This full text paper was peer reviewed at the direction of IEEE Communications Society subject matter experts for publication in the IEEE GLOBECOM 2005 proceedings.

An Integrated QoS Control Architecture for IEEE 802.16 Broadband Wireless Access Systems

Jianfeng Chen, Wenhua Jiao, Qian Guo
Lucent Technologies, Bell Labs Research China
{chenjf, wjiao}@lucent.com

Abstract—**This paper proposes a new integrated QoS architecture for IEEE 802.16 Broadband Wireless MAN in TDD mode. After analyzing the current strategies to provide IntServ for the Internet connection via IEEE802.16-2004 WirelessMAN, a mapping rule and a fast signaling mechanism for providing both InterServ and DiffServ are given under Point to Multi-Point (PMP) and Mesh mode. Comparison and performance analysis of traditional and proposed signaling mechanism are given. The simulation is conducted for VoIP, FTP and HTTP traffic with different QoS requirements. The results show that the proposed integrated QoS control mechanism is more fast and efficient for service setup and maintenance. What is more, bandwidth requirements of different applications can be satisfied by the proposed architecture.**

Keywords- IEEE 802.16, Wimax, Integrated QoS, Wireless Access

I. Introduction

Based on the IEEE 802.16 Wireless Metropolitan Area Network (MAN) air interface standard [1], WiMAX (Worldwide Interoperability for Microwave Access) technology can provide a cost-effective broadband access solution in areas beyond the reach of DSL and cable. The ongoing evolution of IEEE 802.16e will be addressed to support mobile applications. As an under-layer carrier network, the WiMAX network has no restrictions for up-layer services – a mixing of real-time traffic such as voice, multimedia teleconferencing games, and data traffic such as Web browsing, messaging, and file transfers. As defined in [1], there are 4 types of MAC layer services characterized by QoS parameters such as latency, jitter, minimum reserved traffic rate, maximum sustained traffic rate, etc. These service flows can be created, changed, or deleted through the issue of Dynamic Service Addition (DSA), Dynamic Service Change (DSC), and Dynamic Service Deletion (DSD) messages. Each of these actions can be initiated by the SS or the BS and are carried out through a two or three-way-handshake. However, the IEEE 802.16 standard only defines the behavior of MAC layer and PHY layer, a problem arises on how to guarantee the very diverse QoS requirements for all of these applications.

Since an important application in WiMAX network is to provide high speed Internet connection to backhaul network, we focus on the analysis of IP network in this paper. IP network service is based on a connectionless and best-effort model, which is not adequate for many applications that normally require assurances on QoS performance metrics. A number of enhancements have been proposed to enable offering different levels of QoS in IP networks including the integrated services (IntServ) architecture [2], and the differentiated service (DiffServ) architecture [3].

IntServ is implemented by four components: the signaling protocol (e.g. RSVP), the admission control, the classifier and the packet scheduler. These function modules are all defined in [1]. Furthermore, some rules are prescribed to classify DiffServ IP packets into different priority queues based on QoS indication bits in IP header. Therefore, the QoS architecture of PMP mode in IEEE 802.16-2004 can support both IntServ and DiffServ. However, considering the multi-hop mesh mode, although the priority/class field in the Mesh CID may be used to classify different service, QoS is only provisioned insider a one hop range and lack of end-to-end guarantee. To enhance QoS supporting in the 802.16 mesh mode, several proposals have been submitted. We assume connection oriented mesh network defined in [4] in this paper, which borrows the existing PMP signal mechanism, and add some new messages to guarantee the end-to-end QoS requirements. Centralized scheduling is deployed to allocate network resources for data traffic. Therefore, both IntServ and DiffServ can be supported in the PMP and mesh mode defined in IEEE802.16-2004 standard.

In the previous work [5-7], different packet scheduling algorithms are proposed for Wimax network. They all concentrate on the QoS problem in MAC Layer. However, how to guarantee QoS requirements for the high layer services traversing WirelessMAN MAC and PHY layer hasn't been addressed. Two ways for providing cross layer QoS control via WirelessMAN technology may be candidates:

For the first one, the traditional RSVP is used to provide cross layer QoS control. RSVP signaling message can be classified into a special high priority queue (refer to protocol queue below), and be transmitted in the second management connection. Other protocol-specific packet such as Dynamic Host Configuration Protocol (DHCP), Trivial File Transfer Protocol (TFTP), SNMP, etc. also transmitted through this type of connection. In summary, the QoS provision procedure will be consisted of the following two steps: in the first step, the secondary management connection will be shared for RSVP to provide the QoS supporting for up-layer among many IP related messages; in the second step, the primary management connection will be used for DSA/DSC/DSD to provide the MAC layer QoS. The second one is the proposed way. Since there are so many similarities between the

This full text paper was peer reviewed at the direction of IEEE Communications Society subject matter experts for publication in the IEEE GLOBECOM 2005 proceedings.

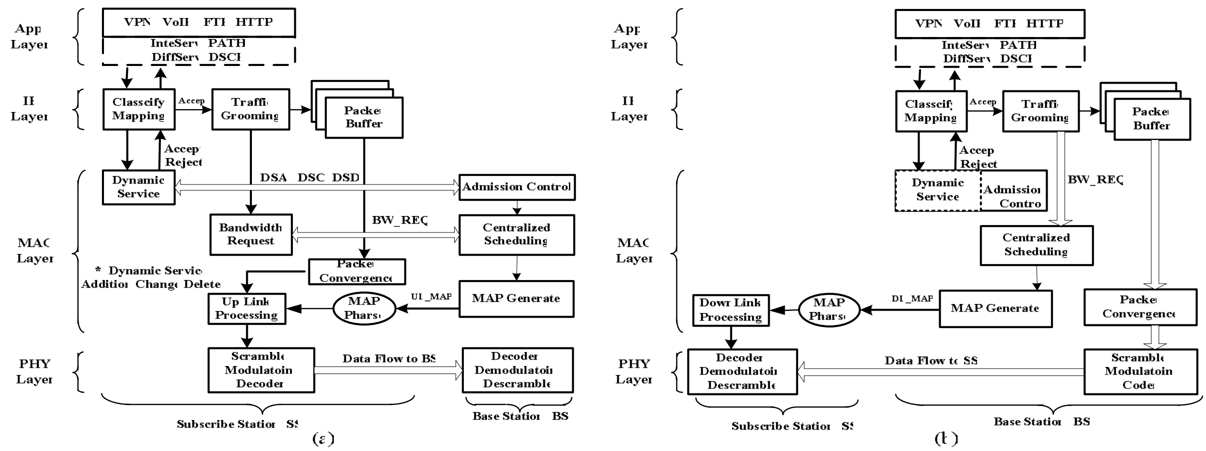

Fig.1 The multi-layer integrated QoS control architecture

processing of RSVP in IP layer and DSA/DSC/DSD in MAC layer, naturally, the mechanism of mapping between tow layers will be superior to the first one in high efficiency and fastness because the first processing step is bypassed.

The paper is organized as follows. In Section 2 we explain the architecture for integrated QoS control in details. In section 3, we give a comparison between the traditional and proposed ways of RSVP processing. Section 4 provides simulation result of our proposed architecture. Section 5 concludes the paper.

II. Architecture for integrated QoS control

In order to provide multi-layer QoS control, a convergence sub-layer is defined in IEEE 802.16 protocol to interface higher-layer protocol data units and perform classification and mapping function. Although some parameters such as source/destination IP address, source/destination port and protocol are defined to fulfill IP packets' classification, it is impossible to acquire necessary of bandwidth and latency requirements for dynamic service.

Since the communication under PMP mode in IEEE 802.16 is connection-oriented, the application must establish the connection with the BS before data transmission. BS will assign the connection with a unique connection ID (CID) to each uplink or downlink transmission. The message exchange for DSA and DSC can be deployed to carry QoS parameters of IntServ services for end-to-end resource (bandwidth/buffer) reservation. For DiffServ services, on the other hand, a number of per-hop behaviors (PHBs) for different classes of aggregated traffic can be mapped into different connections directly. The requirements of a multi-layer integrated QoS control architecture may include: (1) Guarantee different level QoS; (2) Prioritize the traffic classes; (3) Conduct multi-granularity traffic grooming efficiently; (4) Adjust resource allocation dynamically; (5) Share resources fairly. To meet all these requirements, we propose an integrated QoS control architecture as shown in Fig. 1, which implements a cross layer traffic-based mechanism in a comprehensive way. Fig.1-a illustrates the service mapping for uplink traffic. Step 1 and 2 show when a new application flow arrives in IP layer, it will be firstly parsed according to the definition in PATH message (for InteServ) or Differentiated Services Code Point (DSCP for DiffServ); then classified and mapped into one of four types of services (UGS, rtPS, nrtPS or BE). The detailed explanation for traffic classification and mapping strategies is given in the following section. In step 3, the dynamic service model in SS will send request message to the BS, where the admission control will determine whether this request will be approved or not. If not, the service module will inform upper layer to deny this service in step 4; if yes, admission control will notify scheduling module to make a provision in its basis scheduling parameter according to the value shown in the request message, and at the same time the accepted service will be transferred into traffic grooming module in step 5. According to the grooming result, SS will send Bandwidth Request message to BS in step 6. The centralized scheduling module in BS will retrieve the requests (step 7) and generate UL-MAP message (step 8) carrying the bandwidth allocation results. Finally, the SS will package SDUs from IP layer into PDUs and upload them in its allocated uplink slots to BS (step 9-10) after the processing of PHY layer.

The steps of service mapping in downlink direction shown in Fig. 1-b are the same as those in uplink processing. The differences lie in both dynamic service and bandwidth request messages are generated and consumed in BS. Another variance is that SS only need to receive data through PHY channel according to the instruction in DL-MAP message.

A. Traffic Classification and Mapping Strategies for IntServ Services

As shown in Fig. 2, the sender will send a PATH message including traffic specification (TSpec) information. The parameters such as up/bottom bound of bandwidth, delay and

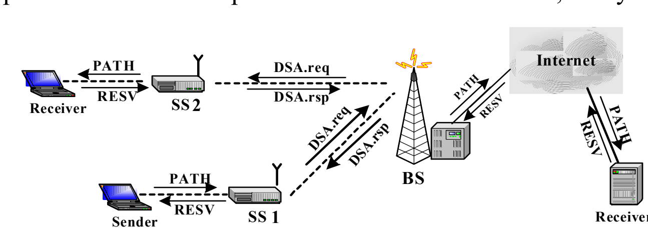

Fig2. Traffic Classification and Mapping for IntServ Services

This full text paper was peer reviewed at the direction of IEEE Communications Society subject matter experts for publication in the IEEE GLOBECOM 2005 proceedings.

TABLE I. Mapping Rules for IntServ Services

Traffic Class	Bandwidth Requirements	Delay / Jitter / Loss Rate	MAC layer Services
Hard QoS guarantee(eg. VPN tunnel, Leased line E1/T1)	*Constant bandwidth*	*Minimum packet delay, jitter and loss rate*	Unsolicited Grant Service
Soft QoS guarantee(eg. VoIP, VOD, digital TV, FTP, gaming.)	*Guaranteed*	*Regular delay, jitter require*	Real-Time Polling Service
	Not guaranteed	*long delay, jitter require*	Non-Real-Time Polling Service
Best effort (eg. HTTP)	*Only basic connection*	*N/A*	Best Effort

TABLE II. Mapping Rules for DiffServ Services

Traffic Class	Service Description	DS Octet (DS5-3)	MAC layer Services
Hard QoS guarantee(eg. VPN tunnel, Leased line E1/T1)	*Critical*	*101*	Unsolicited Grant Service
Soft QoS guarantee(eg. VoIP, VOD, digital TV, FTP, gaming.)	*Flash, Immediate*	*100 / 011/010*	Real-Time Polling Service
	Priority,	*001*	Non-Real-Time Polling Service
Best effort (eg. HTTP)	*Runtime*	*000*	Best Effort

jitter can be easily mapped into parameters in DSA message such as Maximum Sustained Traffic Rate, Minimum Reserved Traffic Rate, Tolerated Jitter and Maximum Latency. According to the response of DSA message, the provisioned bandwidth can be also mapped into reserved specification (RSpec) into RESV message. As illustrated in Table I, four rules are defined to map IP layer services into MAC layer services .

B. Traffic Classification and Mapping Strategies for DiffServ Services

For DiffServ services, DSCP code is deployed for classification. As shown in Fig. 3, the first 3 bits are for class selector, the middle 3 bits are for drop priority. There are three definitions of per-hop behavior (PHB) to specify the forwarding treatment for the packet. Expedited forwarding (EF) [8] is intended to provide a building block for low delay, low jitter and low loss services by ensuring that the EF aggregate is served at a certain configured rate. Assured Forwarding (AF) [8] PHB group is to provider different levels of forwarding assurances for IP packets. Four AF classes are

ToS	P2	P1	P0	T3	T2	T1	T0	Zero
DS Octet	DS5	DS4	DS3	DS2	DS1	DS0	ECN1	ECN0
	(Class Selector)			(Drop Precedence)				

Fig. 3 Differentiated Services Code Point

defined, where each AF class is allocated a certain amount of forwarding resources (buffer space and bandwidth). As illustrated in Table II, four rules are defined to map IP layer service into MAC layer services.

C. Admission Control and Scheduling in BS

Admission control module in BS will collect all the DSA/DSC/DSD requests and update the estimated available bandwidth (C_a) based on bandwidth change. Suppose there are I classes of service and the i^{th} classes of service has totally J_i connection, the available bandwidth equals to:

$$C_a = C_{tatal} - \sum_{i=0}^{I} \sum_{j=0}^{J_i - 1} r\,(i,j) \qquad (1)$$

In which $r(i,j)$ is the traffic rate of the j^{th} connection in the i^{th} class of service flow. When a new service flow comes or an old service flow requests to change its QoS, the following principle should hold: $C_a \geq 0$ (2)

Strict or loose admission control policy can be defined by variation the traffic rate r. For example, let r equals to Minimum Reserved Traffic Rate r_{min}, the access control will be very loose. Proper scheduling algorithms should be designed to ensure bandwidth allocation for accepted connection. In [5], Priority Queue or Deficit Fair Priority Queue (DFPQ) is used as the scheduling mechanism under the access policy of $r = r_{min.}$ For those connections whose r_{min} equals to zero, they can always be accepted. But the QoS of these connections will not be guaranteed. Their connections will be interrupted unless the bandwidth requirements of all other connections can be satisfied. Let r equals to the Average Reserved Traffic Rate r_{exp}, an stricter access policy is defined. In this case, Priority Queue scheduling mechanism can be deployed to cooperate with access control.

The hierarchical structure of the bandwidth allocation in BS is shown in Fig. 4. In this architecture, two-layer scheduling is deployed. Six queues are defined according to their direction (uplink or downlink) and service classes (rtPS, nrtPS and BE). Since service of UGS will be allocated fixed bandwidth (or fixed time duration) in transmission, we will cut these bandwidths directly before each scheduling.

The algorithm of the first layer scheduling can be varied to match the different access policy. DFPQ [5] can be used as the first layer scheduling to match the different access policy. Two policies of initial priority are defined as following:

Service class based priority: rtPS > nrtPS> BE

Transmission based priority: Downlink > Uplink.

For the second layer scheduling, three different algorithms are assigned to three classes of service to match its requirements. We apply earliest deadline first (EDF) for rtPS [10], which means packets with earliest deadline will be scheduled first. The information module determines the packets' deadline, which is calculated by its arrival time and maximum latency. Weight fair queue (WFQ) [11] is deployed for nrtPS services. We schedule this type of packets based on the weight (ratio between a connection's nrtPS Minimum Reserved Traffic Rate and the total sum of the Minimum Reserved Traffic Rate of all nrtPS connections). The remaining bandwidth is allocated to each BE connection by round robin (RR).

III. Comparison between two ways of RSVP

In this section, two ways of providing cross layer QoS control via WirelessMAN technology are compared. For brevity, we

This full text paper was peer reviewed at the direction of IEEE Communications Society subject matter experts for publication in the IEEE GLOBECOM 2005 proceedings.

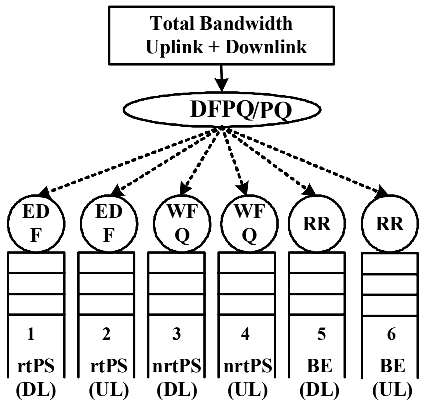

Fig. 4 Hierarchical structure of bandwidth allocation

only describe the process between BS and SS1 in Fig. 2. Tab. 3 and Tab. 4 list the procedures and message exchange when a new service flow is setting up.

As shown in Table III, the negotiation of QoS parameters for a certain traffic flow will be processed twice. For the first time, the traffic parameters are carried in RSVP messages and transmitted through the Secondary Management connection in IEEE802.16 MAC. For the second time, the same parameters are mapped in MAC management message (DSx) and transmitted through the Primary Management Connection. Obviously, because of the redundancy signaling, the time for setup is prolonged.

TABLE III Traditional way of RSVP

SS		BS
1: Received PATH Check if resource are available Update the state, Send PATH	PATH →	2: Received PATH Check whether IP QoS are available;Update the state Transfer PATH to next hop 3: Received RESV Reserve Resource of IP QoS Transfer RESV
4: Received RESV Reserve Resource Map QoS from IP MAC Send DSA-REQ	←RESV DSA-REQ →	5: Received DSA-REQ MAC Admission Control Send DSA-RSP
6:Received DSA-RSP Transfer RESV to previous hop	←DSA-RSP	

When a new RSVP session is establishing to reserve resource, there exists a session setup time, which is the interval between sending PATH message and the receiving of corresponding RESV message.

TABLE IV Proposed way of RSVP

SS		BS
1: Received PATH Check if resource are available MAC layer QoS mechanism Map PATH to MAC QoS Send DSA-REQ	DSA-REQ →	2: Received DSA-REQ MAC Admission Control Send DSA-REQ to next hop
4:Received DSA-RSP Map DSA-RSP to RESV RESV received by IP Layer Transfer RESV to previous hop	DSA-RSP←	3: Received DSA-REQ from the next hop MAC Admission Control Send DSA-RSP

The setup time of traditional way of RSVP can be evaluated as follows: let T_s represents the session set setup time; Δ_{Send} represents latency of the PATH message leaves the sender SS; Δ_P and Δ_R are the packet latency of a PATH and RESV message through a SS (BS).And Δ_{Recv} is the latency for constructing RECV message in the destination SS. Therefore,

$$T_s = \Delta_{Send} + N \times \Delta_P + N \times \Delta_R + \Delta_{Recv} \quad (3)$$

Where N is the number of SS (BS) between sender and receivers, especially PMP mode is within two hops, so in this mode $N = 1$. There are three components in each latency parameters: (1)The signaling message forwarding delay;(2) nonlinear queuing delay Δ_{queue} , for all the signaling messages are transmitted through the secondary management connection, so queuing delay can not be ignored ;(3) MAC layer process overhead -- Δ_M Let L_{Path} and L_{Resv} denote the length of PATH and RESV message respectively, D represents frame duration and L_{frame} denotes the maximum data bits can be transmitted within a frame duration, then, Δ_{Send} , Δ_P , Δ_R , Δ_{Recv} can be shown as:

$$\Delta_{Send} = \left\lceil \frac{L_{Path}}{L_{\text{frame}}} \times D \right\rceil + \Delta_{queue\_Send} + \Delta_{M\_Send} \quad (4)$$

$$\Delta_P = \left\lceil \frac{L_{Path}}{L_{\text{frame}}} \times D \right\rceil + \Delta_{queue\_P} + \Delta_{M\_P} \quad (5)$$

$$\Delta_R = \left\lceil \frac{L_{RESV}}{L_{\text{frame}}} \times D \right\rceil + \Delta_{queue\_R} + \Delta_{M\_R} \quad (6)$$

$$\Delta_{Recv} = \left\lceil \frac{L_{Resv}}{L_{\text{frame}}} \times D \right\rceil + \Delta_{queue\_Rec} + \Delta_{M\_Rec} \quad (7)$$

The first element in each formula shows the forwarding delay. The second element corresponds to queuing delay and third element shows MAC layer process overhead in SS (BS).

Table IV shows the RSVP signaling messages are mapped directly into the MAC messages (DSx), which are transmitted through the Primary Management Connection. In this way, the messages are transmitted only once ingeniously. In the proposed way of RSVP, the whole RSVP session setup time only contain the MAC layer process overhead. There is no message forwarding delay and queuing delay in this effective reserve mechanism, because the PATH, RESV messages are directly mapped into MAC layer message. Note that, there are still other types of messages packets existing in the Secondary Connection, but they have no effect on the RSVP session establish course in the proposed way. We can still calculate the setup time using the (3), but we set Δ_{queue} and Δ_M in each SS (BS) to zero, so the (3) can be rewrite as

$$T_s = \Delta_{M\_Send} + N \times \Delta_{M\_P} + N \times \Delta_{M\_R} + \Delta_{M\_Rec} \quad (8)$$

From the above analysis, by avoiding the redundancy transmission of the same RSVP message, the proposed way of RSVP is superior to traditional way in high efficiency and

This full text paper was peer reviewed at the direction of IEEE Communications Society subject matter experts for publication in the IEEE GLOBECOM 2005 proceedings.

fastness for providing cross layer QoS control via IEEE802.16 MAC layer QoS mechanism.

IV. Simulation Results

In this section, experiment results based on the integrated QoS control architecture are reported. A platform is developed to study simulation process. The platform consists of four-node topology including one BS and three SSs, operating in IEEE 802.16 PMP mode. The total bandwidth and the duration for each frame are assumed to be 10Mbit and 10ms respectively. Each frame is divided into 256 minislots. In this platform, 1Mbit/s bandwidth is reserved for management connections--basic connection, primary management connection, and secondary management connection.

The detail simulation environment is described as follows: (1) the DSx messages transmission delay will be set to one frame duration (10ms). (*2*) The processing time of admission control and reservation-related process may be various according to the performance of BS (SS). In our platform, this process will consume one frame duration (10ms). (3) Both the PATH and RSVP message experience DSx message transmission delay, but for PATH message, the reservation-related process overhead can be not taken into account, because its just update the state in each SS (BS), reservation-related process is bypassed, in the contrast, for RESV message, this process overhead can not be ignored, since the admission control, resource reservation process is actually performed. So, the MAC Layer overhead Δ_M is shown in Table V.

TABLE V MAC Layer Overhead

PATH message		RESV message	
Δ_{M_Send} =10ms	Δ_{M_P} =10ms	Δ_{M_R} =20ms	Δ_{M_Rec} =20ms

The setup time of one VoIP session in two ways of RSVP is evaluated. Let λ the other signaling message average arrival rate during each frame in secondary management connection. Fig 5 shows that when λ increases from 1 to 3, the setup time of transitional way grows, but the setup time of proposed way keeps unchanged. It is also seen that the average setup time of traditional way is much longer than the proposed way.

When the bandwidth of secondary management connection increases, queuing delay of the signaling message is decreased. As Fig 6 shown, the setup time of traditional way decreases a lot when bandwidth for secondary management connection augments, but it is still larger than the setup time of the proposed way.

In the same simulation environment, throughout of the proposed hierarchical QoS control architecture with PQ and DFPQ scheduling and their corresponding admission control strategy are studied. Suppose that, between BS and each SS, there will be one or more service flow for each kind of service in uplink or downlink. Following the mapping rules defined in Table I and II, the VoIP service is mapped into rtPS service; the FTP service is mapped into nrtPS service; and the HTTP service is mapped into BE service. In the simulation all traffic packet arrivals at the beginning of each frame and the packet arrival process for each connection follows the Poisson distribution with different traffic rate. Each connection has specific QoS parameters in terms of Maximum Sustained Traffic Rate, Minimum Reserved Traffic Rate and Maximum Latency requirement. UGS flow requests 4.5Mbit/s in uplink and 4.5Mbit/s in downlink with hard QoS with constant bandwidth. Since UGS flow is allocated constant bandwidth in each frame and 1Mbit/s bandwidth is reserved for the control message, there is only 90Mbit/s available bandwidth for other traffic.

The other types of service flows used in the simulation are given in Table VI.

TABLE VI Input Service Flow

Service Type	Mapped Type	CID	Average Bandwidth (Kbit)	Max. Delay (ms)	Max.sustained traffic rate (Kbit)	Min.reserved rate (Kbit)
VoIP	DL_rtPS	1	10	60	12	8
		2	10	40	12	8
		3	10	20	12	8
VoIP	UL_rtPS	4	7	70	8.4	5.6
		5	7	50	8.4	5.6
		6	6	30	7.2	4.8
FTP	DL_nrtPS	7	6	100	6	4
		8	6	100	5	4
		9	6	100	5	4
FTP	UL_nrtPS	10	4	100	6	4
		11	4	100	5	4
		12	4	100	5	4
HTTP	DL_BE	13	2	240	-	1.6
		14	2	240	-	1.6
		15	2	240	-	1.6
HTTP	UL_BE	16	2	300	-	1.6
		17	1	300	-	0.8
		18	1	300	-	0.8

As indicated in Fig.7, the bandwidth allocated for each type of

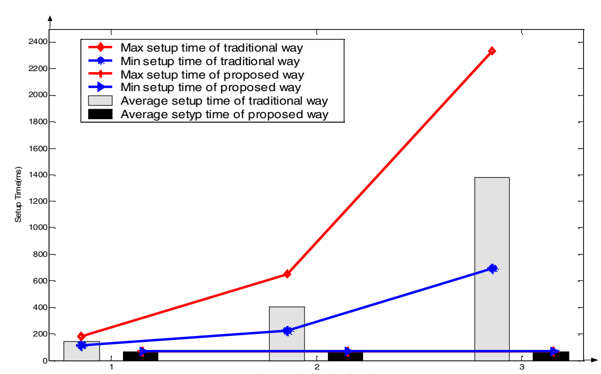

Fig 5 Setup time vs. Arrival rate

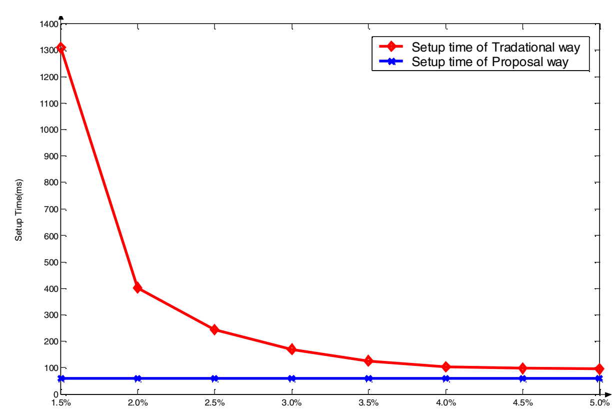

Fig 6 Setup time vs. Bandwidth

This full text paper was peer reviewed at the direction of IEEE Communications Society subject matter experts for publication in the IEEE GLOBECOM 2005 proceedings.

service adapts and follows the traffic rate of data source well. Conclusion can be drawn that our proposed integrated QoS architecture can guarantee the existing bandwidth for the high priority services as well as the low priority services.

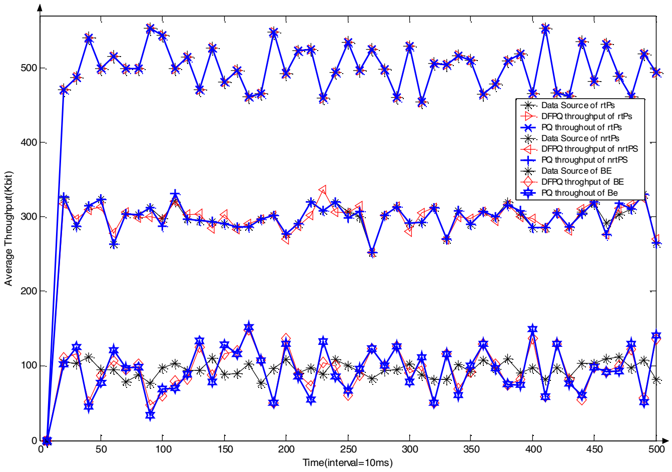

Fig. 7. Input service flow vs. service curve

V. Conclusion

In this paper, we propose an architecture to provide multi-layer QoS control for IEEE 802.16 WirelessMAN for PMP and mesh mode. Both IntServ and DiffServ are supported. Compared with the traditional way of providing cross layer QoS via WirelessMAN, the proposed integrated QoS control is superior in high efficiency and fastness to guarantee the throughput requirements of source traffic.

Reference

[1] IEEE Standard for Local and metropolitan area networks Part 16: Air Interface for Fixed Broadband Wireless Access Systems, October 2004

[2] R. Braden, D. Clark, and S. Shenker, “Integrated Services in the Internet Architecture: an Overview,” IETF RFC 1633, June 1994.

[3] S. Blake *et al.*, “An Architecture for Differentiated Services,” IETF RFC 2475, Dec. 1998.

[4] Kamlesh Rath, Lalit Kotecha,et al, ” Scalable Connection Oriented Mesh Proposal”,IEEE 802.16 Broadband Wireless Access Working Group, March 6, 2003

[5] Jianfeng Chen, Wenhua Jiao, Hongxi Wang, “A Fair Scheduling for IEEE 802.16 Broadband Wireless Access Systems”, ICC2005, May 16-20, Souel, Kerea

[6] Hawa, M.; Petr, D.W.,Quality of service scheduling in cable and broadband wireless access systems, Tenth IEEE International Workshop on Quality of Service, p247-255, 2002

[7] K. Wongthavarawat, and A. Ganz, “Packet Scheduling for QoS Support in IEEE 802.16 Broadband Wireless Access Systems”, International Journal of Communication Systems, Vol. 16, p81-96, 2003

[8] B. Davie *et al.*, “An Expedited Forwarding PHB (Per-Hop Behavior),” IETF RFC 3246, Mar. 2002.

[9] J. Heinanen *et al.*, “Assured Forwarding PHB Group” IETF RFC 2597, June. 1999.

[10] Georgiadis L, Guerin R, Parekh A. Optimal Multiplexing on a Single Link: Delay and Buffer Requirements. Proceedings of IEEE INFOCOM 94; vol. 2, 1994; 524–532.

[11] Demers A, Keshav S, Shenker S. Analysis and Simulation of a Fair Queuing Algorithm. SIGCOMM CCR 19 1989.