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QUALITY OF SERVICE IN AD HOC NETWORKS

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Summary

With the onset of multimedia applications, Quality of Service (QoS) in 802.11-based wireless ad hoc networks has been an essential area to look into. Standard wireless protocols such as IEEE 802.11b and IEEE 802.11e have been deemed unsuitable for multimedia traffic transmission in an ad hoc (multihop) network environment due to the unique network characteristics. As an ad hoc network is infrastructureless and distributed in nature, it gives rise to several challenges in QoS provisioning. In this thesis, we focus on the research of three key areas on QoS in ad hoc networks namely, buffer management in the medium access control (MAC) layer, cross-layer design and flow admission control.

Firstly, we study MAC layer buffer management in the IEEE 802.11e protocol. The IEEE 802.11e MAC protocol provides QoS for multimedia traffic by probabilistic priority queueing. Ad hoc networks tend to generate a large volume of network control packets for route maintenance and these control packets are typically queued in the highest priority queue. As a result, higher priority control traffic is always being served, consuming most of the bandwidth and results in poor network performance for data traffic. We examine this problem and propose a dynamic buffer management scheme to mitigate it. By setting different threshold levels in different priority queues, we allow lower priority data traffic to be served when the higher priority control traffic is deemed to be excessive. Simulation of our proposed scheme has shown that our approach yielded better network performance compared to the standard protocol in terms of packet delivery ratio and average delay.

Secondly, we study the cross-layer interaction between the MAC and Network layers to identify its impact on QoS. We select the IEEE 802.11e MAC protocol and Ad-hoc On Demand Distance Vector (AODV) routing protocol in our study since they are standardized protocols for wireless networks. In IEEE 802.11e MAC protocol, lower priority traffic has a higher probability of being blocked. Hence, the MAC layer will inform the Network layer of a broken link through the link notification function. In this case, AODV will re-route the paths that traverse this link. As a result, higher priority traffic which shares the same link as the lower priority

traffic will undergo the same re-routing procedures. We termed this phenomenon path correlation effect. Under high traffic load, the path correlation effect will be more intense and hence degrade the QoS of higher priority traffic. To break the path correlation effect, we propose a cross-layer design called the Bundled Virtual Circuit (BVC). Our proposed BVC scheme not only addresses the path correlation issues, but also provides priority treatment from the Network layer to the MAC layer. Through our simulations, our proposed cross-layer design approach is proven to provide better network performance than the 802.11e/AODV protocols in terms of packet delivery ratio and delay.

Finally, we examine flow admission control at the routing layer in ad hoc networks. Standard routing protocols such as AODV performs routing on a shortest path basis. In the presence of multiple routes, hotspots are likely to form among the intermediate nodes and thus lead to network congestion. In addition, existing routes are not well-protected from the introduction of new routes. We propose a flow admission control algorithm to be used with AODV. Our algorithm allows routes to be created through available bandwidth and congestion estimation. During the route discovery phase, each node will be gauged on its estimated available bandwidth and its backlog of packets in the MAC buffer. If a node does not have sufficient bandwidth, or has too many backlogged packets compared to the requested flow rate, it will not participate in the route discovery process. From simulations, our new scheme is able to provide better network performance than the standard AODV protocol in terms of delay.

Our work in this thesis focuses on QoS provisioning in ad hoc networks from the MAC and network layer perspectives. By studying the network characteristics and protocols' behavior, we investigate the various problems of providing QoS in an ad hoc network environment and propose three different schemes to improve the QoS provisioning at the MAC and network layers. We believe that our work is able to provide some insights to the research area on QoS in ad hoc networks.

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List of Abbreviations

AC	: Access Category
ANOVA	: Analysis of Variance
AODV	: Ad Hoc On Demand Distance Vector
AP	: Access Point
AQOR	: Ad Hoc QoS On-demand Routing
ATM	: Asynchronous Transfer Mode
BS	: Base Station
BTPS	: Busy Tone Priority Scheduling
BVC	: Bundled Virtual Circuit
CBR	: Constant Bit Rate
CDMA	: Code Division Multiple Access
CGSR	: Clusterhead-Gateway Switch Routing
CSMA/CA	: Carrier Sense Multiple Access/ Collision Avoidance
CSMA/CD	: Carrier Sense Multiple Access / Collision Detection
CTS	: Clear To Send
DBMS	: Dynamic Buffer Management System
DBTMA	: Dual Busy Tones Multiple Access
DCF	: Distributed Coordination Function
DFM	: Direct Function Mapping
DiffServ	: Differentiated Service
DSR	: Dynamic Source Routing
DT	: Derivative Tendency
EDCA	: Enhanced Distribution Channel Access
GID	: Grid ID
GPS	: Global Positioning System
HCCA	: HCF Controlled Channel Access
HCF	: Hybrid Coordination Function
LAR	: Location Aided Routing
MAC	: Medium Access Control
MACA	: Multiple Access w/ Collision Avoidance
MANET	: Mobile Ad Hoc Network

MPLS	: Multi-Protocol Label Switching
QoS	: Quality of Service
OFDM	: Orthogonal Frequency Division Multiplex
OSI	: Open System Interconnection
PBOA	: Progressive Back Off Algorithm
PHY	: Physical
PRUA	: Progressive Ramp Up Algorithm
RREQ	: Route Request
RREP	: Route Reply
RERR	: Route Error
RSVP	: Resource-reservation Protocol
RTS	: Request To Send
TDMA	: Time Division Multiple Access
TOS	: Type of Service
UDP	: User Datagram Protocol
VGID	: Virtual Grid ID
ZRP	: Zone Routing Protocol

Chapter 1

Introduction

1.1. Motivation and Background Information

The idea of Quality of Service (QoS) has been around since the proliferation of the Internet and Asynchronous Transfer Mode (ATM) technologies. The aim is to provide a form of guaranteed and predictable service for users by Service Providers. Since then, it has been considered in individual OSI layers and across different communications technologies with their own set of requirements. With the increase in user demand for bandwidth due to multimedia applications, QoS has been put in a more critical role for ensuring user satisfaction.

Figure 1. An overview of QoS components in Networking

Figure 1 above shows an overview of QoS components in networking concept. Initial QoS provisions has been focused on the IP layer, leading to mechanisms such as Type of Service (TOS) in IP packets to differentiate packets of high priority from those of lower priority. But it has been recognized later that providing QoS in the IP layer without similar provisions in the lower layers cannot guarantee network

performance. For example, making use of TOS to differentiate packets will not be efficient if the MAC sublayer is not able to recognize the difference in their priorities during data transmission. Thus there has been an increased interest in research on QoS support on the lower layers and the mapping of QoS information from higher layers to lower layers effectively.

QoS has been a major research area for various networking technologies in both wired and wireless domains. Due to the different characteristics of the networking technologies, QoS requirements for each of them are different, leading to different protocols designed. As a result, protocols that can be used in one domain generally cannot be used in another effectively. For example, the MAC protocol, CSMA/CD, used in wired networks cannot be used for wireless networks. This is because a wireless node cannot receive and transmit data at the same time, thus unable to detect collisions.

With the deployment of wireless technologies, many conventional protocols that wired networks used have been found to be inapplicable in wireless networks. This results in the development of protocols for wireless networks such as CSMA/CA, MACA etc. Some of these protocols have been able to provide good network performance, leading to their deployment in WiFi etc. However, the same level of network performance cannot be guaranteed for another form of wireless networks, i.e. ad hoc networks, thus requiring a certain extent of redesigning of protocols.

Conventional wireless networks are infrastructure-based, i.e. there exists a centralized controller, either in the form of a Base Station (BS) or Access Point (AP), which takes care of data transmission and scheduling. To illustrate an example, consider the case of a Wi-Fi in an office where a source node A, in the form of a laptop, wants to send some data to a destination node B, say, in the form of a desktop. The laptop will be polled to transmit data packets to the Access Point first. The Access Point will then check the destination address of the data packets in the MAC header and establish a connection to the desktop. It will proceed to send the data packets once the connection is valid. In most instances of conventional wireless networks, data transmission from source nodes will always have to be routed via the centralized controller to their destination. It can be seen that data transmission and

scheduling can be done efficiently by the controller since it has global information of the network within its range. However, a major disadvantage of this type of network is its complete reliance on the controller. A conventional wireless network cannot function, should the BS or AP be damaged or destroyed. Furthermore, such networks cannot be used in places where terrain conditions are too difficult for the construction of an infrastructure or there is low density of users.

On the other hand, ad hoc networks are infrastructure-less, i.e. they have no BS or AP to act as coordinator for data transmission and scheduling. Each node in the network acts as a router. Being independent of any infrastructure support, ad hoc networks can be implemented anytime and anywhere. However, in the case of mobility, the geographical position of each node is always changing with time and thus a connection between two particular nodes is not always available. Furthermore, ad hoc networks have to transmit data over multiple hops and this creates a challenge in ensuring a certain level of QoS. These characteristics make ad hoc networks unique in terms of QoS provisioning as compared to conventional wireless networks. To understand more about QoS issues in wireless ad hoc networks, we shall consider the MAC and Network layer characteristics of wireless ad hoc networks and explain their unique challenges of providing QoS.

a) MAC layer characteristics of wireless ad hoc networks

From the MAC layer perspective, a wireless ad hoc network is characterized by shared bandwidth and contention-based channel access. Such characteristics are mainly due to its independence from infrastructure support. Its non-reliance on physical infrastructure means that it can operate in any location any time. Although this factor is a clear advantage over conventional wireless networks, it also brings about a unique issue, i.e. a lack of centralized coordination with regards to channel allocation. Without centralized coordination, it will be difficult for a node to know when it can start transmitting data into the wireless medium without losses and collisions. Although this issue can be circumvented by the IEEE 802.11 MAC protocol, common problems such as the hidden terminal problem and the exposed node problem are still present.

For multimedia traffic transmission, IEEE 802.11e has been formally standardized as a QoS MAC protocol for wireless local area networks. It provides QoS to different classes of traffic by priority queueing. The standard defines four different Access Category (AC) queues with different contention window values. Higher priority traffic will be queued in AC queues with lower contention window value while lower priority traffic will be queued in AC queues with higher contention window value. In this way, higher priority traffic will be given a higher likelihood of gaining channel access than the lower priority traffic. However, the low contention window values assigned to higher priority traffic can also mean a higher chance of collision in the wireless medium especially when there is a large volume of high priority traffic. In addition, high collision rate can result in wastage of bandwidth and poor network performance since the wireless medium is shared. These factors make QoS provisioning using IEEE 802.11e complicated. We need to analyze the related problems that can arise from implementing such QoS mechanisms at the MAC layer and design appropriate schemes to improve the network performance.

b) Network layer characteristics of wireless ad hoc networks

Routing is mainly focused in wireless ad hoc networks at the Network layer. In centralized wireless networks, data transmission is typically sent between an access point to a client node over a single hop distance. However, this is not the case for wireless ad hoc networks. In wireless ad hoc networks, the source node may not need to be within transmission range of the destination node. Data transmission can be performed through intermediate nodes in cases where source node and destination node are out of transmission range, i.e. multi-hopping. The intermediate nodes will act as routers to ensure data transmission is successful. The path taken by data traffic from a source node to a destination node is known as a route. The creation and maintenance of routes is known as routing.

Standard routing protocols such as Ad Hoc On Demand Distance Vector (AODV) performs routing on a shortest-path basis. This means that routes are constructed in such a way that the number of hops between a source-destination pair is minimized. This is to ensure that packets transmitted along the route will not be subjected to high delay and packet loss due to long routes. However, such routing techniques may lead

to high spots where intermediate nodes have a high number of routes passing through them. Established routes are too focused in a common segment of the entire network, underutilizing the use of other free intermediate nodes. As a result, network congestion may arise, causing high delay and packet loss, leading to poor network performance. We shall research in the means of providing QoS through routing at the network layer and propose measures to improve the standard routing protocols in QoS provisioning.

c) Cross-layer interaction between MAC layer and Network layer

In wireless ad hoc networking, packets usually transverse between the MAC and Network layer and carry network information in their headers. Sometimes, protocols mechanisms in these two layers have their ways of interpreting network problems and perform the necessary actions to overcome them. For example, if the IEEE 802.11 MAC protocol fails to receive a reply message or acknowledgement message after transmitting a request packet or data packet several times, it will interpret the wireless link as broken and inform the routing protocol via the link notification function. If AODV is used as the routing protocol for example, it will make use of this information to perform a local route repair. Such cross-layer interaction between the MAC and Network layer can be studied to understand its impact on QoS provisioning.

Traditionally, protocols in one OSI layer are designed independently of other OSI layers. However, as the higher layers applications become more complicated to suit different user needs, data traffic become more complex in the form of different QoS requirements. Designing of protocols will need to include more network information for better network performance and operations, hence fulfilling the different needs. Cross-layer designing of protocols can play a role in optimizing such network performance. We shall study the cross-layer interaction between the MAC and Network layer and examine any related problems arising from them in the case of QoS traffic transmission. New cross-layer designs shall be proposed to tackle such problems and improve the overall network performance.

Based on the above characteristics, it is necessary to study the various ways of providing QoS from the MAC, Network layer as well as cross-layer perspectives. In

this thesis, I shall concentrate on these three areas to solve the problems of providing QoS support in them. The objective is to propose new schemes to improve the overall QoS performance in terms of packet delivery ratio, throughput and delay.

1.2. Challenges of QoS Provisioning and Research Objectives

We recognize that wireless ad hoc networks have a lot of challenges in providing QoS due to their network environment. Typically an ad hoc network environment will face the following problems, high control overhead, limited bandwidth, route congestion etc. High control overhead is normally incurred due to constructing and maintaining the multi-hop routes. As bandwidth is shared among the neighbouring nodes, an ad hoc network will have limited bandwidth. Routing is also a key issue since improper route selection can easily lead to congested routes. All of these factors will impact on the performance of an ad hoc network. As such, our research objectives will focus on QoS provisioning for ad hoc networks in the areas described as below.

1.2.1 IEEE 802.11e Priority Queues Management

As mentioned in the earlier section, the IEEE 802.11e MAC protocol can provide QoS treatment to high priority traffic by queueing them in an AC queue with low contention window value. While priority queueing does provide a certain level of QoS support, it also faced a potential problem known as starvation. When there is a large volume of high priority traffic, the IEEE 802.11e MAC protocol will serve them first, resulting in the low priority traffic being starved and stuck in their respective AC queues. In extreme cases, the low priority traffic will be dropped due to MAC buffer overflow and hence the MAC protocol may perceive the wireless link as broken. This will potentially cause new control packets to be generated due to route discovery and valuable bandwidth will be consumed by the control overhead.

To solve the above problem, it is necessary to study the behaviour of the IEEE 802.11e MAC protocol and manage the priority queueing and scheduling of different classes of traffic. In our work, we address the above problem by analyzing the amount

of control overhead generated and propose a new dynamic buffer management scheme. The research objective is to manage the high priority traffic dynamically with respect to the current network condition and reduce the likelihood of starvation of the low priority traffic, hence improving network QoS.

1.2.2 Cross-Layer Designing of MAC and Routing Protocol

Cross-layer designing of protocols has been an area of research in optimizing network performance. While standard MAC and routing protocols such as IEEE 802.11b and AODV works well for transmitting non-QoS sensitive traffic in wireless ad hoc networks, they are not well-considered for transmitting QoS sensitive traffic. For example, when IEEE 802.11e is used in conjunction with AODV for ad hoc networking, the low priority traffic will face a high likelihood of being blocked. Under such conditions, the QoS MAC protocol may interpret a broken link and proceed to inform the routing protocol to perform a re-route. Unfortunately, high priority traffic which shares the perceived broken link will have to be re-routed as well. This demonstrates a need to understand the cross-layer interaction well before using the relevant protocols for data transmission.

To address the above problem, we studied the cross-layer interaction between the IEEE 802.11e and AODV protocols and derived the root cause of the problems. Based on the study, we propose a new cross-layer design of the MAC and routing protocols to improve the network performance. In this case, our research objective is to come up with a cross-layer design that can handle the QoS treatment of the different classes of traffic in a more effective and stricter manner.

1.2.3 Routing based on Flow Admission Control

The standard AODV routing protocol creates and maintains routes on a shortest-path basis for wireless ad hoc networks. However, hot spots are likely to occurred in the network as the routing protocol does not take much into consideration the current utilization state of the intermediate nodes during route discovery. Intermediate nodes may have been heavily loaded with multiple routes passing through them, causing

them to be congested. As a result, existing routes will not be well protected from the introduction of new routes during route discovery and suffer congestion unfairly.

To solve the above problem, we analyzed the AODV routing protocol and proposed a flow admission control algorithm to be used during routing. The flow admission control algorithm will help in identifying intermediate nodes that are reaching congestion state. These nodes will not be used to form part of any new routes created, thus protecting any existing routes through them. Our research objective will be to propose an appropriate flow admission control algorithm that can distribute the routes in the entire network evenly and blocking new traffic if necessary to preserve the QoS states of the existing routes.

1.3. Major Contribution of the Thesis

In this thesis, we examine the problems of QoS provisioning from three perspectives, QoS MAC, QoS routing and cross-layer designing. Three schemes are proposed in this thesis addressing individual problem in these perspectives. The major contribution of the thesis can be summarized as follows.

- a. We first focus on the importance of managing the high volume of network control packets in data transmission and proposed a dynamic buffer management system for 802.11e-based networks. Typically, ad hoc networks incur high network control overhead in order to construct new routes and maintain existing ones. Such network control packets are normally queued in the highest priority queue if IEEE 802.11e MAC protocol is used. Although the IEEE 802.11e MAC protocol is specified to provide QoS for WLANs through priority queueing, a high volume of network control packets can easily lead to starvation of lower priority traffic. This will mean that the network control overhead will consume most of the bandwidth and the performance of the data traffic will be poor as a result. To alleviate this problem, our proposed dynamic buffer management scheme will provide a means in which buffer management are done in response to traffic patterns. By setting different threshold levels in different priority queues, we allow lower priority data

traffic to be served when the higher priority control traffic are deemed to be too excessive.

We develop the necessary simulation models and conducted several simulations on them to study and evaluate the benefits of our proposed schemes. From our simulation results, the proposed scheme can provide better buffer management of the control overhead. Network performance has improved in the form of higher throughput and lower delay as compared to the standard IEEE 802.11e performance. Performance can improve by up to 50% in extreme cases of high traffic loading, especially for low priority traffic. The results also indirectly reinforce the fact that the IEEE 802.11e MAC protocol is not suitable for ad hoc networks due to its low contention window values for high priority traffic.

- b. We analyzed the cross-layer interaction of the IEEE 802.11e and AODV protocols and identified a problem. In this case, we explained that independent layer design will not result in optimal performance if cross-layer influence is not properly considered. One such case is the issues arising from the use of the IEEE 802.11e as the MAC protocol. When the IEEE 802.11e is used as the MAC protocol, lower priority traffic has a higher probability of being blocked. Hence, the MAC layer will inform the Network layer of a broken link through the link notification function. Re-routing procedures will be performed by the routing protocol on the perceived broken link. Unfortunately, higher priority traffic that shares the same link as the lower priority traffic will be affected by the re-route procedure as well even though they may have no problems in data transmission. This is termed as the path correlation effect.

To address the path correlation effect, we proposed a new cross-layer design called the Bundled Virtual Circuit. This proposed cross-layer design scheme focuses on providing priority treatment for different classes of traffic from the routing layer to the MAC layer, making use of cross-layer information. By using our cross-layer design, we consider the impact of the cross-layer interaction between both the MAC and Network layers and minimize the path correlation effect. In addition, we are able to provide a stricter form of QoS by imposing such requirements from the Network layer downwards to the MAC layer.

We develop the simulation models of the cross-layer design from the MAC and Network layers and conducted several runs to study and evaluate the performance of our proposed scheme against the standard protocols. Our proposed scheme results in better network performance in the form of higher packet delivery ratio, lower delay and higher throughput. Performance has improved by up to 20% in several cases.

- c. We studied the problem of route congestion in wireless ad hoc networks. Standard routing protocols such as AODV make use of shortest path routing which may often result in hot spots among the intermediate nodes. In addition, existing flows are not well-protected against introduction of new traffic flows, thus often causing packet loss, higher delay due to congestion. To address this problem, we designed a new flow admission control scheme that makes use of bandwidth and congestion estimation for QoS routing and avoiding nodes that are less likely to be congested or facing limited bandwidth.

The flow admission control scheme aims to solve the above problem by performing new route construction on the basis of bandwidth and congestion estimation. Intermediate nodes that have low bandwidth or congestion when compared to the requested requirements will not be allowed to participate in the route construction. We implemented the flow admission control algorithm in our simulation model of the routing protocol and conducted several runs of simulation. Based on the analysis of our results, our scheme has resulted in better network performance in the form of higher packet delivery ratio and lower average delay. Performance has improved by up to 20% in several cases.

1.4. Organization of the Thesis

The remainder of the thesis is organized as follows. Chapter two will conduct a literature survey of the QoS MAC and QoS routing protocols to review and understand the work that have been done. Cross-layer designing will also be discussed in details. Chapter three studies the problem of IEEE 802.11e in providing QoS for

wireless ad hoc networks. A dynamic buffer management scheme is proposed to alleviate the problem. Chapter four will focus on the cross-layer interaction between IEEE 802.11e MAC protocol and AODV routing protocol. The path correlation effect is identified and explained. A new cross-layer design called the Bundled Virtual Circuit will be proposed to solve the above problem. Chapter five will focus on the problem of network congestion at the routing layer. We propose a flow admission control algorithm to be used in routing protocol to solve the problem through bandwidth and congestion estimation. Finally, chapter six will focus on the conclusion and further recommendations for future research directions.

Chapter 2

Literature review

Research on QoS Support in ad hoc networks has been focused on the following areas: QoS Models, QoS resource reservation signaling, QoS routing and QoS MAC[7]. Of these areas, QoS routing and QoS MAC are the most common research areas. Before going into these areas, it is important to understand the characteristics of ad hoc networks that made them unique in terms of QoS provisioning. The following subsections will be organized as follows. Section 2.1 will discuss the QoS MAC issues and some of the QoS MAC protocols that have been proposed. Section 2.2 will give a perspective on QoS routing. Section 2.3 will look into the issues of cross-layer designing.

2.1 QoS Medium Access Control

Figure 2. Data Link Layer Consisting of Medium Access Control and Logical Link Control Sublayers

The MAC sublayer, also known as the Medium Access Control sublayer, lies in the Data Link Layer of the OSI seven layers. It mainly defines the access mechanisms and packet formats and thus provides a mean of channel allocation for a node. It is known that for ad hoc networks, the media is shared and every node can send data at any point in time due to lack of centralized coordination. Furthermore, as certain conditions such as collision cannot be detected in wireless networks given that a node

cannot receive and transmit at the same time, certain measures must be in place to reduce wastage of bandwidth. In such cases, there are two objectives to consider. The first objective is to ensure that data packets reach their destination within delay and loss required by the network application. The second objective is to implement appropriate measures to improve network condition by reducing the impact of network problems such as collision.

In ad hoc networks, ensuring QoS for the MAC sublayer is challenging due to the lack of a centralized controller. Two common problems that naturally arise are the hidden terminal problem and the exposed node problem. The hidden terminal problem arises when two nodes attempt to send data to the same receiver node at the same time. To illustrate an example, consider a three-node network as shown in Figure 3.

Figure 3. Hidden Terminal Problem

In this network, node A and node C are out of transmission range of each other but are within range of node B. If node A and C send a data packet to node B at the same time, there will be a collision since both source nodes do not know the presence of each other. Data transmission is not successful in this case for both source nodes.

The exposed node problem arises when a node overhears a data transmission from another node and thus is inhibited from sending data packets. To illustrate, consider a four-node network as shown in Figure 4.

Figure 4. Exposed Node Problem

In this network, every node is within range of its direct neighbours only. Suppose node C sends a data packet to node D. As node B is within range of node C, it will also “overhear” the data transmission, even though it is not the intended recipient. As a result, node B cannot transmit data to node A because it is “blocked” by node C. This situation can be viewed as under-utilization of bandwidth.

Most MAC protocols [4][5][6][8][9] proposed are centered on solving these two problems, thus improving the efficiency of data transmission. However, they do not guaranteed support for applications with QoS requirements and at best, provide some form of soft QoS guarantee. While there have not been many QoS MAC protocols, there are several mechanisms proposed for QoS support in the MAC sublayer over the years. Figure 5 shows a classification of the mechanisms used.

Figure 5. Classification of QoS MAC Protocols

MAC protocols can be classified into reservation-based and contention based protocols. Reservation-based MAC protocols reserve resources for high priority flows

but can easily lead to wastage when reserved resources are unused. On the other hand, contention-based MAC protocols allocate resources to contending nodes as and when required. For ad hoc networks, reservation-based MAC protocols are difficult to implement as the availability of channel resources is inconsistent. Thus, contention-based MAC protocols are more common in ad hoc networks. The following paragraphs will describe the various mechanisms used in the MAC sublayer for QoS support.

2.1.1 Priority Queueing

Priority queueing has been one of the most common mechanisms used in providing fairness and QoS for networking. With its successful implementation in wired networks, there have been various similar schemes for wireless networks. This is especially reflected in the IEEE 802.11e MAC Protocol [10] which has been a formal standard to provide QoS in 802.11-based networks.

IEEE 802.11e MAC Protocol

A QoS MAC protocol must provide resource reservation and QoS guarantees to real-time traffic [7]. With these considerations, 802.11e has been standardized to provide QoS to multimedia traffic over wireless LANs. It makes use of a new access method called Hybrid Coordination Function (HCF). HCF uses a contention-based channel access method called Enhanced Distributed Channel Access (EDCA) and a contention-free channel access method called HCF Controlled Channel Access (HCCA) for data transfer. HCCA will not be discussed here since it does not support ad hoc networking.

The EDCA is still based on the CSMA/CA (Carrier Sense Multiple Access with Collision Avoidance), extended to incorporate four queues known as Access Category (AC). Each Access Category is an instance of the EDCA and has different fundamental delay (known as Arbitrary Inter Frame Space) and contention window values. In descending order, AC3 has the smallest values followed by AC 2 and so on until AC 0. Thus, AC3 is the highest priority queue while AC 0 is the lowest priority

queue. In the event that more than one AC have their backoff timer expiring at the same time, the one with the highest priority will win the contention and proceed to transmit while the rest will backoff as if there is a collision.

While it has been acknowledged that the 802.11e MAC protocol does provide QoS support for conventional wireless networks, the case is not so for MANETs[38]. The high contention issue caused by the contention window size for high priority traffic in 802.11e raises the question of whether it is suitable for use in MANETs for providing QoS. It is known that when channel load is high, high priority packets will cause starvation of lower priority queues. This situation can be aggravated by the interference and collision they cause in the physical layer by virtue of their contention window value. Data packets will have an even lesser chance of transmission when this occurs and packets can be lost due to buffer overflow. As a result there have been several proposals on improvising this standard to make it more suitable for MANETs.

Adaptive Fair EDCF¹

In this scheme [11], an adaptive backoff threshold value that separates two backoff states is used for each priority queue. This is to allow differentiation between different traffic priorities and taking into account the channel load. The figure below shows the backoff time decrease phase.

Figure 6. Backoff Time Decrease Phase

In the first backoff state, the backoff timer will decrease linearly as in the standard. The remaining backoff timer will be checked to see if it reaches the threshold value. When the threshold value is reached, the queue will start the second backoff state by decreasing its backoff timer exponentially. The threshold value will be based on the

¹ EDCF is the old name for EDCA. This scheme is based on an older draft version of the IEEE 802.11e

current channel loading and adapts accordingly. Thus during low contention periods, a fast backoff will occur to reduce delay and during high contention period, the backoff will slow down to reduce collision. Results shown in this scheme have shown a clear improvement in network performance.

Xiao's Proposal

In Xiao's proposed scheme [12], the author considers two areas to improve on the 802.11e EDCA for ad hoc networks. The first area is the admission control in which he proposes a fully distributed and measurement-based admission control scheme for differentiated services. Focusing on real-time traffic only in this scheme, each node will accept or reject a newly arrived stream based on its local observed measurements. The measurements are made during beacons intervals by individual nodes which will calculate a transmission budget. The transmission budget indicates the allowable transmission time for each AC. A limit will be set based on the transmission count during the previous beacon period and transmission budget calculated. Thus if the budget of one AC is depleted, newly arrived streams will not be accepted while existing streams are not allowed to extend their current transmission time. This helps to protect the existing real-time streams.

With regards to non real-time traffic i.e. data traffic, a local data control mechanism is proposed. Individual nodes will dynamically estimates the following parameters, AIFS[0], CWmin [0] and CWmax [0] based on the traffic load conditions. The dynamic changing of the parameters will rely on one of the two schemes, namely Direct Function Mapping (DFM) and Derivative Tendency (DT). The DFM scheme defines a mapping function for mapping traffic load conditions to the parameters while the DT scheme changes parameters dynamically according to the increased or decreased tendency of traffic load indications.

2.1.2 Busy Tones

Other than considering multiple queues at the MAC layer, the use of busy tones have also been proposed. Busy tones are signals normally outside the channel bandwidth that are broadcasted on a beacon interval to indicate the state of a node. To

illustrate an example, in DBTMA, busy tones have been used to indicate whether a source node or destination node is busy. It has been claimed that through the use of busy tones, DBTMA is able to eradicate hidden terminal and exposed node problems at the expense of the hardware design.

Busy Tone Priority Scheduling Scheme

In BTPS [13], two busy tone signals are used to ensure medium access for high priority source stations. The BTPS works in this way. The high priority source will emit a Busy Tone 1 (BT1) when it wants to transmit a data packet. The receiver, upon detecting the tone signal, will emit a Busy Tone 2 (BT2) to inform its neighbours. When the neighbours heard the tone signals, all low priority sources will delay their transmission by a specific period in order to allow the transmission of high priority packets first.

Though more high priority flows can be supported in this scheme, the throughput is reduced as compared to IEEE 802.11. This is perhaps the tradeoff between scheduling and throughput. The scheme does not address the problem when two high priority nodes want to transmit data to two receivers within the same neighbourhood.

2.1.3 Multi-Channel

Multi-channel setup has also been considered in providing QoS support for MANETs. The idea behind this is mainly to segregate the whole bandwidth into different channels for different traffic load. Similar to the use of busy tones, it extends the concept to splitting the whole data bandwidth into multiple channels for data traffic of different priority. A clear example of such a mechanism is presented in the following paragraph.

A Proposed Multi-Channel MAC

In [14], the total number of channels is fixed which is divided into one control and the rest data channels. With each node having two half-duplex transceivers, a node can sense the control channel for any control packets and the data channels to transmit

or receive data. A node will cache the following data information in its database: code assignment list and free code list.

So if a node wants to transmit a data, it will first sense the control channel to verify whether the medium is busy. If the medium is not busy, the node will send a RTS to the receiver and wait for a CTS from it. Once CTS is received, the node will select a best channel to send the data across and the receiver will acknowledge after the full transmission. Service differentiation is also included in this protocol using three classes of priority namely, urgent, priority and common for different types of data transmission.

Simulation results have shown that throughput has increased and delay reduced for data of higher priority. For data of lower priority, the throughput is lower with higher delay. At lower load, the protocol works as well as IEEE 802.11. At higher load, it performs better than the IEEE 802.11 protocol by about 0.5 Mbps only. There are a few questions about this scheme that is not addressed in details. One question is the allocation of the bandwidth among the various channels. It is not clear that if the bandwidth should be allocated equally or according to priority among the various channels. Another question is the use of the free data channel list in CTS packet. It is not clear how big the new CTS packet size will be. The protocol mentioned is similar to IEEE 802.11 in most aspects.

2.2 QoS Routing

In the network layer, finding valid routes for data transmission is an important issue in ad hoc networks. Normally in ad hoc networks, routes can be broken due to a few reasons. For the case of a static ad hoc network, one main reason is due to traffic congestion in the intermediate nodes along the route. Data traffic are transmitted from a source node to a destination node on a distributed basis. This means that each node in an ad hoc network will only accept incoming traffic or transmit outgoing traffic on the basis of its own perception of the network condition. There is often a lack of global network information on each node and thus the best route cannot be found on a system perspective. In this case, if there is no form of load balancing or similar sort of

mechanisms, routes can be created on a shortest path mode, leading to hot spots within the network. This will create network congestion at certain points of the network, causing possible delay and data losses.

For the case of mobile ad hoc networks, there will be a need to consider the mobility of nodes as well. Due to the mobility of nodes, routes in a mobile ad hoc network often change in a random manner, giving rise to a dynamic nature in the network topology. Routes are made or broken often as a result. The route connectivity is of temporary nature and thus leads to problem of route robustness. Such routing problems are not serious in centralized networks where the surrounding nodes are only a hop away from the BS or AP. However, for ad hoc networks, routes connectivity can seriously impair their performance due to their multi-hop nature for data transmission. A broken link in one of their hops will require immediate attention for route repair or route reconstruction to be done. Thus a well-designed routing protocol has to maintain up-to-date route information and adapt to topological changes quickly. This will help to reduce overhead and minimize data losses.

Another aspect that we need to consider is the suitability of the routing protocol in large networks. The use of multi-hopping to transmit data packets gives rise to the issue of scalability of an ad hoc network. It is known from previous research that as the size of an ad hoc network grows, the throughput of a path will drop as its length increases. This is mainly due to overhead arising from the usage of routing protocols on large networks. This suggests that there is a limit on the effective size of an ad hoc network and thus routing protocols may have to consider practicality on large networks as well. In several cases, some routing protocols that are efficient in small networks have been proven to be inefficient in large networks [2]. Such inefficiency is due to high overhead incurred in containing global network information in every node or interference from other nodes (hidden terminal or exposed terminal problem). As a result, many schemes have been proposed to improve the scalability of ad hoc networks. For example, hierarchical routing protocols such as Zone Routing Protocol (ZRP) [3] and Clusterhead-Gateway Switch Routing (CGSR) [2] have proposed dividing the entire network into several subnets so as to maintain overhead within the locality of the subnets. MAC protocols such as Dual-Busy Tone Multiple Access

(DBTMA) [4][5][6] have proposed using out-of-band signals to eliminate the hidden terminal and exposed node problems.

To elaborate on the requirements of a well-designed routing protocol, consider the case of a typical ad hoc network when there are several mobile nodes. When a node moves out of a neighbourhood, the routing protocol must be able to recognize the change in the routing path and thus discover an alternative path so as to ensure connectivity. Should a new node moves into the neighbourhood, the routing protocol must be able to set up connectivity with the new node and also establish new paths. The new paths should be created to allow load balancing or avoid congested hot spots if possible. Such requirements often pose a challenge in the design of a routing protocol and the situation is often aggravated if the nodes are of high mobility speed. The requirements will even be more stringent if QoS (Quality of Service) paths are required for real-time transmission. Additional mechanisms will be required for bandwidth reservation, low delay etc, leading to a higher complexity of the routing protocols.

Figure 7. Classification of mechanisms used in QoS routing

Although there have been much research done on QoS routing, most of the proposals focused on the guarantee of bandwidth. For most cases, the objectives of a QoS routing protocol is mainly to establish QoS paths which has to contain these ideal properties namely: having a shortest path; least path coupling effects, long route lifetime etc. As such, several mechanisms have been proposed to improve the performance of the routing protocols in an effort to attain a certain level of QoS guarantees. The following paragraphs will describe some of these QoS mechanisms.

2.2.1 Topology-Based Routing

Topology-Based routing refers to setting up of QoS routes by means of the network topology. In this case, we can consider clustering/grid topology. Clustering /Grid refers to dividing the entire networks into smaller manageable groups that are governed by a cluster head. The use of clustering has been around for some time and problems associated with it is that suboptimal routing paths are used since all paths have to be routed through the cluster heads. Furthermore, the cluster heads form a bottleneck under high traffic load. However, as each cluster head has global information of all the nodes in its cluster, it can be used to form QoS paths as proposed in the following protocol.

QoS-Grid

QoS-Grid [15] is a location-based routing protocol with QoS provision. This scheme separates the entire network into several square grids with their own individual grid id (GID). In addition to the original grid, a virtual grid is also added with their own virtual grid id (VGID). Both the original and virtual grids will have their own grid headers which carry different responsibilities. The original grid header is responsible for transmitting packets and controlling the bandwidth while the virtual grid header is responsible to help the original grid header to transmit data to a neighbouring grid. Both the grid headers are elected through an election procedure.

During the route discovery phase, when a node needs to transmit data to another node, it will broadcast a route request (RREQ) packet which includes information on bandwidth demands. The original grid header (GH) will check for available bandwidth upon hearing the RREQ packet. If there isn't sufficient bandwidth to support the demand, the packet will be disregarded, otherwise, the destination node will be checked to see in which grid it is. Typically, the GH will forward the packet to the destination node if it is within the same grid or send to neighbouring virtual grid headers (VGH) if the node is in another grid.

Upon receiving the RREQ packet, the destination node will reply with a route reply packet (RREP) to the relevant grid headers along the path. Bandwidth will be

reserved by each grid header and a QoS path will be set up in this manner. Should the path fails to meet the bandwidth requirements in the process, the RREP packet will be dropped and the route discovery phase will start all over again.

Although the lifetime of the paths in this protocol has improved with the expense of a longer hop count, it is likely that the processing delay will be long due to the election procedure as well as the extra steps in forwarding control packets through the grid headers. It is also expected that this protocol will not be able to guarantee a large throughput due to a longer hop count. Bottlenecks could exist at the grid headers as well when the channel load is high.

2.2.2 Algorithm-based

Algorithm-based QoS routing heavily depends on the algorithm used in their paths discovery phase. In such protocols, the method to determine QoS paths is mainly supported by some form of algorithms used in calculating the actual bandwidth that can be acquired for QoS support. Unfortunately, such routing protocols are often based on ideal network conditions and can be difficult to implement practically due to their complexity. Nevertheless, they do provide a valuable guide to future QoS routing protocols.

Zhu's Proposal

A QoS routing protocol for ad hoc networks using TDMA is proposed [16]. Its objective is to establish bandwidth guaranteed QoS routes in small networks with limited mobility. Based on AODV, the QoS routes are only built when required. For each traffic flow, the routing protocol will find the route and slots for each link on the route. Using an efficient algorithm, the protocol will calculate the bandwidth to reserve. As such, QoS paths will be established.

Although it has been shown network performance has improved using this algorithm, the problem of having suboptimal paths as a result still exists. Furthermore,

this protocol is not able to support high mobility networks, thus limiting its areas of application. Finally, multiple QoS paths cannot be supported with this algorithm.

Lin's Proposal

Lin proposed a QoS routing protocol [17] derived from DSDV. The protocol is considered in networks using CDMA over TDMA and contains end-to-end bandwidth calculation and bandwidth allocation. What is interesting about this protocol is that it is able to work in standalone ad hoc networks as well as mobile networks interconnected with wired networks. For a source-destination link, the end-to-end available bandwidth is computed using a proposed bandwidth calculation algorithm. Based on the available bandwidth, slots are assigned a different manner for source nodes, destination nodes and intermediate nodes using a reservation algorithm. Similarly route maintenance and new calls are handled by a standby routing algorithm and new call algorithm respectively.

It has been shown based on simulation results that this protocol is effective for multimedia ad hoc wireless networks and ATM interconnected networks. For ATM interconnection, it has shown to provide better handoff and better call admission control.

AQOR

AQOR (Ad Hoc QoS on-demand Routing) [18] is a resource reservation-based routing and signaling algorithm. Similarly to the above two protocols, QoS is supported in terms of bandwidth and delay. In this protocol, detailed computational methods are developed to estimate the available bandwidth and end-to-end delay in order to perform accurate admission control and resource reservation. It also includes mechanisms to provide route recovery in an adaptive manner and recovery from QoS violation.

Based on the network simulation results, it has been shown to provide better QoS through accurate estimation of traffic load and effective admission control.

Adaptive QoS Routing based on Local Performance Prediction

The adaptive routing scheme [19] is based on the prediction of the local performance in MANETs. To predict the local performance, the protocol makes use of a performance prediction mechanism that includes local information collections and local QoS performance computations. Such adaptive mechanism requires the harmonious cooperation of cross-layer functions as well as hybrid local information update mechanism. Besides having the prediction mechanism, a distributed routing strategy is also proposed that makes use of the predicted QoS performance.

The protocol functions in this way. First, affected parameters are extracted from the mobile environment. The parameters are taken from other layers which include information such as Signal-to-Noise Ratio etc. Node and channel classification is performed and mobility and its effects are normalized. Second, local information will be managed through monitoring and information exchange. This ensures that the information are continuously updated. Third, the information will be translated into QoS performance predictor through the use of theoretical computation such as queueing theory and MAC layer analysis. Finally, a distributed dynamic source routing strategy is used in which the predicted QoS performance is used in the establishment of QoS routes.

2.2.3 Position-based Routing

The use of position-based QoS routing is to provide a certain level of QoS by means of knowing the nodes' position. One important advantage that this form of QoS routing has is the availability of a common clock to all the nodes in the network. Typically, position-based routing can only be done if knowledge of every node location can be obtained. This has to be done through the use of Global Positioning System or other similar means. Thus with the use of GPS, a common clock can be obtained for every node and this helps greatly in provide QoS for real-time traffic in terms of clock synchronization. As ad hoc networks are distributed by nature, it will be difficult to implement a common clock for every node otherwise.

Erbas' Proposal

Erbas suggested a position based QoS routing architecture in [20]. He argued that current QoS routing algorithms are insufficient as they work only under certain circumstances. Furthermore, a number of constraints such as conflict-free reservation and distributed nature of ad hoc networks make finding an optimal slot scheduling a NP-hard problem. Thus it will be easier to make use of knowledge of resources in the whole mobile network environment to provide QoS. This will be done through position-based routing.

In his proposal, the entire ad hoc network is divided into grids in which every grid will have a location server that contains global information of the entire network. Before establishing a QoS path, these servers will be consulted, thus eliminating the use of flooding and periodic updates. Only the servers will exchange network information on a periodic basis and thus reduce overhead to a great extent.

2.2.4 QoS Multipath Routing

QoS Multipath Routing is a challenging area for research. The main issue in QoS multipath routing is to find multiple paths that can fulfill the QoS requirements of the corresponding traffic. It has been mentioned earlier that finding one QoS path is already very difficult, let alone finding multiple QoS paths. However, the rewards for finding multiple paths are great. For a start, QoS can be provided at a better guaranteed level since multipath routing is less affected by mobility. Load balancing techniques can be used thus enabling QoS re-negotiation or sharing of QoS requirements among available paths. This will allow more flexibility in QoS provision and a better probability of meeting QoS requirements with lower available resources.

Chen's Proposal

Chen proposed an on-demand, link-state, multipath QoS routing protocol in [21]. In his proposal, the protocol calculates the end-to-end path bandwidth of QoS multipath routing under a CDMA-TDMA channel model. The protocol consists of the

following phases namely, on-demand, link-state delivery/collection, uni-path discovery, multi-path discovery, multi-path reply and multi-path maintenance phases. In the first phase, QRREQ packets containing QoS information are sent out from the source to the destination. The destination node will collect all the QoS information of every path from the QRREQ packets. In the subsequent uni-path discovery phase, the destination node will attempt to reserve bandwidth along a uni-path. If not, the protocol will then attempt to create multi-path paths in the multi-path discovery and reply phases. Multi-path maintenance will be done in the subsequent phase.

Through these phases, the protocol may offer a multi-path route if the MANET does not have sufficient network bandwidth, or provide a uni-path route if the MANET has sufficient network bandwidth. Simulation results have shown better link utilization and higher success rate in establishing QoS paths for network load.

Sun's Proposal

An adaptive Multi-path QoS routing scheme is proposed in [22]. In this proposal, the protocol makes use of the most updated local information in every node to perform QoS routing. The routing is done adaptively through the use of forward error correction and multi-path routing mechanisms in an adaptive manner. The whole routing mechanism consists of three portions: a modified dynamic source routing, a local statistical computation and link monitoring function, and an integrated decision-making function in every node. The dynamic source routing is in charge of route discovery and collection of QoS-related information. The second portion is used to manage and build a table of the local routing information. The third portion is in charge of making decision. Through these functions, multiple QoS paths are established and less affected by network changes due to the adaptive nature of the protocol.

2.3 Quality of Service across OSI Layers

As mentioned earlier in Chapter 1, QoS was initially considered at the IP and Transport layer, thus leading to a variety of QoS protocols such as RSVP, DiffServ,

MPLS etc. While most of these protocols do provide a certain level of QoS for wired networks, the same cannot be said for wireless networks. This is because of the fundamental difference in their lower layers, i.e. the PHY layer. Wireless networks make use of vacuum or air as their physical medium which is shared and contains a high level of interference by nature. Due to the fact that no two nodes within range can transmit data at the same time, there must be some form of coordination such that all nodes can transmit data in an organized manner. This is especially true in the case for a centralized wireless network where coordination is performed by the AP or BS. However, for MANETs, QoS issues are extremely challenging. Not only there is an absence of a form of centralized coordination, there are also other problems typically found in wireless networks that make traditional QoS mechanisms such as RSVP difficult, if not impossible, to implement.

To provide QoS in MANETs, the approach in designing QoS mechanisms have to be different than traditional methods. In wired networks, QoS provisioning are mainly considered on a top-down approach from the IP/Transport layer to the MAC layer. The upper layers will be dealing with QoS mechanisms such as classification, resource reservation signaling, while the lower layers will be dealing with scheduling according to the upper layers requirements. Although there is nothing wrong with this QoS approach, ad hoc networks face a different set of problems and requirements that suggest a different form of perspective needed. For a start, QoS in the lower layers are much more critical in MANETs. By virtue of its characteristics, the lower layers will normally have a higher impact than the upper layers. In other words, it has to be recognized that QoS in the upper layers cannot provide QoS guarantee without the support of QoS mechanisms in the lower layers. Thus when it comes to QoS provisioning in MANETs, it may be wiser to consider the lower layers first i.e. the MAC layer followed by the Network layer and upper layers. This explains the vast research work done in QoS at the lower layers (even at the PHY) for wireless networks.

In the earlier chapter, a literature survey on QoS protocols in the MAC and routing layer has been given and provided an insight into the QoS provisioning at the lower layers. However, there is still an area that has been around in recent years and plays an important role in understanding QoS across different layers of the OSI model. This

research area is identified as the cross-layer interaction between the OSI layers and helps in explaining the reason behind the need to consider QoS on a multiple-OSI layers perspective. The following section will discuss this issue in greater details.

2.3.1 Impact of Cross-Layer Interaction on QoS

It is of common knowledge that a majority of wireless networks protocols have been designed based on the OSI Reference Model as shown below.

Figure 8. OSI Reference Model

The main reason behind the designing of protocols based on the OSI model can be linked to the proliferation of the Internet. Due to the successful implementation of the Internetworking, the OSI reference model becomes the de-facto model for designing other forms of networks such as wireless networks. Looking in the context of wireless ad hoc networks, MAC protocols operate in the Medium Access Control layer while routing protocols operate in the Network layer. Data packets in ad hoc networks are passed down from the upper layers to the physical layer where they are transmitted by physical medium (e.g. air) from one source node to a destination node. The destination node, upon capturing a data packet, will pass the packet up to the upper layers for further action. Cross-layer interaction is defined as the mutual information

exchange between layers in the OSI reference model. Figure 9 shows a simplified diagram of cross-layer interaction between OSI layers. The reaction of protocols in each layer upon receiving such information will depend on the nature of the protocols. Past designs of MAC and routing protocols have always been done without consideration of its impact on other layers. The influence of a MAC or routing protocol on its adjacent layers has been assumed to be negligible.

Figure 9. A Simplified Diagram of Cross-Layer Interaction between OSI Layers

However, recent research [23] has suggested the need for understanding cross-layer interaction and cross-layer design. Poor performance of common protocols has been linked to a lack of understanding of the interaction of the different layers. As such, two questions appear on this research area: Firstly, is there a need to take into consideration the mechanisms involved in adjacent layers when designing a protocol? Secondly, can the information from other layers (e.g. MAC sublayer) be used in designing an efficient protocol or optimizing the performance of an existing protocol for a particular layer (e.g. Network layer)? The second question leads to the concept of cross-layer designs. Some cross-layer designs [26][27] have been proposed recently, suggesting a trend towards cross-layer designing of protocols.

For the first question, some hints on the importance of cross-layer interaction can be found in [23][24][31]. [23] explains the effect of mobility and interaction between various input parameters on the performance of protocols designed for wireless ad-hoc networks. It showed that designing of only one layer such as a MAC protocol or routing protocol in isolation is meaningless. Using experiments in which three basic

mobility models: grid mobility model, random waypoint model and exponential correlated random model are used; it measures the existence of interaction between the MAC protocols and routing protocols. In this study, CSMA, IEEE 802.11, DCF and MACA are used in conjunction with AODV, DSR and LAR scheme I. The ANOVA (Analysis of Variance) mathematical technique is used in determining whether there is interaction between the MAC and routing protocols. What is interesting about this study is that it came to the following conclusions. No combination of MAC and routing protocol dominated the rest of the combinations over all mobility models and response variables. There is a possibility that the performance of a MAC layer protocol can be improved by designing a compatible routing protocol and vice versa. Such conclusions could mean that the use of a particular combination of MAC protocol and routing protocol depends heavily on the characteristics of the ad hoc network and its applications.

In [31], two routing protocols, Dynamic Source Routing (DSR) and Ad Hoc On-Demand Distance Vector (AODV), are compared and analyzed. The performance variance are analyzed using three parameters, varying network load, mobility and network size while the performance metrics evaluated are packet delivery fraction, average end-to-end delay of data packets, normalized routing load and normalized MAC load. It is shown from the experiment that MAC load is a good measure for predicting application performance. For good performance, the interlayer interactions must be taken into account when designing protocols for wireless ad hoc networks. Thus, given these findings, it can be understood that to design a new combination would require taking into account of both the layers as well as its application to be applied.

Pertaining to the second question, the concept of cross-layer design has been used in solving various types of problems. In [27], two cross-layer design of MAC protocols namely, Progressive Back Off Algorithm (PBOA) and Progressive Ramp Up Algorithm (PRUA) are proposed to outperform CSMA/CA in terms of achievable throughput and energy efficiency. In [28], a MobileMAN architecture is proposed. The architecture mainly focus on cross-layer design across all seven layers to provide the following advantages for MANETs: cross-layer optimization for all network functions, improved local and global adaptation, full context awareness at all layers

and reduced overhead. [29] makes use of a “cross-layer” design such as swift-OFDM, low-latency packet awareness coder and adaptive noise filtering design to deliver better video over wireless means. It proposes a cross-layer protocol design to support a new framework called UDP-Lite. This framework results in better bandwidth utilization by delivering partially damaged packets to the real-time application.

Despite the apparent advantages in optimizing network performance and providing QoS, the use of cross-layer interaction and design too liberally has been cautioned for the following reasons[32]. Firstly, having a cross-layer protocol will mean its effect will affect other layers easily. This can easily lead to unintended consequences if not properly designed and lead to unpredictable network performance instead. Secondly, cross-layer design will lead to adaptation loops due to interaction among different protocols. Thirdly, there is a possibility that a parameter can be controlled by two adaptation loops at the same time. Should such a case occur, there will be conflict of protocols. Thus it is important to make sure to provide time-scale separation among the loops for system stability. Finally, the concept of cross-layer design will mean higher cost in terms of coding. Having several cross-layer designs will mean developing unstructured codes that may be hard to maintain. Furthermore, the lack of modularity in coding will mean difficulty in updating the codes.

In summary, there is a tradeoff between modularity and performance when it comes to cross-layer designing. Even though there are hints of performance optimization when cross-layer designs are used, there is also the danger of instability in the system and increase in cost for codes maintenance. It is necessary to consider if the increase in cost will be outweighed by a larger increase in network performance. This tradeoff is an area that needs to be researched before a more conclusive statement on its practicality can be given.

2.3.2 Approach to QoS Protocols Design

In Chapter One, it has been stated that the primary objectives of the research project is to investigate ways of providing QoS for ad hoc networks. So far, QoS MAC, QoS Routing and cross-layer interaction have been discussed. It is now

necessary to define an approach to ensure QoS for ad hoc networks and it is evident from the earlier section that QoS in upper layers has to be supported by QoS in lower layers to ensure complete QoS in MANETs. With this idea in mind, the following approach is used.

Figure 10. Framework of QoS Approach

Figure 10 shows a framework of the approach to be used for the research. For a start, based on a bottom-up approach, QoS in the MAC layer is studied first and ways of improving QoS are investigated. The plan is to design a new QoS MAC protocol. QoS routing will then be considered and built on the new QoS MAC protocol. QoS routing protocols designed will have to be complementary to the QoS MAC protocol. Thus, any cross layer influence between the MAC and Network layer has to be examined carefully at this stage. QoS in higher layers will be considered in the future. The QoS objectives for both the MAC and routing layers have been identified in the framework and examples of MAC and routing protocols have been considered. For

QoS MAC, the priority queueing mechanism in 802.11e will be studied first and a proposed queueing management scheme will be detailed in the next chapter. AODV will be considered in the routing layer and implementation of QoS mechanisms with these protocols will be examined.

Chapter 3

Buffer Management for 802.11e-based Ad Hoc Networks

Quality of Service (QoS) provisioning has been one of the main research areas for mobile ad hoc networks (MANETs). This area has become increasingly important given the proliferation of multimedia services and applications, each having its own QoS requirements. However, most of the existing medium access control protocols are unable to meet the QoS requirements arising from multiple traffic types, e.g. multimedia traffics. The IEEE802.11e standard defines a medium access control (MAC) protocol that provides QoS for multimedia traffic in wireless LANs. However, the performance of the IEEE802.11e MAC under ad hoc networking conditions has not been studied thoroughly. In this chapter, the challenges of using the IEEE802.11e MAC under ad hoc networking conditions are studied and a buffer management scheme is also proposed to ensure better performance under such conditions.

3.1. Motivation

From the framework in the earlier chapter, the MAC layer will be considered first in providing QoS for ad hoc networks. From the literature survey in Chapter 2, the QoS mechanisms in the MAC layer can be categorized into multi-channel, busy tones and priority queueing. Of all these, priority queueing has been increasingly popular recently due to the development of 802.11e products. Furthermore, recent works have suggested that 802.11e do provide a certain level of QoS in the MAC layer for Wi-Fi. Thus any initial QoS proposals on the MAC layer will be based on 802.11e .

Unlike WiFi and infrastructure networks, there are quite a large amount of communications coming from control packets in ad hoc networks. Control packets are used to find paths, maintain topology information etc. In the case of mobile ad hoc networks, due to instability of network topology, the amount of control traffic is huge. According to [31], the amount of control traffic of routing protocols of AODV and DSR could be as two to seven times as large of the amount of data traffic in terms of packet numbers. Therefore, how to deal with such big amount of control traffic is a very crucial issue in the QoS design in 802.11e-based ad hoc networks.

One of the challenging issues for 802.11e in ad hoc networks is this: if strict priority queueing is deployed at the MAC layer to schedule different kinds of packets, the high priority packets will cause starvation of the lower priority packets, especially, when control packets are put in the high priority queue, the control packets will consume most of the bandwidth, and the performance of data packets will become poor. This is aggravated by the fact that there are a higher number of control packets than data packets in ad hoc networks.

In order to handle starvation of lower priority traffic, one effective way is to employ effective buffer management for high priority traffic. There will be a need to cap the transmission of high priority traffic when the low priority traffic has reached a state of congestion and eventual buffer overflow. To handle that, it is necessary to take into account the state of the low priority buffers when transmitting high priority traffic from their buffers. This will help to reduce packet loss due to starvation and

improve network performance. Based on this principle, a buffer management scheme is proposed in the next subsection.

3.2. Proposed 802.11e-based Buffer Management Scheme

A buffer management scheme is proposed based on the IEEE 802.11e MAC protocol to alleviate this problem. We shall call this scheme Dynamic Buffer Management Scheme or DBMS for short. Due to the dynamic nature of ad hoc networks, the network conditions for an ad hoc network can be in many forms and thus cannot be easily taken care of by a static scheme. The DBMS aims to provide a dynamic scheme in which buffer management are done in response to traffic patterns. Similar to [35][36], we use a simplified example to explain the basic idea of DBMS in the following.

Figure 11. Simplified Example of a Queueing Model for 2-Priority Traffic

Figure 11 shows a simplified queueing model for a two-priority traffic model. We assume only two types of data packets; high priority and low priority data packets. To explain this scheme, any arrival packet can be enqueued if the current queue length is less than a threshold value TH . If the current queue length has exceeded the threshold TH , only high priority packets will be enqueued subjected to the maximum queue length. For each packet priority type, a packet loss counter is maintained to record the number of packets that has been dropped. Each counter will be influenced by a set of control parameters: *upperbound_loss* (*ubl* for low priority packets, *ubh* for high priority packets), *modification_step* (*mod_l* for low priority packets, *mod_h* for high

priority packets). Each time the loss counter for high priority packets incremented by a value of ubh , the TH value will decrease by mod_h . Likewise, if the loss counter for low priority packets incremented by a value of ubl , the TH will be increased by mod_l . In this manner, the threshold TH will be managed in a dynamic form.

Figure 12. DBMS on 4 EDCA Queues

This algorithm is now extended to the 802.11e queues where the algorithm is used on a single queue with multiple thresholds. We consider a four-priority queue system in which AC3 is the highest priority queue followed by AC 2, AC 1, AC 0 in descending orders. Each EDCA queue will have a threshold value TH corresponding to itself as well as its control parameters. The algorithm works in this way. Suppose a packet of priority n arrives to an EDCA queue AC n . The combined queue length of AC3 to AC n will be used to compare against the threshold TH n . If the combined queue length is less than TH n , the packet will be accepted, otherwise it will be dropped. When the packet is dropped, two loss counters will be incremented. The low priority loss counter(n) will be incremented and compared to $ubh[n]^2$. If the loss counter has reached $ubh[n]$, then all thresholds (TH $n+1$ to 3) will be decreased by their respective $mod_h[n]$ values. Likewise, if the high priority loss counter (n) incremented and reached $ubl(n)$, the threshold TH n will be incremented by $mod_l[n]$. A full algorithm is provided in the following.

<i>priority</i>	discarding priority for arriving packet
<i>current_queue_length</i>	current queue occupancy

² In this case, ubh will be changed to $ubh[n]$ to correspond to the right AC n .

$TH(n)$	discarding threshold $TH(n)$
$ubh[n]$	loss bound for decrease $TH(n)$
$mod_h[n]$	modification step for decrease $TH(n)$
$ubl[n]$	loss bound for increase $TH(n)$
$mod_l[n]$	modification step for increase $TH(n)$
$LL(n)$	low priority packet loss counter
$LU(n)$	high priority packet loss counter

for every arrival packet pkt do

$n = \text{get_priority}(pkt)$

$current_queue_length = \text{sum of all queue length from AC priority to AC3}$

 if $current_queue_length < TH(n)$

 accept pkt

 else

 discard pkt

 if n is not the highest priority then

$LL(n) ++$

 if $LL(n) > ubh[n]$ then

$LL(n) = LL(n) - ubh[n]$

 if the higher threshold can be reduced

 for all threshold m from $n+1$ to 3

$TH(m) = TH(m) - mod_h[m]$

 endfor

 endif

 endif

endif

$LU(n) ++$

if $LU(n) > ubl[n]$ then

$LU(n) = LU(n) - ubl[n]$

if own threshold can be increased

$TH(n) = TH(n) + mod_l(n)$

endif

```

endif
endelse
endif
endfor

```

Figure 13. Algorithm for DBMS

The rationale for this algorithm can be described in an intuitive manner. Real-time traffic is time-sensitive in nature and thus need to be transmitted as fast as possible for QoS. The high volume of control packets generated in ad hoc networks can cause unnecessary consumption of bandwidth especially if the control packets are retransmitted in the event of route changes. Therefore, it is necessary to monitor the queues length such that if too many real-time and data packets are accumulated in the queue, it is necessary to reduce the number of control packets accumulated and transmit the data packets instead.

In the algorithm above, there is a form of inter-dependency among all the queues. When a particular queue has too many packets and thus have to drop packets, it will force higher priority queues to reduce their acceptable queue length while increasing its own acceptable queue length. In this way, the packets in the particular queue will be given some form of priority over others in such situations. This can also introduce some flexibility in the priority queueing scheme.

In the worst case scenario when too many packets are dropped, there can be a situation in which higher priority queues reduce their acceptable queue length by an unacceptable margin. This will mean that higher priority packets will be penalized heavily over lower priority packets. Thus the threshold values for each EDCA queue have to operate within a minimum and maximum bound to prevent this.

3.3. Simulation Results

To further justify the effectiveness of the DBMS scheme, a simulation is conducted on both a static network and a mobile network scenario. For both scenarios, the total number of nodes is 200 with varying number of source nodes ranging from

10 to 100. The composition of the source nodes being audio sources, video sources and non-real time data sources are 20%, 30% and 50% respectively. All source nodes transmit packets in a constant bit rate manner. The transmission range of each node is 100m with a bit rate of 11 Mbps. The network area is 1250m by 800m and the routing protocol used is AODV. Glomosim is used as the simulator. Following simulation scenarios conducted in previous literature, the simulation time is set to 10 minutes and each source node is transmitting at 4 packets/sec. The maximum queue length is 100 and the TH for each EDCA queue is 50 initially. The values of ubh and ubl is 5 and the modification step is 1^3 . All packet loss counters are initialized to 0. The TH for each EDCA queue are allowed to vary from a minimum value of 25 to a maximum value of 75.

Let us consider the first case of the static network. In this case, all the 200 nodes are uniformly distributed within the network area. The following parameters are considered:

Average end-to-end delay – (Total time taken for all packets to travel from source nodes to destination nodes) / (Total number of packets)

Average throughput – (Total number of bits received per second) / (Total number of sessions)

Figure 14 and 15 shows the simulation results of the average delay and the average throughput per node for both 802.11e without and with the DBMS scheme.

³ These values are proposed to illustrate the effectiveness of this scheme. It is recognized that these values may not be optimal and requires further studies to understand the influence of these values on the network performance.

Figure 14. Comparison of both schemes in terms of delay in static network environment

Figure 15. Comparison between both schemes in terms of throughput in static network environment

From figure 14, it can be seen that the average end-to-end delay for 802.11e using DBMS scheme has been reduced to a certain extent as the number of source nodes gets larger. If we compare the average end-to-end delay for all traffic types for both 802.11e without DBMS and 802.11e with DBMS, it can be seen that for all traffic types, the delay has been reduced.

Figure 15 displays the comparison of throughput. In terms of throughput, 802.11e with DBMS has shown to have better audio throughput than normal 802.11e although the improvement seem to be marginal. Nevertheless, such improvement can be enhanced through further research in the future. Both the results have suggested that

proper management of the control packets and data packets can lead to enhanced network performance. These results prove the effectiveness of the DBMS scheme under static network.

Let us consider the second case for a mobile network. In this case, the random waypoint model is adopted with a speed range of 5-10 m/s and a pause time of 30s. We shall examine the packet delivery ratio and average delay under such conditions through the use of Glomosim.

Packet Delivery Ratio – (Total number of packets received successfully) / (Total number of packets sent)

Figure 16. Comparison of both schemes in terms of packet delivery ratio

Figure 17. Comparison of both schemes in terms of average delay in mobile network

Figure 16 and figure 17 shows the simulation results of the packet delivery ratio and average end-to-end delay for both 802.11e without DBMS and 802.11e with DBMS under a mobile network scenario.

From the simulation results, it is clear that 802.11e with DBMS performs better than 802.11e without DBMS in terms of packet delivery ratio and average end-to-end delay. All the traffic types perform better under DBMS scheme and thus helps to justify the effectiveness of the DBMS scheme. Once again, it is shown that if proper management of the high control overhead is done, the performance of 802.11e can be improved with little side effects. However, it is recognized that further research has to be done in order to make the scheme perform even better.

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3.4. Concluding Remarks

The ability of the 802.11e MAC protocol to provide QoS in an ad hoc network environment is dependent on the management of the various traffic packets. To enhance the network performance through the proper management of the traffic packets, a proposed dynamic buffer management scheme (DBMS) has been proposed. Simulation results have shown that the use of the DBMS scheme has improved network performance although some of the improvement are only marginal.

Strictly speaking, the proposed DBMS algorithm is not fully dynamic as it depends on the assignment of values for the control parameters. The impact of the control parameters have to be studied using simulation. However, from the proposed algorithm, the range of values for some parameters can be inferred. For example, $mod_h(n)$ must be kept small ($= 1$) as it has a wider impact on several queues as compared to $mod_l(n)$. $ubl(n)$ must be larger than $ubh(n)$ so that in the event of packet loss, the affected queue will increase its threshold first before decrease other queues threshold as a final resort. Part of the future work recommended will be focused on improving the algorithm.

Chapter 4

Cross Layer Designing in Ad Hoc Networks

To meet the needs of QoS requirement of multimedia traffic in wireless networks, IEEE 802.11e protocol has been standardized as the QoS MAC protocol. The medium access control (MAC) layer of 802.11e has provided QoS support through priority scheduling for different types of traffic. However, the 802.11e QoS mechanism has an impact on the higher layers i.e. Network layer and create new issues that need to be considered seriously. For example, there exists a path correlation between different data types especially when they share a common link in the network layer. Under high traffic load, the correlation effect will cause many re-route procedures for paths which are shared by different data types as lower priority traffic is likely to be blocked. Such re-route procedure will downgrade the QoS service for the high priority traffic as the common link is broken for all traffic. To break the correlation effect, in this paper, we propose a cross-layer scheme called: Bundled Virtual Circuit to deal with the scheduling and routing in wireless ad hoc networks. The key feature of BVC is taking in account of the influence of priority scheduling in MAC layer when designing routing scheme at network layer. The proposed scheme could provide better QoS service for wireless ad hoc networks with 802.11e from simulation results.

4.1. Motivation

As stated in the earlier chapter, cross layer designing is one method in improving QoS of ad hoc networks. The main idea behind cross-layer designing is to make use of cross-layer information for better representation of network condition. This will facilitate better decision making for protocols when it come to handling changes in network condition. In this chapter, we shall examine the cross-layer influence of the IEEE 802.11e on the network layer and how we can make use of cross-layer designing to improve the performance of an ad hoc network.

IEEE 802.11e has been standardized as a QoS standard for 802.11-based networks. It provides QoS support for multimedia traffic through priority scheduling. This QoS MAC protocol may bring new issues in upper layers, i.e. Network layer. However, most QoS protocols for ad hoc networks have been too focused on their respective OSI layers, neglecting the influence from other layers. Furthermore, few of them considered the issues arising due to their adaptation of the 802.11e. In the priority scheduling of 802.11e, the lower priority traffic has a higher probability of being blocked. Hence, the MAC layer will inform the Network layer of a broken link through the link notification function. For existing routing protocols eg. AODV, they will re-route the paths including the link. Therefore, the higher priority traffic which share the same link as the lower priority traffic will face the same re-route procedures. We termed this phenomenon *path correlation effect*. There exists a path correlation when different data types share a common link along their paths. Under high traffic load, the path correlation effect will be more intense as lower priority traffic flows are more likely to be blocked at the MAC layer. The QoS of high priority traffic will be downgraded as a result. This is a challenge that needs to be addressed carefully.

4.2. A Proposed Cross Layer Design of Routing and Scheduling for QoS Services in Ad Hoc Networks

In order to break the path correlation effect, we propose a Bundled Virtual Circuit scheme that couples routing and scheduling. The main feature of the Bundled Virtual

Circuit scheme is to provide differentiated services consistently across both Network and MAC layers. The scheme also provides a bundled technique to deal with high volumes of control traffic in order to ensure strict QoS treatment for different data types. For our proposed Bundled Virtual Circuit scheme, the QoS MAC protocol is based on 802.11e while the QoS routing protocol is a modified AODV explained later. The cross-layer design couples the operation of a MAC protocol and a routing protocol and is based on the framework illustrated in figure 10.

4.2.1. MAC Layer Design

In the MAC layer, we design a queueing scheme called the Bundled Control and Data Priority Queueing (Bundled for short). We still adopt the 802.11e Access Control (AC) queue structure except that AC3 will be used to hold audio packets, AC2 be used to hold video packets and AC1 be used to hold data packets. The reason behind this mapping is due to the traffic characteristics of the various services. Audio traffic is generally delay-intolerant and any delay or packet drop can be perceived by end user easily. Video traffic has a slightly higher tolerance for delay as compared to audio traffic and thus can be placed at a lower priority. Non real-time traffic is delay-tolerant and packet transmission can be conducted with a longer delay. Thus audio traffic is mapped onto AC3 being the highest priority traffic with the smallest delay requirement, followed by video traffic and data traffic in AC2 and AC1 respectively. The main idea behind the design is that network control packets will have to be classified into different priorities. A control packet will be prioritized according to the type of data packets associated with it. So for example, if a source node is transmitting audio packets, then any control packets generated for these audio packets as a result will be classified in the same AC queue. Thus, the control traffic will be separated into control_audio, control_video and control_data. The rationale for this design is to ensure a stricter form of differentiated services in the MAC layer and this will be explained in more details in later paragraphs.

One of the challenging issues for 802.11e in ad hoc networks is that: if strict priority queueing is deployed at the MAC layer to schedule different kinds of packets, the high priority packets will cause starvation of the lower priority packets, especially,

when control packets are put in the high priority queue, the control packets will consume most of the bandwidth, and the performance of data packets will become poor. This is aggravated by the fact that there are a higher number of control packets than data packets in ad hoc networks.

Network control packets, Route Requests (RREQ), Route Reply (RREP) are used whenever a new route is required for a traffic stream, be it audio, video or data. Similar differentiation for control packets is necessary for the following reasons. If control packets are always given highest priority regardless of their corresponding traffic type, higher priority traffic such as real time packets will be penalized by the control packets which are associated with low-priority data packets. This will downgrade the QoS for high priority packets. To give an illustration, we use a simple example as shown in Fig 18.

Figure 18. An Example Scenario for 802.11e

Suppose S1 is a data source and has a data packet and a corresponding control packet to send while S2 is an audio source and has an audio packet and a corresponding control packet to send at the same time. Both source nodes will have to send out control packets for route discovery. However, S2 should be accorded higher priority as it is obvious that its traffic is of higher priority. S1 and S2 will have to contend for channel access using CSMA/CA. But given that all control packets are the same priority, there may be a situation in which that the control packet from S1 win the contention and gain access to the channel instead of S2, thus hampering S2's

access to the channel. As a result, S2 will be penalized in a way as it has to give way to control packets for lower priority traffic, in this case, control packet from S1.

Figure 19. An Example Scenario for the Bundled Scheme

To ensure that high priority packets are not penalized by the control packets in such situation, the following proposal is made. In the proposed scheme, network control packets will be classified into different priorities. A control packet will be prioritized according to the type of traffic associated with it. So for example, if a source node is transmitting audio packets, then any control packets generated for these audio packets as a result will be classified in the same AC queue. As shown in Figure 19, using the same example scenario as Figure 18, the control packets and their corresponding traffic are queued in the same AC queue. For S1, both the control and data packets will be queued in AC 1. For S2, both the control and audio packets will be queued in AC3. Thus when the data packets are transmitted to the destination node D, the audio packet will not be penalised as a result. The Network layer will be discussed in the next subsection.

4.2.2. Network Layer Design

For the network layer, we design a virtual circuit (VC) scheme based on the AODV protocol. As mentioned earlier, all the packets will be classified in the AC queues in the MAC layer. This will bring a new issue to the Network layer due to this

change. This new issue is the path correlation effect. To deal with this issue, AODV will be modified. When a lower priority traffic, say, data packet, is blocked at the MAC layer and notify the Network layer of a broken link, the VC scheme will only set the broken link to data traffic and re-route the data traffic by using other links. Higher priority traffic, e.g. audio or video that share this link will not be affected and can continue to be transmitted via this link. The rationale for this change can be explained as follows.

For AODV, shortest path are set up based on source-destination information regardless of traffic type. Thus whether a route will break depends highly on whether a particular packet can reach its destination within a reasonable period. The problem here is that there exists a correlation between traffic types that share a common link. Audio traffic will not have much problem making use of this link as it is queued in the highest priority queue. However, for low priority traffic such as non real-time data packets, they will face fierce contention at the MAC layer due to the presence of high priority traffic. When low priority traffic cannot be sent out successfully, a route will be considered broken and a Route Error (RERR) packet will be generated according to existing AODV mechanisms to perform re-route procedures. This situation will cause routes that are still usable by high priority traffic to be classified as broken due to low priority traffic problems which is inappropriate. Such procedures will downgrade the QoS for high priority traffic.

Figure 20. An Example Scenario for AODV

To illustrate, Figure 20 shows an example scenario for the AODV routing protocol. Suppose the network is initialized in such a way that S1, S2 and S3 have

audio, video and data packets respectively to destination D. There are two intermediate nodes IN1 and IN2 along the path. {A} denotes an audio route entry per hop; {V} denotes a video route entry per hop; {D} denotes a non real-time data route entry per hop. Thus {A, V, D} will share the common link from IN1 to IN2. If the data traffic cannot be transmitted successfully due to contention issues or insufficient bandwidth etc, the link of IN1 to IN2 will be considered to be broken and RERR will be generated to all the source nodes. Consequently, all the three routes are classified as broken. There will be underutilization of bandwidth as audio and video routes can still be supported.

Figure 21. An Example Scenario for VC scheme

To solve this issue, all nodes will be keeping three routes corresponding to traffic types. In the event, that a link is broken due to low priority traffic problem, the relevant low priority path information will be updated as broken while keeping the high priority path information intact. This will help to eliminate the correlation issue between the different data types due to common link. To illustrate our new scheme, Figure 21 shows a example scenario for the VC scheme. In this case, all the nodes will have an audio route table, a video route table and a data route table. Given the same situation, if IN2 is not able to transmit data packets to D due to contention issues, insufficient bandwidth etc, a RERR will be generated. However, in this case, only the data route will be marked as broken and the audio and video routes are still intact. Thus there will be no underutilization of bandwidth and minimal link breakage.

In short, the combination of the mechanisms used in Bundled VC scheme can be modeled as having priority treatment of data traffic in both Network and MAC layers in a coupled manner.

4.3. Simulation Results

Glomosim is used as the simulator. There are two simulation scenarios. For both scenarios, three types of traffic are defined namely, audio, video and data. For the bundled scheme at the MAC layer, audio, video and data packets are queued in the AC3, AC2 and AC1 queues respectively. At the network layer, AODV control packets consist of RREQ, RREP and RERR packets. RREQ will not be queued as they are broadcasted in nature. Thus only RERR and RREP packets will be queued according to the type of packets they are supporting. To facilitate the functionality of this scheme, the control packets (RREP and RERR) will be further classified into Control_Audio, Control_Video and Control_Data. So if a RREP is created for audio traffic, then the RREP will be classified as Control_Audio. The same applies to RERR. For the virtual circuit at the Network layer, our Bundled VC scheme will be modified to have three instances of the routing mechanisms for audio, video and data traffic. This applies to network buffers as well.

The parameter for both simulation scenarios are also defined as follows. The network area is 1250m by 800m and the total number of nodes is 200. The nodes are uniformly distributed in the static network scenario and the nodes are randomly distributed in the mobile network scenario. The number of source nodes is varied from 20 to 100 nodes and the traffic load is CBR at 4 packets/sec. The simulation time is 10 mins. The transmission range is 100m with a bandwidth of 11 Mbps. The ratio of source nodes of audio:video:data traffic is 2:3:5 respectively. We have selected 802.11e and AODV as they are commonly used in ad hoc networks studies. Thus, the network performance of the 802.11e/AODV versus the Bundled VC scheme will be compared.

The first scenario considers the performance under a static network. In this scenario, the metrics used are the packet delivery ratio and the average end-to-end

delay. The packet delivery ratio is defined as the total number of packets received over the total number of packets sent. The average delay is defined as the average time taken for a packet to be transmitted from a source node to a destination node.

Figure 22. Packet Delivery Ratio in Static network

Figure 23. Average Delay in Static Network

From the above simulation results, it can be observed that the Bundled VC scheme has a higher packet delivery ratio than the 802.11e/AODV protocols. The Bundled VC scheme also incurs lower delay. Such improvement in packet delivery ratio is partly due to the VC scheme at the Network layer. In a static network, the reason for

any links break will be mainly due to contention at the MAC layer. As the dependency between the different types of routes is eliminated, any traffic contention that affects lower priority routes will not influence high priority routes. Thus the effect of a link break will be more restricted as compared to AODV. This is also coupled by the fact that the Bundled VC ensures priority scheduling from the Network layer to the MAC layer due to its design. A high priority packet will be given high priority treatment starting from the Network layer and not from the MAC layer as compared to 802.11e only. These two mechanisms help to improve packet delivery ratio and average delay.

The second scenario considers the performance under a mobile network. In this case, the speed of the nodes is 1-3m/s with varying pause time and the number of source nodes is 50; other parameters are the same as before. The average network throughput and average end-to-end delay are measured in this case where average throughput is defined as the total number of bits received over the total number of nodes in the network.

Figure 24. Average Delay in Mobile Network

Figure 25. Average Throughput in Mobile Network

From the simulation results above, Bundled VC generally incur lower delay as compared to 802.11e/AODV for different pause times. This is expected for similar reasons as the first scenario. For the average throughput, it can be observed that the throughput is higher for audio and video traffic but lower for data traffic as compared to 802.11e/AODV. This is expected as the Bundled VC is a stricter form of priority queueing mechanism. Audio and Video traffic in this scheme are given stricter QoS treatments and thus adversely affects the data traffic especially at lower pause times. However, as the main aim is to ensure QoS for high priority traffic, this scheme is still justifiable in the sense that audio and video traffic are given better QoS treatment though at a higher expense for data traffic.

4.4. Concluding Remarks

In this chapter, cross-layer design for QoS protocols has been explored and analyzed. The key idea behind cross-layer design is to ensure accurate network information is communicated correctly between different layers to facilitate effective actions in response to current network conditions and traffic needs.

A cross-layer design at the Network and MAC layer has been proposed. This Bundled VC design mainly makes use of traffic type information to facilitate decision making and traffic differentiation at these two layers. Although the cross-layer

interaction in this scheme is not tightly coupled, the Bundled and VC mechanisms do complement each other in a way, thus providing improvement in network performance compared to two protocols that are designed independently.

Recommended future work will involve designing a more tightly coupled cross-layer protocol. It will be necessary to consider cross-layer interaction not only between adjacent layers i.e. MAC and Network layer, but also between non-adjacent layers such as Physical and Network. The influence of mechanisms at different layers would also be investigated from both bottom-up and top-down perspectives. The possibility of designing cross-layer protocols that span more than two layers should also be explored.

Chapter 5

Flow Admission Control in Ad Hoc Networks

One of the main problems that affect QoS in wireless ad hoc networks is the multi-hop network nature which leads to problems such as sharing of low bandwidth, high control overhead generation and congestion. Low bandwidth leads to high contention for network resources. The high contention may make ad hoc networks management very challenging. High control overhead will increase bandwidth consumption. Congested routes further aggravate the existing problem by causing more control packets to perform route maintenance. In addition, established routes are not well-protected and are subjected to changes in traffic loading, thus reducing the QoS provided and wasting network resources. Thus we propose a flow admission control scheme at the routing layer to mitigate the above problem by taking pre-emptive measures through bandwidth and congestion estimation. This will reduce unnecessary control overhead for route maintenance and select a proper route for a flow, thus improve overall network performance. Not only that, established routes will be protected from any changes in traffic loading for the duration of the route lifetime. Simulation results will verify that the proposed scheme results in good network performance.

5.1. Motivation

One main reason why QoS provisioning in wireless ad hoc network is more challenging as compared to centralized wireless network is due to its multi-hop nature. In wireless ad hoc networks, packets can be forwarded via intermediate nodes from source to destination without the need for centralized coordination. While this feature provides certain advantages in scenarios where network deployment has to be quick and cost-effective, it is also one of the main problems when it comes to ensuring end-to-end QoS.

There are various reasons in which network routes can fail to provide QoS to traffic via multi-hopping. The first reason is due to a lack of bandwidth in wireless ad hoc networks. As the wireless medium is shared among neighboring nodes, contention of resources will normally occur, making effective utilization of bandwidth difficult to be achieved. Often, the introduction of new flow will change the dynamic of the existing network states, causing more contention as a result.

The second reason is due to high network control overhead. Multi-hop data transmission requires a high volume of network control overhead in creating or maintaining network connectivity. Each single link created between two intermediate nodes will require the roughly the same amount of control overhead as a link created between a WLAN access point and a node. For multi-hopping, the amount of control overhead will be proportional to the number of hops. From the network layer perspective, there is a relationship between routing and control overhead, i.e. any changes in network condition that can affect network routes may cause more control overhead. For example, a broken route can easily cause a route maintenance process which is a chain reaction of producing control overhead along the route. This results in high control overhead which can lead to poor network performance, especially when the route is long.

The third reason is due to congestion caused by imbalanced traffic loading. In a multi-hop network, improper path selection can easily lead to congestion in intermediate nodes located in the intersection of various routes. Normally, established

routes are not well-protected and are subjected to such traffic changes. The consequences often results in the hot spot problem, in which loss of packets or high delay is experienced in the congested intermediate nodes.

Taking a pre-emptive step, the likelihood of congested routes can be reduced through the implementation of flow admission control scheme during the route discovery phase. Nodes that are likely to be reach congestion state will be avoided during route construction. By ensuring that flows are distributed evenly within network constraints, unnecessary control overhead required for route search and maintenance can also be avoided in the early phase. Established routes will also be protected from new traffic flows that can be disruptive to their present states.

Based on the above principle, we introduce a flow admission scheme that performs routing through available bandwidth and congestion estimation. During the route discovery phase, each node will be gauged on its estimated available bandwidth. The requested flow rate is compared with the available bandwidth to see if it can be admitted into the node. To provide better QoS, the backlog packets in an intermediate node has also been considered in order to prevent longer queueing delay. If a node has held a large amount of backlog in its buffers, it will not admit the flow as well. If a node is able to satisfy both of the above criteria, it will participate in the route discovery phase and be part of the eventual route established. If it is not able to satisfy any of the criteria, it will remain silent throughout the route discovery phase. More details of the proposal will be presented in later sections.

5.2. Routing and Control Management in Wireless Ad Hoc Networks

We can consider control overhead in two perspectives: useful and non-useful. Control packets that are created and managed to perform their required functionalities can be termed as “useful” control overhead. For example, if route requests and replies are created that manage to result in a route being constructed and good traffic performance eventually, these control packets can be seen as useful. On the other

hand, there will be situations in which control packets are generated and yet are not able to perform their functions well due to poor network condition. Following the earlier example, if a constructed route happens to involve some congested nodes, there will be chances that packets along this route may be dropped, in the mean time, affecting the existing flows pass the congested nodes, resulting in more control packets being created due to local route repair etc. In such cases, these control packets can be considered as non-useful. While we cannot eliminate such cases completely, the ideal case is to minimize such situations as much as possible through proper flow admission.

In our proposed scheme, we aim to provide an optimal route for a flow through the use of flow admission control during the routing search stage. The optimal route should provide some form of bandwidth reservation and be less likely to reach a congested state. The route should be protected sufficiently from any changes in traffic condition that can affect any existing QoS provision.

We recognize that flow admission control in wireless ad hoc networks is more challenging than centralized wireless network. Due to multi-hop network nature, it is difficult to get accurate parameters to be used as criteria for proper flow admission. This is especially so when contention in the wireless medium makes it difficult to accurately reflect true network condition and gauge whether a flow should be admitted. On top of that, there is always the route length bias in which the throughput of a flow decreases with longer route length. Thus, in our proposal, we purely make use of estimated parameters in view that the network condition can be dynamic.

5.3. A Routing Scheme based on Flow Admission Control for Wireless Ad Hoc Networks

We assume a shared single channel physical layer for all the nodes. As a wireless node's capacity has to be shared by all the traffic flows through it. In order to conduct admission control properly, we need to measure the available bandwidth and compare with the requested flow rate. We also consider backlog traffic in the node buffers and

reserve bandwidth based on their expected delay bound as well. We assume each class i has delay bound D_i . The next two subsections will provide an explanation of the model from both perspectives individually. The third subsection will provide an explanation of our proposal in details.

5.3.1. Available Bandwidth

C	Shared link capacity of a node
q_j^i	Average rate of a flow j /class i
D_i	Delay bound for class i
T	Estimated transmission time per hop
x_i^k	Number of hops for flow k of class i to reach intermediate node
m	Number of priority classes
n	Number of flows
w_i^k	Number of bits waiting in a queue belonging to a flow k of class i
n_i	Number of flows of class i at an intermediate node

Table 1. List of Notations

Let us assume that a typical node in a wireless ad hoc network has a limited bandwidth C to service incoming traffic flows. We denote an incoming packet of a particular flow as q_j^i where i is the priority class of the flow and j is the number of such flows.

We assume that there are a total of n flows and m classes in the network. Class i has n_i flows at an intermediate node. When a new flow say q_i^{new} , sends a route request to an intermediate node during the route discovery phase, it should satisfy the following inequality:

$$q_i^{new} + \sum_{i=1}^m \sum_{k=1}^{n_i} q_i^k \leq C \quad (1)$$

(1) considers the bandwidth allocation for the flows based on the average rate. Based on the above inequality, nodes that do not have sufficient available bandwidth to accept the requested flow rate will drop the route request packets. In this way, packet loss due to low bandwidth can be avoided.

5.3.2. Backlog Traffic

Figure 26. Illustration of delay bound parameter reduced by T per hop

We define a congested node when it has traffic inflows more than it can cope. Thus a node can be congested when it has a low bandwidth (due to sharing of bandwidth with multiple neighbours or poor network condition etc) and its queue length is high (meaning that packets are not able to be transmitted fast enough). For better QoS, we also consider backlog in the buffers. This second criteria aims to take into account these factors.

We introduce a soft delay bound parameter D_i to ensure more weight given to higher priority traffic. We also like to provide some form of priority given to traffic with shorter hops so to justify the control overhead generated. To do this, we allow the soft delay bound parameter to be reduced by the transmission time T per hop as in Figure 26. For simplicity, we assume consistent transmission time across all hops given that the network topology to be simulated is a grid topology. It can be seen that as the number of hops x_i^k grows longer, the delay bound parameters will be smaller.

We assume there are m class traffic in the network, class i has n_i flows. Assume that at any instant, an intermediate node contains $\sum_{i=1}^m \sum_{k=1}^{n_i} w_i^k$ bits in total waiting in the buffer. Now a node will avoid congestion to provide better delay guarantee, it need to satisfy the following inequality:

$$C - \sum_{i=1}^m \sum_{k=1}^{n_i} \frac{w_i^k}{D_i - x_i^k T} \geq 0 \quad (2)$$

The above inequality means that a node must contain sufficient bandwidth capacity to serve its backlog traffic within a reasonable number of hops such that the required delay guarantee could be met.

In this way, we could avoid to select some nodes with huge amount of backlog traffic waiting in the buffer, which could cause longer delay and violate delay bound.

5.3.3. Flow Admission Control Scheme

Our proposed flow admission scheme will make use of a combination of the above two criteria. During the route discovery phase, network control packets in the form of route requests will be broadcast to the entire network. When a node receives a route request, it will only forward the route request when

$$C - \sum_{i=1}^m \sum_{k=1}^{n_i} q_i^k - \sum_{i=1}^m \sum_{k=1}^{n_i} \frac{w_i^k}{(D_i - x_i^k T)} \geq 0 \quad (3)$$

The above inequality means that a node must contain sufficient bandwidth capacity to meet its existing traffic flows and backlog traffic within a reasonable number of hops in order to meet the required delay guarantee. It should be noted that the inequality includes the flow rate for the new route request as well. If a node has sufficient bandwidth after taking into account its existing flows and buffer length, it will proceed to forward the route request and be part of the eventual route established. Otherwise, it will just drop the route request. During the period when the node is part

of a route, it will reserve bandwidth pertaining to the particular incoming flow corresponding to the route request. A node will continue to admit flows in this manner until its bandwidth has been totally reserved for both incoming and outgoing traffic.

The beauty of this scheme is that it is able to strike a balance indirectly between admitting more flows and facing congestion. When a node has experienced a change in network condition (such as high noise level, heavy contention etc), outgoing packets will be transmitted at a lower rate than usual. Under such a situation, the number of bits stuck in the buffer will increase and the node will reach congestion state. The flow admission scheme will proceed to reserve more bandwidth for existing admitted traffic flow by not admitting new incoming traffic. Thus, route requests for new traffic flow will face a higher probability of being dropped in congested nodes. In summary, a node will only participate in route discovery if it has sufficient bandwidth and is not likely to be congested.

5.4. Simulation Results

We use Glomosim as our network simulator. We model the flow admission control scheme into AODV routing protocol and 802.11e MAC protocol as both of these protocols are common standards suitably used for wireless ad hoc networks. To implement the flow admission scheme in simulation, we piggybacked the bandwidth and congestion information into the route requests and route replies. As such, we will compare the performance between the standard 802.11e/AODV versus our 802.11e/AODV with flow admission scheme. For the simulation, we define three classes of traffic, namely class 1, class 2 and class 3 in descending order of priorities. They will be queued into AC2, AC1 and AC0 MAC buffers. All the source nodes are located at one end of the topology and send traffic to the destination nodes located at the other end of the topology. The source-destination pairs are purposely selected such that the routes constructed are not necessary in a straight manner end to end. The network nodes are placed 100 m apart from each other and the transmission range is 100 m. Each source node will transmit all 3 classes of traffic.

In the flow admission scheme, the delay bound parameters are arbitrarily defined as 200ms, 300ms and 500ms for class 1, class 2 and class 3 respectively. Each node will drop packets when they do not meet the delay bound upon arrival at the receiving nodes. Thus the simulation results will reflect only those packets that have met the QoS requirements. The simulation will be run for a total of 600 seconds. The traffic model is VBR. Each packet is 512 bytes long. The source nodes will transmit packets for 60 seconds periods alternate with 30 seconds silent interval. Routes will expire during the 30 seconds silent interval and new routes will be constructed when it is time to send packets again. This is to ensure some form of dynamic changes in the network condition and to examine how our proposed scheme will adapt to the changes.

The network scenario is a 25-node network in a 5 by 5 grid topology. The packet rate is an average of 20 packets per second to simulate a moderately-loaded network condition. The simulation is run by varying the number of source nodes from one to five. The simulation results shall provide the average end-to-end delay, packet delivery ratio and delay distribution of a 5 source nodes scenario.

Figure 27. Average delay for each class of traffic with and without the flow admission control scheme

Figure 27 shows the average end-to-end delay for each class of traffic with and without the flow admission control scheme. The average end-to-end delay is defined as the average time taken for a packet to travel from a source node to a destination node. From the above results, it can be seen that the average delay for all 3 traffic classes with flow admission control is better than the rest without flow admission.

This is largely due to the pre-emptive measures taken during the route discovery phase where the routes are carefully chosen based on their expected available bandwidth and congestion level. With the flow admission algorithm, nodes that have insufficient bandwidth or reaching a high congestion level will drop any route requests packets. Existing traffic flows in these nodes will be protected and new flows will be forced to find routes that will not pass through them. Thus packets will not suffer longer delay due to backlog and the average end-to-end delay will be lower as compared to that without flow admission control.

Figure 28. Packet delivery ratio for class 1 traffic with and without flow admission control scheme

Figure 29. Packet delivery ratio for class 2 traffic with and without flow admission control scheme

Figure 30. Packet delivery ratio for class 3 traffic with and without flow admission control scheme

Figure 28, 29 and 30 shows the packet delivery ratio for each traffic class with and without flow admission. We define the packet delivery ratio as number of packets received successfully divided by the number of packets sent. From the simulation results above, the packet delivery ratio of our proposed scheme is better for all traffic classes as compared to the standard protocols. There are a few reasons that lead to this result. There is more packet loss when the standard protocols are used as it is more difficult to meet the delay bound. As there is no flow admission control in the standard protocols, congestion in the intermediate nodes causes packets to be dropped. Even when the packets managed to arrive to the destination nodes, the packets are not able to meet the delay bound D_i for their respective classes and thus are dropped as well. When our proposed flow admission control scheme is used, routes established incur less congestion, thus there is less packet loss at both the intermediate nodes and destination nodes since they are more able to meet the delay bound.

Figure 31. Delay Distribution for 5 sources with and without flow admission control scheme

Figure 31 shows the cumulative delay distribution for a simulation scenario with 5 source nodes. We select the 5 source nodes scenario as this scenario produces the most number of packets. The result shows the percentage of packets that is delivered within the delay range. From the results, our proposed scheme is able to deliver packets with a stricter delay range as compared to the standard protocols. A larger percentage of the packets incur lower delay using the flow admission control scheme as compared to the packets under the standard protocols. Under the flow admission control scheme, the packets are routed through less congested routes with higher bandwidth. Thus there is better performance in terms of delay distribution for the flow admission control scheme as compared to the standard protocols.

5.5. Concluding Remarks

We have proposed a flow admission scheme that is based on available bandwidth and congestion level. With our perspectives on transmitting and receiving bandwidth, we will able to derive a general model and the algorithm from which we based our proposal on. Simulation results have shown that the proposed scheme performs better than the standard protocols. However, there is further room for improvement. For example, our scheme is still not able to reserve bandwidth on a priority basis for different flows from different sources completely. While this can be done easily for a single source-destination pair, it is challenging to do so for multiple flows from multiple source-destination pairs.

Another limitation is that the scheme may not work well in large networks when there are a large number of nodes. A longer number of hops in such networks will result in difficulty in meeting the delay bound parameters. This is an inherent characteristic of large wireless ad hoc networks and thus this problem will not be solved easily. However, our proposed scheme is able to filter out such long routes and prevent them from being constructed in the first place. This will be beneficial from a practical perspective since traffic with high QoS requirements will more likely to be dropped if they do not meet them in real-life applications. Thus rather than allowing such flows to be established, consume bandwidth and failed eventually, we took the pre-emptive step of not allowing such flows to occur and allow other flows higher probabilities of meeting QoS requirements by protecting them.

Chapter 6

Conclusion

In summary, we have investigated the ways of providing QoS in ad hoc networks at the MAC and network layer. Three QoS schemes have been proposed focusing on MAC layer, network layer and cross-layer designing. For QoS provisioning at the MAC layer, the dynamic buffer management scheme has been proposed. While simulation has shown favourable results for this scheme, more improvement can be made. Future research on this area can be focused on finding the optimized threshold value of the various AC queues length under various network conditions. Other aspects can be focused on improving the queueing algorithm such that it is adaptive enough to optimize its parameters in the face of changing traffic loading.

The cross-layer design, Bundled Virtual Circuit, has been proposed as well. Presently, the cross-layer design is still considered loosely coupled. Future research on this area can focus on making the coupling of the MAC and routing protocol design even tighter. However, one has to be mindful of the potential problems that can surface as a result of the tighter coupling. It is also necessary to consider the kind of application that is going to be used when cross-layer designing of protocols is being done.

The final QoS proposed scheme is the routing scheme based on flow admission control. Future work on this scheme can focus on providing some form of priority allocation of bandwidth for different flows from different source-destination pairs. It is expected that this area of work will be quite challenging as a balance need to be kept between admitting too many flows and maintaining the necessary QoS.

From a research overview perspective, we believe that cross-layer designing has a huge potential impact in ad hoc networking applications. Cross-layer designing can be considered as customization of protocols according to network needs and characteristics. The dynamic nature of ad hoc networks has made it necessary for

cross-layer designing to be done for specific desired performance. Future work on cross-layer design can focus on designing non-adjacent protocol layers design or cross-layer designing of multiple OSI layers. It will also be necessary to consider whether it can be implemented practically when such cross-layer designs are being proposed. The diagram below summarizes the scope of the research work that we have done.

Figure 32. Scope of Research

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