Cross-Layer QoS Support in the IEEE 802.16 Mesh Network

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Abstract—**In this paper, we propose a framework for QoS support in the IEEE 802.16 Mesh network. For performance improvement over the two basic scheduling schemes recommended in the standard, centralized and distributed scheduling, the framework adopts the idea of BS-controlled route selection and delay-based scheduling. Core mechanisms including mapping of IP QoS classes to 802.16 QoS types, admission control, minimal-delay-first route selection, tag-based fast routing, and delay-based scheduling are proposed and presented in the paper. Simulation study has shown that the average delay as well as the variation of delay per hop in the proposed scheme is smaller than that of the distributed scheme and much smaller than that of the centralized scheme. Furthermore, the proposed scheme can also achieve higher throughput (under heavy input load) than the contrasts and generate much smaller signaling overhead.**

Key words: 802.16, WiMax, Mesh, QoS

1. INTRODUCTION

Broadband Wireless Access (*BWA*) technology provides an easy, time-saving, and low-cost method for deployment of next generation (beyond 3G) network infrastructure. Since 1998, IEEE 802.16 working group has launched a standardization process called *Wireless Metropolitan Area Network* (*Wireless MAN^{TM}*) for BWA. The newly released specification of 802.16 (*IEEE Std 802.16-2004*) [1] focuses on fixed location wireless access and can support up to 134 Mbps bit rate. Moreover, the standardization of a new 802.16 interface, *802.16e* [2], to support wireless access with high mobility has also been completed recently. The *WiMax Forum* (*Worldwide Interoperability for Microwave Access*) [3], [4], a wireless industry consortium with about 100 members including major vendors such as *AT&T*, *Fujitsu*, *Intel*, and *Siemens Mobile*, is supporting 802.16 technology and promoting its commercial use, which means 802.16 is becoming the most important technology in BWA.

The basic *PMP* (*Point to Multipoint*) configuration of 802.16 network consists of a *base station* (*BS*) and a couple of *subscriber stations* (*SS*) that connect to the BS via high-speed wireless link. The BS acts as a gateway to the Internet. Legacy LANs or even more complex subnet systems can connect to the 802.16 network via SS. An 802.16 network (including the Legacy LANs that connect to the SS) can cover a large geographical area since the distance between the BS and the SS can be up to 30 miles (in the case of 802.16-2004). On the other hand, as an extension of 802.16 PMP configuration, the *802.16 Mesh* mode provides that there is no need to have direct link from subscriber stations to the base station and a node can choose the links and path with best quality to transmit data and avoid the congested area.

There are two basic mechanisms to schedule data transmission in the IEEE 802.16 mesh network [1]: *centralized* and *distributed* scheduling. In centralized scheduling, the BS works like the cluster head and determines time slot allocation of each SS. In order to transmit data packets, the SS is required to submit the request packet (Layer 2 frame namely *BW_REQ*) to the BS via the control channel. The BS grants the access request by sending the slot allocation schedule called *UL_MAP* (*uplink* map for slot access) to all SS nodes. Since all the control and data packets need to go through the BS, the scheduling procedure is simple, however a longer path in the mesh network is inevitable.

On the other hand, in distributed scheduling, every node competes for channel access using an election algorithm based on the scheduling information of the two-hop neighbors. Distributed scheduling is more flexible in terms of route selection (e.g. shortest path route can be used) at the cost of higher signaling overhead for the exchange of scheduling information. Some research work [5]–[7] for routing and scheduling improvement in the 802.16 mesh network has been proposed in the literature. In this paper, we focus on the QoS framework and propose associated mechanisms for QoS support in the 802.16 mesh network.

The remainder of the paper is organized as follows. First of all, we present the overall architecture as well as the novel features of the proposed QoS framework at the BS and SS in section 2. Key mechanisms in the proposed framework for QoS support in IEEE 802.16 Mesh network are presented in section 3. Simulation study for performance evaluation and comparisons is presented in section 4. Finally, section 5 concludes this paper.

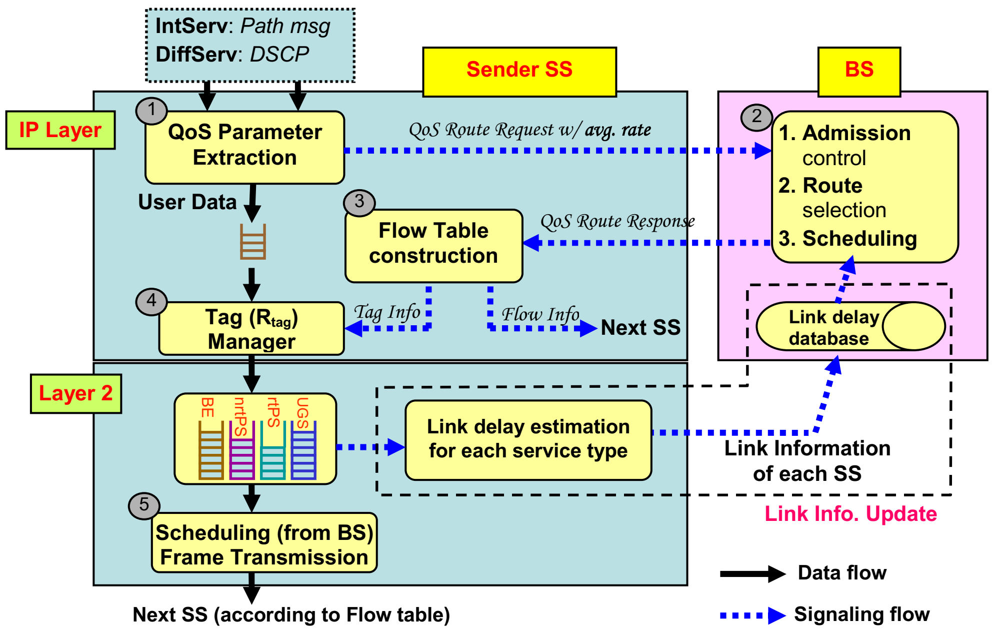

Figure 1. Cross-layer QoS Framework for IEEE 802.16 mesh mode

2. CROSS-LAYER QOS FRAMEWORK

As mentioned in section 1, there are both advantages and disadvantages in the basic centralized and distributed scheduling schemes for the IEEE 802.16 mesh network. The centralized scheduling scheme has the advantage of centralized control with better and more effective QoS support but suffers from the longer transmission path, which increases the consumption of link capacity. On the other hand, the distributed scheduling has the advantage of using shortest-path route but suffers from the larger signaling cost due to 2-hop neighbors competition for channel access. Therefore, we try to design a QoS framework that makes the best of the advantages of the centralized and distributed scheduling schemes and avoids their disadvantages as much as possible.

Figure 1 displays the architecture of the proposed QoS framework at the BS and SS nodes. The main idea behind the framework is that we take advantage of the centralized control for scheduling and route selection. However, we avoid the longer transmission path by adopting the flow setup phase and maintaining routing information at each SS for QoS flows to provide more efficient route control. Novel features of the QoS framework are listed as follows:

(1) The framework adopts cross-layer integration that incorporates some IP layer functionalities in the BS and SS nodes, such as *mapping of L3 service types to L2 service types* (item ① in Figure 1), *admission control* and *route selection* according to current load of the network (item ②), *flow table setup* for routing in the mesh network (item ③), etc.

(2) The BS works as the centralized controller of QoS support, maintains topological and current link state information, and is responsible for admission control, route selection, and scheduling of data transmission (item ②).

(3) After the BS determines the routing path for an accepted flow, the routing path is established before data transmission via setting up the flow table (item ③) at each SS along the path. A routing tag denoted by R_{tag} is assigned and added in the flow table for fast routing the traffic of the flow (item ④).

(4) Subscriber stations access the data channel in the allocated time slots according to the instruction (*UL-MAP*) from the BS, and transmits data packets to the next hop according to the value of R_{tag} added in the header of the data frame and the flow table (item ⑤). Note that using R_{tag} in 802.16 data frame header for fast packet routing is similar to the idea of *Multi-Protocol Label Switching* (*MPLS*) [8]. Moreover, each SS estimates its current link delay (the system time of each QoS queue in the SS) and reports its link state to the BS on a regular basis.

3. QOS MECHANISMS

In this section, we present the core mechanisms in the proposed framework for QoS support in the IEEE 802.16 mesh network.

3.1. L3 to L2 QoS mapping

Since IEEE 802.16 belongs to Layer 2 technology in network layering architecture, the user of 802.16 is its

	IP QoS →	802.16 QoS
IntServ	*Guarantee Service (GC)*	*Unsolicited Grant Service (UGS)*
IntServ	*Controlled Load (CL)*	*Real-time Polling Service (rtPS)*
DiffServ	*Expedited Forwarding (EF)*	*Real-time Polling Service (rtPS)*
DiffServ	*Assured Forwarding (AF)*	*Non-Real-time Polling Service (nrtPS)*
	Best Effort (BE)	*Best Effort (BE)*

Figure 2. Mapping from IP QoS to 802.16 QoS

R_{tag}	Next Hop	Delay Bound	Service Type
2910	SS3	20ms	rtPS
2260	SS2	15ms	rtPS

Figure 3. E.g. Entry in the flow table at the SS

MAC generic header	Mesh subheader	R_{tag}	Network layer PDU

Figure 4. Extra field R_{tag} added in the MAC frame

upper layer, i.e. Layer 3 or IP layer. Thus, to support QoS in the 802.16 mesh network, we must also consider existing IP QoS frameworks and design a mapping between IP QoS to 802.16 QoS. There are mainly two QoS frameworks in IP layer: *Integrated Service* (*IntServ*) [9], [10] and *Differentiated Service* (*DiffServ*) [11], each of them defines different classes of QoS. We adopt a simple and static mapping from IP QoS to 802.16 QoS types [12] in the proposed framework as illustrated in Figure 2.

3.2. Admission control

The admission control of the proposed framework is based on the average rate of the new QoS flow and the current load in the mesh network. Each flow must provide its data rate in the flow setup phase by sending *QoS route request* message to the BS as illustrated in Figure 1 (item ②). The BS applies the admission control for the request and sends back the response message.

A new flow is accepted if the remaining capacity of the channel can support the required bandwidth (data rate) of the flow. However, two factors must be considered in estimating the required bandwidth for a flow and the remaining capacity of the channel. First, since there is only one physical link for the whole mesh network, the required bandwidth of a flow is proportional to the hop count of the route. Second, the idea of *spatial reuse* in slot allocation, in which more than one SS can access the channel at the same time, is adopted in the proposed scheduling algorithm, so the effective channel capacity is affected by the *spatial reuse factor* denoted by *SRF* in the paper. For instance, if there are always two SS nodes can access the channel at the same time, the value of *SRF* will be 2, and the effective channel capacity will be double of the original link capacity.

In summary, the BS will accept the new flow if *LinkCapacity*SRF* – *CurrentLoad* > (*AvgRate* of the flow) * (*hop count* of the shortest route), in which the value of *SRF* is dynamically calculated at the run-time, *CurrentLoad* is calculated according to the link state report from SS nodes, and the *hop count* of the shortest route is only used as a reference in the admission control stage.

3.3. Route selection

The BS determines the route for each accepted flow. For the sake of load distribution as well as delay minimization, selection of the next SS is based on the strategy of *minimal-delay-first* route instead of the shortest route. The delay information (the system time) for each QoS type at every SS is estimated and reported to the BS periodically. Note that as the lowest priority service type, *BE* (*best-effort*) flows use the shortest route.

It's worth mentioning that the minimal-delay-first route selection has the advantage of load distribution over its shortest path counterpart, since delay-based cost reflects the load at the SS, which means the minimal-delay-first route tends to select a route with minimal end-to-end load in the mesh network.

3.4. Routing tag and flow table setup

All the SS nodes on the selected route for the new flow must be notified by the BS in order to set up the associated flow table entry for routing of the flow data. A unique routing tag (denoted by R_{tag}) for the flow is assigned by the BS for fast routing in the mesh network. The structure of the entry in the flow table is displayed in Figure 3. Moreover, an extra field for the routing tag is defined and added in the header of the 802.16 MAC frame as shown in Figure 4. Each SS along the route checks the value of the R_{tag} field in the MAC frame and looks up the flow table to determine the next hop of the data frame.

3.5. Delay-based scheduling

The scheduling algorithm in the framework is similar to the centralized scheduling controlled by the BS but with delay considerations. Rules in the scheduling algorithm include: (1) *UGS* flows have higher priority than *rtPS* flows, *rtPS* flows higher than nrtPS, etc. (2) in the same service type, the SS with higher load has higher priority. (3) Moreover, an additional mechanism is adopted for

Simulation parameters	Value
Network Size	*5x5 Mesh*
Link Capacity	*5 Mbps*
Time Frame Size	*10 ms*
# of slots per frame	*10*
# of flows per service type	*5*
Data rate of each flow	*5Mbps*
Rate variation of rtPS, nrtPS, BE flows	*128 Kbps*
Flow arrival rate	*1 flow/sec*
Flow departure rate	*1 flow/sec*
Link state report interval	50ms

Figure 5. Simulation parameters

real-time flows such as *UGS* and *rtPS* to reduce the access delay by giving higher priority to those data frames that have been waiting a longer time in the queue More specifically, the data frames with the waiting time exceeding the delay bound specified in the flow setup phase have higher priorities than those frames with smaller waiting times.

4. PERFORMANCE EVALUATION

4.1. Simulation parameters and performance criteria

Simulation study has been conducted to evaluate proposed mechanisms. Two contrasts are compared with the proposed scheme: *centralized scheduling with routing via BS* and *distributed scheduling with shortest path routing*. The mesh network in the simulation is a 5x5 mesh and the BS is located in the corner. Link capacity of the network is 5Mbps. A time frame structure with size 10ms is defined for slot allocation.

There are in total 20 flows (5 flows for each of the four service types) in each round of the simulation. Flows with ID 1~5 are *UGS* flows, ID 6~10 *rtPS flows*, etc., and a larger flow ID in each service type is assigned to the flow with a longer Euclidean distance between the source SS and the destination SS. Simulation parameters are summarized in Figure 5.

Three performance criteria are defined for comparison: (1) *Average delay (ms) and delay variation per hop*, (2) *Average throughput (Kbps)*, and (3) *Average signaling cost (# signal packets per MAC frame transmission)*.

4.2. Simulation results

As shown in Figure 6 and Figure 7, the average delay as well as the variation of delay per hop under flow data rate 5Mbps (heavy input load) in the proposed scheme is smaller than that of distributed scheme and much smaller than that of the centralized scheme. The reason of the poor delay performance of the centralized scheme is twofold: (1) the longer path increases the consumption of the link capacity that is similar to the effect of input load increase, (2) no spatial reuse in the scheduling makes the effective capacity in the network smaller than that of the proposed scheme. On the other hand, the proposed scheme does not beat the distributed contrast too much since the shortest path route is used in the distributed scheme. However, some gain (20% decrease in delay at the best case) is still achieved by the minimal-delay first route selection as well as delay-based scheduling in the proposed scheme over the distributed scheme.

Figures 8 display the throughput of the scheme under flow data rate 5Mbps. As expected, the centralized scheme suffers from poor throughput performance due to the same reasons of poor delay performance. The proposed scheme outperform slightly the distributed scheme in average throughput because the effect of load distribution.

Signaling cost of the schemes is shown in Figure 9, in which the distributed scheme presents the most signaling cost due to 2-hop information exchange in competition of channel access. The signaling cost of the centralized scheme is larger than that of the proposed scheme because of the longer path that increase the number of the BW_REQ messages issued by the SS nodes en route to the BS for channel access.

5. CONCLUSIONS

The new Wireless-MAN standard, IEEE 802.16, provides broadband, wide coverage, and QoS support in the MAC layer. Two configuration modes for IEEE 802.16 were introduced in the standard: *PMP* (*Point to Multipoint*) and *Mesh*. In the Mesh mode, there is no need to have direct link from subscriber stations (SS) to the base station (BS). Data frames can be transmitted directly between two neighboring SS nodes and sent to the destination node hop-by-hop. Therefore, routing and scheduling for QoS support are important issues in IEEE 802.16 Mesh mode.

We proposed a cross-layer QoS framework for IEEE 802.16 Mesh networks in this paper. Core mechanisms including mapping of IP QoS classes to 802.16 QoS types, admission control, minimal-delay-first route selection, tag-based fast routing, and delay-based scheduling were presented in the paper. Simulation results have demonstrated that the proposed framework as well as the associated mechanisms can achieve the better performance in terms of delay, throughput, and signaling cost over the basic centralized and distributed scheduling scheme recommended in the standard.

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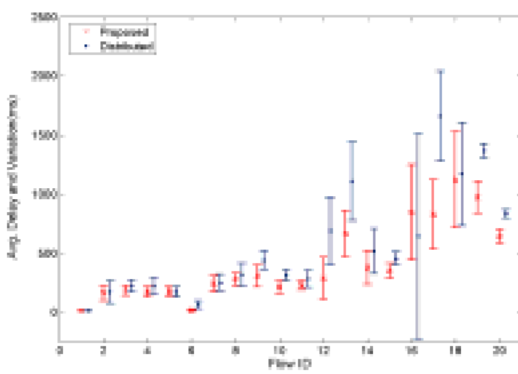

Figure 6. Delay performance per hop with flow data rate 5 Mbps: Proposed vs. Distributed

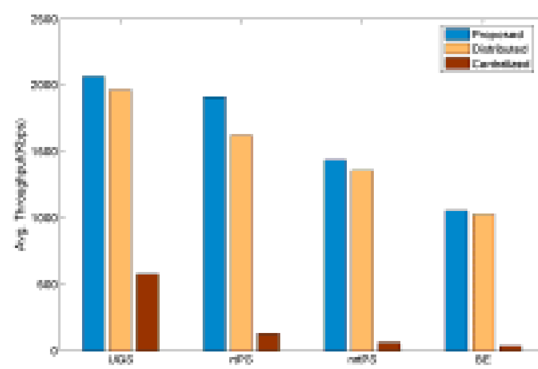

Figure 8. Throughput of different service types

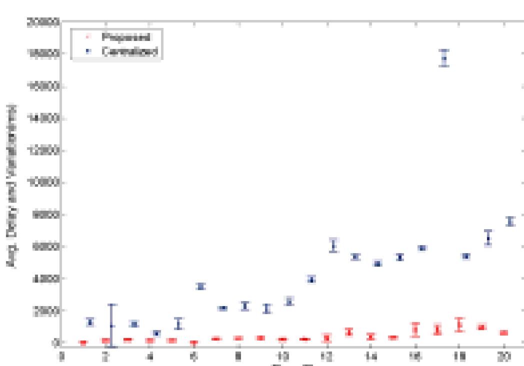

Figure 7. Delay performance per hop with flow data rate 5 Mbps: Proposed vs. Centralized

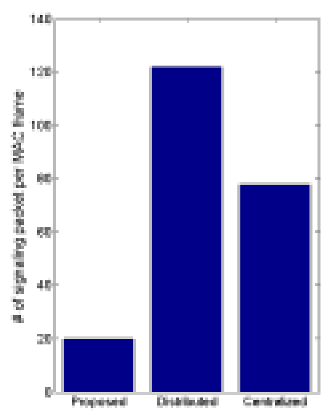

Figure 9. Signaling cost (# signal frames per data frame