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Design of Multi-hop Qos Scheduling for IEEE 802.16 Networks

Yi-Ting Mai*[1], Chun-Chuan Yang[2], Jeng-Yueng Chen[1], and Cheng-Jung Wen[2]
[1]Department of Information Networking Technology, Hsiuping University of Science and Technology, Taichung City, 41280, Taiwan
[2]Department of Computer Science and Information Engineering, National Chi Nan University, Nantou County, 54561, Taiwan
Corresponding author, e-mail: wkb@wkb.idv.tw

Abstract
Broadband wireless networks are increasing in popularity owing to current advances in technology. For large area network deployment, IEEE 802.16 mesh networks can provide a wide coverage, high speed and high quality multimedia service. IEEE 802.16 mesh configuration eliminates the need to have direct links between subscriber stations (SSs) and the base station (BS); a node can choose the links and path of the highest quality to transmit data and avoid the congested areas. To provide better Quality of Service (QoS) over the 802.16 network, the network layer 3 (L3) and layer 2 (L2) QoS must be integrated. Hence, cross-layer mechanisms were designed and incorporated into our previously proposed IEEE 802.16 QoS frameworks. Taking into consideration resource utilization and QoS requirements, we devised various scheduling schemes to determine their effects on the IEEE 802.16 mesh network. Our performance evaluation demonstrates that the proposed framework with enhancement scheduling has higher throughput, lower delay and signal cost than comparable systems. In this paper, we provide an appraisal of our proposed scheme.

Keywords: *802.16, WiMAX, Mesh, QoS, EQ*

1. Introduction

The IEEE 802.16 working group has launched a standardization process called the *Wireless Metropolitan Area Network (Wireless MAN^{TM})*. To provide long distance wireless network access, the IEEE 802.16 tries to achieve for different physical frequencies. Its purpose is to facilitate the optimal use of bandwidth 2–66 GHz as well as the interoperability among devices from different vendors. In the standard, 2 to 11 GHz and 10 to 66 GHz band, there are two defined two versions of 802.16a [1] and 802.16c [2] respectively. The 10-66 GHz bands, provide a high data rate up to 134 Mbps between two devices within radio *LOS (Line-of-sight)*; the 2–11GHz bands, both licensed and license-exempt, are addressed in IEEE Project 802.16a initially, and the recently released specification of 802.16 (IEEE Std 802.16-2004/d [3]) focuses on fixed location wireless access and supports up to 75Mbps bit rate within radio *NLOS (Non-line-of-sight)*. Moreover, the standardization of a new 802.16 interface, 802.16e [4], which supports wireless access with high mobility and has also been completed recently [5]. It provides one of potential solutions to B3G/4G architecture. The *WiMax Forum (Worldwide Interoperability for Microwave Access)*, 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 *broadband wireless access (BWA)*.

The basic *PMP (Point to Multipoint)* configuration of an 802.16 network consists of a *base station (BSs)* and a couple of *subscriber stations (SS)* that connect to the BS via a high-speed wireless link, as illustrated in Figure 1(a). 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 the 802.16 PMP configuration,

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the 802.16 mesh mode provides that SSs can choose the link to connect the BS or other SSs, and the structure is shown in Figure 1(b).

There are two basic mechanisms to schedule data transmission in the IEEE 802.16 mesh network [3]: centralized and distributed scheduling. In centralized scheduling, the BS works like the cluster head and determines the 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 the *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. In centralized scheduling-based research works [6][8], different scheduling and routing mechanisms were proposed to improve the performance by lowering the interference of routes and reducing the congestion near the hotspot of the BS. However, longer path creates more link consumption, which further causes a significant decrease in network utilization. For designing QoS mechanisms, most of the centralized-based research works [9][10] focused on the construction of the routing tree based on different QoS types. For real time traffic, [11] proposed the idea of different proportion to divide the control sub-frame and the data sub-frame. It is well accepted that the centralized control manner is helpful to simplify bandwidth allocation. But the reduction of performance impact of centralizing scheduling in QoS supporting is rarely addressed in the literature.

On the other hand, in distributed scheduling, every node competes for channel access using the *pseudo-random election* algorithm based on the scheduling information of the two-hop neighbors. Distributed scheduling is more flexible in terms of route selection (e.g. the shortest path route can be used) at the cost of higher signaling overhead for the exchange of scheduling information. Some research works [12][13] focused on the improvement of the throughput by modifying the original distributed access scheme, and some articles [14][16] tried to identify and model the effect of parameters in distributed scheduling for assigning different traffic types to achieve QoS support. Considering QoS support for whole flow in 802.16 mesh network, these articles [17][19] wanted to reserve whole flow path bandwidth beforehand in mesh network with distributed scheduling to avoid the SSs 2 hop competition overhead in each data packet transmission. Despite the performance benefit of distributed scheduling over centralized scheduling, the complicated behavior of distributed scheduling makes it difficult to provide precise bandwidth allocation, which also makes it inappropriate in QoS support.

To support the Quality of Service (QoS) of the 802.16 mesh network, the following four essential criteria must be satisfied:

(1) There must be QoS integrated signaling protocols between the IP layer and the 802.16 layer.

(2) Because the IP layer and the 802.16 MAC layer take different approaches for processing user traffic, there must be traffic mapping mechanisms between the two layers to provide traffic flow with the appropriate QoS.

(3) There must be QoS and service adaptation mechanisms to dynamically adjust the end-to-end service qualities of the traffic flow to assign the available network resources in the 802.16 mesh network as the Internet backbone. Networks should regard as high priority the re-adjustment of resources among all classes of traffic flow to satisfy the requested QoS.

(4) To support the higher priority traffic flow, a different scheme should be used to achieve the traffic requirement, such as a lower delay.

In this paper, we examine the advanced QoS framework and associated mechanisms for multi-hop QoS support of the 802.16 mesh network. We design a cross-layer framework in which we introduce an adjustment of the traffic QoS scheduling. The system effect of the proposed scheme is appraised through a simulation of its operation. Furthermore, the further discussion has shown in the end of simulation.

The rest of the paper is organized as follows. First of all, it presents the overall architecture as well as the novel features of the previous proposed QoS framework at the BS and SS in section 2. The key mechanisms in our proposed framework with QoS support in WiMAX mesh network are presented in section 3. Simulation studies for performance evaluation and comparisons are shown in section 4. Finally, section 5 concludes this paper.

2. The Proposed Method

There are both advantages and disadvantages of using 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 a longer transmission path which increases the consumption of link capacity. On the other hand, the distributed scheduling has the advantage of using the shortest-path route, but suffers from a larger signaling cost due to competition between 2-hop neighbors for channel access. We designed a QoS framework that captures the advantages of the centralized and distributed scheduling schemes while avoiding their disadvantages as far as possible. In previous work [20], our proposed QoS framework considered both L3 and L2 layers to design a cross-layer QoS support. Figure 2 displays the construction of the proposed QoS framework at the BS and SS nodes. The main idea behind the framework is to take advantage of the centralized control on scheduling and route selection. However, our scheme avoids 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.

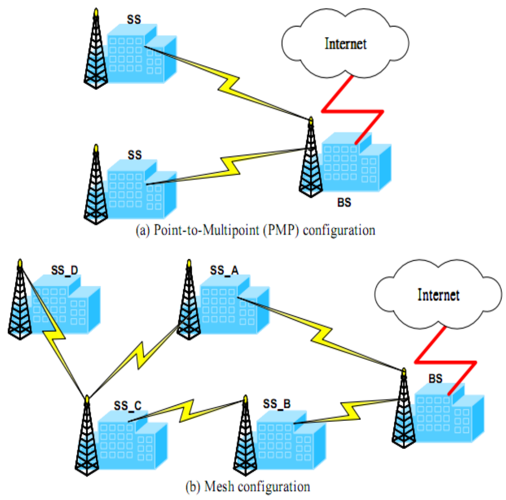

Figure 1. Two Configurations in IEEE 802.16

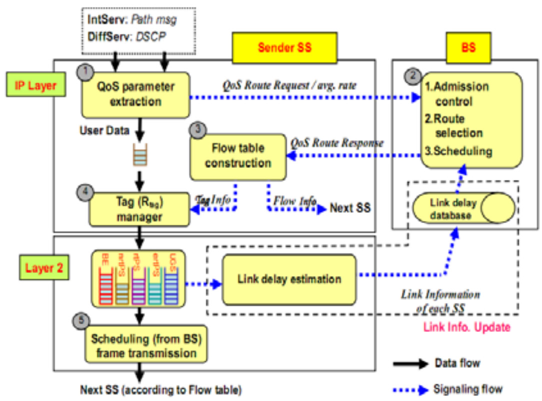

Figure 2. Cross-layer QoS framework

3. Research Method

To satisfy criteria 1 and 2 for the QoS of the 802.16 mesh network mentioned earlier, a cross-layer framework should be constructed. In our previous work [20], some basic mechanisms with a cross-layer QoS framework were proposed, such as the QoS mapping rule, admission control policy, and routing tag construction. However, the crucial basic framework for QoS scheduling was still lacking, Here, we take a step further to offer QoS scheduling to achieve QoS support in IEEE 802.16 mesh networks, thereby satisfying criteria 3 and 4. The details are shown below.

3.1. Scheduling

The IEEE 802.16 standard provides the QoS required for successfully operating multimedia services in BWA systems. Five types of services are offered in IEEE 802.16 [4], namely, *Unsolicited Grant Service (UGS), extend real-time Polling Service (ertPS), real-time Polling Service (rtPS), non-real-time Polling Service (nrtPS),* and *Best Effort (BE)*. Among these, *UGS* is suitable for supporting real-time multimedia traffic which requires sufficient bandwidth and minimal delay.

IEEE 802.16 does not include a specific scheduling algorithm for point-to-multipoint (PMP) or mesh modes [3][4] because neither mode is included in the mandatory modules required for standardized operation. However, the scheduler operation plays an important role in the performance of the whole system; hence, scheduling algorithms have attracted growing attention in recent years. Thus far, a small number of proposals for scheduling algorithms for IEEE 802.16 have emerged. These proposals, which focus primarily on the PMP mode, are mostly based on extensions and combinations of ideas that have already been applied to systems prior to IEEE 802.16, such as the IEEE 802.11 wireless local-area network. To fulfill the requirements of each service type in this study, we initiated three approaches: (1) designing a special bandwidth request for traffic with the highest priority on UGS, (2) adding the weight of delay for different substations (SSs) within the same service type, and (3) using an appropriate scheme for slot allocation. The details are presented below.

3.1.1. Expedited Queue

In the PMP mode, a few SSs connect to the base station (BS) via a high-speed wireless link. In the initiation of UGS, the BS requests the allocation of a fixed bandwidth for a *constant bit rate (CBR)* traffic session. However, ertPS, rtPS, and nrtPS are polling services that need to make dynamic requests to the BS in each timeframe. Consequently, these service types are designed for *variable bit rate real-time (VBR-rt)* traffic or lower-priority non-real-time traffic. However, this gives rise to different situations in the IEEE 802.16 mesh mode. Data traffic may be divided into multiple hops according to the flow path, so a traditional bandwidth request must be sent by each hop in the intermediate SSs. The QoS types only apply different priorities such as the PMP state of the polling service. Since UGS traffic has the highest priority and a fixed bandwidth requirement, it is not necessary to allocate bandwidth to UGS on a per-timeframe basis; thus, as is the case in the PMP mode, a one-time request is sufficient in UGS. To support UGS traffic with an initial *bandwidth request (BW-REQ)*, we need to apply the concept of cut-through switching from the *asynchronous transfer mode (ATM)* network. In our proposed *Expedited Queue (EQ)* scheduling scheme, when UGS traffic satisfies the requirements of the admission control policy, the resource allocation function should consider both the per-hop *BW-REQ* and the end-to-end route path. Our *EQ* scheme provides an absolute QoS guarantee of the highest priority for UGS traffic. We add a special queue to each SS for supporting UGS traffic without using a scheduling scheme. When the sender SS in UGS makes a *BW-REQ*, the BS allocates the slots based on its request slots and hop number of the route path (*request slots * hop count*). For example, when the sender connects to SS1 and the receiver is inside *SS6*, the path is *SS1_SS2_SS5_SS6*, as illustrated in Figure 3. Therefore, BS can allocate three slots to the whole path bandwidth requirement when it receives a request from *SS1* without receiving respective requests from *SS1, SS2,* and *SS5*. The *EQ* scheme can lead to reductions in signal overheads and end-to-end delays. The maximum transmission delay can be found as D_{max} in Equation (1).

$$D_{Max} \leq \left\lceil \frac{IP_{SDU} \times Hop\_count}{Size_{timeframe}} \right\rceil \times T_{timeframe} \tag{1}$$

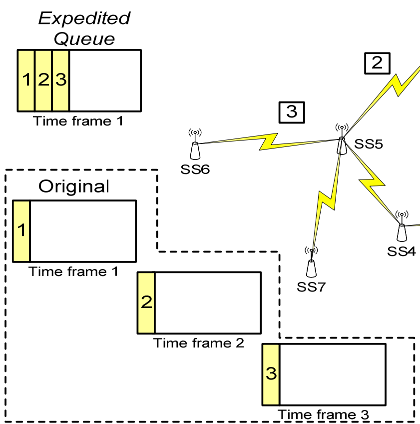

Figure 3. Concept of Expedited Queue

3.1.2. Delay-based Weight Design

The proposed scheduling algorithm in the framework is similar to the centralized scheduling controlled by the BS, but with delay consideration. The following rules apply to the proposed scheduling algorithm: (1) UGS flows have higher priorities than ertPS flows; ertPS flows are also higher in priority than rtPS, etc; (2) Within the same service type, the SS with the higher load has a higher priority; (3) An additional mechanism is adopted for real-time flows such as UGS, ertPS 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 waiting time exceeding the delay bounds specified in the flow setup phase have higher priorities than those frames with shorter waiting times. An elaborate weighting function integrating the above rules is designed to determine the access sequence that acts to minimize the access delay of real-time data packets as explained below:

The weighting function is used by the BS to determine the transmission priority (denoted by *XMT*) of each queue at each SS. The BS collects the queue length (in the number of data frames) of each service type at SS_i, i.e. $D_{UGS,i}$, $D_{ertPS,i}$, $D_{rtPS,i}$, $D_{nrtPS,i}$, and $D_{BE,i}$. For delay-constrained service types such as UGS, ertPS and rtPS, one more parameter (denoted by $W_{UGS,I}$, $W_{ertPS,i}$ and $W_{rtPS,i}$) of the data frame number in the queue where the queuing time exceeds the delay bound, is also collected. In order to give delayed UGS, ertPS and rtPS data frames higher priorities in scheduling, we define a delay compensation factor (denoted by *DC* and *DC*=5 in our simulation) for $W_{UGS,i,}$ $W_{ertPS,i}$ and $W_{rtPS,i}$. The weighting functions for UGS, ertPS and rtPS queues are therefore defined respectively as follows:

$$XMT_{UGS,i} = W_{UGS,i} \times DC + (D_{UGS,i} - W_{UGS,i})$$
$$XMT_{ertPS,i} = W_{ertPS,i} \times DC + (D_{ertPS,i} - W_{ertPS,i})$$
$$XMT_{rtPS,i} = W_{rtPS,i} \times DC + (D_{rtPS,i} - W_{rtPS,i})$$

Note that the values of *XMT* for nrtPS and BE queues are simply $D_{nrtPS,i}$ and $D_{BE,i}$.

3.1.3. Slot Allocation Policy

QoS support aims to achieve the highest possible link utilization while maintaining a fair bandwidth distribution. Scheduling schemes such as *priority queue (PQ), weighted fair queuing (WFQ)*, and *weighted round robin (WRR)* are frequently used to achieve QoS support. In the *PQ* scheme, packets from the queue with the highest priority are always served first. Thus, the *PQ* scheme achieves the highest performance with regard to delay and jitter for traffic with the highest priority. However, the disadvantage of the *PQ* scheme is that if a higher-priority queue is always full, the lower-priority queues are starved of service. Hence, the *WFQ* scheme is proposed where the order of service of a particular packet is determined based on the arrival time and packet size. In the third scheduling scheme, *WRR*, which is similar to the *WFQ* scheme, the queue from each class is assigned a weight and is serviced in a round-robin fashion. In every round of service, the number of packets serviced from a queue is proportional to its associated weight and mean packet size. A queue will be continuously serviced unless its weight is exhausted, or there is no packet left in the queue. Although the round-robin procedure in *WRR* increases the queuing delay and jitter for QoS traffic, it overcomes the problem of starvation in lower-priority queues, and provides flexible QoS support. Since a fixed time slot is designed in the 802.16 time frame structure, we can use the *WRR* scheme to replace *WFQ* in our proposed framework. In our study, we evaluate both the *WRR* and *PQ* schemes in this proposed framework to determine which scheme is better suited for use in 802.16 mesh networks.

4. Results and Discussion

4.1. Simulation Environment and Parameter

An enhancement simulation study has been conducted to evaluate the proposed routing and scheduling scheme. Two major contrasts are compared with our proposed schemes: centralized scheduling with routing via BS and distributed scheduling with minimal-hop-count routing. The IEEE 802.16 mesh network in the simulation is a 5x5 mesh (Figure 4) and the BS is located at the center. Link capacity of the network is 20 Mbps by using Microsoft

Visual C++ 6.0 on Windows XP. A time frame structure with 10 ms period is defined for slot allocation. Other parameters used in the simulation are displayed in Table 1.

There are total 25 flows (5 flows for each of the five service types) in each round of the simulation. Flows with ID 1~5 are UGS flows, ID 6~10 ertPS 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. The source SS and destination SS of each flow are randomly selected from the 802.16 mesh network. Three performance criteria are defined for comparison: (1) *Average delay (ms)* of data frames per hop (SS), (2) *Average throughput (Mbps)*, and (3) *Average signaling cost (average number of signaling packets per time frame)*.

4.2. Performance Comparison

As shown in Figure 5-Figure 7, for different service types under total data flow rates of 0.5, 2.5, and 5Mbps, respectively, the average delay and the delay variation per hop in the proposed schemes are smaller than those in the centralized schemes and considerably smaller than those in the distributed scheme.

Some of our observations and interpretations are as follows:

(1) The delay performance of the proposed schemes is better than those of the centralized schemes and considerably better than that of the distributed scheme.

(2) The poor delay performance of the centralized schemes can be attributed to the following two reasons: First, the longer path (all flow paths must go through the BS) used in these schemes increases the consumption of link capacity, which has an effect similar to that of an increase in input load. Second, the absence of spatial reuse (SR) in standard centralized schemes makes the effective network capacity smaller than that of our proposed scheme. Even if SR is incorporated to modify the centralized schemes, the longer path still degrades the delay performance, and the combination of a longer path and the absence of SR degrade considerably the delay performance of standard centralized schemes (w/o SR). The proposed scheme outperforms the distributed scheme to such an extent that even the distributed scheme has incorporated the minimal-hop-count route. The main reason is based on the data subframe allocation after the three-way handshake procedure; as per the pseudo-random election algorithm, only one SS can win the contention scheme between two hop neighbors. The distributed scheme needs more time to allocate a data slot to the winning SS, which results in a greater system delay due to a large number of losing SSs having data in the queue. It is worth noting that all the schemes proposed in this study exhibit almost the same delay performance even if different route selection rules are applied; this is because the rules are applied to a shorter path.

(3) The average delay for all the five schemes exponentially increases with the data flow rate in rtPS, nrtPS and BE because the higher-priority traffic in UGS and ertPS is not saturated. However, the significant increase in the delay of the centralized schemes indicates that these schemes reach saturation at the SSs much earlier than the other three schemes. As mentioned above, the major reason arises from the routing mechanism used in the centralized schemes.

(4) Our proposed schemes and the distributed scheme are applied at a higher capacity based on SR in SSs with higher concurrent transmission. Moreover, our proposed schemes allow a more effective load distribution when the data flow rate increases. Therefore, under heavy loads, the proposed schemes show an even better delay performance than the other schemes.

As shown in Figure 8, with total input flow rates ranging from 0.5Mbps to 10Mbps, the average throughput gradually increases with the data rate. The distributed scheme has lower system utilization than the centralized schemes in light load; we can observe intersecting cross-curves changing in different loads. This is due to the longer path in the centralized schemes. However, the limitation of the centralized scheme is that its throughput performance is worse than that of our proposed scheme owing to the same reasons as those provided above for the poor delay performance with longer paths. When the data rate increases, the centralized scheme reaches the saturated point (the decreasing of throughput in heavy load) more easily than the other schemes. This is because using SR enhances the link capacity and increases the time required to reach saturation. Finally, our proposed scheme beats the other schemes in terms of average throughput because of the effect of load distribution due to the delay-based route selection and scheduling; in addition, the proposed scheme has a higher

SRF value. For very heavy loads, our proposed scheme shows higher throughput when the minimal-delay-first [9] methodology is used than when the minimal-hop-count methodology is used; however, the maximal gain is only 5%. This indicates that the minimal-hop-count route selection is appropriate for IEEE 802.16 mesh networks.

The average signaling cost of the schemes is shown in Figure 9. The distributed scheme incurs the highest signaling cost because it incorporates a two-hop information exchange as opposed to channel access. Our proposed scheme has a slightly higher signaling cost than the centralized schemes because it carries out periodic reporting. However, the signaling cost does not increase with the load because all the mesh SSs sending requests almost simultaneously over a unit timeframe when the total data rate is 2.5Mbps. Furthermore, little difference is noted between the proposed schemes with different routing rules; the reason is the higher activity of the SSs due to the large distribution area in the minimal-delay-first route. According to the simulation result, the reduction ratio of the signaling cost of the proposed scheme over the distributed scheme can be up to 45%, but it is only higher by 8% than the centralized schemes.

4.3. Performance Comparison

As shown in the previous section, our proposed scheme without EQ outperformed the centralized and distributed scheduling schemes. Therefore, we shall report only the simulation results of our proposed scheme with and without EQ. As shown in Figure 10, the EQ scheme has the advantage of a lower average delay in UGS flow. This results from the UGS flow being allocated whole path slots, so the end-to-end delay can be smaller than a timeframe period (7.4ms in our simulation). In Figure 11-Figure 14, the two schemes almost overlap because the other service types do not apply the EQ scheme. However, there is a slight difference in the nrtPS and BE because of the UGS flow allocation, and therefore the lower priority queue might be pushed to the next time frame in the flow initiation. The total throughput shown in Figure 15 is almost the same in both schemes. The reason is that the EQ scheme only affects the delay performance in the mesh network. Furthermore, the EQ scheme only needs to send a UGS request to the sender SS, so the EQ scheme decreases the total signal by about 5% in Figure 16.

4.3. Performance Comparison

To compare the WRR and PQ scheduling schemes and to design our simulation scenarios, we apply WRR and PQ in our proposed scheme. Since WRR can overcome the problem of starvation in lower-priority services, we focus on the heavy load state (from 3.5Mbps to 5Mbps). In Figure 17 and Figure 18, the average delays in the UGS and ertPS traffic are almost equal because we have assigned a higher priority and larger weight to the WRR case. Moreover, the PQ scheme has a slightly smaller delay than the WRR scheme in rtPS and nrtPS (Figure 19-Figure 20), but the PQ scheme causes a greater delay than the WRR scheme in BE (Figure 21). This is because, under heavy loads, the WRR scheme allocates limited bandwidth for each service type, so the lower priority of BE ensures that the delay associated with BE is greater. The difference in average throughput is evident only with lower-priority services under heavy load conditions (Figure 22-Figure 26). Moreover, both schemes (WRR and PQ) have no effect on the signal cost (Figure 27) because they only affect the average throughput and average delay.

Table 1. Simulations Parameters

Description	value
Network size	5×5 mesh
Link capacity	20 Mbps
Time frame duration	10 ms
# of slots per time frame	200
# of flows per service type	5
Average date rate per service type flows	0.1~1 Mbps
Variation of data rate per non-UGS flow	±25%
State report interval	50ms
Weight for WRR scheduling scheme	UGS:10, ertPS:6, rtPS:3, nrtPS:2, BE:1

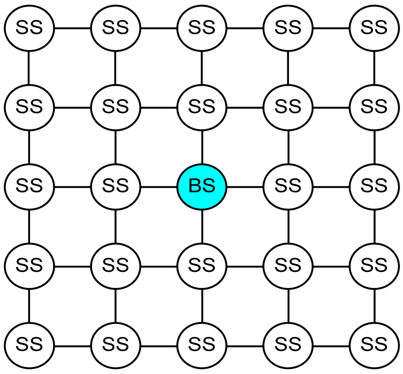

Figure 4. Simulation Topology

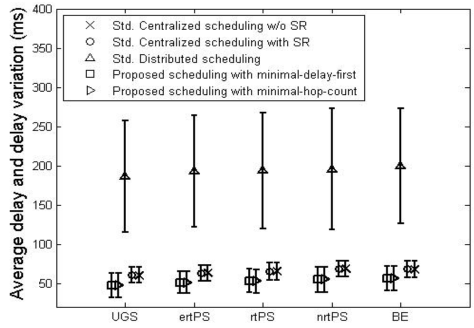

Figure 5. Delay and Delay Variation with Total Flow Data Rate 0.5Mbps

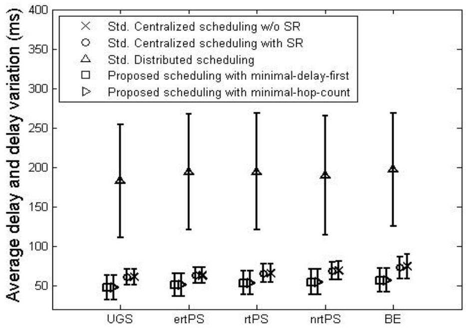

Figure 6. Delay and Delay Variation with Total Flow Data Rate 2.5Mbps

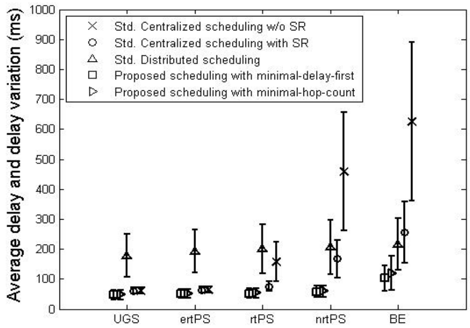

Figure 7. Delay and Delay Variation with Total Flow Data Rate 5Mbps

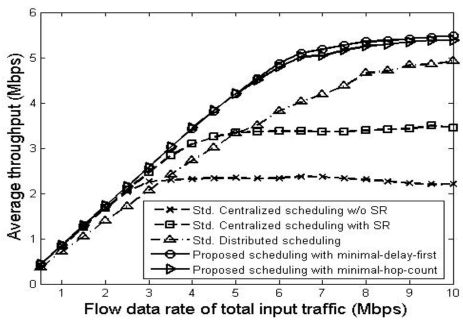

Figure 8. Average Throughput of All Flows

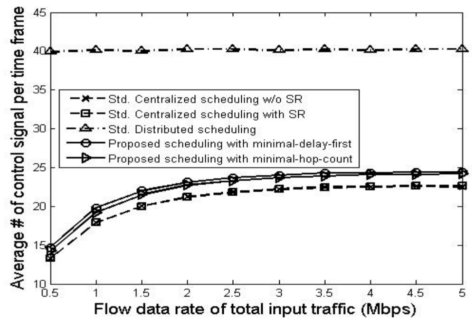

Figure 9. Average Signaling Cost

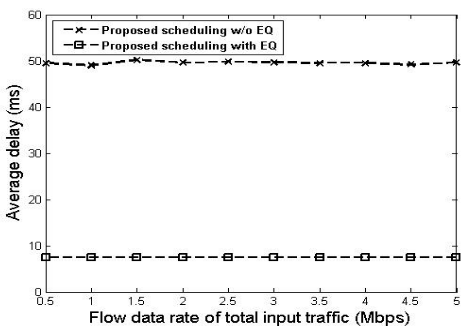

Figure 10. Average Delay of UGS Flows

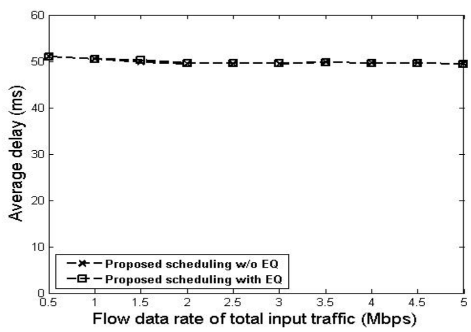

Figure 11. Average Delay of ertPS Flows

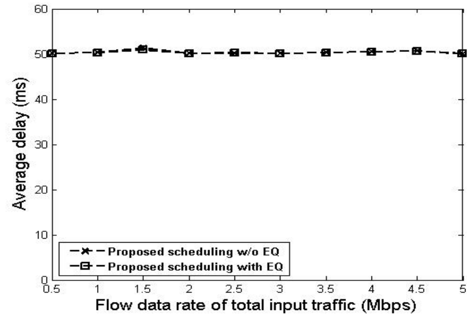

Figure 12. Average Delay of rtPS Flows

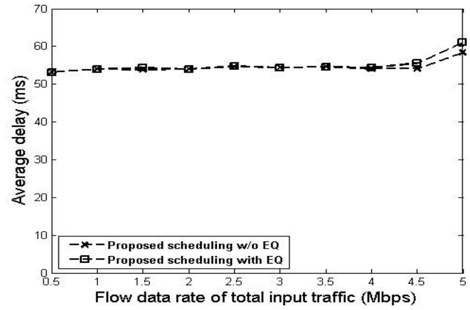

Figure 13. Average Delay of nrtPS Flows

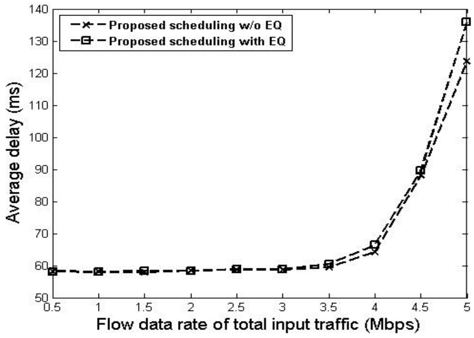

Figure 14. Average Delay of BE Flows

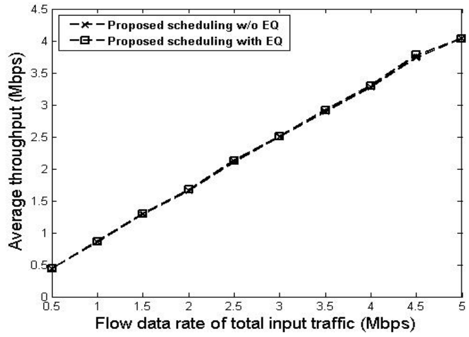

Figure 15. Average Throughput of All Flows

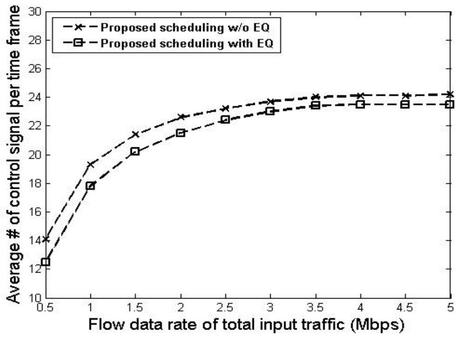

Figure 16. Average Signaling Cost

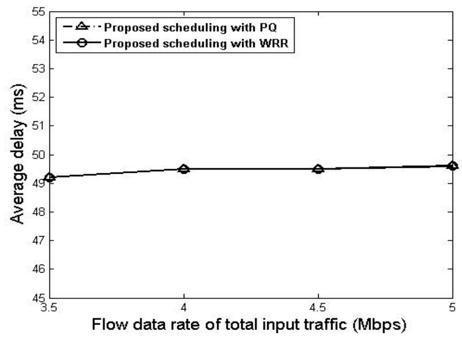

Figure 17. Average Delay of UGS Flows

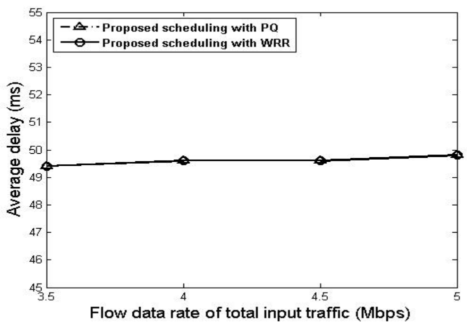

Figure 18. Average Delay of ertPS Flows

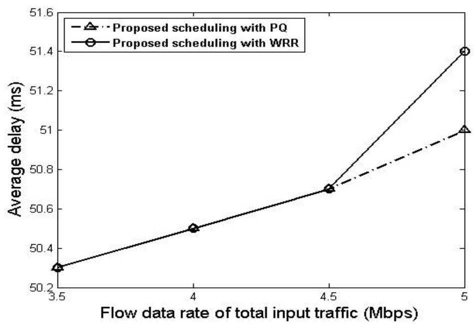

Figure 19. Average Delay of rtPS Flows

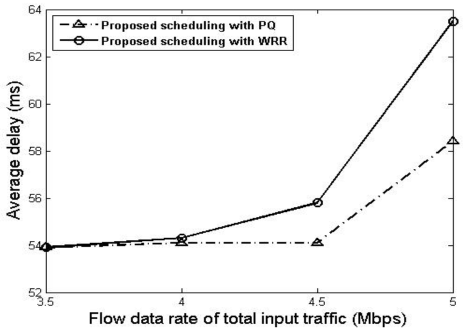

Figure 20. Average Delay of nrtPS Flows

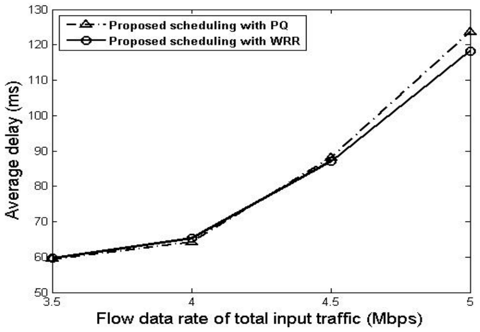

Figure 21. Average Delay of BE Flows

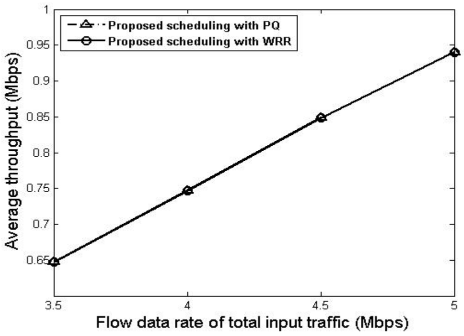

Figure 22. Average Throughput of UGS Flows

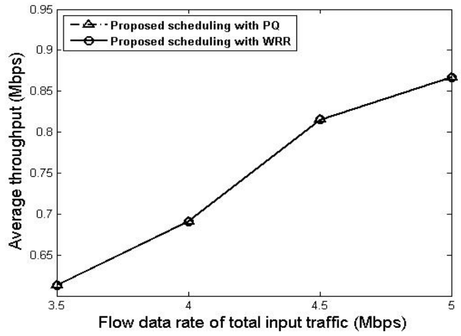

Figure 23. Average Throughput of ertPS Flows

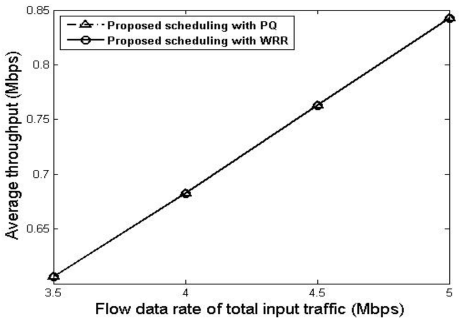

Figure 24. Average Throughput of rtPS Flows

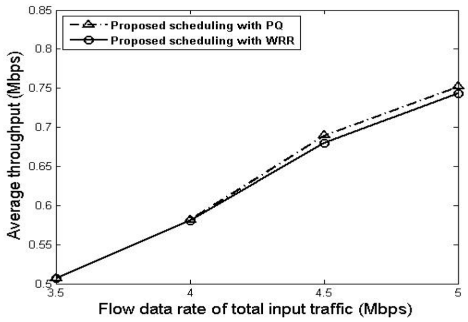

Figure 25. Average Tthroughput of nrtPS Flows

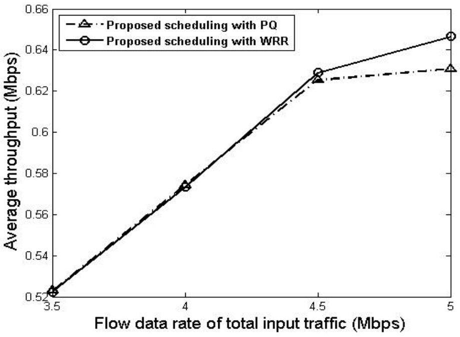

Figure 26. Average Throughput of BE Flows

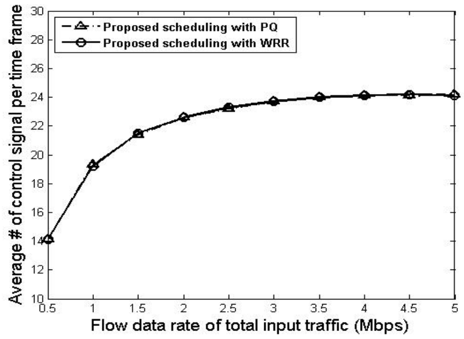

Figure 27. Average Signaling Cost

5. Conclusion

In the IEEE 802.16 mesh mode structure, there is no need to have a direct link between SSs and the BS. This allows a more flexible approach for network deployment. Data frames in the 802.16 mesh mode can be transmitted directly between two neighboring SS nodes and sent to the destination node in the hop-by-hop manner. Therefore, routing and scheduling for QoS support are important issues in the IEEE 802.16 mesh network. Two basic scheduling schemes associated with their corresponding routing mechanisms, viz. the centralized scheme and the distributed scheme, are defined in the 802.16 standard. Following our investigations on the performance problems of each of the basic schemes, we propose more efficient routing and scheduling mechanisms and a cross-layer QoS framework incorporating the proposed routing and scheduling mechanisms in this paper. The core mechanisms in the framework include expedited queue and delay-based scheduling. To achieve the higher priority traffic requirement, the expedited queue can decrease the performance of the transmission time dramatically. From our simulation results, the proposed framework and the associated mechanisms can improve performance in terms of delay, throughput, and signaling cost over the basic centralized and distributed scheduling schemes.

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