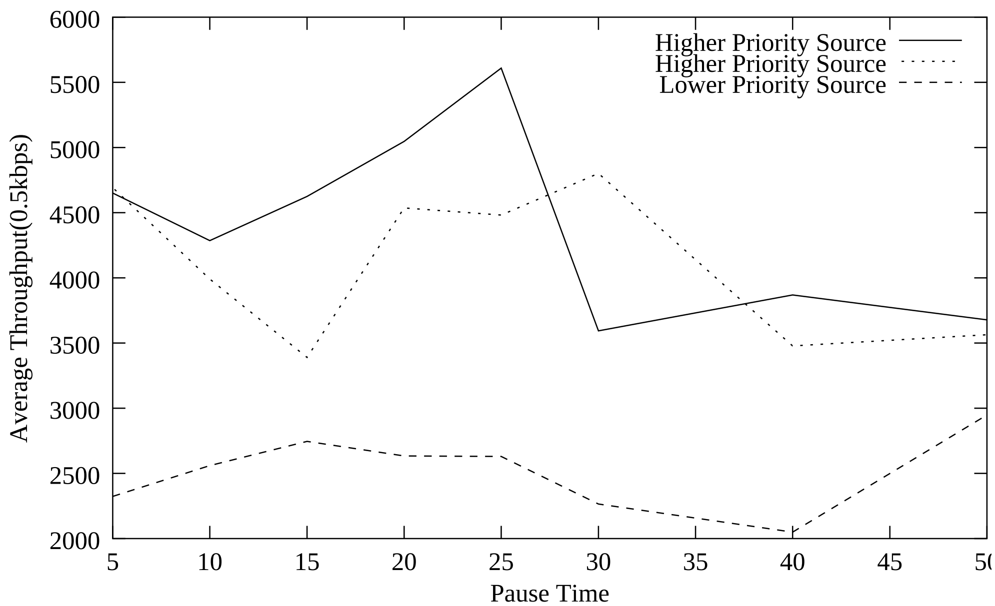

Figure 22. Throughput For Three sources - QoS(Unicast)

4.4. Experiment 3. The objective of the experiment is to study the effects of mobility and to validate the soft-state mechanism (see chapter 3 section 5) implemented in the framework. the timeout value for the soft-state is chosen as $2 \times MAODVREFRESH\text{-}MESSAGERATE$[20]. The reason for the time out value is, if a packet is not sent by a node which, made the reservation for this timeout value then the node must have either moved out of the transmission range or left the multicast session. The objective is to show that the framework adapts to the higher nodal mobility, removes the invalid reservations and still is able to provide the differential services. Since the invalidation is performed is based on the time-out value without the use of any additional control commands, the framework does not use any additional bandwidth. The throughput service differentiation and the average delay a packet experiences for two senders with similar QoS requirements and an other source is randomly selected with a lower priority. This experiment uses scenario files generated with the speed varying from 0 to 30 meters/sec with different pause times.

Figure 23 shows average delay for the packets using the QoS framework originating from two higher priority sources and a lower priority source. Figure 24 shows the average delay for the packets using the best-effort framework and Figure 25 shows the average delay for the packets using the multicast protocol which uses multiple unicasts at the router. From Figure 23 and 25 it can be seen that higher priority packets experience lower delays compared to the lower priority source. Figure 26,27 and 28 show the throughput for the flows originating from all three sources. Proposed framework performs better than best-effort and also provides higher bandwidth utilization compared to the multiple unicast framework. From the graphs it can be seen that the framework allocates the bandwidth correctly. If a node makes a reservation and leaves the transmission range then two scenarios are possible. If another equal priority node wants to transmit it can still transmit because the traffic belongs to the same class and hence there is no wastage of the bandwidth, however if the lower priority node wants to transmit; it will wait for time-out value to invalidate the reservation and then resume the transmission. For a moderate mobile environment where the probability of both the lower and higher priority nodes moving at the same time to the same transmission range is very less and in these cases the drop in bandwidth utilization is acceptable and as can be seen from the graph there is no bandwidth utilization drop compared to experiments 1 and 2. Note that there is a throughput drop with the increased drop in all the 3 cases and is significantly high in the case of best-effort and slightly high in the case of multicast protocol with multiple unicasts, this is due to the increased channel holding time due to RTS/CTS exchanges.

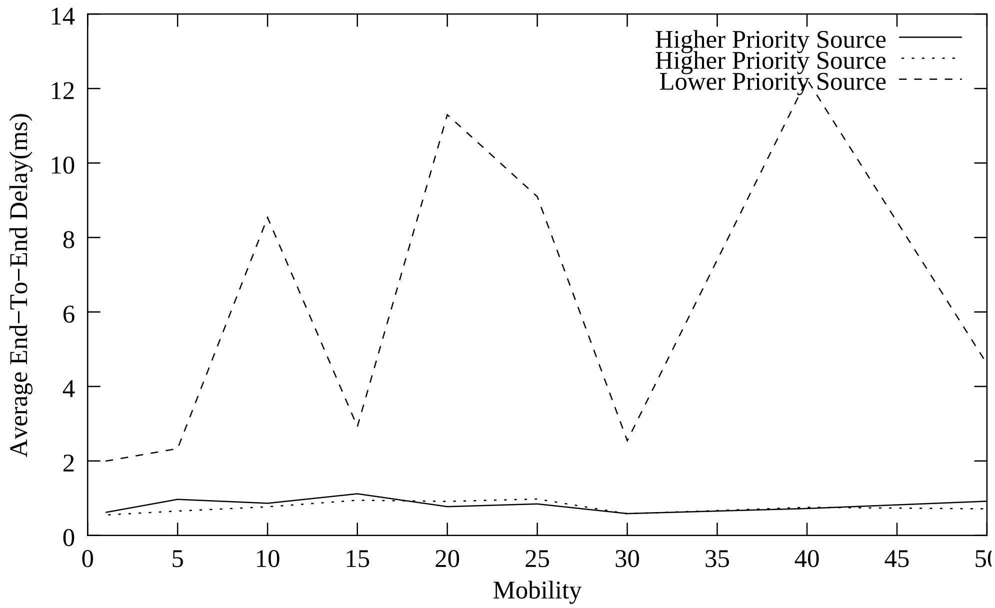

Figure 23. Average Delay With Varying Mobility - QoS Framework

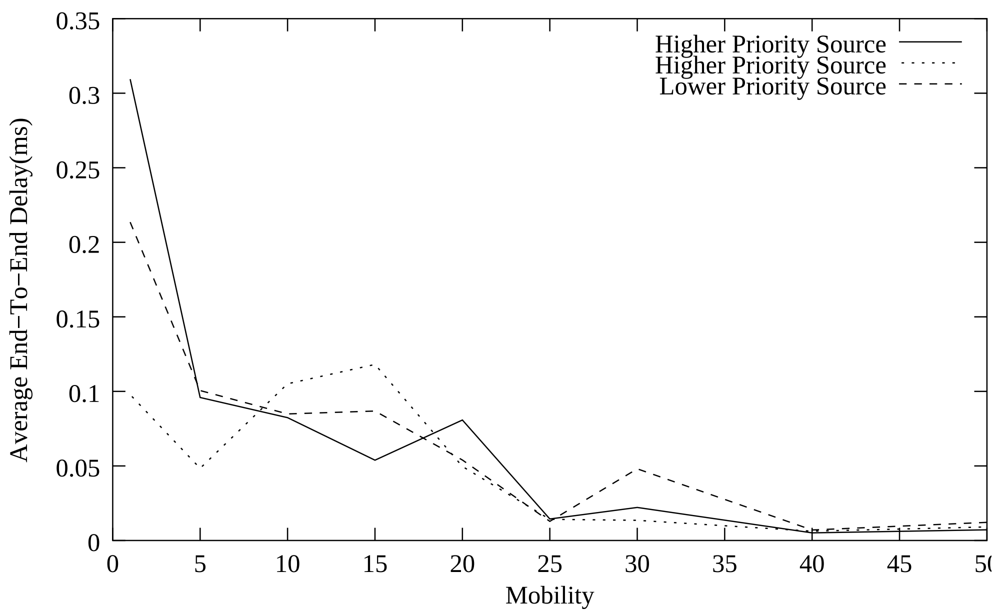

Figure 24. Average Delay With Varying Mobility - Best-Effort Service

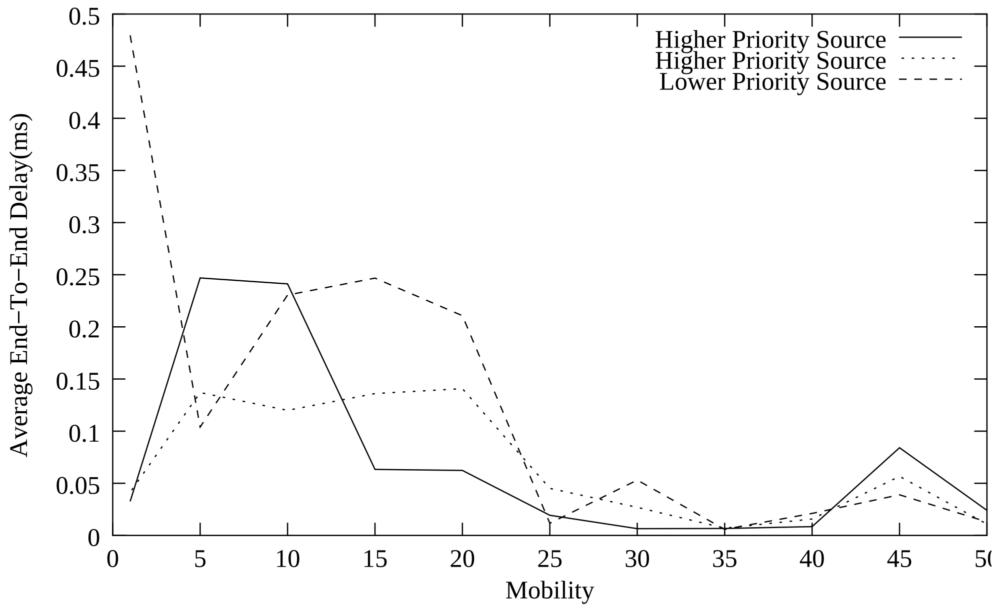

Figure 25. Average Delay With Varying Mobility - QoS Framework (Unicast)

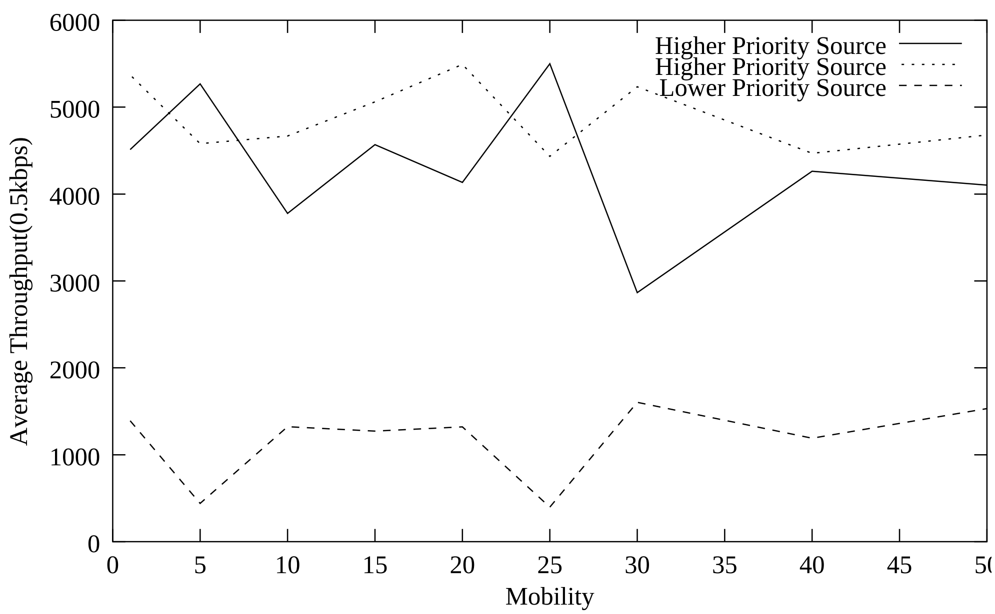

Figure 26. Throughput For Three sources with varying mobility -QoS

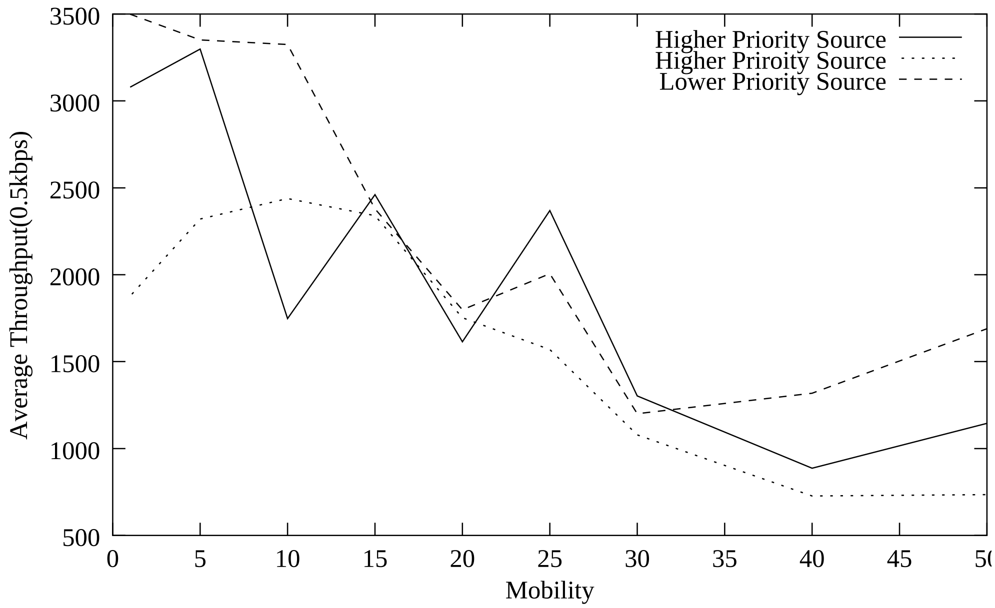

Figure 27. Throughput For Three Sources With varying mobility - Best-Effort

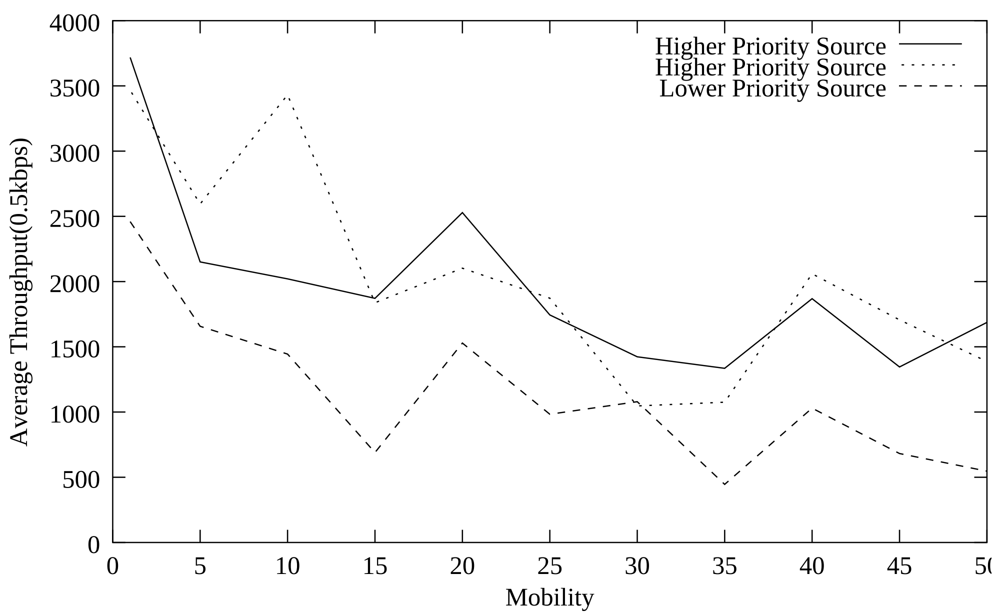

Figure 28. Throughput For Three Sources with varying mobility - QoS(Unicast)

4.5. Experiment 4. The objective of this experiment is to study the performance of the framework for a dense multicast group. In this experiment the number of nodes are increased from 20 to 70. The throughput service differentiation and the average delay a packet experiences for two senders with similar QoS requirements and another source is randomly selected with a lower priority. This experiment uses a scenario files generated with the number of nodes varying from 20 to 70, pause time varying from 5 to 15 and a speed of 1 meters/sec.

Figure 29 shows average delay for the packets using the QoS framework originating from two higher priority sources and a lower priority source. Figure 30 shows the average delay for the packets using the best-effort framework and Figure 31 shows the average delay for the packets using the multicast protocol which uses multiple unicast at the router. From Figure 29 and 31 it can be seen that higher priority packets experiences lower delays compared to the lower priority source. Figures 32,33 and 34 show the throughput for the flows originating from all three sources. Proposed framework performs better than best-effort and also provides correct throughput service differentiation compared to best-effort and multiple unicast framework. From the graphs it can be seen that the framework allocates the bandwidth correctly, however the packets experience higher delays compared to the best-effort, this is because the average throughput in case of proposed framework average throughput is almost twice that provided by the best-effort and also because of the collision and mobility, there are situations where the bandwidth remains unused. However the framework does a better job in ensuring the allocation of bandwidth based on the QoS requirements and the experimental data also shows the increased packet delivery ratio(Number of actual receivers received the packet / Number of actual receivers)for higher priority sources.

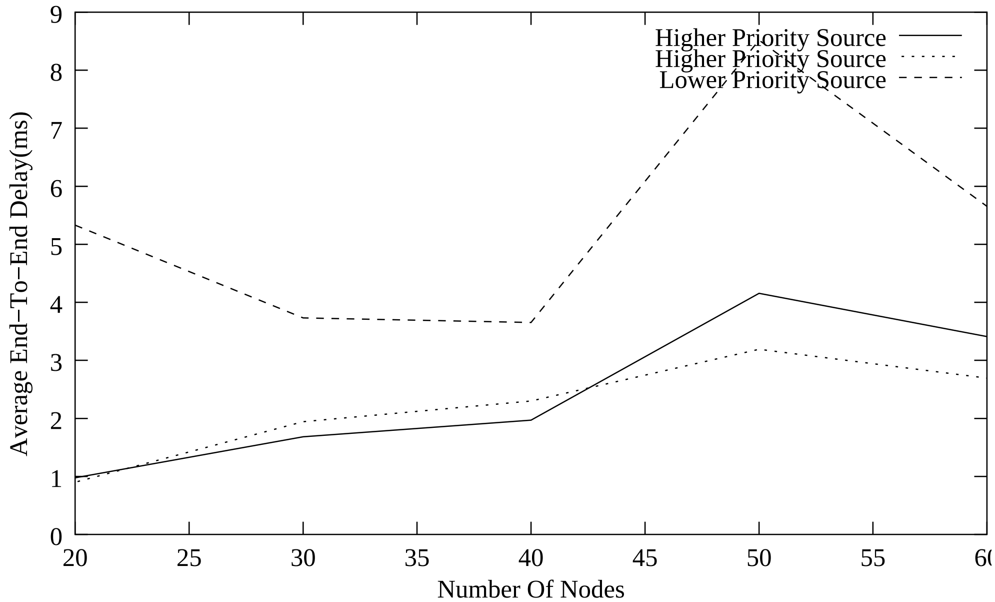

Figure 29. Average Delay With Varying Nodes-QoS Framework

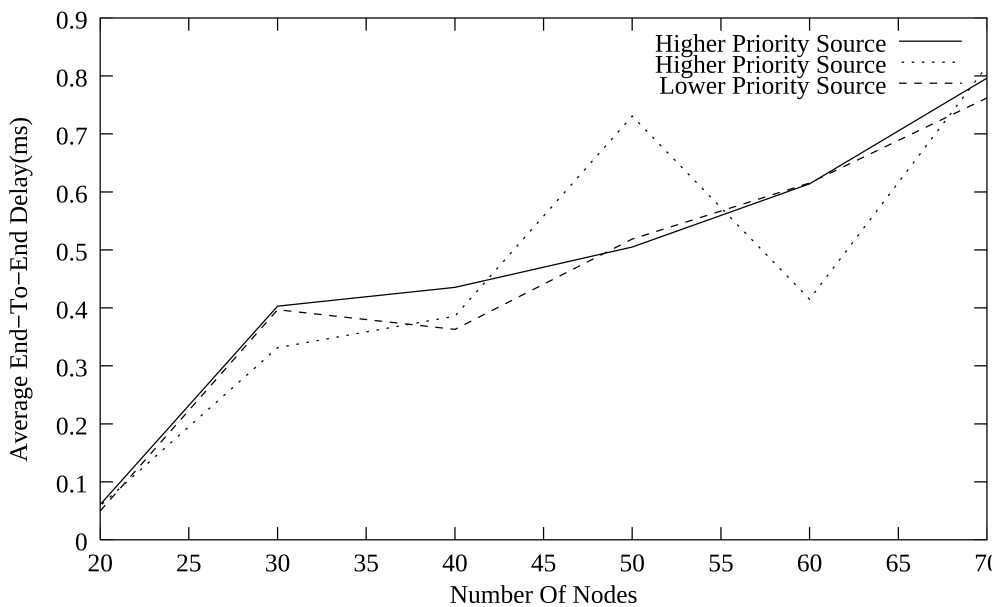

Figure 30. Average Delay With Varying Nodes-Best-Effort

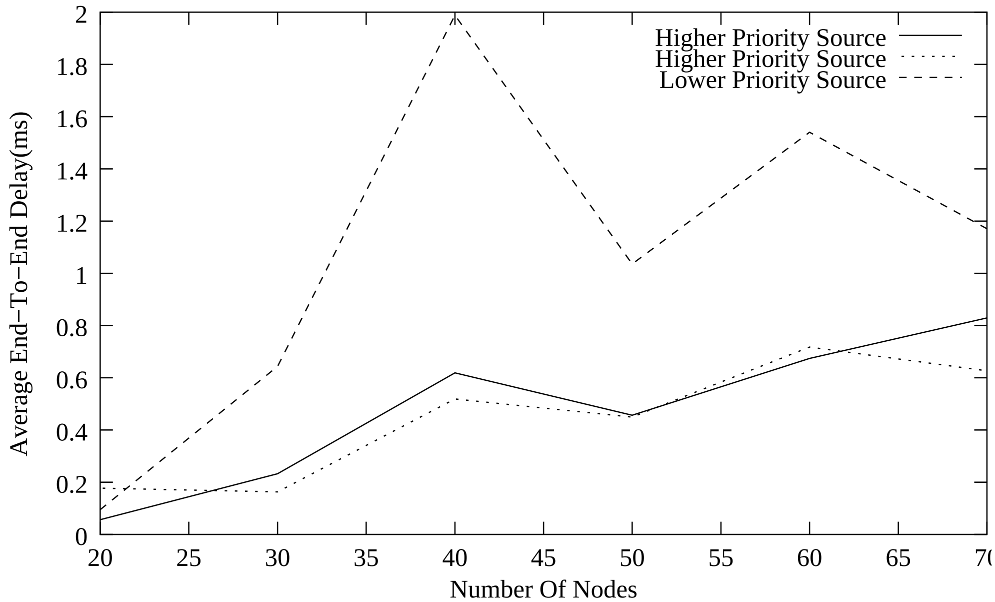

Figure 31. Average Delay With Varying Nodes - QoS Framework(Unicast)

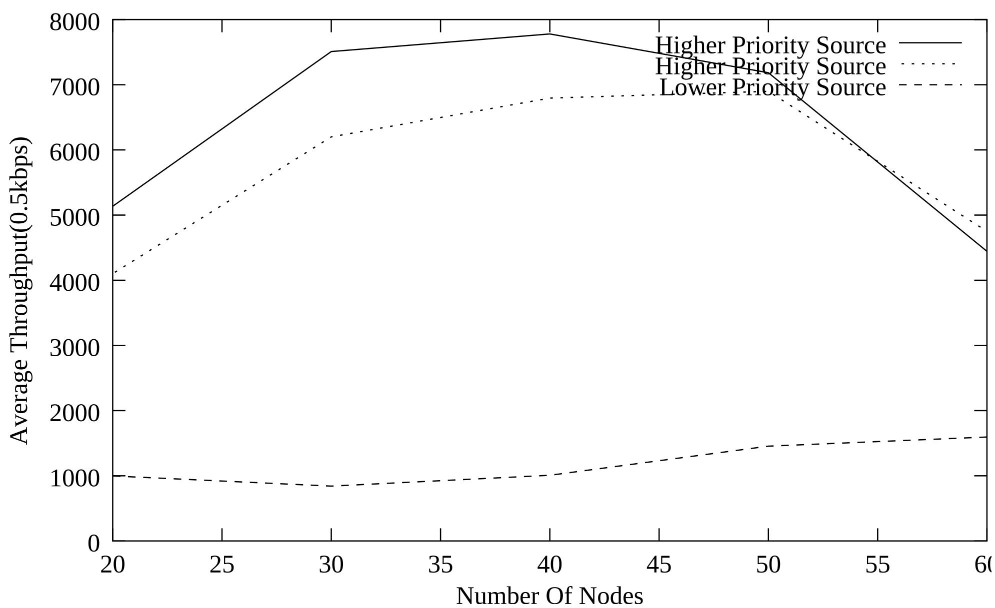

Figure 32. Throughput For Three sources with varying number of nodes - QoS

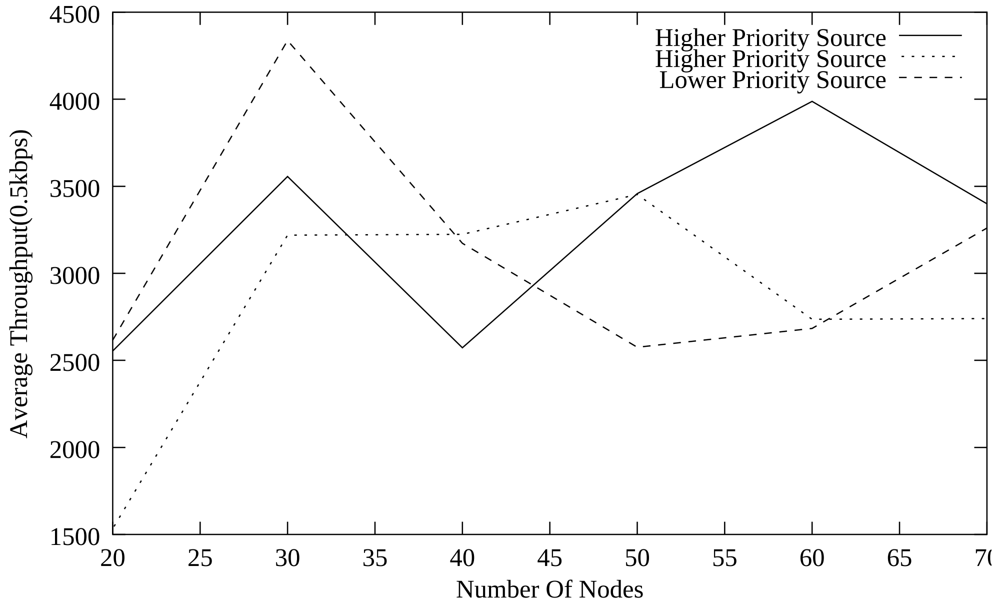

Figure 33. Throughput For Three sources with varying number of nodes - Best-Effort

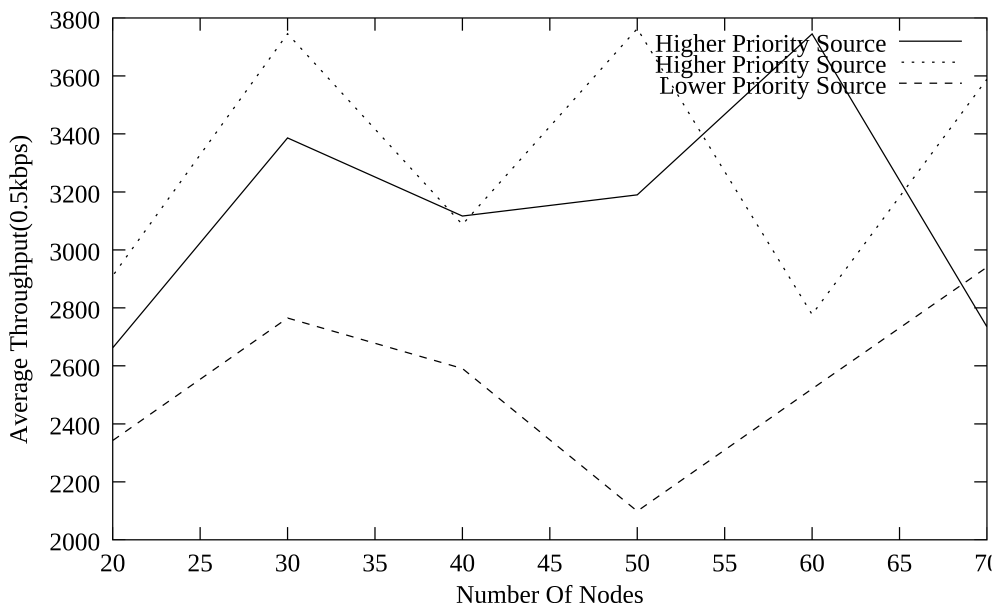

Figure 34. Throughput For Three sources with varying number of nodes - QoS(Unicast)

CHAPTER 5

CONCLUSIONS AND FUTURE-WORK

1. Conclusions

Majority of applications in Mobile ad hoc networks are in the areas where rapid deployment and dynamic re-configurations are necessary. These applications(Virtual Conference Room, Class Rooms ..etc) typically involve group of people collaborating for a task requiring dynamic sharing of information among multiple recipients. These applications also require QoS scheduling to work correctly. In this research work a dynamic distributed scheduler has been developed for a mobile node. The MAC scheduler has been developed to provide service differentiation among multiple multicast senders and it exploits the broadcast nature of the wireless medium to construct a prioritized schedule. The scheduler does not use any additional control messages to reserve the resources(bandwidth). The bandwidth sharing is controlled by using the local schedule table. A Two-level service differentiation is used, one at the network interface queue to provide service differentiation among multiple flows originating at the node, and the second one at a transmission range level to provide prioritized bandwidth sharing among all the nodes in the same transmission range. The comparative study of this framework is done with frameworks that use best-effort and unicast mechanism to achieve the same. The parameters used for comparison were rate of mobility, speed of the node and by varying the number of nodes in a multicast session. The framework correctly allocates the bandwidth to different flows based on the priorities and provides higher throughput and lower delays to the high priority sources. The framework also adapts to the varying mobility and error conditions.

2. Future Work

The experimental results indicate that the scheduler works as expected, the scheduler achieved a better performance in throughput,end-to-end delay and service differentiation. The results are very encouraging in the sense that more sophisticated versions of the MAC algorithms may be able to improve upon the performance. In the current design of the scheduler, MAC protocol is assumed to be reliable, future implementations of the MAC scheduler should design a reliable MAC multicast protocol. The combination of the reliable MAC multicast protocol and the scheduler could be the next step in designing a more robust QoS framework.

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APPENDIX A

ALGORITHMS AND SCRIPTS

Algorithm 2: Insert Algorithm

```
switch Traffic do
    case Routing Protocol
        Set Queue Type To Routing Queue
    case Data Packets
        switch Examine Priority do
            case HIGH
                Set Queue Type To HIGH-PRIORITY
            case LOW
                Set Queue Type To LOW-PRIORITY
            case DEFAULT
                Set Queue Type To BEST-EFFORT
        end
end
if Interface Queue q is Full then
    drop the packet
    return
else
    Insert the Packet
end
```

Algorithm 3: Remove Algorithm

```
for (q = 0; q <= IFQ_MAX; q++) do
    if queue q has a packet to transmit then
        set Queue Type to q
        break
end
Packet P=Remove(q)
UpdateQueueDelay()
Return Packet P
```

1. Network Simulator Installation and Senario Generation

1.1. Installation of Network Simulator. To install NS follow the steps outlined below

- Download NS Source code from http://www.isi.edu/nsnam/ns/ns-build.html
- Run the Install script
- Add the following environment variables to the progile file of your shell
  1. export LD_LIBRARY_PATH=NS/ns-allinone-2.1b8a/otcl-1.0a7:NS/ns-allinone-2.1b8a/lib
  2. export TCL_LIBRARY=NS/ns-allinone-2.1b8a/tcl8.3.2/library
- Run the Validate script to make sure that all the modules are installed correctly.

1.2. Scenario Generatio. In this research work, NS scenario generator program setdest is used to create random scenarios. To generate the scenarios go to NS/ns-allinone-2.1b8a/ns-2.1b8a/indep-utils/cmu-scen-gen/setdest/ directory and modify the make-scen.csh file to vary the parameters of your choice. The setdest program takes the following parameters to create the scenario

setdest $-n < nodes > -p < pausetime > -s < maxspeed > -t < simulationtime > -x < maxX > -y < maxY >$

Nodes: Number of nodes used for simulation

Pause Time: Rate of Mobility

Max Speed: Speed at which the node travels

Simulation Time: total Simulation time

2. Network Simulator Script

```
SET OPT(STOP) 200

SET TRAFFIC          CBR
SET XX               800
SET YY               800


### READ COMMAND LINE ARGUMENTS
IF {$ARGC > 1} {
   SET SPEED  [LINDEX $ARGV 0]
   SET MOB [LINDEX $ARGV 1]
   SET NN  [LINDEX $ARGV 2]
   SET FLOW [LINDEX $ARGV 3]

} ELSE {
   PUTS "USAGE: NS MULTI-AODV-TEST.TCL <SPEED> <MOB> <NUMBER OF
NODEX> <NUMBER OF FLOWS>"
   PUTS ""
   PUTS "<SPEED> IS 5,10,15,20,25,30,40,50"
   PUTS "<MOBILITY> IS 0-20"
   PUTS "<NN> IS 20-70"
   PUTS "<FLOWS> IS 2-16"

   EXIT 1
}


SET NS_ [NEW SIMULATOR]

SET TOPO [NEW TOPOGRAPHY]

$TOPO LOAD_FLATGRID 800 800

SET TRACEFD [OPEN AODV-$NN-$SPEED-$MOB-$FLOW-TEST W]
$NS_ TRACE-ALL $TRACEFD

#UNCOMMENT TWO LINES, TO SEE NAM TRACE FOR THE SIMULATION
#SET NF [OPEN AODV-$NN-$SPEED-$MOB-TEST.NAM W]
#$NS_ NAMTRACE-ALL-WIRELESS $NF 800 800

SET GOD_ [CREATE-GOD $NN]
```

Figure 35. Network Simulator Script

```
$NS_ NODE-CONFIG -ADHOCROUTING AODV \
                                        -LLTYPE LL \
                                        -MACTYPE MAC/802_11 \
                                        -IFQLEN 50 \
                                        -IFQTYPE PRIQUEUE \
                                        -ANTTYPE ANTENNA/OMNIANTENNA \
                                        -PROPTYPE PROPAGATION/TWORAYGROUND
\
                                        -PHYTYPE PHY/WIRELESSPHY \
                                        -CHANNEL [NEW
CHANNEL/WIRELESSCHANNEL] \
                                        -TOPOINSTANCE $TOPO \
                                        -AGENTTRACE ON \
                                        -ROUTERTRACE ON \
                                        -MACTRACE OFF \
                                        -MOVEMENTTRACE OFF

FOR {SET I 0} {$I < $NN} {INCR I} {
             SET NODE_($I) [$NS_ NODE]
             $NODE_($I) RANDOM-MOTION 0;

}

PUTS "LOADING CONNECTION PATTERN ..."
SOURCE "$TRAFFIC-$FLOW-TEST"

PUTS "LOADING SCENARIOS FILE..."
SOURCE "./SCEN/SCEN-800X800-$NN-$MOB-$MOB-$MOB"

FOR {SET I 0} {$I < $NN} {INCR I} {
             $NS_ AT $OPT(STOP) "$NODE_($I) RESET";
}

#UNCOMMENT TWO LINES, TO SET THE INITIAL POSITION OF THE NODES
#FOR {SET I 0} {$I < $NN} {INCR I} {
     $NS_ INITIAL_NODE_POS $NODE_($I) 20
#}

$NS_ AT $OPT(STOP) "PUTS \"NS EXISTING...\"; $NS_ HALT"
PUTS "STARTING SIMULATION ..."
$NS_ RUN
```

Figure 36.