

**QUALITY OF SERVICE WITH DIFFSERV ARCHITECTURE IN  
HYBRID MESH/RELAY NETWORKS**

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The Academic Faculty

by

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# **QUALITY OF SERVICE WITH DIFFSERV ARCHITECTURE IN HYBRID MESH/RELAY NETWORKS**

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*To my lovely wife*

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## LIST OF SYMBOLS AND ABBREVIATIONS

3G	3rd Generation
4G	4th Generation
AC	Access Category
AC_BE	Access Category for Best Effort traffic
AC_BK	Access Category for Background traffic
AC_VI	Access Category for Video traffic
AC_VO	Access Category for Voice traffic
ACK	Acknowledgement
AdmittedQoSParamSet	an Admitted Set of QoS Parameters
AF PHB	Assured Forwarding Per-Hop Behavior
AIFS	Arbitration Inter-Frame Space
AP	Access Point
ATM	Asynchronous Transfer Mode
BE	Best Effort
BS	Base Station
CDF	Cumulative Distribution Function
CID	Connection Identification
CPE	Customer-Provided Equipment
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
CTS	Clear-To-Send
CW	Contention Window
Cwmax	maximum Contention Window

Cwmin	minimum Contention Window
DCF	Distributed Coordination Function
DE PHB	Default Per-Hop Behavior
DiffServ	Differentiated Services
DiffServ TC	DiffServ traffic conditioner
DIFS	Distributed Inter-Frame Space
DL	DownLink
DL-MAP	DownLink MAP message
DSA-ACK	Dynamic Service Addition Acknowledgement message
DSA-REQ	Dynamic Service Addition Request message
DSA-RSP	Dynamic Service Addition Response message
DSCP	Differentiated Services Code Point
DSSS	Direct-Sequence Spread Spectrum
EDCA	Enhanced Distributed Channel Access
EF PHB	Expedited Forwarding Per-Hop Behavior
ER	Edge Router
ertPS	extended real-time Polling Service
FTP	File Transfer Protocol
HCF	Hybrid Coordination Function
HTTP	Hypertext Transfer Protocol
IP	Internet Protocol
IPTV	Internet Protocol television
IPv4	Internet Protocol version 4
IPv6	Internet Protocol version 6
MAC	Medium Access Control

MAC CPS	MAC Common Part Sublayer
Mbps	Megabit per second
MMR	Mobile Multi-hop Relay
MSDU	MAC Service Data Unit
nrtPS	non real-time Polling Service
OFDM	Orthogonal Frequency-Division Multiplexing
OFDMA	Orthogonal Frequency-Division Multiple Access
PCF	Point Coordination Function
PHB	Per-Hop Behavior
PHY	Physical layer
QoS	Quality of Service
QoSParamSet	a Set of QoS Parameters
rtPS	real-time Polling Service
RTS	Request-To-Send
SDU	Service Data Unit
SFID	Service Flow Identification
SS	Subscriber Station
SS CS	Service-Specific Convergence Sublayer
TCP	Transmission Control Protocol
TDMA	Time Division Multiple Access
ToS	Type of Service
TXOP	Transmission Opportunity
UDP	User Datagram Protocol
UGS	Unsolicited Grant Service
UL	UpLink

UL-MAP	UpLink MAP message
VoIP	Voice over Internet Protocol
WiMAX	Worldwide Interoperability for Microwave Access
WLAN	Wireless Local Area Network
WMM	Wi-Fi multimedia
WMN	Wireless Multi-hop Network

## SUMMARY

The objective of this research is to develop an optimized quality of service (QoS) assurance algorithm with the differentiated services (DiffServ) architecture, and a differentiated polling algorithm with efficient bandwidth allocation for QoS assurance in the hybrid multi-hop mesh/relay networks. These wide area networks (WANs), which will employ a connection-based MAC protocol, along with QoS-enabled wireless local area networks (WLANs) that use a contention-based MAC protocol, need to provide an end-to-end QoS guarantee for data communications, particularly QoS-sensitive multimedia communications.

Due to the high cost of construction and maintenance of infrastructure in wireless networks, engineers and researchers have focused their investigations on wireless mesh/relay networks with lower cost and high scalability. For current wireless multi-hop networks, an end-to-end QoS guarantee is an important functionality to add, because the demand for real-time multimedia communications has recently been increasing. For real-time multimedia communication in heterogeneous networks, hybrid multi-hop mesh/relay networks using a connection-based MAC protocol, along with QoS-enabled WLANs that use a contention-based MAC protocol can be an effective multi-hop network model, as opposed to multi-hop networks with a contention-based MAC protocol without a QoS mechanism. To provide integrated QoS support for different QoS mechanisms, the design of the cross-layer DiffServ architecture that can be applied in wireless multi-hop mesh/relay networks with WLANs is desirable.

For parameterized QoS that requires a specific set of QoS parameters in hybrid multi-hop networks, an optimized QoS assurance algorithm with the DiffServ architecture is proposed here that supports end-to-end QoS through a QoS enhanced WAN for multimedia communications.

For a QoS assurance algorithm that requires a minimum per-hop delay, the proper bandwidth to allow the per-hop delay constraint needs to be allocated. Therefore, a polling algorithm with a differentiated strategy at multi-hop routers is proposed here. The proposed polling algorithm at a router differentially computes and distributes the polling rates for routers according to the ratio of multimedia traffic to overall traffic, the number of traffic connections, and the type of polling service.

By simulating the architecture and the algorithms proposed in this thesis and by analyzing traffic with the differentiated QoS requirement, it is shown here that the architecture and the algorithms produce an excellent end-to-end QoS guarantee.

# **CHAPTER 1**

## **INTRODUCTION**

Because of the increasing demand on wireless broadband Internet access, wireless single-hop networks with a wired backbone, such as WLANs [1] and cellular networks have been popularly used and widely deployed. However, due to the high cost of network construction and maintenance, a promising solution for providing connections of networks in regions without any infrastructure is to establish a wireless multi-hop network (WMN) [2]. A WMN is a network of nodes in a mesh/relay topology consisting of terminal nodes and routers that compose a mesh/relay cloud. Mesh/relay clouds are connected to the Internet through a mesh/relay gateway. WMNs can be classified into infrastructure WMNs with a multi-hop topology of routers, or client WMNs with a multi-hop topology of clients [3]. This study will focus on infrastructure WMNs.

Currently-deployed commercial multi-hop networks in industry have used the IEEE 802.11 technology as a radio technology [4, 5]. The coverage of the IEEE 802.11-based WMNs has been wide spread because of their easy and rapid deployment and good extendibility. However, the wireless communication industry has realized that the IEEE 802.11 standard is not suitable for commercial WMNs because its medium access control (MAC) protocol is not designed for multi-hop wireless networks. Since the MAC is a contention-based, distributed protocol, it cannot guarantee QoS. Thus, WMNs using the contention-based MAC protocol cannot provide a QoS guarantee for multimedia communication applications such as VoIP, IPTV, and videoconferencing [6]. However, the QoS guarantee is an important functionality for the MAC protocol of future WMNs



because the demand for multimedia communication has recently been growing [7]. In addition, due to the nature of the MAC protocol, IEEE 802.11-based WMNs also result in serious unfairness among multimedia traffic for users [8]. However, providing an equitable distribution of stable services for all users within the coverage of a WMN is the most important feature of commercial WMNs.

To overcome the shortcomings of contention-based radio technology for multi-hop networks, an emerging technology in wireless communication markets, WiMAX [9], can be deployed as a multi-hop backbone network technology. WiMAX, which is based on IEEE 802.16 standards [10, 11], offers a high bandwidth of 70 Mbps in a 50 km range, generally for a large outdoor environment, and it incorporates class-based and connection-based QoS features at the MAC layer. In many countries, it has already been successfully deployed and highly evaluated as one of the most promising technologies for 4th generation (4G) communication. As WiMAX becomes more successful in wireless communication markets and broadens its coverage, the WMNs of IEEE 802.16 can be a promising network model providing fast data transmission and stable multimedia communication.

The IEEE 802.16d [10] standard has already defined a mesh mode, and the task group 802.16j of the IEEE 802.16 mobile multi-hop relay (MMR) study group has recently been working on the standardization of fixed and mobile relay-based infrastructure WMNs [12]. Although an IEEE 802.11 task group is currently working on a mesh standard for IEEE 802.11-based WMNs, IEEE 802.11s [13], the standard has to be regarded as a technology different from the existing IEEE 802.11 standards and cannot be backward compatible to the deployed IEEE 802.11-based WMNs because IEEE

802.11s adopts time division multiple access (TDMA), which distinctly differs from the MAC protocol of the IEEE 802.11 standards [14]. In addition, the QoS scheme of IEEE 802.11s for stable multimedia communications is still in the preliminary stage.

As a radio technology for last-mile communication, the most popularly and widely deployed wireless networks since the original version of the standard IEEE 802.11 was released in the 1990s [1] have been the IEEE 802.11 WLANs. To provide user-level QoS support in IEEE 802.11 WLANs, task group e under the IEEE 802.11 working group has standardized IEEE 802.11e [15], an amendment to the IEEE 802.11 standard. IEEE 802.11e assigns a priority of traffic according to four access categories (ACs): voice, video, best effort, and background. As a commercial version of WLANs with QoS support, Wi-Fi multimedia (WMM) [16] is based on IEEE 802.11e.

By investigating these wireless standards, the hybrid multi-hop mesh/relay networks that use the connection-based MAC protocol with WLANs using the contention-based MAC protocol could serve as an effective network architecture for QoS support in WMNs since the 4G drafts [17] recommend the integration of wireless standards such as WLANs, WiMAX, and 3G cellular networks [18, 19, 20, 21]. Figure 1 shows the topology of the hybrid multi-hop networks. In addition, the heterogeneous WMNs, with classified QoS and parameterized QoS can provide QoS support for clients using multimedia applications.

Therefore, to provide a QoS guarantee for multimedia communications, the hybrid of mesh/relay networks and WLANs using IP bridging with QoS support are introduced. In addition, for classified QoS, a cross-layer design of the DiffServ architecture [22] in the hybrid multi-hop networks with classified QoS-enabled WLANs is proposed to

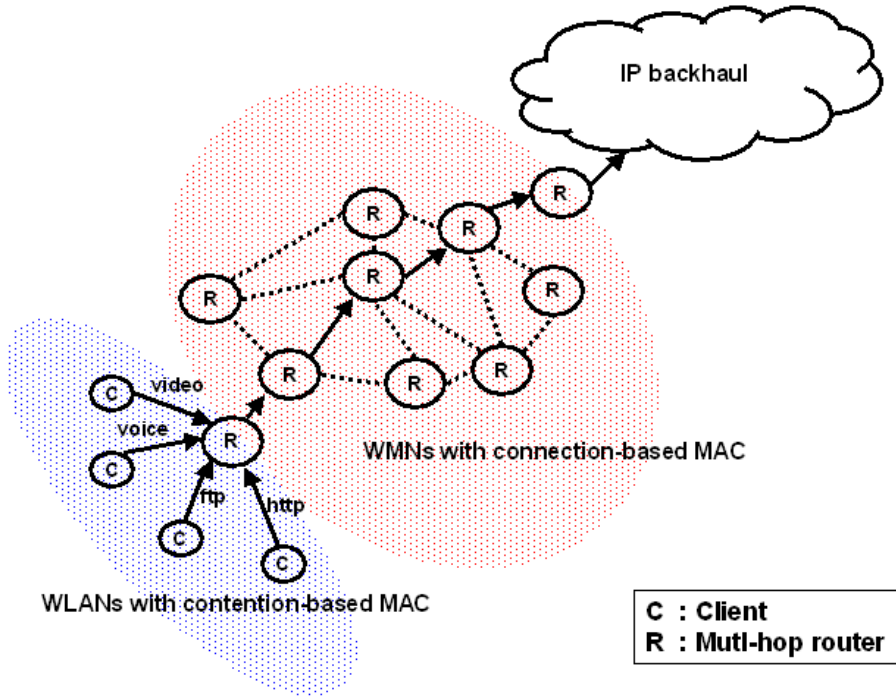


Figure 1. Topology of hybrid multi-hop networks

provide an end-to-end QoS guarantee for data and multimedia communications. Furthermore, a delay assurance algorithm with the DiffServ architecture for the hybrid multi-hop networks is proposed that supports parameterized end-to-end QoS for data transmissions, especially delay-sensitive multimedia communications. Moreover, to provide efficient bandwidth allocation according to the delay assurance algorithm, a polling algorithm with a differentiated strategy for characteristic parameters of the different classes traffic is investigated. By simulating the architecture and the algorithms proposed in this thesis and analyzing traffic with the differentiated QoS requirement using MATLAB [23] and OPNET Modeler 14 [24] for consistent and realistic simulations, it is shown that the architecture and the new algorithms produce an excellent QoS guarantee.

The remainder of the thesis is organized as follows. Chapter 2 provides the background of MAC protocols and QoS mechanisms for wireless multi-hop networks. Chapter 3 introduces the hybrid multi-hop networks with WLANs. Chapters 4 and 5 propose the cross-layer design of the DiffServ architecture and the delay assurance algorithm for the hybrid multi-hop networks. Chapter 6 investigates the polling algorithm with a differentiated strategy, and Chapter 7 draws conclusion from this work.

## **CHAPTER 2**

### **BACKGROUND**

#### **2.1 Contention-Based MAC for Wireless Multi-Hop Networks**

##### **2.1.1 Distributed coordination function**

The contention-based MAC protocol of IEEE 802.11 [1] is the distributed coordination function (DCF), which employs a CSMA/CA algorithm and an optional collision avoidance (CA) mechanism using request-to-send (RTS)/clear-to-send (CTS). To prevent packet collisions and bandwidth waste, the CSMA/CA protocol uses carrier sensing (CS) and collision avoidance mechanisms. In carrier sensing, a transmitter monitors the channel to decide if the channel is busy or idle. If the channel is busy, the transmitter waits until the channel becomes idle for the duration of a distributed inter-frame space (DIFS) and then calculates a random back-off time that is computed in the interval of  $[0, CW] \times \text{aSlotTime}$ . After the back-off time, the transmitter sends a packet. If a packet collision occurs as a result of two or more transmitters sending a packet at the same time, the transmitters have to calculate a new back-off time in the range of  $[0, 2 \times CW + 1] \times \text{aSlotTime}$ .

To prevent a hidden terminal problem, the DCF also contains a virtual carrier sense algorithm that uses exchanges of RTS/CTS frames. If a transmitter wants to send a message to a receiver, the transmitter first sends an RTS frame. If the receiver receives the RTS frame, the receiver announces to its neighbor nodes that the sender will get permission to send a packet by issuing a CTS frame. The duration field in the RTS and

CTS frames informs the neighbor nodes of the duration of the transmission. If the packet arrives at the receiver without an error, the receiver responds to the transmitter with an ACK packet.

### **2.1.2 DCF for multi-hop networks**

Because the DCF is originally designed for single-hop networks [25], the protocol produces serious problems for multi-hop networks. First of all, DCF-based WMNs still have a hidden terminal problem [26]. To prevent the hidden terminal problem, the DCF uses an RTS/CTS mechanism, but it works well only for conventional WLANs with infrastructures in which all nodes in a coverage area communicate through an access point (AP). In the case of multi-hop networks, neighbor nodes outside the communication range of the RTS/CTS sender cannot sense the messages, and the RTS/CTS mechanism is often not used in multi-hop backbone networks because it is not effective on long distance backhaul radio communications. Therefore, the DCF in multi-hop networks produces a hidden terminal problem.

Another problem is from the binary exponential back-off scheme of the DCF [27], which tends to provide more opportunities to send a packet to the latest successful node. If a node fails to send a packet, it doubles the previous back-off time window size. Therefore, the wait time of the node that failed to send data is more likely to be longer than that of the node that has just sent data successfully. This characteristic of the algorithm causes more serious unfairness in WMNs. For example, data passing through several nodes can be dropped at the last hop, right before the destination, because the destination node is busy receiving the data from the another node that has started sending

its data successfully. Therefore, a node sending data in WMNs may experience much longer delay and less stable throughput than one in the WLANs' infrastructure.

Moreover, because the DCF is a contention-based MAC protocol, one node with a large traffic load tries to use as much bandwidth as possible [28]. In single-hop networks, the protocol efficiently yields a higher data transmission rate. However, in multi-hop networks, it exacerbates the problem of unfairness in data transmission among nodes and the overall performance of the network.

Furthermore, the DCF is not appropriate for multimedia communications in WMNs [29]. To provide a QoS guarantee for multimedia communications in wireless multi-hop networks, the control of delay and throughput is important. However, the instability and unfairness of throughput and delay due to the DCF in IEEE 802.11-based WMNs compromise the performance of delay-bounded traffic such as multimedia communications. Because of these problems, multimedia services, which require constant QoS support, cannot maintain QoS for more than a few simultaneous users.

## **2.2 QoS Mechanisms for Hybrid Multi-Hop Networks**

### **2.2.1 QoS of IEEE 802.16 multi-hop networks**

#### **Overview**

The MAC protocol of IEEE 802.16 [10] is a connection-oriented, TDMA-based mechanism. Because of these characteristics, WiMAX can simultaneously and equitably provide multimedia services such as VoIP, IPTV, and video conferencing, which require a QoS guarantee.

The IEEE 802.16 MAC layer has two main sublayers, the service-specific convergence sublayer (SS CS) and the MAC common part sublayer (MAC CPS). The service-specific convergence sublayer describes how the service data units (SDUs) of an upper layer entity such as Ethernet, ATM, and IP are encapsulated into MAC service data units (MSDUs) on the MAC common part sublayer, and how the MSDUs are classified with connection IDs (CIDs), QoS parameters, and QoS classes.

The IEEE 802.16 standard defines five different types of traffic classes: (1) Unsolicited grant service (UGS) is designed for real-time traffic with fixed-size data packets generated periodically, so a fixed amount of bandwidth that minimizes delay is allocated; (2) real-time polling service (rtPS), which supports a variable bit rate for real-time traffic and provides uplink bandwidth allocation based on a polling scheme that can guarantee QoS for delay requirements, is suitable for variable rate real-time applications; (3) extended real-time polling service (ertPS), developed with the efficiency of both UGS and rtPS, supports variable-size data packets at periodic intervals and provides dynamic bandwidth allocation; (4) non-real-time polling service (nrtPS), designed for variable bit rate traffic with delay, uses a polled approach that maintains a minimum data rate, but it does not ensure the transmission of packets; and (5) best effort (BE) supports data traffic that does not require any QoS support [30].

The MAC common part sublayer of IEEE 802.16 provides connection establishment, connection management, and bandwidth allocation. To provide stable QoS support and allocate the bandwidth efficiently, the sublayer uses a TDMA-based scheduling algorithm. According to the results of scheduling, the base station (BS) broadcasts the uplink and the downlink MAP messages (UL-MAP and DL-MAP) to subscriber stations (SS). The



messages inform the SSs of the start and end times of their uplink/downlink transmission, the start time of the uplink allocation, and downlink preambles for synchronization. The scheduling algorithm of IEEE 802.16, which maintains stable and simultaneous data transmission even under overload and over-subscription conditions, distinctly differs from the MAC protocol of IEEE 802.11. Because of the scheduling algorithm, the BS can control QoS parameters by balancing bandwidth assignments for the traffic requirements of the SSs.

### **Connection-oriented MAC protocol**

The MAC protocol of IEEE 802.16 is a connection-oriented mechanism [31]. Through connections, all traffic, including packet-based traffic such as the IP and Ethernet, is transmitted. Therefore, the establishment of MAC layer connections is required before data exchange. The connection setup is the first process that guarantees QoS, assigns a service flow ID (SFID), and negotiates the QoS parameters for data traffic. Both sender and receiver stations negotiate QoS parameters, such as a maximum sustained traffic rate, a minimum reserved traffic rate, maximum latency, and so on, for data traffic flow. The SS CS of a sender station requests the creation of a MAC connection to its MAC CPS, and the MAC CPS sends a dynamic service addition request message (DSA-REQ) with a set of QoS parameters (QoSParamSet) to the MAC CPS of a receiver station. Upon receiving the DSA-REQ message, the receiver station assigns a unique SFID for the service flow within the DSA-REQ. If the service flow is successfully admitted to a connection, the receiver station sends back the dynamic service addition response message (DSA-RSP) with the SFID, a CID, and an admitted set of QoS parameters (AdmittedQoSParamSet). If the sender station successfully receives the

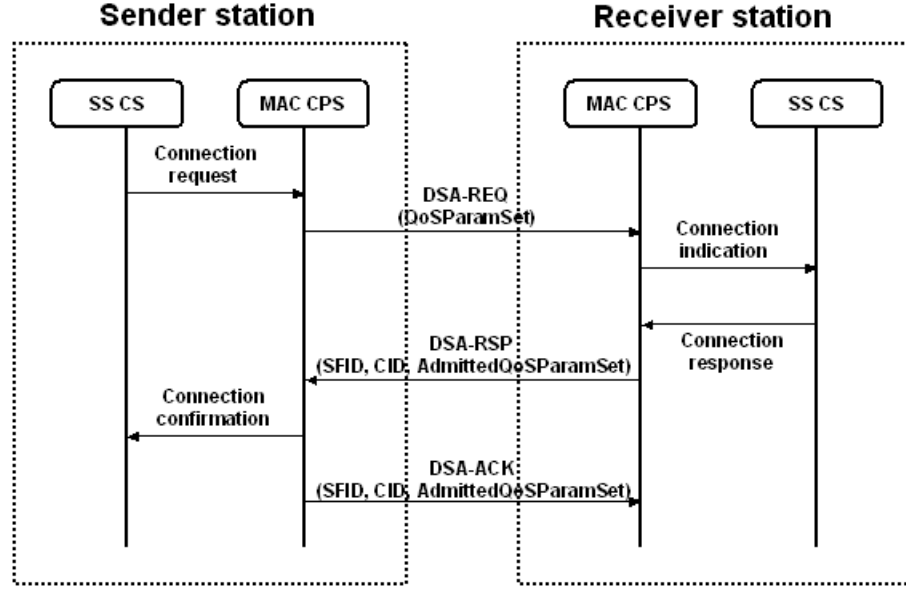


Figure 2. Process of a connection setup for traffic flow in connection-based MAC

DSA-RSP message, it sends a dynamic service addition acknowledgement message (DSA-ACK) to the receiver station. The process of a connection setup for traffic flow is demonstrated in Figure 2.

The mesh mode of IEEE 802.16d [10] and the MMR draft of IEEE 802.16j [12, 32] use the described MAC layer connection setup process and the class-based QoS mechanism.

### 2.2.2 QoS of IEEE 802.11e WLANs

The MAC scheme of IEEE 802.11e [15] is a hybrid coordination function (HCF). Combining the DCF and the point coordination function (PCF) of the IEEE 802.11 standard with an enhanced QoS mechanism, the HCF provides prioritized and parameterized QoS access to the wireless medium. The contention-based access method of the HCF is the enhanced distributed channel access (EDCA). Because WMM has only a distributed medium access mechanism, the EDCA is mainly focused on.

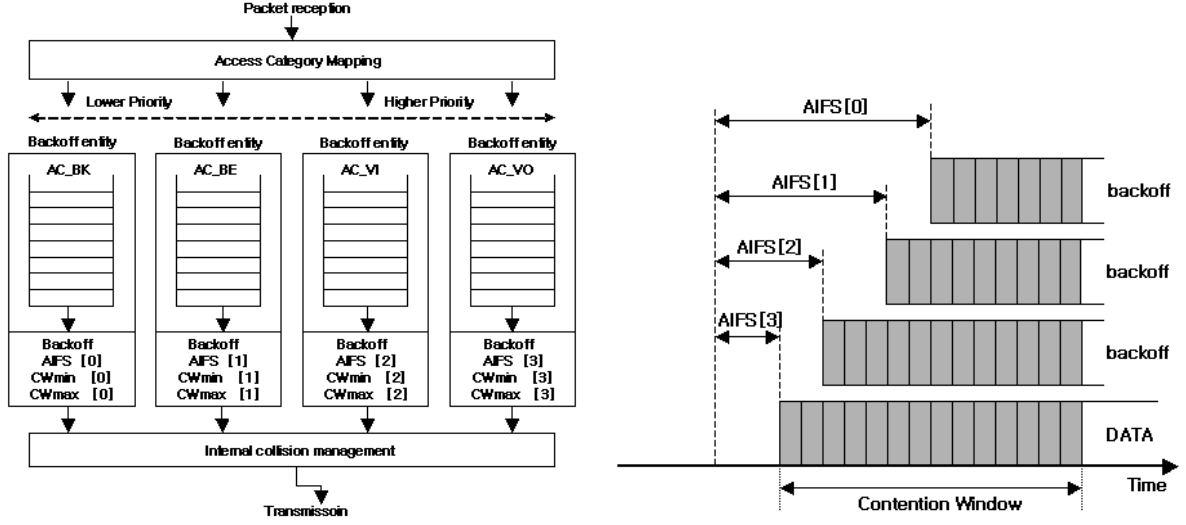


Figure 3. Four access categories of IEEE 802.11e

The EDCA provides QoS support using different ACs with their independent back-off entities. The ACs with four prioritized back-off entities are shown in Figure 3: AC\_BK for background traffic, AC\_BE for best effort traffic, AC\_VI for video traffic, and AC\_VO for voice traffic. With each AC, a set of EDCA parameters is associated. The parameters include an arbitration inter-frame space (AIFS [AC]), a minimum contention window (CWmin [AC]), and a maximum contention window (CWmax [AC]). The set of parameters, announced by an access point (AP), can change over the data transmission time. The back-off entities with the same AC in the stations in the coverage of an AP use the same EDCA parameter set. In stations where an AC competes with other ACs to obtain a transmission opportunity (TXOP), the AC starts a back-off timer after sensing that the channel is idle for an AIFS [AC]. Therefore, a smaller AIFS [AC] indicates a higher medium access priority. Each AC chooses a back-off time according to a uniform distribution over an interval of  $[0, CW [AC]] \times aSlotTime$ . The initial size of CW [AC] is CWmin [AC] and doubles to CWmax [AC] when a packet collision

occurs. Basically, a smaller  $CW_{min}$  [AC], inducing a shorter medium access delay, gains more opportunities to access the channel.

When the back-off times of two or more back-off timers in a station expire at the same time, the station experiences a virtual collision that is resolved by an internal collision management module of the station. To avoid an actual collision, the management module provides a TXOP for the AC with the highest priority. The other ACs make the size of a CW [AC] double and start back-off timers as if a packet collision had occurred between stations.

### **2.2.3 QoS of DiffServ for hybrid multi-hop networks**

The DiffServ [22] architecture provides a scalable, coarse-grained, and class-based QoS guarantee. It is useful, particularly for a heterogeneous network environment, because of its low complexity and high flexibility. It also provides a differentiated services code point (DSCP) in its differentiated services (DS) field of each IP packet header, which is the same as the type of service (ToS) field of an IPv4 packet header and the traffic class field of an IPv6 packet header. The value indicates the per-hop behavior (PHB) that a packet experiences at each node [33].

The PHB, which defines the packet-forwarding properties associated with a class of traffic, maintains a mapping mechanism between a DSCP and the forwarding properties. Theoretically, because a DSCP is a 6-bit value, DiffServ can have up to 64 different traffic classes. These are put into four PHB categories: default (DE) PHB, expedited forwarding (EF) PHB, assured forwarding (AF) PHB, and class selector PHB. When traffic is defined as DE PHB, it is treated as best-effort service traffic, which does not ensure QoS guarantees such as low delay and assured bandwidth. Any traffic that does

not belong to the other defined classes is placed in the DE PHB category. EF PHB is for traffic that has the characteristics of low delay and high bandwidth. The PHB is suitable for real-time applications such as IPTV and VoIP. DiffServ provides higher priority queuing for traffic with EF PHB than that with the other traffic classes.

AF PHB supports a controlled traffic mechanism using prioritized queues and bandwidth allocation. The PHB provides assurance of delivery as long as traffic does not exceed a certain rate. When traffic exceeds the constraint rate, it is more likely to be dropped in a situation where there is congestion. AF PHB defines four AF classes, each of which contains packets that have drop precedence (high, medium, or low). Therefore, AF<sub>x</sub>y means that the traffic has x class and y drop precedence. Class selector PHB is for backward compatibility with the precedence field in the ToS of the IP header, which was used before DiffServ was developed. Each precedence value can be mapped to a DiffServ class.

### **2.3 Polling Services for Wireless Multi-hop Networks**

The process by which a receiver station allocates bandwidth to an individual sender station or a group of sender stations for bandwidth requests is referred to as “polling” [10, 11]. The polling mechanism defines a simple access operation that guarantees bandwidth allocation on demand. The polling technique is needed when a receiver station cannot grant enough bandwidth to all users. In other words, the receiver station can directly assign available bandwidth to each sender station.

When a receiver station individually polls a sender station, it is unicast polling. For unicast polling, the receiver station allocates sufficient bandwidth for the sender station to respond with a bandwidth request without transmitting any explicit message. After

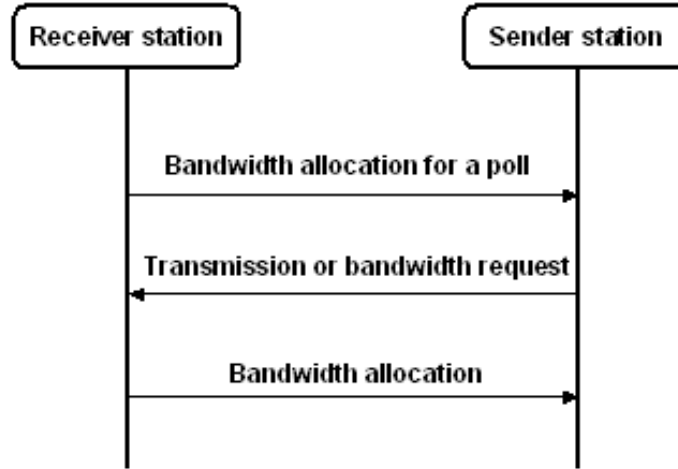


Figure 4. Unicast polling mechanism

bandwidth allocation for the polling, the scheduler of the sender station decides if a standalone bandwidth request or a request piggybacked with data is proper for a bandwidth request. According to the standard, the sender station uses the bandwidth allocation for data transmission, bandwidth requests, or bandwidth requests piggybacked in data transmission, and a receiver station executes unicast polling on a per-station basis. Figure 4 depicts the unicast polling mechanism.

When the bandwidth allocation is not available for the individual polling of all sender stations, a receiver station polls a group of sender stations using a multicast polling service, which is a contention-based polling mechanism [34]. If a multicast group is polled, the sender stations in the group can ask the receiver station for an uplink bandwidth allocation. After receiving a demand, the receiver station examines the requests of the sender stations according to its service-level agreements, the radio network state, and the scheduling algorithm. It then allocates bandwidth for data transmission to the sender stations. Thus, the multicast polling service saves bandwidth compared with the unicast polling service. As in unicast polling, the polled sender station

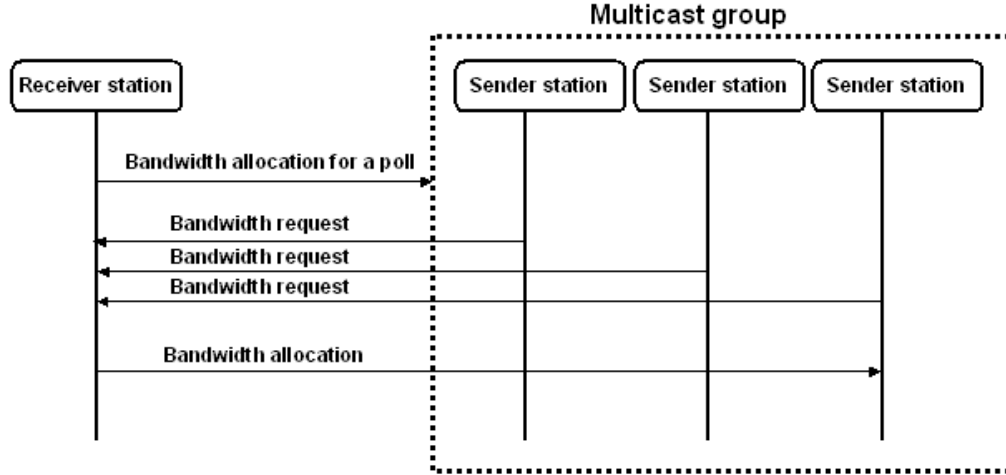


Figure 5. Multicast polling mechanism

is allocated bandwidth without any explicit message. Multicast polling with bandwidth allocation associated with a multicast connection ID (CID) of a group differs from unicast polling with the bandwidth allocation associated with a basic CID of a sender station. To prevent collisions in the multicast polling, only sender stations with bandwidth requests in a polled multicast group can participate in the bandwidth request contention. Not granting a data transmission for a certain number of continuous frames means that the sender station loses the contention for bandwidth. Figure 5 shows a multicast polling mechanism.

## 2.4 Related Work

Many earlier studies have already proven that IEEE 802.11 is not sufficient for wireless multi-hop mesh/relay networks. In [26], the authors claim that DCF does not function well in multi-hop ad hoc networks. According to simulations, throughput is extremely unstable when TCP connections occur, and the network experiences serious unfairness problems among the TCP connections. The results show that instability and unfairness stem from the DCF. According to [35], multi-hop transmissions of mesh

networks are completely different from single-hop transmissions of infrastructure mode networks. In [36], the simulations of a simple mesh network show that an IEEE 802.11-based mesh network yields unfairness and unpredictability of data transmissions, and its authors claim that the problems result from packet collisions in the wireless channel with a contention-based MAC protocol.

Although several papers have focused on the integration of IEEE 802.11 and IEEE 802.16 technologies [37, 38, 39], they do not consider the scenario of mesh/relay networks and QoS for multimedia communications, focusing on only the interoperability of the technologies. In [40, 41], a QoS architecture supporting the integration of IEEE 802.11 and IEEE 802.16 is proposed. However, the authors, providing only a simple set of parameters mapped between IEEE 802.11 and IEEE 802.16, do not include any details of the mapping functionality in practice. In addition, the papers show neither the implementation nor a performance analysis of the proposed architecture. In [42], the authors introduce a base station hybrid coordinator that combines the central base station of IEEE 802.16 with the hybrid coordinator of IEEE 802.11e at a common 5 GHz frequency band. However, most current WiMAX deployments are in the 3.5 GHz band, and IEEE 802.11 WLAN deployments are in the unlicensed 2.4 GHz band. The results of simulations show that as the number of stations increases from one to four, throughput decreases as much as 80%.

The authors in [43] propose an integration model for IEEE 802.11 WLANs and WiMAX on customer-provided equipment (CPE) and develop an adaptive scheduling algorithm providing an uplink delay bound and a buffer bound for real- and non-real-time traffic over the backhaul network. The paper provides a polling algorithm only for



WiMAX, and it does not produce any WLAN-related implementation or simulation results. Introducing an interworking model with relevant simulations and empirical analysis, [44] proposes a complete interworking strategy of IEEE 802.11e and IEEE 802.16e. However, the independently-developed IEEE 802.11e and the IEEE 802.16e simulators are not directly connected during simulations, for it is assumed that all traffic occurs in a cell of WiMAX. Therefore, the results of the simulations could be misleading. In addition, it does not clearly describe what QoS scheme is applied to the interworking model.

For DiffServ in wireless networks, [45] studies the correlations in the management of the traffic between DiffServ and IEEE 802.11e, focusing on the hierarchical QoS signaling interface in IEEE 802.11e WLANs with an infrastructure. However, it does not provide any simulation results that could verify the performance of the management scheme and QoS signaling interface. In [46], the authors, introducing QoS issues in the IEEE 802.11-based wireless backbone, investigate DiffServ over the wireless backbone in terms of QoS routing and MAC mechanisms. However, they just provide open issues, potential solutions, and research directions without any verification.

For polling services in IEEE 802.16, [47] suggested a method using multicast polling to support different delay requirements for VoIP applications. Using separate multicast polling groups for extended real-time polling service (ertPS) and best effort (BE) with different QoS requirements, the authors set different backoff parameters according to the delay and loss targets. However, the method, which is useful for a specific application, VoIP, does not consider other applications using the unicast polling service with different service classes, except ertPS and BE. The authors in [48] proposed

a simple mechanism for reducing the overhead from polling signals. The mechanism sends only one request per SS that carries the aggregated bandwidth for all its connections. However, the idea, which stems from the notion that all bandwidth requests experience potential collisions during the request contention period, is misguided because collisions do not occur in unicast polling. In [49], a polling-based opportunistic deficit round robin scheduling scheme for the uplink flows in WiMAX networks was proposed. The scheme attempts to balance worst-case fairness in bandwidth allocation with the delay requirements of traffic while taking the varying nature of the wireless channel into account. Although the scheme assumes the all traffic attains a common polling interval, WiMAX networks can produce a separate polling interval for every traffic connection. In addition, the scheme cannot be applied to multi-hop networks because the scheme is designed just for single hop networks.

## **CHAPTER 3**

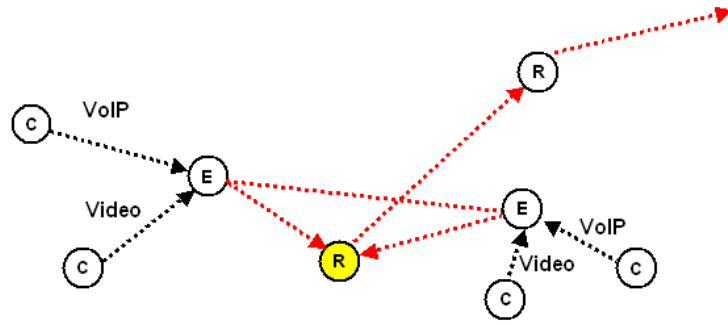
### **HYBRID MULTI-HOP NETWORKS WITH WLANS**

Existing commercial multi-hop wireless networks have been using the contention-based MAC protocol for multi-hop routers and clients. However, the contention-based MAC cannot support QoS for multimedia communications in multi-hop networks because the MAC protocol is designed for single-hop wireless networks [50].

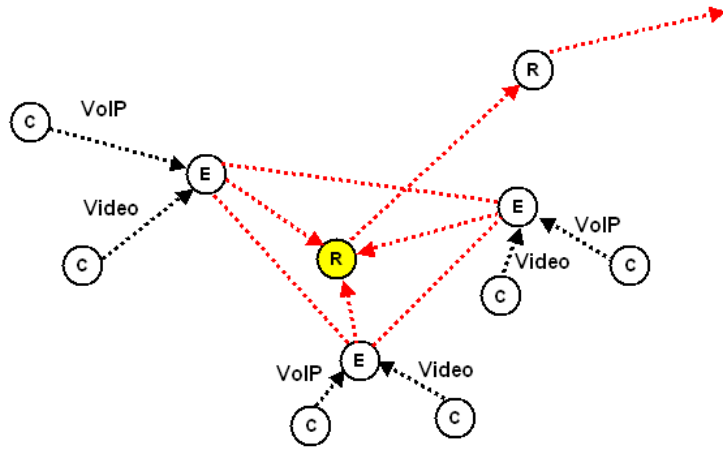
In the proposed hybrid multi-hop mesh/relay networks, the connection-oriented communication technology for communications between routers is applied to support a QoS guarantee for multimedia communications. An edge router with a dual radio interface communicates with clients using the existing contention-oriented communication protocol and with routers using a connection-oriented communication protocol.

#### **3.1 Network Architecture**

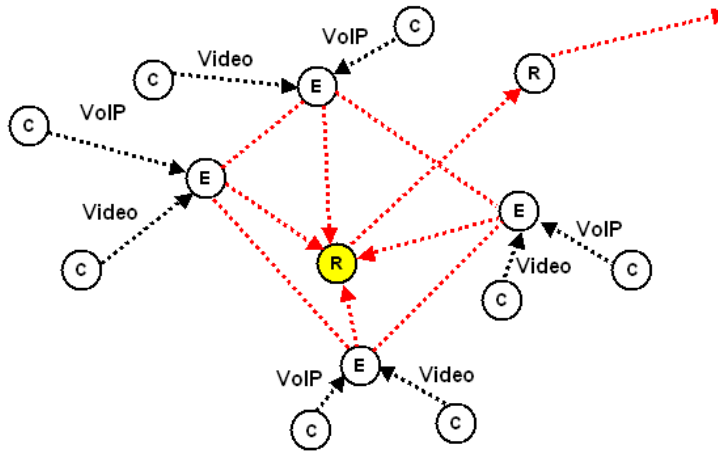
Typically, infrastructure WMNs consist of clients and routers. Routers with a multi-hop mesh/relay topology can route data traffic from clients to a destination. In the WMNs, routers have three types of functionality: Edge routers communicate with clients; infrastructure routers communicate with other routers; and gateway routers route data traffic to the Internet. Figure 6 shows the WMNs with multi-hop mesh/relay topologies of various complexities.



(a) Two edge routers



(b) Three edge routers



(c) Four edge routers

Figure 6. Multi-hop network topologies according to the number of routers  
(C: client; E: edge router; R: infrastructure router)

WMNs with the contention-based MAC protocol have used the DCF for both communication among routers and communication between an edge router and clients.

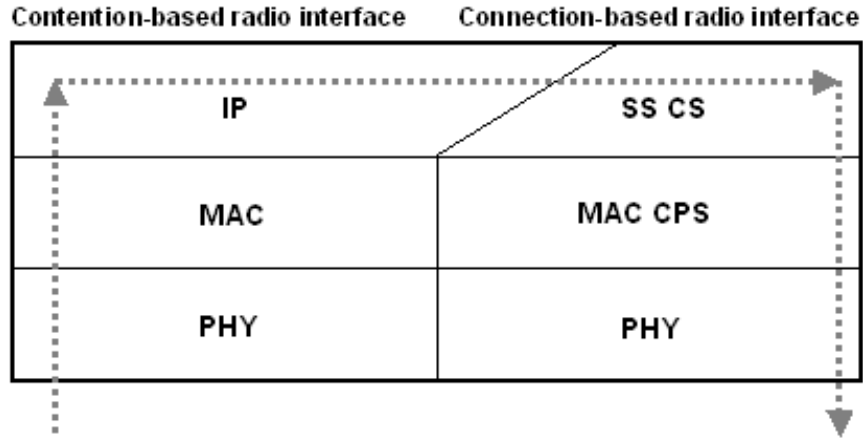


Figure 7. IP bridging with QoS support at an edge router

In the networks, an edge router with a contention-based MAC interface communicates with clients and other routers using the DCF. The proposed hybrid multi-hop networks use the connection-based MAC protocol for communications between routers to support a QoS guarantee for multimedia communications. An edge router with a dual radio interface communicates with clients using the contention-based MAC protocol and with routers using the connection-based MAC protocol.

In the hybrid mesh/relay networks, the edge router uses IP bridging as a packet bridging technology. Figure 7 shows the structure of IP bridging at the edge router. The contention-based MAC interface of the router receives data packets from clients using the contention-based MAC protocol. Through an IP layer above the interface, the data packets are bridged to the convergence sublayer of the connection-based MAC interface and categorized into QoS classes according to the types of service (ToS) of the packets. The bridging mechanism, which maintains QoS support between the edge router and the clients, offers a number of advantages. Because it is independent from the MAC and physical layers, it can interface between standards without any modification of them, and be implemented with low complexity. In addition, its implementation in existing multi-

hop networks is easy and flexible. Through IP bridging between connection- and contention-based MAC interfaces, hybrid multi-hop networks can guarantee QoS for constant and simultaneous multimedia communication traffic among clients even though they use the contention-based MAC protocol.

### **3.2 Simulation and Results**

To observe the enhanced QoS performance of the proposed hybrid multi-hop networks, the IEEE 802.11 and the IEEE 802.16 standards are applied to the contention-based and the connection-based communication protocol networks, respectively. Therefore, to compare the proposed network with the IEEE 802.11-based multi-hop network, it is deployed the hybrid multi-hop network of IEEE 802.16 with IEEE 802.11 WLANs with three types of topology complexity (Figure 6) using WiMAX and WLAN models in OPNET Modeler. To observe the instability and unfairness of data traffic in the IEEE 802.11-based WMN and the performance enhancement in the proposed network architecture for constant and simultaneous multimedia communications, it is assumed that edge routers send all data traffic from clients to an infrastructure router. At the infrastructure router, the throughput, the delay, and the delay variation of multimedia traffic from clients are measured to analyze the results of the simulation. For the physical layer parameters of the IEEE 802.11-based WMN, direct-sequence spread spectrum (DSSS) is used for communications between a client and an edge router and orthogonal frequency-division multiplexing (OFDM) for communications between routers [51]. In the case of the hybrid mesh/relay network, the DSSS is used between a client and an edge router, and wireless orthogonal frequency-division multiple access (OFDMA) 20 MHz,

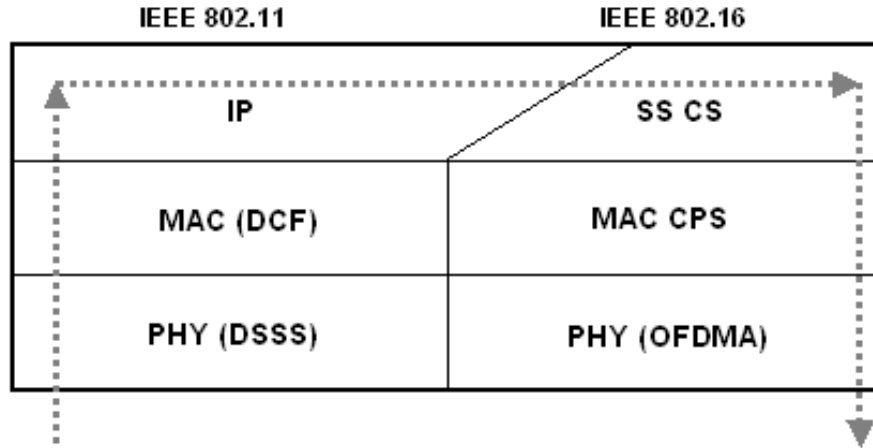


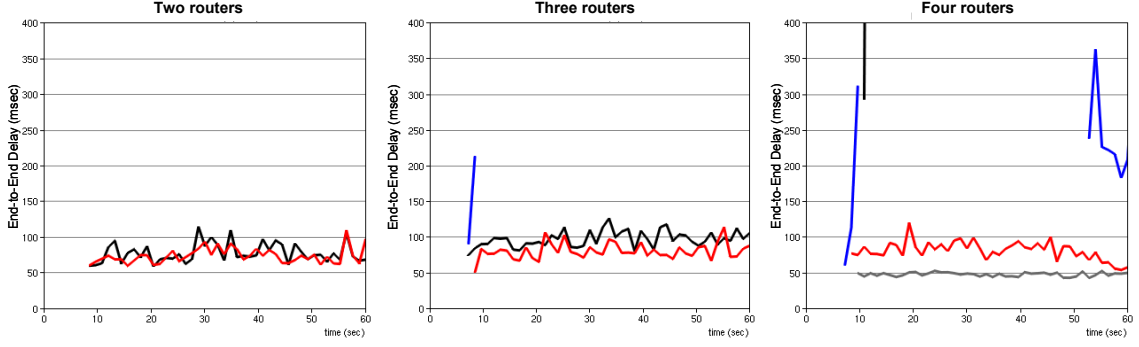
Figure 8. IP bridging with QoS for simulation

TABLE 1  
SPECIFICATIONS OF APPLICATIONS FOR PERFORMANCE ANALYSIS

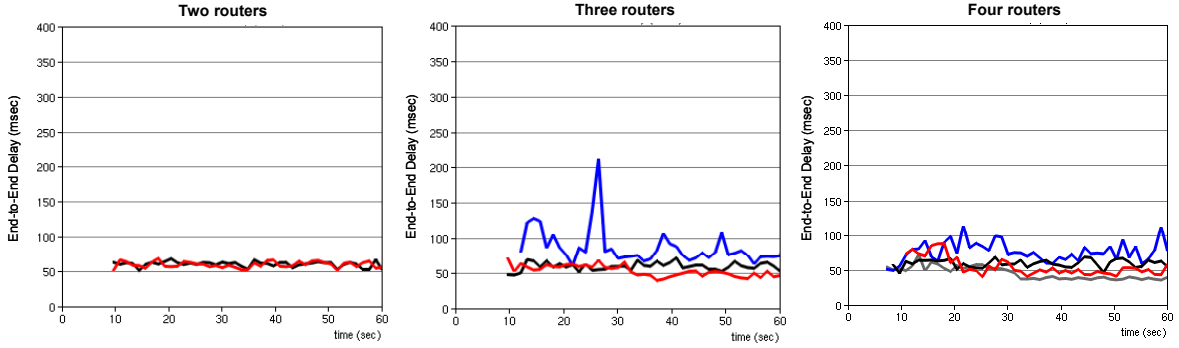
Video conferencing		VoIP	
Frame interval	10frames/sec	Silence length	exp (0,65)
		Talk length	exp (0.352)
Frame size	128×120 pixels (17280 bytes)	Encoder Scheme	G.711(silence)
ToS	Interactive multimedia	ToS	Interactive voice

which is a default setting of the WiMAX model in OPNET Modeler, is used between the routers [52].

For IP bridging in the hybrid mesh/relay network, the IP layer bridges the data packets to the service-specific convergence sublayer of the IEEE 802.16 interface and categorizes them into IEEE 802.16 QoS classes according to the ToS of the packets. Figure 8 describes IP bridging with QoS as used for simulation. Two clients in the coverage of an edge router use a video conferencing application and a VoIP application, both defined in OPNET Modeler. The traffic of the VoIP application with interactive voice as a ToS is associated with the UGS QoS class of IEEE 802.16, and the traffic of the video conferencing application with interactive multimedia as a ToS is associated with to the



Wireless multi-hop networks with the contention-based MAC



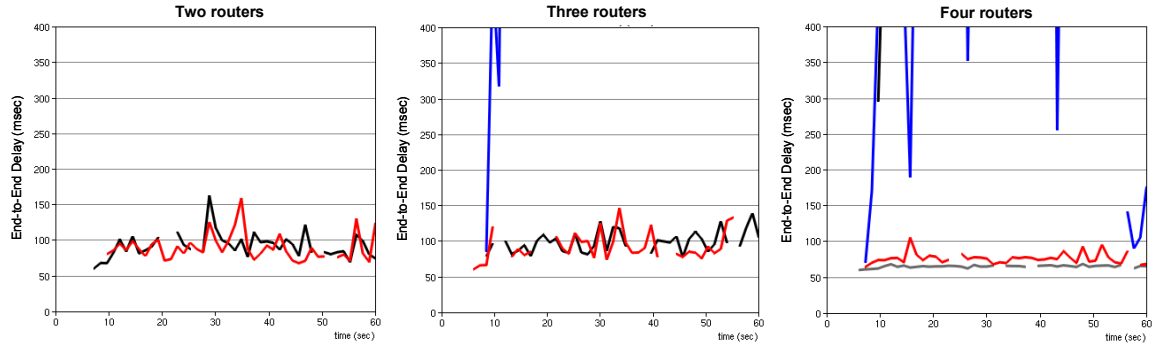
Wireless multi-hop networks with the connection-based MAC

Figure 9. Delay of video conferencing traffic

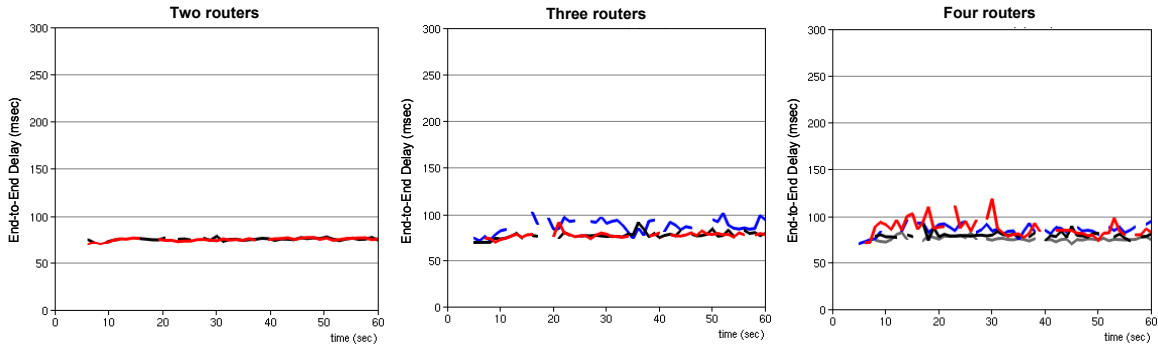
rtPS QoS class of IEEE 802.16. Clients with these applications are simulated for 60 seconds. Table 1 shows the specifications of the applications in detail.

Figures 9, 10, 11, and 12 obviously show more serious unfairness among the multimedia traffic of the clients in the IEEE 802.11-based WMN than in the hybrid multi-hop network of IEEE 802.16, as the complexity of the multi-hop network increases. In the graphs, differently colored lines indicate traffic from different clients in three network topologies of Figure 6. In the topology with two edge routers, the traffic of two video conferencing clients and two VoIP clients has good fairness and QoS performance for throughput and delay. However, in the network with three edge routers, a video conferencing client and a VoIP client in the coverage of one edge router experience much





Wireless multi-hop networks with the contention-based MAC

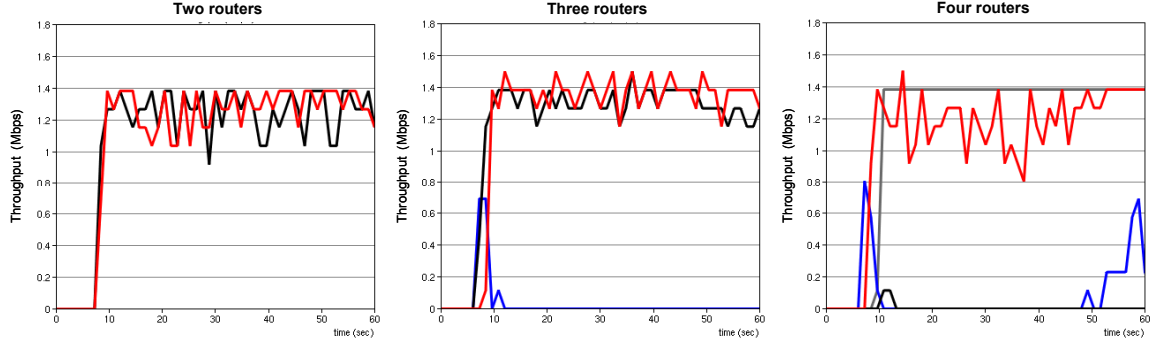


Wireless multi-hop networks with the connection-based MAC

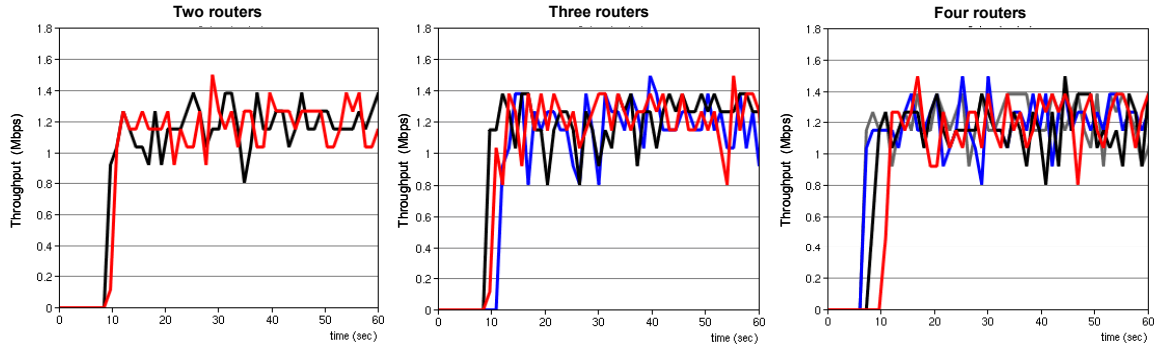
Figure 10. Delay of VoIP traffic

lower throughput and longer delays than clients in the coverage of the other two edge routers.

In the case of the network with four routers, four clients in the coverage of two of the routers suffer extremely serious low throughput and long delays. Video conferencing clients with a high traffic load were seen to have more throughput unfairness and poorer throughput QoS than VoIP clients, and VoIP clients suffer a more inequitable delay distribution and poorer delay performance than video conferencing clients. From the results of the simulation of the topology, two of the eight clients could not use any multimedia application, and another two clients experienced extremely poor quality. It is definitely expected that the problem will become even more serious if the number of



Wireless multi-hop networks with the contention-based MAC

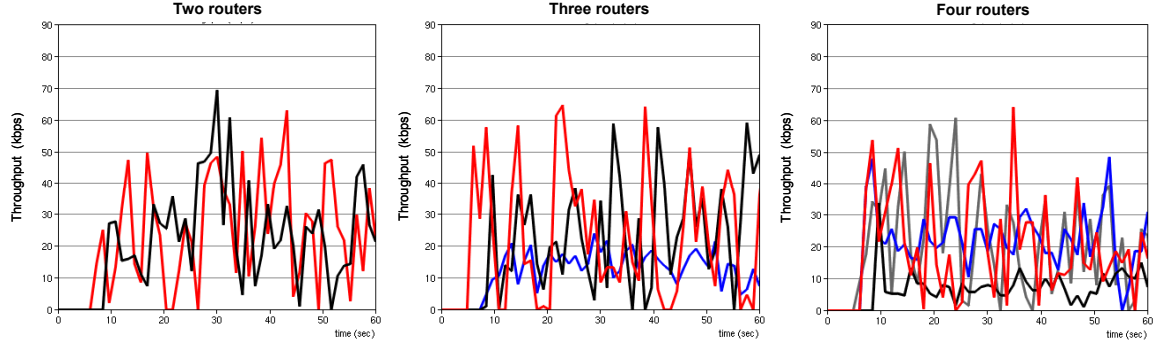


Wireless multi-hop networks with the connection-based MAC

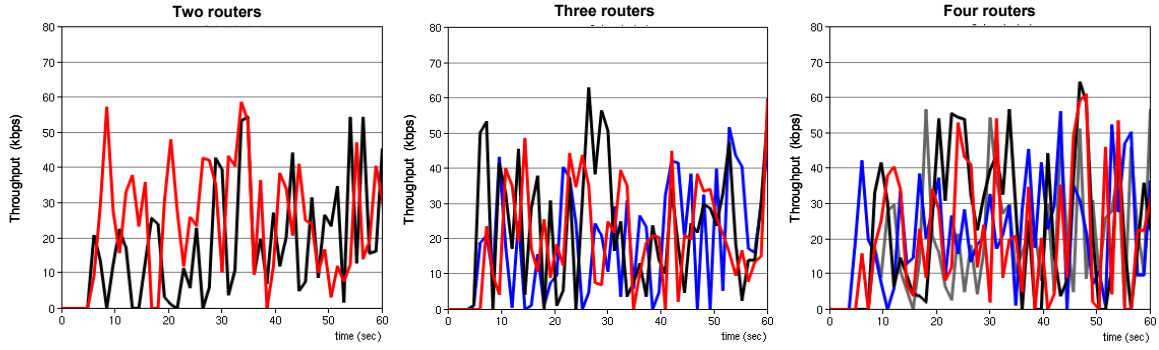
Figure 11. Throughput of video conferencing traffic

clients was increased. In particular, the problem is seriously important for commercial WMNs because some subscribers of commercial WMNs would not be able to use data service at times.

However, the proposed hybrid multi-hop network using the connection-based MAC protocol provides a QoS guarantee for all clients regardless of the complexity of the multi-hop network. Clients using video conferencing and VoIP maintain fairly-distributed throughput and low-bounded delay because traffic from IEEE 802.11 clients using the contention-based MAC protocol transfers to the connection-based IEEE 802.16 traffic using IP bridging with QoS support, and for traffic requirements, the connection-



Wireless multi-hop networks with the contention-based MAC



Wireless multi-hop networks with the connection-based MAC

Figure 12. Throughput of VoIP traffic

based scheduling mechanism with QoS balances bandwidth allocation between the routers.

Tables 2 and 3 show the average throughput and the average delay of video conferencing traffic and VoIP traffic in the IEEE 802.11-based WMN and the proposed hybrid WMN according to the complexity of the networks. In the IEEE 802.11-based WMN with four edge routers, the highest throughput of video conferencing clients is 1.14 Mbps, but the lowest throughput is 4 kbps, and the shortest delay of VoIP clients is 65 msec, but the longest delay is 13,320 msec. The results show how serious the problem of unfairness of traffic in IEEE 802.11-based WMNs is. However, in the proposed hybrid WMN, even in the case of the topology with four edge routers, all clients maintain fairly-

TABLE 2  
AVERAGE THROUGHPUT

Topology	Client	Video (Mbps)		VoIP (kbps)	
		802.11	Hybrid	802.11	Hybrid
(a)	1	1.093	0.975	21.5	23.8
	2	1.081	0.987	23.0	17.2
(b)	1	1.156	1.011	21.8	19.9
	2	1.133	1.030	21.4	22.4
	3	0.029	0.946	12.2	18.7
(c)	1	1.039	0.982	19.3	20.2
	2	0.004	1.005	6.8	22.3
	3	0.079	1.059	20.4	21.7
	4	1.140	1.075	20.5	18.5

TABLE 3  
AVERAGE DELAY

Topology	Client	Video (msec)		VoIP (msec)	
		802.11	Hybrid	802.11	Hybrid
(a)	1	73	60	90	75
	2	77	60	92	75
(b)	1	80	53	92	78
	2	97	60	99	78
	3	559	87	8697	88
(c)	1	81	55	76	87
	2	993	60	13320	80
	3	242	76	1572	86
	4	58	45	65	76

distributed throughput and low-bounded delay. In addition, Table 4 shows that the hybrid WMN produces much lower standard deviation, related to jitter, than the IEEE 802.11-based WMN. This is an important factor for stable multimedia communications, because IEEE 802.16 provides a class-based QoS algorithm for low-bounded delay while the contention-based MAC protocol of IEEE 802.11 does not provide any delay-related QoS mechanism.

### 3.3 Contributions

This Chapter has presented the hybrid multi-hop mesh/relay networks using a connection-based MAC protocol with WLANs using a contention-based MAC protocol. The proposed network architecture provides class-based QoS for the traffic of clients using contention-based MAC by using IP bridging with QoS support at an edge router. For traffic requirements, the connection-based scheduling mechanism balances bandwidth allocation and delay between routers. Simulation results have shown that the proposed hybrid multi-hop network architecture can provide an excellent QoS guarantee for simultaneous multimedia communication for all users, and achieve more fairly-distributed throughput and lower-bounded delay.

TABLE 4  
STANDARD DEVIATION

		Video ( $\times 10^{-3}$ )		VoIP ( $\times 10^{-3}$ )	
Topology	Client	802.11	Hybrid	802.11	Hybrid
(a)	1	10	4	18	0
	2	13	3	17	0
(b)	1	11	7	19	3
	2	11	5	14	3
	3	577	26	3677	8
(c)	1	12	12	7	9
	2	699	5	7508	3
	3	116	13	1102	5
	4	2	8	1	2

## **CHAPTER 4**

### **CROSS-LAYER DESIGN OF DIFFSERV ARCHITECTURE**

In wireless networks, to provide QoS support, two kinds of QoS mechanisms, classified QoS and parameterized QoS, can be used. Classified QoS defines several QoS classes and packet traffic properties according to each class [53]. The QoS scheme assigns a proper QoS class for packet traffic according to traffic requirements, and the traffic is transmitted according to the traffic characteristics of the assigned class. In addition, if the QoS scheme has a class-based priority architecture, the QoS scheme provides more bandwidth and lower delay for packet traffic with a higher priority than that with a lower priority. Therefore, classified QoS can be simple and flexible.

Parameterized QoS provides a specific set of QoS parameters such as bandwidth and delay that are determined from the various QoS algorithms for a packet traffic flow [54]. Each traffic flow attains optimal traffic characteristics from the parameterized QoS scheme. Typically, parameterized QoS is more complex than classified QoS because the QoS scheme needs to produce an optimized set of QoS parameters from complicated QoS algorithms.

First of all, to apply the classified QoS for the hybrid multi-hop networks with QoS-enhanced WLANs, a cross-layer design of the DiffServ architecture is proposed to provide an end-to end QoS guarantee for data and multimedia communications. DiffServ is a scalable, coarse-grained, and class-based QoS architecture effective for a heterogeneous network environment because of its low complexity and high flexibility.

In heterogeneous multi-hop networks, the DiffServ architecture maintains consistent end-to-end QoS support [55].

## 4.1 QoS Architecture

The proposed hybrid multi-hop network, consisting of classified QoS-enabled clients with a contention-based MAC protocol, wireless multi-hop backbone routers with a connection-based MAC protocol, and IP backhaul networks, comprises three types of routers according to their functionality: Edge routers transmit data traffic among clients and other routers; infrastructure routers communicate with other routers; and gateway routers transmit data traffic among IP backhaul networks and other routers. Figure 13 introduces the hybrid multi-hop mesh/relay network with classified QoS-enhanced WLANs. QoS-enabled clients using the contention-based MAC protocol send the data traffic to the wireless multi-hop backbone network with a connection-based MAC protocol through an edge router with a dual radio interface of the contention- and connection-based MAC protocols. In the wireless multi-hop backbone network, the

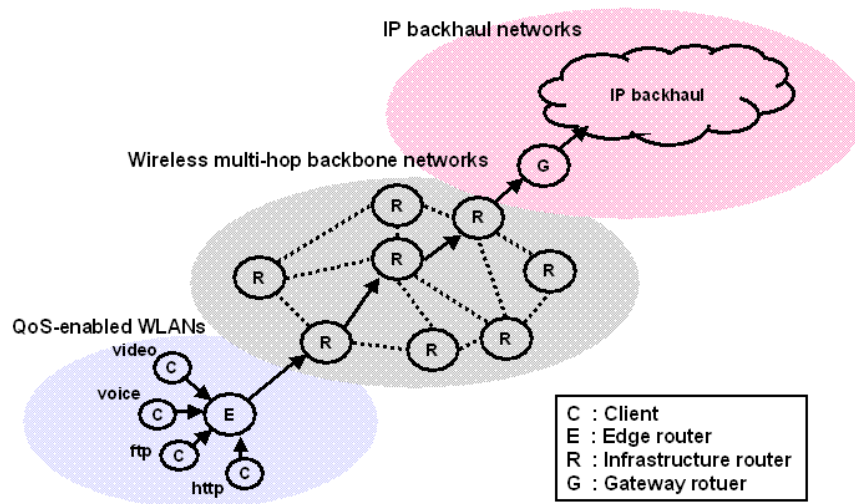


Figure 13. Hybrid multi-hop mesh/relay networks with classified QoS-enhanced WLANs

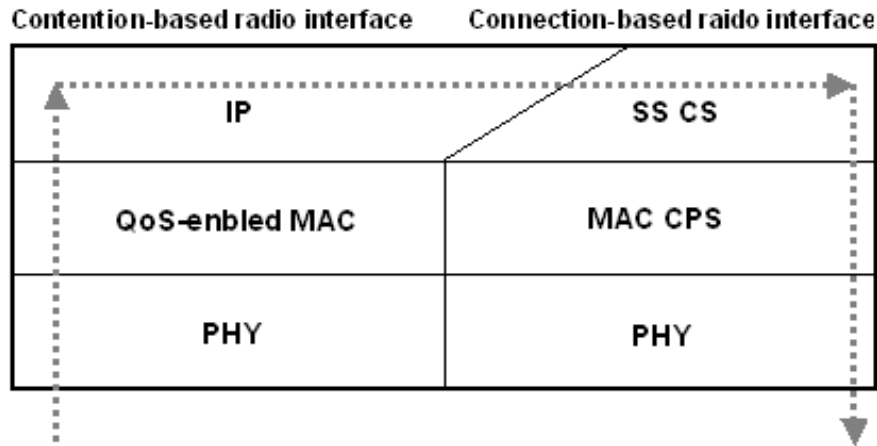


Figure 14. IP bridging with DiffServ at an edge router

TABLE 5  
QoS MAPPING TABLE

DiffServ PHB	Contention-based AC	Connection-based QoS class
BE	AC_BK	BE
AF1y	AC_BE	nrtPS
AF4y	AC_VI	rtPS, ertPS
EF	AC_VO	UGS

traffic is routed to the IP backhaul networks by infrastructure routers through a gateway router.

The edge router uses IP bridging with DiffServ as a bridging technology. Figure 14 shows the structure of the bridging mechanism at the router. The contention-based MAC interface of the router receives data packets from classified QoS-enabled clients. Through an IP layer above the interface, the data packets are bridged to the convergence sublayer of the connection-based MAC interface and categorized into QoS classes according to the PHB categories associated with the DSCPs of packets by using a classified QoS mapping table. Table 5 explains the QoS mapping table in detail. This mechanism maintains QoS support between the edge router and the clients. One of the advantages of the IP bridging with DiffServ is the integration of the heterogeneous radio



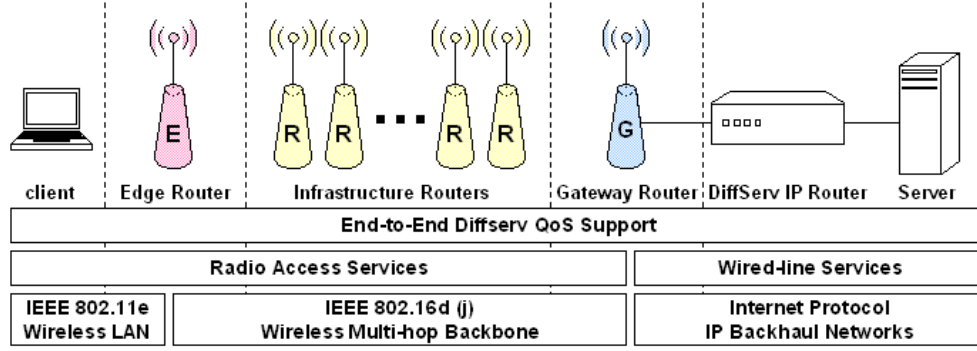


Figure 15. Structure of DiffServ QoS architecture in hybrid multi-hop networks

technologies with different QoS mechanisms. Because it is independent from the MAC and physical layers, it can be applied to the standards without any modification. In addition, because the convergence sublayer of the connection-based MAC is originally designed to manage packets from the IP layer as traffic flow, it can be implemented with low complexity and high flexibility [56].

In addition, the gateway router with a dual interface of the connection-based MAC and DiffServ routes the traffic from the infrastructure routers using the connection-based MAC protocol to the IP backhaul networks through the DiffServ interface. Specifically, the traffic packets from the connection-based MAC sublayer at the gateway router are carried to assigned DiffServ QoS queues according to their DSCPs by the DiffServ traffic conditioner (DiffServ TC) and then transmitted to a destination server in the backhaul networks. Through the mechanism, the gateway router provides QoS support between the wireless multi-hop backbone network and IP backhaul networks.

In the heterogeneous multi-hop networks, the cross-layer design of the DiffServ architecture maintains consistent QoS support. Figure 15 demonstrates the structure of the DiffServ architecture for end-to-end QoS support in the hybrid multi-hop networks, and Figure 16 depicts traffic flow on the DiffServ architecture in the hybrid multi-hop

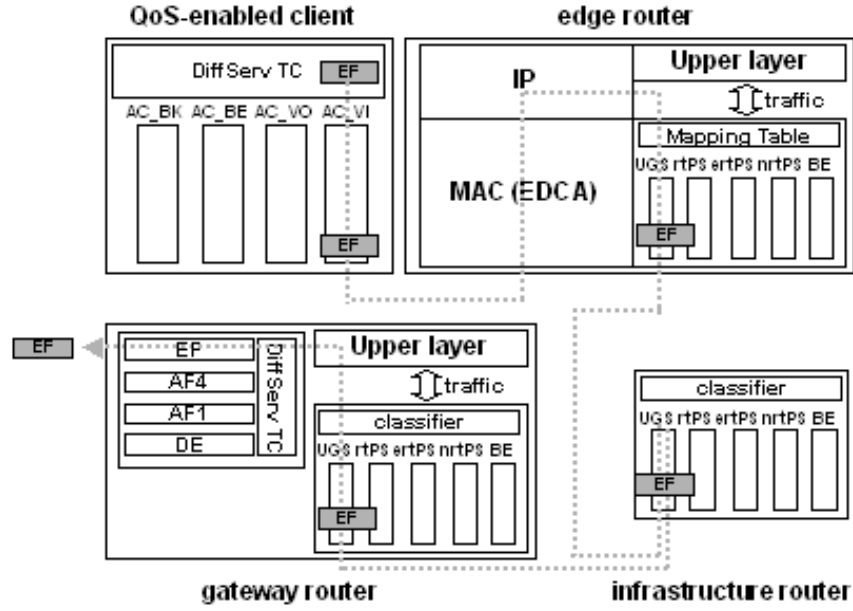


Figure 16. Traffic flow on DiffServ architecture in hybrid mesh/relay networks

network. In the multi-hop network, classified QoS-enabled clients assign appropriate DSCPs to their traffic according to the type of applications by the DiffServ TC. According to the PHB associated with the DSCP, the traffic with a QoS class is sent through an appropriate channel access category associated with the QoS class to an edge router, which allocates a set of QoS parameters for the traffic flow using IP bridging with the QoS mapping table and sends the traffic flow to a wireless multi-hop backbone network through an infrastructure router.

Through several infrastructure routers by a mesh/relay routing algorithm, the traffic is routed to a gateway router maintaining class-based QoS support. The gateway router sends the traffic, which is classified into a PHB according to the DSCP by DiffServ TC, to the IP backhaul networks through its routing interface with the DiffServ mechanism. In the IP backhaul networks, the IP routers with the DiffServ functionality route the traffic to a destination, maintaining DiffServ QoS support. Therefore, the proposed

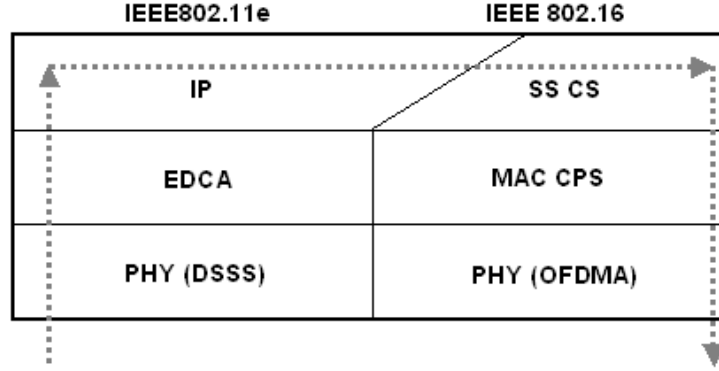


Figure 17. Structure of IP bridging with DiffServ between IEEE 802.11e/16

hybrid multi-hop network architecture can provide the entire network with end-to-end QoS support.

## 4.2 Simulation and Results

For simulations, in the proposed hybrid multi-hop network, IEEE 802.11e and IEEE 802.16 are applied to the radio technologies of the classified QoS enabled-clients with the contention-based MAC protocol and wireless multi-hop backbone routers with the connection-based MAC protocol, respectively. The DiffServ architecture on the hybrid multi-hop network of IEEE 802.16 with IEEE 802.11e WLANs is deployed using the WiMAX and WLAN models in OPNET Modeler.

In deployment, IEEE 802.11e with DSSS equips EDCA as the contention-based MAC protocol with classified QoS between a client and an edge router. The parameters of the four ACs of the EDCA for the simulation are described in Table 6. The routers communicate using IEEE 802.16 with wireless OFDMA 20 MHz, which is a default setting of the WiMAX model in OPNET Modeler. Table 7 shows the parameters of IEEE 802.16 WiMAX OFDMA. Figure 17 shows that the specific structure of IP bridging with DiffServ between EDCA of IEEE 802.11e (the contention-based MAC

TABLE 6  
PARAMETERS OF ACCESS CATEGORIES FOR THE DIFFSERV ARCHITECTURE

AC	AIFS ( $\mu$ s)	CWmin	CWmax	TXOP
AC_BK	150	31	1023	One MSDU
AC_BE	70	31	1023	One MSDU
AC_VI	50	15	31	One MSDU
AC_VO	50	7	15	One MSDU

TABLE 7  
IEEE 802.16 OFDMA PARAMETERS

Radio parameters	Value
Base frequency (GHz)	5
Bandwidth (MHz)	20
Duplex method	TDD
Frame duration (msec)	5
Symbol duration ( $\mu$ sec)	102.86
# of data subcarrier in UL	1120
# of data subcarrier in DL	1440
UL Capacity (Msps)	5.0944
DL Capacity (Msps)	6.336

TABLE 8  
SPECIFICATIONS OF APPLICATIONS FOR THE DIFFSERV ARCHITECTURE

	VoIP	Video	File	Web
Packet size (byte)	1024			
Packet interval (sec)	0.0035			
PHB	EF	AF43	AF11	BE
Transfer protocol	UDP	UDP	TCP	TCP

protocol with classified QoS) and MAC of IEEE 802.16 (the connection-based MAC protocol), which consists of the service-specific convergence sublayer and the MAC common part sublayer, on the edge router. In addition, the classified QoS mapping table of the ACs of IEEE 802.11e, the PHBs of DiffServ, and the QoS classes of IEEE 802.16 is described in Table 7.

In the multi-hop network, four IEEE 802.11e clients are operated using four applications with different QoS classes: video conferencing, a VoIP, a file transfer using

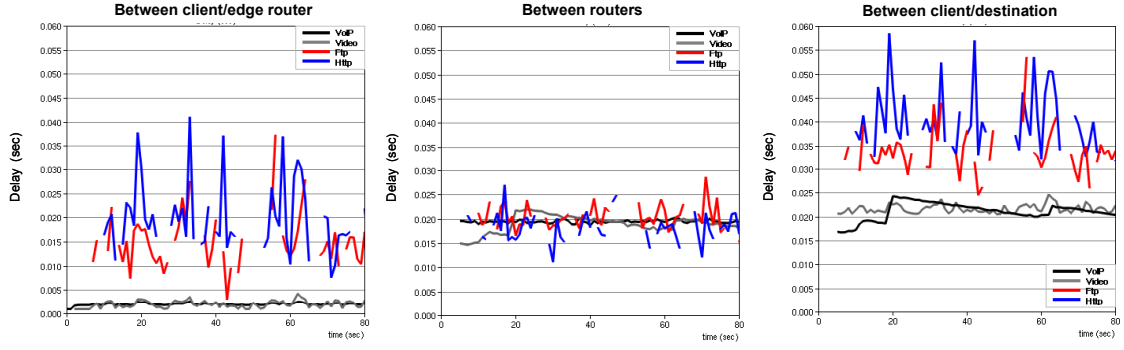


Figure 18. Delay of traffic of four applications without the DiffServ architecture

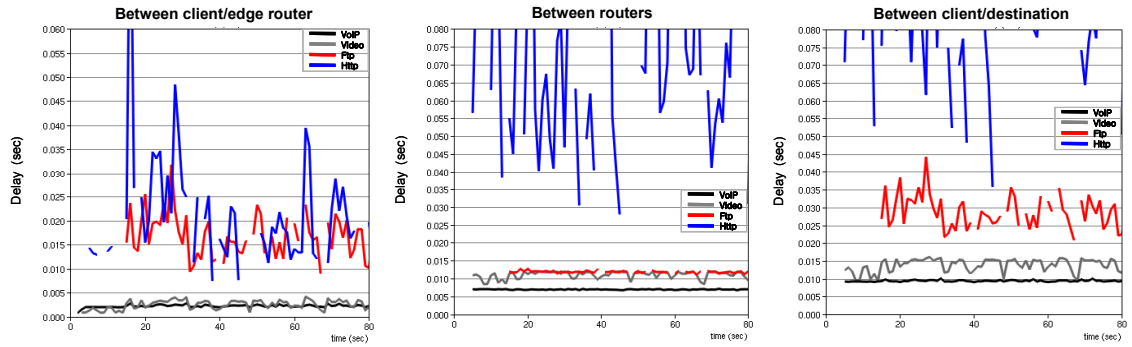


Figure 19. Delay of traffic of four applications with the DiffServ architecture

FTP, and web browsing using HTTP. Table 8 shows the specifications of the applications. In the simulations, the traffic of the clients runs for 80 seconds.

First of all, to study the effect of the DiffServ architecture in the hybrid multi-hop networks, simulations run without applying any QoS architecture to the networks (Figure 13). Figure 18 shows the results of the simulations. As a result, between clients and the edge router, the EDCA of IEEE 802.11e differentiates the delay of traffic according to the type of traffic of the applications. QoS-enabled MAC provides QoS support for multimedia traffic with higher priority. However, the classified QoS does not maintain in multi-hop backbone networks because of the lack of classified QoS mapping between QoS classes of IEEE 802.16 and ACs of IEEE 802.11e. Regardless of the type of traffic,

all traffic with different QoS classes is equally treated in the backbone networks. Therefore, no multi-hop network can guarantee the end-to-end QoS of traffic, particularly multimedia traffic.

However, after the DiffServ architecture is applied to the hybrid multi-hop networks, the results of the simulations show that the cross-layer design of the DiffServ architecture with the QoS mechanisms of IEEE 802.11e and IEEE 802.16 provides an excellent end-to-end QoS guarantee for multimedia communications in the entire network. Figure 19 shows that the QoS architecture differentiates the delay of traffic according to the type of QoS class of traffic. The delay of traffic of the VoIP and video conferencing applications is always much lower than that of FTP and HTTP applications from IEEE 802.11e clients to the destination server. In addition, the multimedia applications experience only slight or no jitter, which is an important factor for real-time traffic. The results indicate that the cross-layer design of the DiffServ architecture maintains QoS support differently according to the type of traffic.

### **4.3 Contributions**

A cross-layer design of the DiffServ architecture is proposed in hybrid multi-hop mesh/relay networks with QoS-enabled WLANs. The QoS mechanisms of the contention-based MAC protocol with classified QoS for clients, the connection-based MAC protocol for a wireless multi-hop backbone network, and Internet protocol for IP backhaul networks in the proposed DiffServ QoS architecture produce a synergistic effect of providing end-to-end QoS support for the multi-hop mesh/relay network.

The DiffServ architecture using classified IP bridging yields consistent classified QoS support in the entire network. The results of realistic simulations show that the

proposed QoS architecture design can provide an excellent end-to-end QoS guarantee that satisfies the classified traffic requirements of particular applications.

## **CHAPTER 5**

### **OPTIMIZED END-TO-END DELAY ASSURANCE ALGORITHM**

To support QoS in wireless networks, parameterized QoS, the second QoS mechanism, is also effective. For packet traffic flow, parameterized QoS provides a specific set of QoS parameters derived from QoS algorithms. Traffic flow with optimal traffic characteristics from the QoS scheme can transmit to a destination, maintaining end-to-end QoS support [57].

For the parameterized QoS for the hybrid multi-hop networks with QoS-enhanced WLANs, an optimized delay assurance algorithm with the DiffServ architecture is proposed to support end-to-end QoS for data transmissions, particularly delay-sensitive multimedia communications. To provide delay assurance for data traffic, the algorithm in each router optimally computes the maximum per-hop latency of the routers according to the delay constraint of the applications, the delay between clients and an edge router, and the actual accumulated delay before the next hop.

First of all, before presenting the optimized delay assurance algorithm, a simple adaptive delay assurance algorithm with the DiffServ architecture is proposed for hybrid multi-hop networks. In this case, the delay assurance algorithm is designed for the wireless multi-hop networks with a small change in the per-hop channel condition. According to the delay constraint of applications and the delay between clients and an edge router, the algorithm in an edge router adaptively calculates the maximum per-hop latency of the routers for delay assurance [58].





packet delay between a client and an edge router,  $n$  is the number of end-to-end hops of a traffic connection in the multi-hop backbone network after executing a routing scheme, and  $k$  is a constant.

Using extended IP packet header information, a client sends the data packets of an application with an end-to end delay constraint,  $D_c$ , to an edge router. On the IP layer of the edge router, the proposed algorithm calculates the maximum per-hop delay using the information from packet headers and routing tables. From timestamps in incoming IP packet headers from the client, the algorithm gains the packet delay between the client and the edge router,  $d_e$ . It computes the expected packet delay between a gateway router and the destination of traffic,  $d_i$ , using the timestamp in the IP packets from the gateway router. The algorithm can attain the number of end-to-end hops of a traffic connection,  $n$ , from the routing table that routers update from path routing messages of the gateway router using a centralized routing scheme. If the delay,  $d_e + d_i$ , is longer than the end-to end delay constraint, the maximum per-hop delay is set to a small delay value that divides the packet delay between the client and the edge router by a constant value to transmit the packet, which does not have any enough the delay budget, as soon as possible. After the algorithm obtains the maximum per-hop delay, the edge router includes the delay value into a set of QoS parameters of a QoS message and sends the message to the next hop router. The other routers use the maximum delay value as a QoS parameter until the traffic arrives at the gateway router. From the gateway router, the packet traffic with delay budget  $d_i$  arrives at the destination to satisfy the end-to-end delay constraint of the application. Figure 21 shows the definition of the delays.

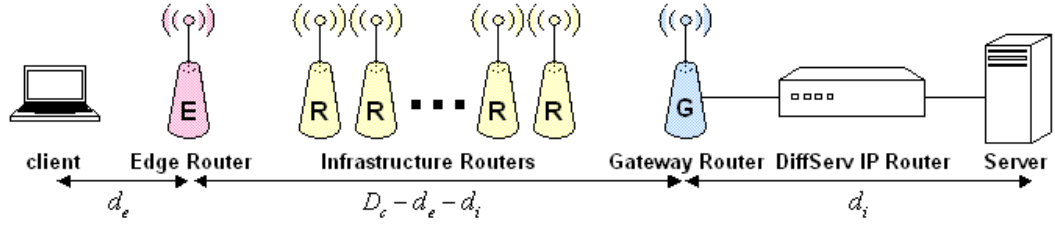


Figure 21. Delay definitions for the adaptive delay assurance algorithm

The delay assurance algorithm with the proposed DiffServ architecture maximizes the effect of end-to-end QoS support. For example, a client using a VoIP application with an end-to-end delay constraint sends data packets with the EF PHB of the DiffServ classes to an edge router using a QoS class with the highest priority in QoS-enabled MAC. In the edge router, the traffic with a set of QoS parameters, including the highest QoS class of the connection-based MAC protocol and the maximum latency from the proposed algorithm, is forwarded to other routers. Through a gateway router and IP backhaul routers with the DiffServ mechanism, the packet traffic with the EF PHB arrives at the destination to maintain an excellent QoS guarantee.

### 5.1.2 Simulation and results

For simulations in the proposed hybrid multi-hop network, IEEE 802.11e and IEEE 802.16 are applied to the radio technologies of the classified QoS-enabled clients with the contention-based MAC protocol and wireless multi-hop backbone routers with the connection-based MAC protocol, respectively. The hybrid mesh/relay network of IEEE 802.16 and IEEE 802.11e with the DiffServ architecture is deployed, and the delay assurance algorithm using the WiMAX and WLAN models in OPNET Modeler is installed. For deployment, IEEE 802.11e with DSSS as the radio technology is used between a client and an edge router. Figure 22 depicts the structure of the delay

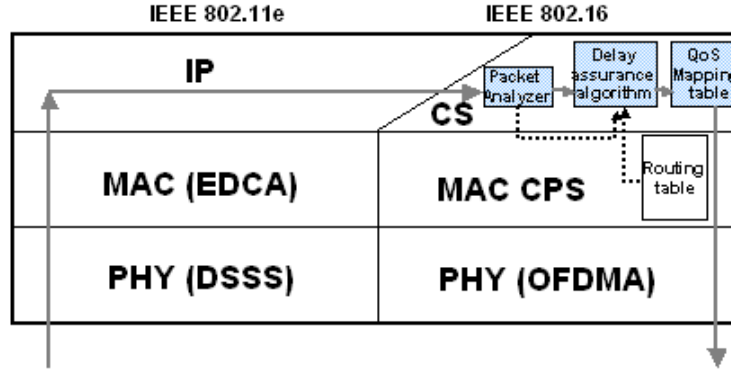


Figure 22. Structure of the delay assurance algorithm for simulation

TABLE 9  
PARAMETERS OF ACCESS CATEGORIES FOR THE DELAY ASSURANCE ALGORITHM

AC	AIFS ( $\mu$ s)	CWmin	CWmax	TXOP
AC_BK	90	63	127	One MSDU
AC_BE	70	63	127	One MSDU
AC_VI	70	7	15	One MSDU
AC_VO	50	7	15	One MSDU

assurance algorithm at an edge router for simulation. The parameters of the four ACs of IEEE 802.11e are described in Table 9. Between the routers, IEEE 802.16 with wireless OFDMA 20 MHz, which is a default setting of the WiMAX model in OPNET Modeler, is used.

Table 5 shows the classified QoS mapping table among the PHB categories of DiffServ, the ACs of IEEE 802.11e, and the QoS classes of IEEE 802.16. According to the mapping table, consistent classified QoS support can be maintained in the entire network. It is assumed that the execution of a routing scheme produces a path of three hops between a gateway router and an edge router. The routing scheme can attain the number of end-to-end hops of a traffic connection from the routing table that routers update from the path setup/creation messages of the gateway router using a centralized routing scheme that operates on the MAC CPS in the routers [59].

TABLE 10  
SPECIFICATIONS OF APPLICATIONS FOR THE DELAY ASSURANCE ALGORITHM

	VoIP	Video	File	Web
Packet size (byte)	1024			
Packet interval (sec)	0.002			
PHB	EF	AF43	AF11	BE
Transfer protocol	UDP	UDP	TCP	TCP

In the multi-hop network architecture, four clients send the traffic of four applications—video conferencing, VoIP, file transferring using FTP, and web browsing using HTTP—for 80 seconds (Figure 13). The specifications of the applications are shown in Table 10. It is assumed that the end-to-end delay constraints of VoIP and video conferencing applications are 120 msec and 220 msec [60, 61], respectively, and the traffic delay between a gateway router and a destination in the IP backhaul networks is maintained at 12 msec and 21 msec, respectively.

In Figure 23, the algorithm successfully guarantees a maximum delay of VoIP and video conferencing applications in the wireless multi-hop backbone network according to the delay constraints of the applications. For the traffic of the VoIP application, the traffic delay is 75.1 msec at 50 seconds when the traffic arrives at an edge router. The algorithm computes the maximum per-hop delay as 10.9 msec. In fact, the actual traffic delay between an edge router and an infrastructure router is 9.8 msec at 50 seconds; and the longest traffic delay between the edge router and the infrastructure router is 9.9 msec between 50 and 80 seconds. For the video conferencing application, the traffic delay between a client and an edge router is 144.4 msec at 50 seconds; and the maximum per-hop delay from the algorithm is 18.2 msec. The actual traffic delay between an edge router and an infrastructure router is 15.6 msec at 50 seconds; and between 50 seconds and 80 seconds, the highest delay value is 16.6 msec.

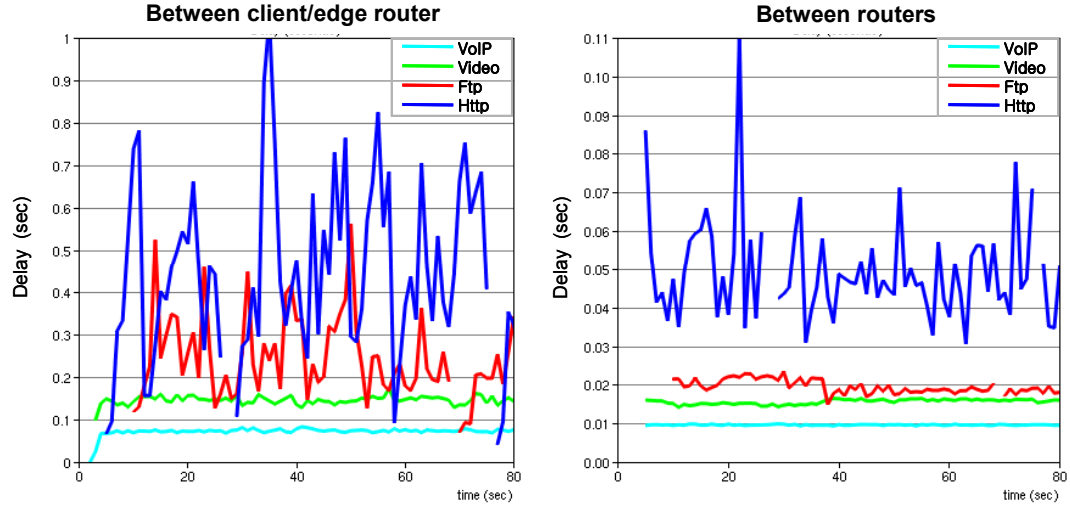


Figure 23. Delay of traffic of four applications with the delay assurance algorithm

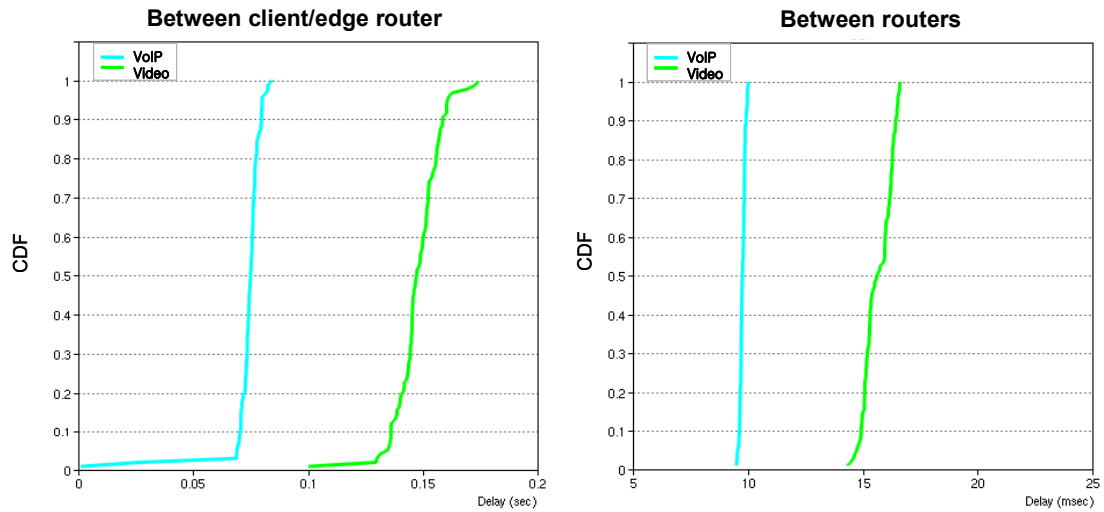


Figure 24. CDF of the traffic delay of multimedia applications

Figure 24 shows the maximum delay guarantee using the cumulative distribution function (CDF) of the traffic delay of the VoIP and video conferencing applications. The average maximum per-hop delay for the traffic of VoIP and video conferencing applications is 11 msec and 16.33 msec respectively. Therefore, on the basis of the

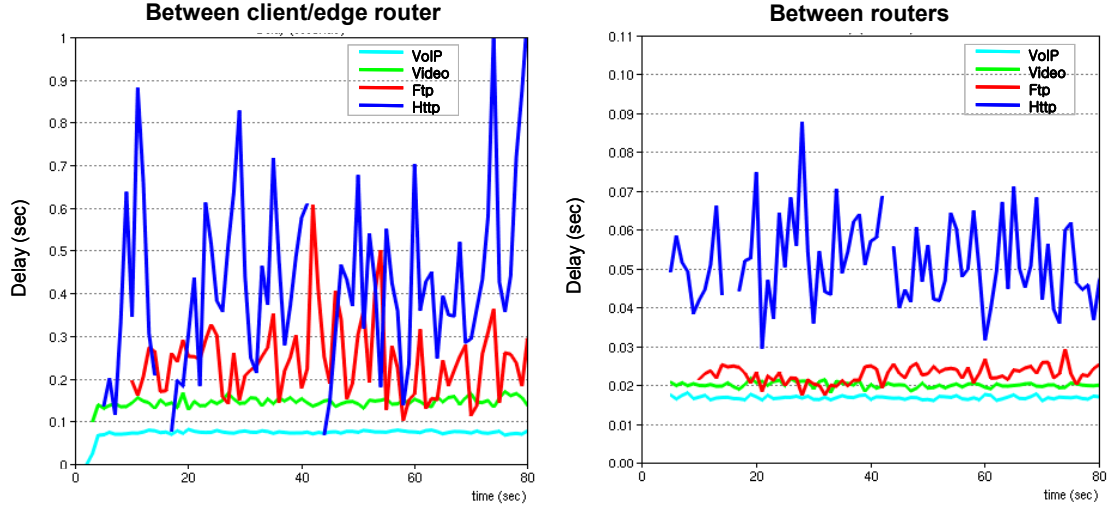


Figure 25. Delay of traffic of four applications without the delay assurance algorithm

average maximum per-hop delay, the adaptive delay assurance algorithm provides delay assurance for 100 percent of VoIP traffic and 90 percent of video conferencing traffic.

In the case without the proposed delay assurance algorithm, because of no per-hop delay budget for end-to-end delay assurance, the delay of the multimedia traffic between routers is longer and more widely-distributed in the tradeoff for the decrease in the delay of file transferring and web browsing traffic, for which a small delay is not an important factor. Figures 25 and 26 explain the problem using the delay distribution of the traffic of four applications and the CDF of the traffic delay of the VoIP and video conferencing applications without the proposed algorithm. The tradeoff considerably exacerbates the performance of VoIP and video conferencing applications by increasing the delay of multimedia applications and decreasing the delay of non-multimedia applications between routers.

In addition, the DiffServ architecture with the QoS mechanisms of IEEE 802.11e and IEEE 802.16 provides an excellent end-to-end classified QoS guarantee for

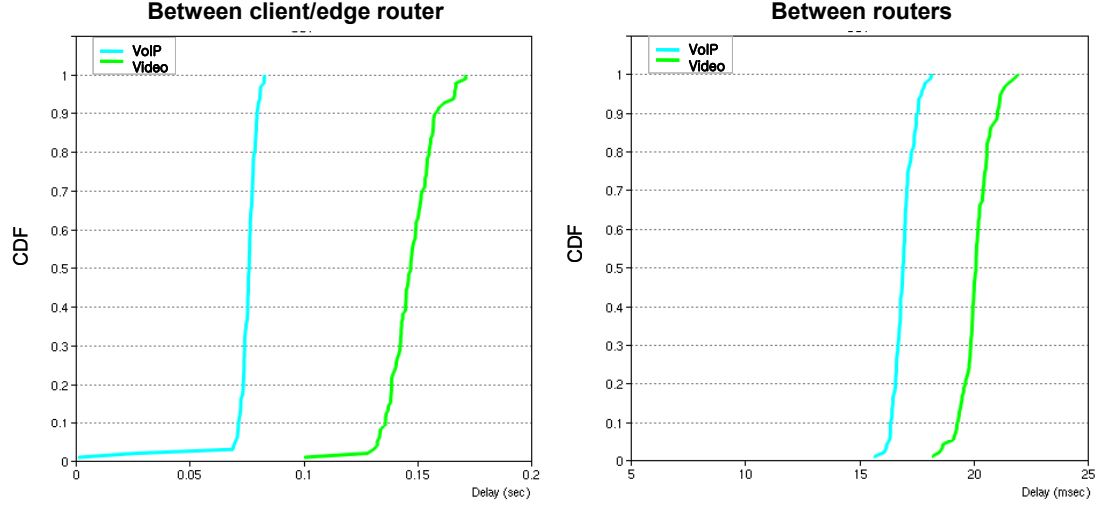


Figure 26. CDF of traffic delay of multimedia applications without the algorithm

TABLE 11  
DELAY STANDARD DEVIATIONS

	Client / Edge router	Edge / Mesh router
VoIP	3.07 msec	0.11 msec
Video Conferencing	8.11 msec	0.57 msec

multimedia communications in the entire network. For the traffic of VoIP and video conferencing applications, delay standard deviations are very small, suggesting that multimedia applications experience only slight or no jitter, an important factor for real-time traffic. Table 11 shows the delay standard deviations. Figure 27 also shows that the proposed architecture distributes throughput differently according to the type of traffic to provide end-to-end QoS support for multimedia applications.

## 5.2 Optimized Delay Assurance Algorithm

Due to the natural characteristics of the wireless medium, the channel conditions for wireless multi-hop communication dynamically change [62]. If multimedia traffic in hybrid multi-hop networks experiences dynamic changes in wireless channel conditions



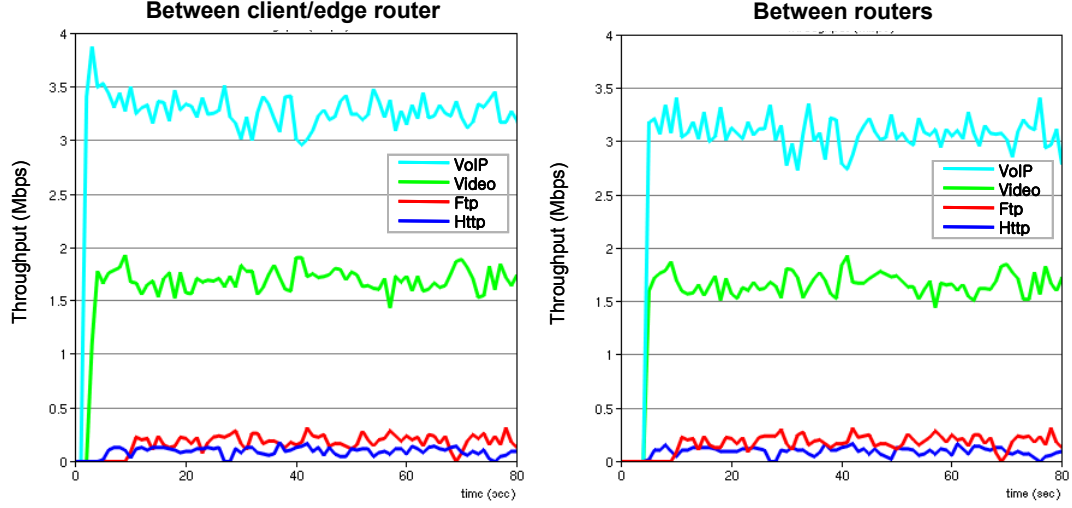


Figure 27. Throughput of traffic of four applications for the delay assurance algorithm

in every hop in the traffic connection path, each multi-hop router with the same maximum per-hop delay constraint will encounter problem meeting the delay assurance requirement by using the adaptive delay assurance algorithm because the maximum per-hop delay has already been induced from the prior wireless channel condition. The adaptive delay assurance algorithm needs to be enhanced for consideration of the current wireless channel condition. Therefore, an optimized delay assurance algorithm is proposed for a dynamic change in the channel condition that computes an optimal maximum per-hop delay on the basis of the current per-hop channel condition at every router. The delay assurance algorithm delivers much better delay assurance performance for the hybrid multi-hop networks with a dynamic change in the wireless channel condition than the adaptive delay assurance algorithm.

### 5.2.1 Algorithm

Multimedia traffic experiences different channel conditions at every router node with a distinct communication environment. Therefore, before sending traffic to the next

router, every router in the traffic path needs to obtain a proper per-hop delay budget for the current channel condition. The optimized delay assurance algorithm assigns an optimal maximum per-hop delay for the present channel condition to every multi-hop router according to the current delay budget and the past actual delay to adjust the maximum per-hop delay for a dynamic change in the per-hop channel condition.

For hybrid multi-hop networks with  $n+1$  hops, a wireless backbone network has  $n$  hops because the first hop occurs between a client and an edge route. For wireless backbone networks with  $n$  hops, the remaining delay budget at the first router, the edge router, is  $D_c - d_i - d_e$ , which is reduced from the end-to-end delay constraint of an multimedia application ( $D_c$ ) by the expected packet delay between a gateway router and a destination in the IP backhaul networks ( $d_i$ ) and the packet delay between a client and an edge router ( $d_e$ ). According to the delay budget and the number of remaining hops,  $n$ , the first maximum per-hop delay is

$$D_1 = \frac{D_c - d_i - d_e}{n},$$

which is the same as the adaptive delay assurance algorithm. If an actual per-hop delay in the first hop is  $T_1$ , then according to the remaining delay budget ( $D_c - d_i - d_e - T_1$ ) and the number of remaining hops ( $n-1$ ), the second maximum per-hop delay at the second router is

$$D_2 = \frac{(D_c - d_i - d_e) - T_1}{n-1}.$$

In the same way, if an actual per-hop delay in the second hop is  $T_1$ , the third maximum per-hop delay is

$$D_3 = \frac{(D_c - d_i - d_e - T_1) - T_2}{n - 2}.$$

Therefore, the proposed optimized delay assurance algorithm at the  $(k+1)_{th}$  router iteratively computes the maximum per-hop latency for the next hop according to the remaining delay budget  $(D_c - d_i - d_e - \sum_{i=1}^{k-1} T_i)$ , the actual delay from the  $k_{th}$  router to the  $(k+1)_{th}$  router ( $T_k$ ), and the number of remaining hops  $(n-k)$ . The maximum per-hop latency for the  $(k+1)_{th}$  hop is

$$D_{k+1} = \begin{cases} \frac{D_c - d_i - d_e - \sum_{i=1}^k T_i}{n - k} & (D_c - d_i - d_e - \sum_{i=1}^k T_i > 0) \\ D_k & (D_c - d_i - d_e - \sum_{i=1}^k T_i \leq 0) \end{cases} \quad (0 \leq k \leq n-1),$$

where  $D_c$  is the end-to-end delay constraint of an application,  $d_i$  is the expected packet delay between a gateway router and a destination in the IP backhaul networks,  $d_e$  is the packet delay between a client and an edge router,  $T_i$  is the actual delay in the  $i_{th}$  hop,  $n$  is the number of end-to-end hops of a traffic connection in the multi-hop backbone network

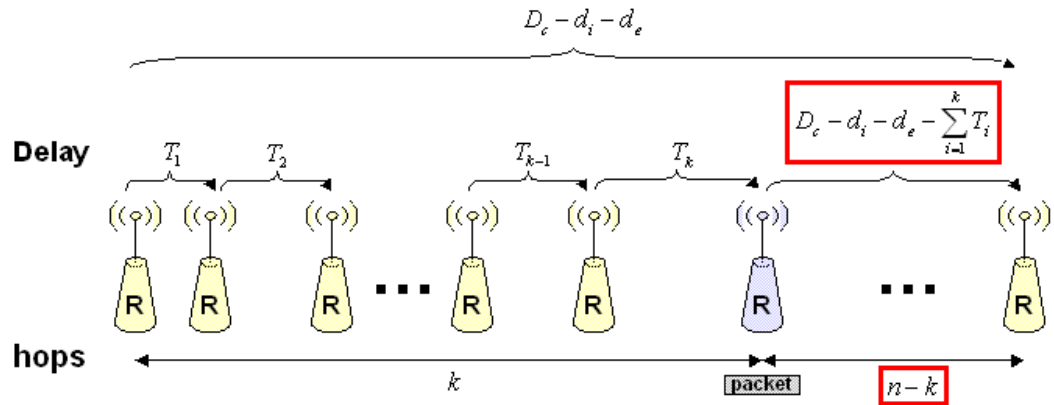


Figure 28. Mechanism of the optimized delay assurance algorithm

after executing a routing scheme, and  $k$  is the number of current hops. Figure 28 explains the mechanism of the optimized delay assurance algorithm.

Although the formula distinctly explains the algorithm, to simplify the complexity of the computation in the algorithm and to minimize the amount of shared information exchange among routers for the practical implementation of the algorithm in hybrid multi-hop networks, the optimized delay assurance algorithm of the implementation version is

$$D_1 = \frac{D_c - d_i - d_e}{n}$$

$$D_{k+1} = \begin{cases} \frac{\{n - (k - 1)\}D_k - T_k}{n - k} & (\{n - (k - 1)\}D_k - T_k > 0) \\ D_k & (\{n - (k - 1)\}D_k - T_k \leq 0) \end{cases} \quad (1 \leq k \leq n - 1)$$

. By applying the formula for realistic implementation of the algorithm, all routers can attain the maximum per-hop delay using the maximum per-hop delay and the actual delay for the previous hop.

### 5.1.2 Simulation and results

In the proposed hybrid multi-hop network, consisting of the classified QoS-enabled WLANs with the contention-based MAC protocol and wireless multi-hop backbone routers with the connection-based MAC protocol, the adaptive delay assurance algorithm and the optimized delay assurance algorithm are installed using OPNET Modeler and MATLAB for simulations. It is assumed that the execution of a routing scheme produces a path of traffic connection between a gateway router and an edge router, and from the routing scheme, the routing table provides the number of end-to-end hops of a traffic connection for the delay assurance algorithms. For installation, the contention-based MAC protocol between a client and an edge router and the connection-based MAC

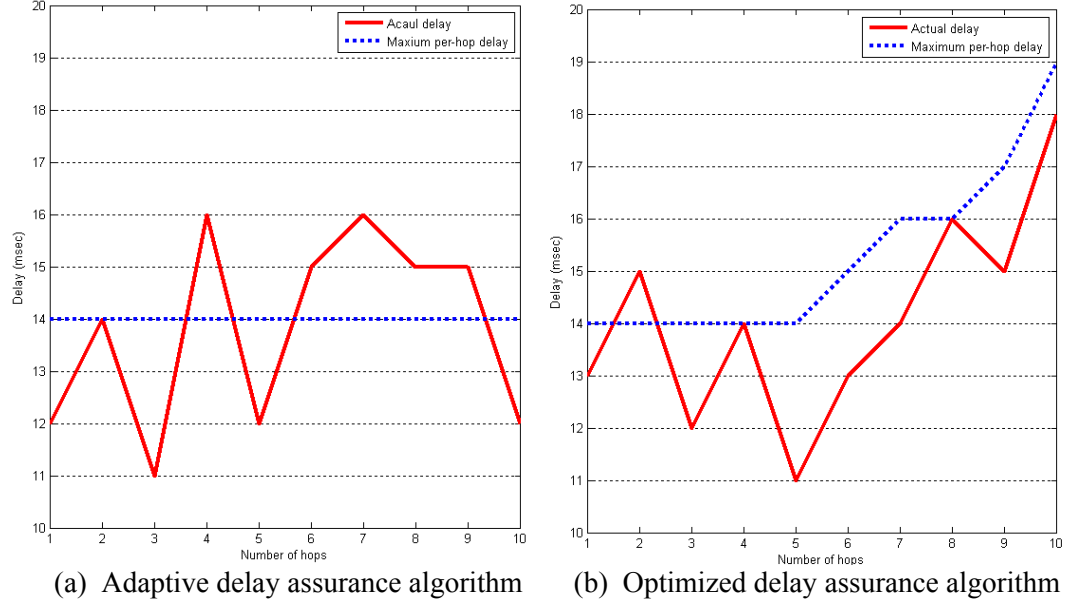


Figure 29. Delay of a packet per hop

TABLE 12  
SIMULATION ENVIRONMENT PARAMETERS

Parameters	Value
Delay requirement (msec)	220
Maximum delay between client/edge router (msec)	82
Minimum delay between client/edge router (msec)	65
Number of hops in multi-hop backbone network	10(variable)
Number of packets	100
Confidence level for delay assurance (%)	95
Number of experiments	100

protocol between the routers are simulated as the radio communication interface. The variation in delay between a client and an edge router is set larger than between the routers because of the difference between the contention-based and connection-based MAC protocols.

To generate multimedia traffic, the video conferencing application with the end-to-end delay constraint of 220 msec runs in the hybrid multi-hop networks. After applying both delay assurance algorithms to the video conferencing application, it is observed how the multimedia traffic satisfies the delay requirement in the wireless channel environment

with a dynamic change. Table 12 describes the simulation environment parameters from the simulation results using OPNET Modeler.

First of all, to study the effect of the two delay assurance algorithms on multimedia traffic in hybrid multi-hop networks with ten hops, the delay in the video conferencing application is measured in every hop. Figure 29 shows the delay of a packet per hop according to each delay assurance algorithm. As shown in the graphs, in a good channel condition, the optimized delay assurance algorithm assigns a longer maximum per-hop delay with less bandwidth allocation than the adaptive delay assurance algorithm to conserve the bandwidth of the multimedia traffic and to provide more opportunity for bandwidth allocation to other traffic. In other words, even in the good channel condition in which bandwidth can be saved, the adaptive delay assurance algorithm tends to waste bandwidth by assigning the same maximum per-hop latency with the same bandwidth allocation to all routers.

In the bad channel condition, if the actual delay in the previous hop cannot maintain the required per-hop delay, the algorithm cannot provide any solution for delay assurance in the current hop because the past distributed maximum per-hop delay is improper for the current per-hop delay requirement satisfying the end-to-end delay constraint of the multimedia application. However, the optimized delay assurance algorithm provides efficient bandwidth allocation in the current hop because the algorithm attempts to set a higher maximum per-hop delay with less bandwidth allocation and save bandwidth for other traffic if the real delay in the previous hop is shorter than the required per-hop delay. Although the actual delay in the previous hop is longer than the maximum per-hop latency, the algorithm sets a new maximum per-hop delay to meet the end-to-end delay

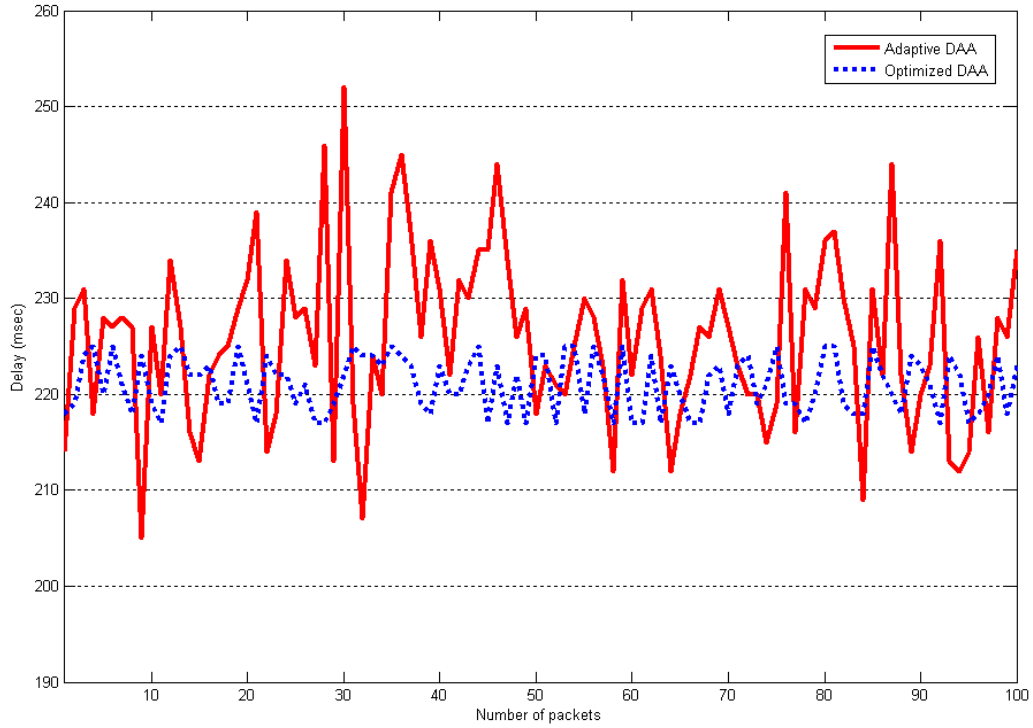


Figure 30. Delay of the packets from two delay assurance algorithms

requirement of the application in hybrid multi-hop networks. Therefore, the optimized delay assurance algorithm provides the flexible delay requirement assignment and efficient bandwidth allocation in the hybrid multi-hop networks in the event of a dynamic change in the wireless channel condition.

In addition, to investigate the end-to-end delay trend of multimedia traffic in hybrid multi-hop networks, the delay of 100 packets in the video conferencing application is measured. Figure 30 shows the delay of the packets from the two delay assurance algorithms.

The optimized delay assurance algorithm convergently distributes the end-to-end delay of packets around 220 msec, the end-to-end delay requirement. However, the adaptive delay assurance algorithm expands the variance of the end-to-end delay

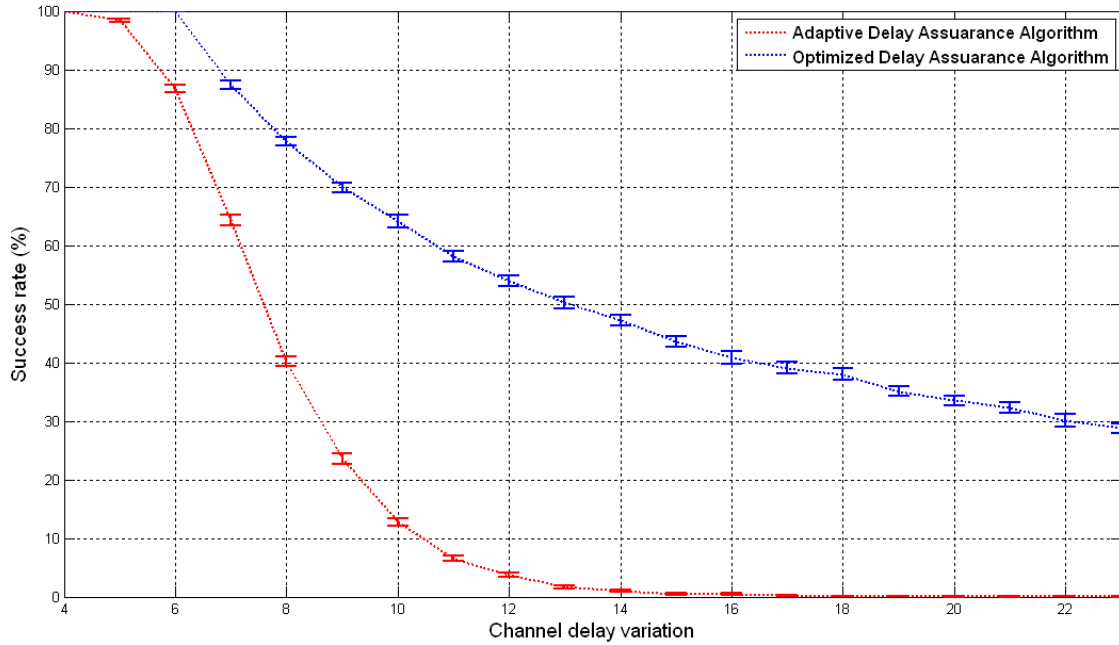


Figure 31. Success rate of delay assurance according to the channel condition

distribution of packets, and most packets experience longer end-to-end delay than the delay constraint. That is, the optimized delay assurance algorithm is more robust at meeting the end-to-end delay requirement of multimedia traffic than the adaptive delay assurance algorithm.

Furthermore, to compare the performance of the two algorithms while undergoing a dynamic change in their channel conditions, the video conferencing application runs 100 times using two delay assurance algorithms, and the success rate of their end-to-end delay assurance is studied at the confidence level of 95% according to the extent of the delay variance, which indicates the channel condition change. Figure 31 explains the success rate of delay assurance in the cases of the two delay assurance algorithms. The results show that the optimized delay assurance algorithm produces a higher rate of success at delay assurance than the adaptive delay assurance algorithm as changes in the channel condition becomes more serious because of the adjustable assignment of the delay



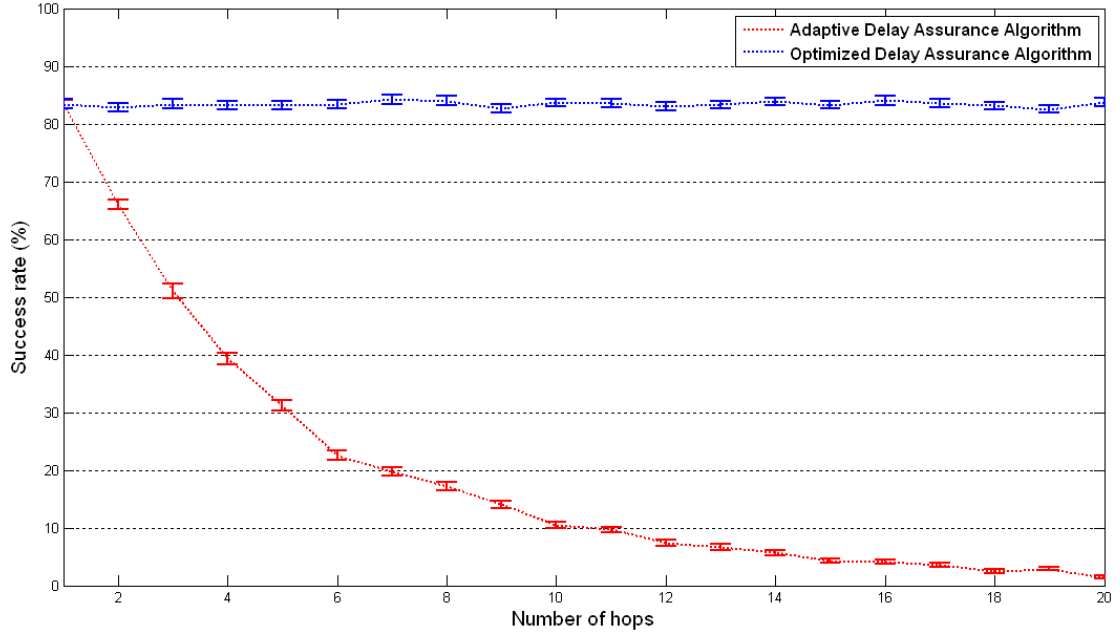


Figure 32. Success rate of delay assurance according to the number of routers

requirement and the cost-effective allocation of the bandwidth of the delay assurance algorithm. However, the adaptive delay assurance algorithm is not likely to adjust dynamic changes in the communication environment because it computes the common, fixed maximum per-hop delay for all routers once at the edge router.

Moreover, to observe the difference in the success rate of the delay assurance of the two delay assurance algorithms at a confidence level of 95% as the number of routers increases, the multimedia application with two delay assurance algorithms runs 100 times in the hybrid multi-hop networks. Figure 32 demonstrates the success rate of delay assurance in the cases of the two delay assurance algorithms. The graphs show that as the number of multi-hop routers increases, the optimized delay assurance algorithm yields more robust performance for delay assurance than the adaptive delay assurance algorithm because the possibility of a change in the channel condition increases as the number of routers increases. Therefore, the optimized delay assurance algorithm, which

is more sensitive and adjustable to changes in the communication channel condition, produces a higher rate of success at delay assurance.

### **5.3 Contributions**

First of all, an adaptive delay assurance algorithm with the DiffServ architecture is proposed in hybrid multi-hop mesh/relay networks. The proposed algorithm and the DiffServ architecture produce an excellent synergistic effect, providing end-to-end QoS for the hybrid multi-hop networks. The algorithm provides parameterized QoS support by maintaining the end-to-end delay of an application, and the DiffServ mechanism yields a classified QoS guarantee in the entire network. In the case of small changes in the channel condition, the adaptive delay assurance algorithm with a simple structure and low complexity efficiently performs delay assurance for multimedia traffic in hybrid multi-hop networks.

However, in the channel condition with a dynamic change, the algorithm could not rapidly adjust to changes in the channel condition and maintain delay assurance. To make up for the shortcomings of the algorithm, an optimized delay assurance algorithm is also proposed that flexibly allots the delay constraint and efficiently allocates bandwidth to hybrid multi-hop networks. The results of simulations show that as changes in the channel conditions become more dynamic and the number of routers increases, the optimized delay assurance algorithm produces a higher rate of success at delay assurance than the adaptive delay assurance algorithm. Therefore, the proposed algorithms can provide an excellent QoS guarantee that satisfies the traffic requirements of applications in hybrid multi-hop networks.

## **CHAPTER 6**

### **DIFFERENTIATED POLLING ALGORITHM**

#### **FOR DELAY ASSURANCE**

Efficient bandwidth allocation is an important process if multimedia traffic is to arrive at a destination within the delay constraint because the packets of traffic are transmitted at the rate of the bandwidth. For the delay assurance algorithm, which produces a per-hop delay requirement in hybrid multi-hop networks, a proper bandwidth corresponding to the per-hop delay constraint needs to be allocated. In multi-hop networks, when the maximum per-hop latency is computed at a multi-hop router to meet the delay requirement and the packets are transmitted to the next router within the maximum per-hop latency, the next router that receives the packet traffic should allot an appropriate bandwidth to the current router.

For the bandwidth request and grant in wireless multi-hop networks, a process whereby a multi-hop router allocates bandwidth to a router or a group of routers for bandwidth requests is referred to as a polling service. The polling service for the connection-based MAC protocol simply operates bandwidth allocation on demand. The polling technique enables a router with the connection-based MAC protocol to provide sufficient bandwidth grant for all routers. The typical polling algorithm for the connection-based MAC protocol, which allocates bandwidth for the polling service in proportion to the requested bandwidth for the actual traffic, just accounts for the amount of requested bandwidth and ignores the influence of the characteristics of the traffic such as the ratio of multimedia traffic to overall traffic and the number of traffic connections.

However, to guarantee QoS, the polling mechanism for bandwidth allocation should reflect the nature of the traffic [63].

Therefore, a polling algorithm with a differentiated strategy is proposed for characteristic parameters of traffic at the multi-hop routers. The differentiated polling algorithm at a router differentially computes and distributes the polling rates for routers according to the ratio of multimedia traffic to overall traffic, the number of traffic connections, and the type of polling service. In addition, an efficient bandwidth allocation mechanism associated with the optimized delay assurance algorithm and the differentiated polling algorithm is investigated. The bandwidth allocation scheme yields the minimum reserved traffic bandwidth that corresponds to the maximum per-hop delay from the delay assurance algorithm for a multi-hop router. First of all, the relationship between the polling service and the delay for the polling algorithm with delay assurance is studied.

## 6.1 Delay Analysis

Generally, the network delay consists of four types of delays: (1) A processing delay is the time it takes the routers to process a packet header; (2) queuing delay is the time a packet remains in a routing queue; (3) transmission delay is the time it takes to push the packet's bits onto the link; and (4) propagation delay is the time it takes a signal to reach its destination. The network delay is expressed as

$$D = D_{processing} + D_{queuing} + D_{transmission} + D_{propagation} .$$

Because processing delay and propagation delay are negligible in the literature, the delay becomes

$$D = D_q + D_t ,$$

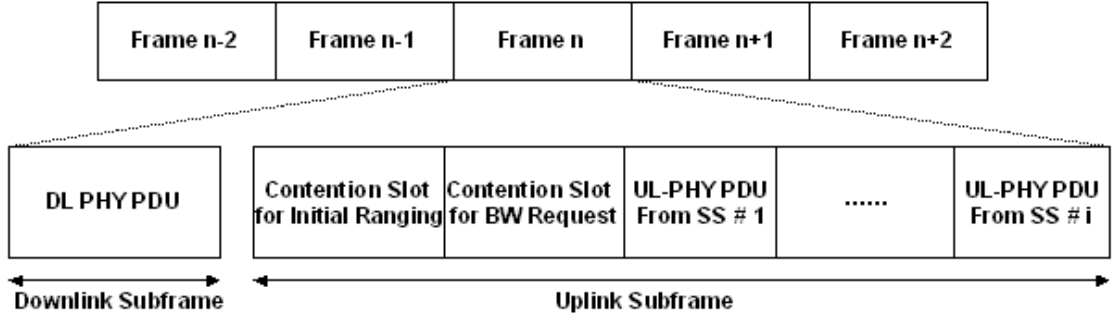


Figure 33. Frame structure of the connection-based MAC protocol

where  $D_q$  is the queuing delay and  $D_t$  is the transmission delay. Therefore, queuing delay is

$$D_q = D - D_t,$$

and the range of the queuing delay [40] is

$$0 \leq D_q \leq \max D - \min D_t.$$

The router receiving traffic determines the group of routers transmitting traffic, assigns their bandwidth requirements, and performs the polling service once every  $k$  frames for every router. Figure 33 describes the frame structure of the connection-based MAC protocol. To choose the best polling interval of  $kT_f$ , where  $T_f$  is the duration of a frame, a router with the delay requirement must determine that the polling interval is less than the queuing delay constraint. In addition, a packet needs to wait for  $(k+1)T_f$  to be transmitted because polling is done once every  $kT_f$ , and scheduling is performed in  $T_f$  [49]. Figure 34 describes the polling mechanism in the frame structure of the connection-based MAC protocol. Therefore, the relationship between the maximum time of the entire polling process and the queuing delay is

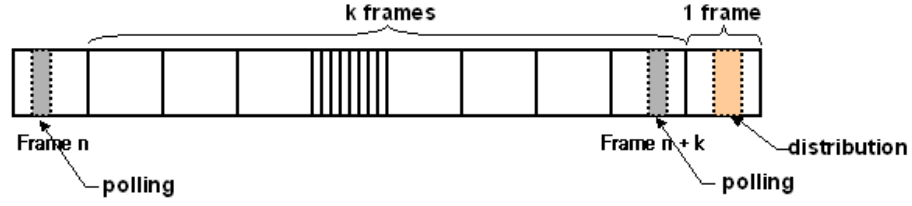


Figure 34. Polling mechanism in frame structure of the connection-based MAC protocol

$$(k+1)T_f \leq D_q,$$

where  $k$  is the number of frames for the polling service, and  $T_f$  is the duration of a frame. Applying the condition of the queuing delay for hybrid multi-hop networks, the maximum delay is

$$\max D = D_h,$$

where  $D_h$  is the maximum per-hop delay.

For packet traffic transmission, the router receiving traffic should receive the packet before the router sending traffic transmits another packet in the wireless channel because multiple packets cannot occupy a wireless channel. As a result, the transmission delay closely correlated with the bandwidth of the wireless link is

$$D_t = L/R,$$

where  $L$  is the size of the packet, and  $R$  is the effective bandwidth of the wireless link [64]. Figure 35 explains the relationship between the transmission delay and the bandwidth. Therefore, the minimum transmission delay is

$$\min D_t = \frac{L}{R_{\max}}.$$

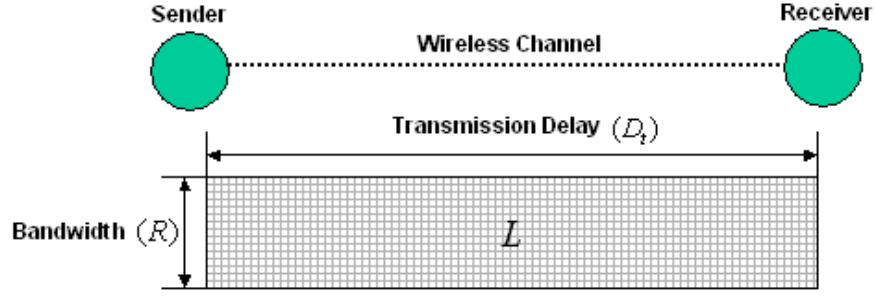


Figure 35. Relationship between transmission delay and bandwidth

From the relationships, the range of the polling interval for the hybrid multi-hop networks is

$$T_f \leq kT_f \leq D_h - \frac{L}{R_{\max}} - T_f.$$

## 6.2 Differentiated Polling Algorithm

The multi-hop router needs to poll the routers around the router at a certain polling rate to allocate the QoS requirements of bandwidth and delay. A high polling rate quickly adapts the QoS requirements to any rapid changes in the traffic rate for the router. In other words, the frequent polling, updating the most current information, successfully meets the QoS requirements. However, it also produces bandwidth overhead required by the poll signaling mechanism. Infrequent polling with a very low overhead does not satisfy QoS requirements [65]. Therefore, an appropriate polling rate for the demand on traffic undergoing rapid changes is crucial for stable communication with QoS support. Thus, a novel polling algorithm with a differentiated strategy is proposed for delay assurance according to the characteristic parameters of traffic at the router. The algorithm for the delay assurance of a router computes and distributes the differentiated polling rates for routers sending data traffic to the router according to the ratio of

multimedia traffic to overall traffic, the number of traffic connections, and the type of polling service, either a unicast or multicast polling service.

Because multimedia applications should continuously maintain a stable traffic rate over a certain value, a multi-hop router with the high percentage of multimedia traffic among all possible traffic should have more polling opportunities to maintain low delay and jitter for data transmission. In addition, the number of traffic connections is also an important factor in polling rate decisions because the traffic rates of many traffic connections are more likely to change, and a router with many connections requires a higher polling rate to allocate more bandwidth from a router to adjust the traffic rate to changes. Moreover, when a multicast group of routers loses a polling opportunity, all clients with the contention-based MAC protocol, belonging to routers in the group, will have no opportunity to request bandwidth allocation. Thus, the algorithm gives the priority of polling to multicast groups rather than unicast routers.

To simplify the computation of the polling interval, it is assumed that the polling interval is in inverse proportion to the characteristic parameter of traffic such as the ratio of multimedia traffic and the number of traffic connections. The polling interval is

$$T_i = \frac{T_{\min} - T_{\max}}{c_{\max}} \times c + T_{\max} \quad (0 \leq c \leq c_{\max}),$$

where  $T_{\min}$  is the minimum polling interval for the normal operation of a system,  $T_{\max}$  is the maximum polling interval for the normal operation of a system,  $c$  is the characteristic parameter of traffic, and  $c_{\max}$  is the maximum value of the characteristic parameter of traffic. From a delay analysis, the polling interval is  $kT_f$ , the minimum polling interval



is  $T_f$ , and the maximum polling interval is  $D_h - \frac{L}{R_{\max}} - T_f$ . Therefore, the polling interval for delay assurance is

$$kT_f = \frac{T_f - \left( D_h - \frac{L}{R_{\max}} - T_f \right)}{c_{\max}} \times c + D_h - \frac{L}{R_{\max}} - T_f \quad (0 \leq c \leq c_{\max}).$$

The polling algorithm calculates two kinds of polling intervals according to the ratio of multimedia traffic to all traffic and the number of traffic connections at a router without consideration of the type of polling service. As the ratio of multimedia traffic and the number of traffic connections become larger, the router requires a shorter polling interval, which means a higher polling rate. As a result, the number of frames associated with differentiated polling intervals according to the multimedia traffic ratio and the number of traffic connections is

$$k_n = \frac{2T_f R_{\max} - D_h R_{\max} + L}{T_f R_{\max} n_{\max}} \times n + \frac{D_h R_{\max} - L}{T_f R_{\max}} - 1 \quad (0 \leq n \leq n_{\max})$$

$$k_m = \frac{2T_f R_{\max} - D_h R_{\max} + L}{T_f R_{\max} m_{\max}} \times m + \frac{D_h R_{\max} - L}{T_f R_{\max}} - 1 \quad (0 \leq m \leq m_{\max}),$$

where  $k_n$  is the number of frames corresponding to a polling interval for the number of traffic connections at a router,  $k_m$  is the number of frames corresponding to a polling interval for the ratio of multimedia traffic to overall traffic at a router,  $n$  is the number of traffic connections in an edge router,  $m$  is the ratio (percentage) of multimedia traffic to overall traffic in a router,  $n_{\max}$  is the maximum number of traffic connections a router can manage, and  $m_{\max}$  is the maximum value of the ratio (percentage).

From the frame numbers for the polling intervals, the algorithm obtains a basic frame number for the polling interval using the weighted mean of the frame numbers without considering the type of polling service. The basic frame number is

$$k_b = \lfloor \sqrt{k_n k_m} \rfloor.$$

Using the basic frame number and the frame duration, the basic polling interval and the basic polling rate are

$$T_b = \frac{1}{R_b} = k_b T_f,$$

where  $T_b$  is the basic polling interval, and  $R_b$  is the basic polling rate. The size of the bandwidth request header and the polling rate produce the required bandwidth by polling the signals of an edge router. The required bandwidth is

$$B_b = \frac{F}{T_b} = F \times R_b,$$

where  $B_b$  is the bandwidth for the polling signals, and  $F$  is the size of the bandwidth request header.

To generate more polling opportunities for the multicast groups, the algorithm allocates more bandwidth to polling for a group of routers using a multicast polling service than it does for a router using a unicast polling service.

$$\begin{cases} B_u = \alpha \times B_b \\ B_m = \beta \times B_b \end{cases} \quad (\alpha \leq \beta),$$

where  $B_u$  is the bandwidth needed for unicast polling,  $B_m$  is the bandwidth needed for multicast polling, and  $\alpha$  and  $\beta$  are constant values scaling the bandwidth for unicast and multicast polling. Because the remaining bandwidth from subtracting the total minimum

reserved bandwidths allocated to traffic from an entire uplink bandwidth can be used for polling services, the algorithm gains  $\alpha, \beta$  by adjusting  $\alpha$  and  $\beta$  from

$$B_{uplink} - B_{alloc} - \sum_i B_{u_i} - \sum_j B_{m_j} > 0,$$

where  $B_{uplink}$  is an entire uplink bandwidth, and  $B_{alloc}$  is the total minimum reserved bandwidths from the efficient bandwidth allocation scheme. Finally, the algorithm can yield an optimal polling interval for unicast and multicast polling services using the duration of a frame,  $\alpha$ , and  $\beta$ . The optimal polling intervals are

$$T_{unicast\_opt} = \frac{1}{R_{unicast\_opt}} = k_{unicast\_opt} \times T_f = \left\lfloor \frac{k_b}{\alpha} \right\rfloor \times T_f$$

$$T_{multicast\_opt} = \frac{1}{R_{multicast\_opt}} = k_{multicast\_opt} \times T_f = \left\lfloor \frac{k_b}{\beta} \right\rfloor \times T_f.$$

### 6.3 Bandwidth Allocation

To meet the maximum per-hop delay from the optimized delay assurance algorithm, the differentiated polling algorithm produces the minimum queuing delay, which is the polling interval. Using the maximum per-hop delay and the minimum queuing delay, an efficient bandwidth allocation scheme for the QoS assurance of multimedia traffic is proposed. As explained earlier, the transmission delay is

$$D_t = D - D_q.$$

Because the transmission delay can be expressed as  $L/R$  [66], the bandwidth allocated for the delay constraint and the queuing delay is

$$R = \frac{L}{D - D_q}.$$

Applying the maximum per-hop delay,  $\max D_h$ , from the delay assurance algorithm and the minimum queuing delay,  $\min D_q$ , for the formula of bandwidth allocation, the minimum reserved bandwidth becomes

$$\min R = \frac{L}{\max D_h - \min D_q} = \frac{L}{\max D_h - (k_{opt} + 1)T_f}.$$

## 6.4 Simulation and Results

The hybrid multi-hop network is deployed using the connection-based MAC protocol with QoS-enabled WLANs using the contention-based MAC protocol, and the differentiated polling algorithm is installed using the WiMAX and WLAN models in OPNET Modeler. For the deployment, IEEE 802.11e with DSSS is used between a client

TABLE 13  
PARAMETERS OF ACCESS CATEGORIES

AC	AIFS ( $\mu$ s)	CWmin	CWmax	TXOP
AC_BK	90	63	127	One MSDU
AC_BE	70	63	127	One MSDU
AC_VI	70	7	15	One MSDU
AC_VO	50	7	15	One MSDU

TABLE 14  
IEEE 802.16 OFDMA PARAMETERS

Radio parameters	Value
Base frequency (GHz)	5
Bandwidth (MHz)	20
Duplex method	TDD
Frame duration (msec)	2
Symbol duration ( $\mu$ sec)	102.86
# of data subcarrier in UL	1120
# of data subcarrier in DL	1440
UL Capacity (Msps)	5.0944
DL Capacity (Msps)	6.336

and an edge router, which communicate with the contention-based MAC protocol with QoS support. The parameters of the four ACs of the IEEE 802.11e are described in Table 13. Between routers with the connection-based MAC protocol, IEEE 802.16 with wireless OFDMA 20 MHz is used. Table 14 shows the IEEE 802.16 OFDMA parameters.

The multi-hop network consists of four routers using the unicast polling service and three groups of routers using the multicast polling service. Figure 36 describes the topology of the multi-hop network and the traffic specifications of the routers and the group of routers, which includes the ratio of multimedia traffic to overall traffic, the number of traffic connections, and the maximum per-hop delays from the delay assurance algorithm. The four routers receive packet traffic from the four IEEE 802.11e clients with one FTP traffic connection and three video conferencing traffic connections, four IEEE 802.11e clients with two FTP traffic connections and two video conferencing

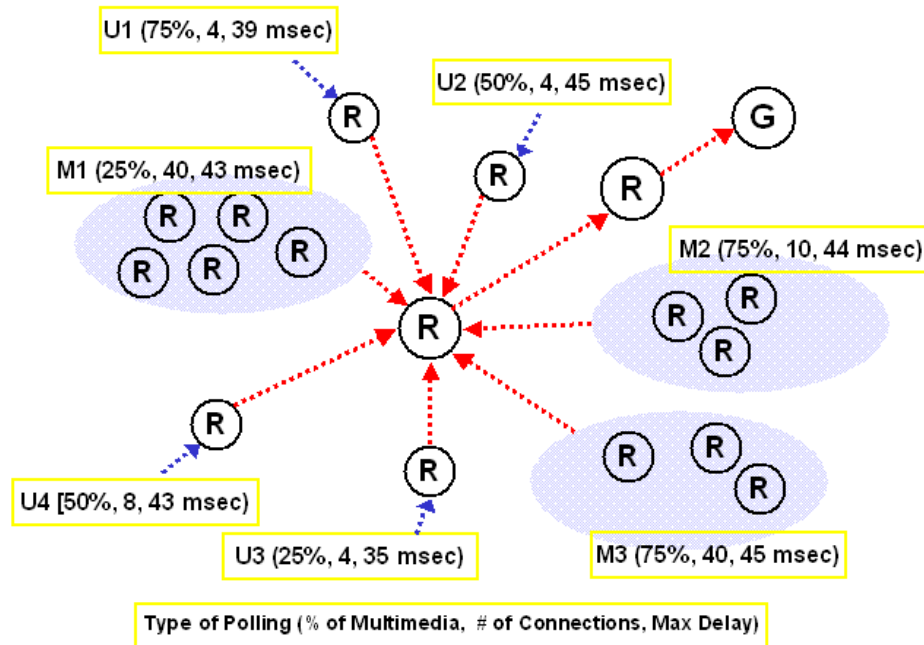


Figure 36. Multi-hop network topology and traffic specifications

TABLE 15  
PARAMETERS IN DIFFERENTIATED POLLING ALGORITHM

Parameters	Value
$R_{\max}$	1.5 Mbps
$T_{\max}$	2 msec
$L$	1500 bytes
$m_{\max}$	100 %
$n_{\max}$	10 (unicast) 50(multicast)
$F$	6 bytes

traffic connections, four IEEE 802.11e clients with three FTP traffic connections and one video conferencing traffic connection, and eight IEEE 802.11e clients with four FTP traffic connections and four video conferencing traffic connections. Three multicast groups of routers receive traffic from IEEE 802.11e clients with multimedia traffic ratios of 25% and 40 traffic connections, 75% and 10 traffic connections, and 75% and 40 traffic connections, respectively. The total maximum bandwidth of the traffic of the video conferencing and FTP applications is 1.5 Mbps, which is the maximum bandwidth allocated for a router to send the traffic. For the simulation, the parameters used in the proposed polling algorithm are shown in Table 15. The simulation assumes that if total requested bandwidth from routers exceeds the uplink bandwidth, the bandwidth request from one of routers can be rejected using admission control.

To evaluate the performance of the differentiated polling algorithm, the proposed polling algorithm is compared with the proportional polling algorithm, which is implemented in the OPNET WiMAX model, with a polling rate 8 times as fast as the packets/sec rate of the minimum reserved traffic rate. Table 16 shows that the differentiated polling algorithm and the efficient bandwidth allocation scheme successfully provide an appropriate polling interval and a minimum reserved traffic

TABLE 16  
TRAFFIC ADMISSION STATISTICS

	Proportional	Differentiated
Uplink bandwidth (Msps)	2.096	2.096
Admitted bandwidth (Msps)	1.678	2.052
# of admitted clients	40	80
# of rejected clients	40	0

TABLE 17  
POLLING RATES AND OVERHEADS IN PROPORTIONAL AND DIFFERENTIATED POLLING ALGORITHMS

	Req. BW (kbps)	Polling interval (msec/poll)		Polling overhead (bps)		Admission	
		Prop.	Diff.	Prop.	Diff.	Prop.	Diff.
Unicast 1	480	4	12	15360	4000	Admitted	Admitted
Unicast 2	521	3	20	16672	2400	Admitted	Admitted
Unicast 3	705	3	16	22560	3000	Admitted	Admitted
Unicast 4	428	4	10	13696	4800	Admitted	Admitted
Multicast 1	444	N/A	14	N/A	3429	Rejected	Admitted
Multicast 2	461	4	16	14752	3000	Admitted	Admitted
Multicast 3	545	3	6	17440	8000	Admitted	Admitted

bandwidth that guarantees QoS in the multi-hop network. In the case of the proportional polling algorithm, the bandwidth requests by 40 clients at the multimedia traffic ratio of 25% are rejected, and the utilization of uplink bandwidth is 80%, which means that 20% of the uplink bandwidth is wasted because of rejected traffic. However, in the case of the proposed polling algorithm, all the traffic in the network is admitted and the utilization of uplink bandwidth is 97.9%, both of which provide evidence of efficient bandwidth allocation.

As shown in Table 17, the typical polling algorithm, which allocates bandwidth for the polling service in proportion to the requested bandwidth for the actual traffic, neglects the effect of multimedia traffic and the number of traffic connections on changes in traffic rates. For example, three routers with the unicast polling service and different multimedia traffic ratios use similar polling rates, indicating that the routers cannot instantly adjust bandwidth allocation to changes in traffic rates. In addition, even though

multicast groups have different ratios of multimedia traffic and the number of traffic connections, they use the same polling rate. However, the proposed polling algorithm, which assigns polling intervals that vary according to the multimedia traffic ratio and the number of traffic connections, efficiently adapts bandwidth allocation using the bandwidth allocation scheme to changes in traffic rates. Furthermore, in Table 17, we can observe that the differentiated polling algorithm yields more polling opportunities for multicast groups by assigning higher polling rates even though the typical polling algorithm does not consider the type of polling service.

## **6.5 Contributions**

A differentiated polling algorithm with an efficient bandwidth allocation scheme is proposed for hybrid multi-hop networks with WLANs. The proposed algorithm for delay assurance produces a sufficient polling interval that is more conducive to providing end-to-end QoS and efficient bandwidth allocation for data transmission and multimedia communication in the heterogeneous multi-hop network. The algorithm provides a suitable adaptation of bandwidth allocation for polling services to changes in traffic rates by differentiating polling rates with high bandwidth utilization. Realistic simulation results from OPNET Modeler show that the proposed differentiated polling algorithm can support excellent QoS for all users in the networks.



## **CHAPTER 7**

### **CONCLUSIONS AND FUTURE RESEARCH**

The proposed network architecture, providing class-based QoS for client traffic using the contention-based MAC protocol by using IP bridging with QoS support in an edge router, is hybrid multi-hop mesh/relay networks using the connection-based MAC protocol with WLANs using the contention-based MAC protocol. For traffic requirements, the connection-based scheduling mechanism balances the bandwidth allocation and the delay between routers. By comparing the proposed hybrid multi-hop network with a multi-hop backbone network using the contention-based MAC protocol, it has been provided as strong evidence that the proposed hybrid multi-hop networks can render an excellent QoS guarantee of simultaneous multimedia communication for all users and achieve more fairly-distributed throughput and lower-bounded delay than multi-hop networks with the contention-based MAC protocol.

In addition, for classified QoS in a hybrid multi-hop network with a QoS-enabled WLAN, a cross-layer design with the DiffServ architecture is proposed. Cooperation of the contention-based MAC protocol with classified QoS for clients, the connection-based MAC protocol for the wireless multi-hop backbone network, and the Internet protocol for IP backhaul networks in the proposed DiffServ QoS architecture produce effective end-to-end QoS support for the multi-hop mesh/relay network. The DiffServ architecture, which uses classified IP bridging between wireless nodes with different MAC protocols yields consistent classified QoS support and provides an excellent end-to-end QoS

guarantee that satisfies the classified traffic requirements of applications in the entire network

Furthermore, to add parameterized QoS support in hybrid multi-hop mesh/relay networks, an adaptive delay assurance algorithm with a DiffServ architecture has been developed. The proposed algorithm and DiffServ architecture, producing an excellent synergistic effect, provide end-to-end QoS for hybrid multi-hop networks. By providing classified QoS support from the DiffServ architecture to the entire network, the proposed delay assurance algorithm yields a parameterized QoS guarantee by meeting the end-to-end delay requirement of applications.

Although the adaptive delay assurance algorithm with low complexity assures a delay constraint of the multimedia traffic with small changes in the channel condition, in a channel condition with larger dynamic changes, the algorithm was not able to perform rapid adjustment for maximum delay assurance. However, the proposed optimized delay assurance algorithm can assure an adaptable assignment of delay constraint and efficient allocation of bandwidth. The optimized delay assurance algorithm is much more robust in the dynamic channel condition than the adaptive delay assurance algorithm.

Moreover, for QoS assurance in hybrid multi-hop networks, a differentiated polling algorithm with an efficient bandwidth allocation scheme has been proposed. The proposed polling algorithm for QoS assurance produces a sufficient polling interval and efficient bandwidth allocation for the end-to-end QoS of multimedia communication in the heterogeneous multi-hop network. The polling algorithm is excellent at adapting bandwidth allocation to changes in traffic rates, by differentiating polling rates with high bandwidth utilization and a low rejection of traffic connections.

For future work, a routing algorithm will be investigated for QoS assurance in the hybrid multi-hop mesh/relay networks using the connection-based MAC protocol with QoS-enabled WLANs with the contention-based MAC protocol. In addition, the proposed QoS assurance algorithms will be applied for the coexisting networks of hybrid multi-hop networks with different MAC protocols and homogeneous multi-hop networks with the same MAC protocol.

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## **VITA**

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