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Design of the QoS framework for the IEEE 802.16 mesh networks

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SUMMARY

IEEE 802.16 (WiMax) technology is designed to support broadband speeds over wireless networks for the coming era of broadband wireless access (BWA). IEEE 802.16 is expected to provide transmission of high-rate and high-volume multimedia data streams for fixed and mobile applications. As an extension of point-to-multipoint (PMP) configuration, the IEEE 802.16 mesh mode provides a quicker and more flexible approach for network deployment. Multimedia networking requires quality-of-service (QoS) support, which demands elaborate mechanisms in addition to the four service types defined in the specification. By examining standard centralized and distributed scheduling/routing schemes in the mesh mode from QoS aspect, a BS-controlled and delay-sensitive scheduling/routing scheme is proposed in the paper. Associate mechanisms including admission control, flow setup and link state monitoring are also proposed. Integration of the proposed mechanisms is presented as a complete QoS framework. Simulation study has demonstrated that the average delay as well as the delay jitters per hop in the proposed scheme is smaller than that of the distributed scheme and much smaller than that of the centralized scheme. Furthermore, proposed mechanisms can also achieve higher throughput than the contrasts and generate much smaller signaling overhead, making the proposed framework a promising scheme for multimedia support in the IEEE 802.16 mesh network. Copyright © 2009 John Wiley & Sons, Ltd.

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KEY WORDS: IEEE 802.16; WiMax; mesh networks; QoS

1. INTRODUCTION

Broadband wireless access (BWA) technology is aiming to provide an easy, time-saving, and low-cost method for deployment of next generation (beyond 3G) network infrastructure. Since 1998,

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IEEE 802.16 working group has launched a standardization process called wireless metropolitan area network (Wireless MANTM) 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.

As illustrated in Figure 1(a), the basic point-to-multipoint (PMP) configuration of 802.16 network consists of a base station (BS) and a couple of subscriber stations (SSs) 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 SSs to the BS and a node can choose the links and path with best quality to transmit data and avoid the congested area. For example, in Figure 1(b) a traffic flow originated from subscriber station SS_D can be transmitted along either the path [SS_D, SS_C, SS_A, BS] or the path [SS_D, SS_C, SS_B, BS] for Internet access. Moreover, the mesh mode can provide a more flexible and faster approach for network deployment.

There are two basic mechanisms to schedule data transmission in the IEEE 802.16 mesh networks [1]: centralized and distributed scheduling. In the centralized scheduling scheme, 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 (a 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 (following the uplink path and then the downlink path), operations of scheduling as well as routing at each SS are simple. However, a longer path in the mesh network is inevitable. On the other hand, in the distributed scheduling scheme, every mesh 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 (for instance, minimal-hop-count routes can be used) at the cost of higher signaling overhead for the exchange of the scheduling information. Since the IEEE 802.16 mesh mode is intended for large-area wireless network deployment to support multimedia transmission, and as we know that QoS support cannot be accomplished merely by defining different service types, scheduling and routing control have to be designed from QoS aspect. As presented in the following section, neither standard centralized nor distributed scheduling/routing mechanism is competent for multimedia QoS support. In this paper, a BS-controlled and delay-sensitive scheduling/routing scheme is proposed for better QoS support in IEEE 802.16 mesh network. Mechanisms of admission control, QoS flow setup and link state monitoring are also proposed to work together with the scheduling/routing scheme. Integration of the mechanisms is presented as a QoS framework. Minor mechanisms adopting similar ideas as in the previous work in the literature, including QoS mapping from L3 to L2 and admission control, are also presented for completeness of the framework.

The remainder of the paper is organized as follows. First of all, a survey of the related work is presented in Section 2. In Section 3, we present the overall architecture as well as the novel

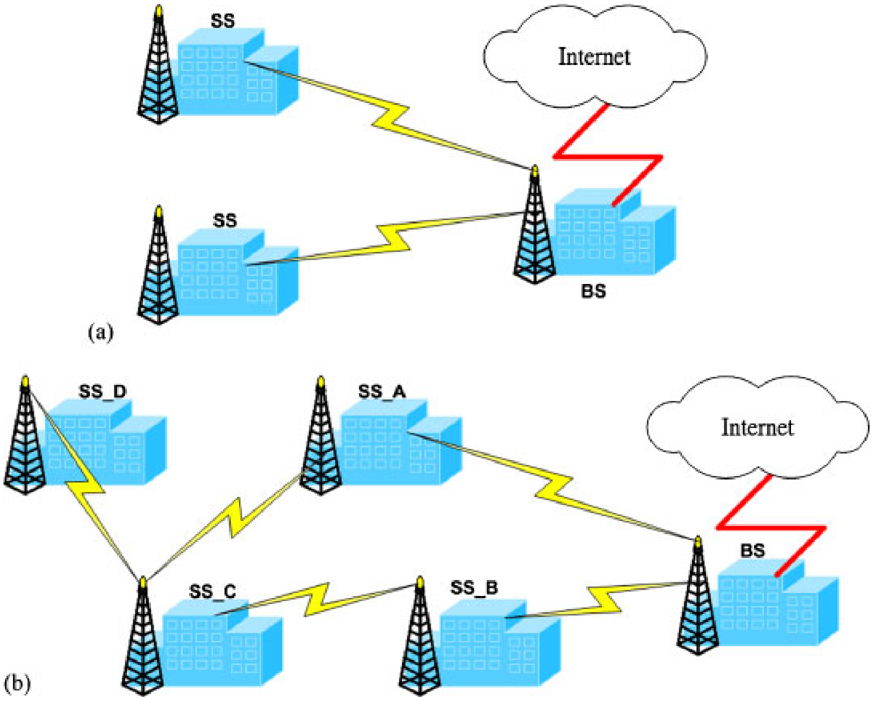

Figure 1. Two configurations in IEEE 802.16: (a) point-to-multipoint (PMP) configuration and (b) mesh configuration.

features of the proposed QoS framework at the BS and SS. Key mechanisms in the proposed framework for QoS support in IEEE 802.16 mesh networks are presented in Section 4. Simulation study for performance evaluation and comparisons is presented in Section 5. Finally, Section 6 concludes this paper.

2. RELATED WORK

IEEE 802.16/WiMAX uses a connection-oriented MAC protocol that provides a mechanism for the SS to request bandwidth from the BS. IEEE 802.16 uses the frame-based transmission architecture with variable length. It supports both frequency-division duplex (FDD) and time-division duplex (TDD) transmission modes. In order to avoid congestion between the control signal and data traffic, a transmission frame (including downlink part and uplink part) is further divided into the control sub-frame and the data sub-frame.

IEEE 802.16 was designed to support multimedia service via different QoS types. Mechanisms relating to QoS support in IEEE 802.16, such as admission control and bandwidth allocation, were extensively researched in the literature. Most of the QoS-related research work in IEEE 802.16 was mainly focused on the PMP mode [5–10]. For large-scale deployment, IEEE 802.16 mesh mode is a more suitable solution, since the mesh mode allows the SS to connect to other SSs. Owing to the different link styles, network management in the mesh mode is quite different from that in the PMP

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mode. The IEEE 802.16 mesh MAC protocol is based on time division multiple access (TDMA). Time is partitioned into frames of fixed duration. Each frame consists of a control sub-frame and a data sub-frame, and unlike the PMP mode, there is no clear division between the downlink and the uplink sub-frame. As mentioned in Section 1, there are two standard scheduling mechanisms for channel access in the mesh mode: centralized scheduling and distributed scheduling. We survey each of the scheduling mechanisms and the related research work in the following sub-sections.

2.1. IEEE 802.16 centralized scheduling

In centralized scheduling, the BS works like a cluster head and determines how the time slots are shared among the SSs. Because all the control and data packets need to go through the BS, it acts just like the BS in PMP networks. In this case, the scheduling procedure is simple and it is easy to manage the mesh network. Centralized scheduling is coordinated by the BS to ensure collision-free request and transmission over the links in the mesh network. In the standard, only one SS node can request or transmit in each mini-slot. To improve the system utilization, it is necessary to allow more than one SS to access the mesh network at the same time. For this reason, the interference issue is one of the most significant factors that limit the network capacity and scalability in the IEEE 802.16 mesh network. The common goal of the concurrent transmission schemes of centralized scheduling in the literature is to achieve a better spectral utilization while limiting mutual interference in neighboring nodes by properly designing radio resource allocation and route formation mechanism.

The IEEE 802.16 standard is a Layer 1 and Layer 2 protocol, so it does not specify how the traffic will be routed in the mesh topology. In centralized scheduling-based research works [11–16], 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 introduces more link consumption, which further causes a significant decrease in network utilization. For designing QoS mechanisms, most of the centralized-based research works [17, 18] focused on the construction of the routing tree based on different QoS types. For real-time traffic, Schwingenschlogl *et al.* [19] 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 literatures.

2.2. IEEE 802.16 distributed scheduling

In comparison with centralized scheduling, distributed scheduling provides better routing path without always requiring the traffic going via the BS. In distributed scheduling, each node competes for channel access using a pseudo-random election algorithm based on the scheduling information of the two-hop neighbors, and data sub-frames are allocated through a request/grant/confirm three-way handshaking procedure. Therefore, the distributed scheduling mechanism is more flexible and efficient in terms of system utilization and data transmission. Some research works [20–22] focused on the improvement of the throughput by modifying the original distributed access scheme, and some [23–25] tried to identify and model the effect of parameters in distributed scheduling for assigning different traffic types to achieve QoS support. Despite of 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.

In this paper, by taking into consideration the pros and cons in the centralized and distributed scheduling, a hybrid scheduling and routing scheme is proposed, and based on which we elaborate the complete QoS framework and associated mechanisms for QoS support in the 802.16 mesh network.

3. CROSS-LAYER QOS FRAMEWORK

As mentioned in Section 2, there are both advantages and disadvantages in the basic centralized and distributed scheduling schemes for the IEEE 802.16 mesh networks. The centralized scheduling scheme has the advantage of centralized control with better and more effective QoS support, but suffers from the longer transmission path. Since there is only one physical wireless link in the mesh network, a longer transmission path implies that a packet goes through the link many times and results in the increase of the consumption of link capacity. On the other hand, the distributed scheduling scheme has the advantage of using minimal-hop-count 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 2 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 (the traffic flow applying for IP QoS service) to provide more efficient route control. Novel features of the QoS framework are

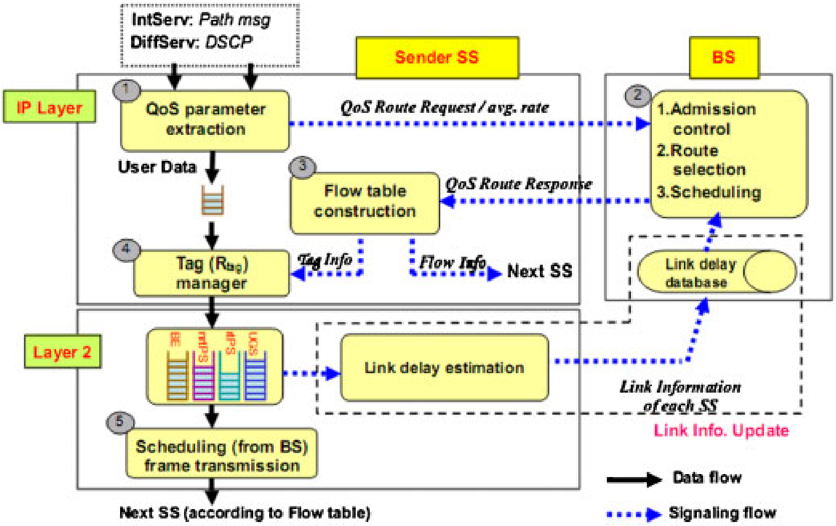


Figure 2. Cross-layer QoS framework for IEEE 802.16 mesh mode.

listed as follows:

1. (1) The framework adopts cross-layer integration that incorporates some IP layer functionalities at the BS and SS nodes, such as processing and interpretation of IP header, mapping of L3 service types to 802.16 service types (item ① in Figure 2), 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. (2) The BS works as the centralized controller of QoS support, maintains topological and current link state information (in the link delay database), and is responsible for admission control, route selection and scheduling of data transmission (item ②).
3. (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. (4) Subscriber stations access the data channel in the allocated time slots according to the instruction (UL_MAP) from the BS, and transmit data packets to the next hop according to the value of Rtag added in the header of the data frame and the flow table (item ⑤). Note that using Rtag in the header of 802.16 data frame for fast packet routing is similar to the idea of *multi-protocol label switching* (*MPLS*) [26]. 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 for updating the link delay database on a regular basis.

4. QOS MECHANISMS

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

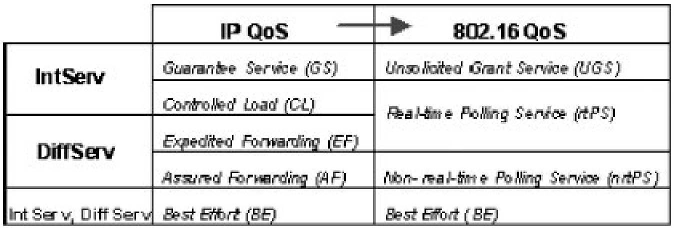
4.1. L3 to L2 QoS mapping

Since IEEE 802.16 belongs to Layer 2 technology in the network layering architecture, the user of 802.16 is its 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*) [27, 28] and *differentiated service* (*DiffServ*) [29]; each of them defines different classes of QoS. We adopt a simple and static mapping from upper layer to 802.16 QoS types in the proposed framework as illustrated in Figure 3.

4.2. Admission control

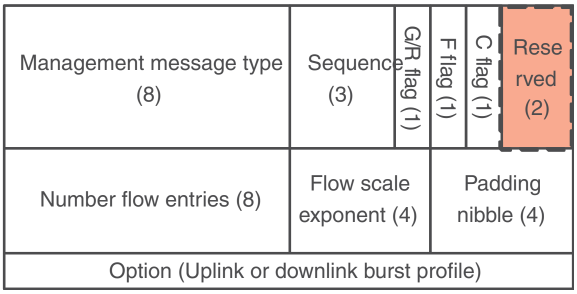
The admission control scheme of the proposed framework is based on the average rate of the new QoS flow and the current load in the mesh network. Each flow must provide its data rate in the flow setup phase. The field of '*Flow scale exponent*' in the header of MSH message as displayed in Figure 4 is used to indicate the bandwidth (data rate) requirement of a flow. The BS calculates the required bandwidth of the flow according to the following Equation [1]:

$$\mathrm{BW}_{\mathrm{Flow\_ID}} = 2^{\mathrm{Flowscaleexponent}+14\,\mathrm{bits/s}}$$



	IP QoS →	802.16 QoS
IntServ	Guarantee Service (GS)	Unsolicited Grant Service (UGS)
	Controlled Load (CL)	Real-time Polling Service (rtPS)
DiffServ	Expedited Forwarding (EF)	
	Assured Forwarding (AF)	Non-real-time Polling Service (nrtPS)
Int Serv, Diff Serv	Best Effort (BE)	Best Effort (BE)

Figure 3. Mapping rule from IP QoS to 802.16 QoS.



Management message type (8)	Sequence (3)	G/R flag (1)	F flag (1)	C flag (1)	Reserved (2)
Number flow entries (8)	Flow scale exponent (4)		Padding nibble (4)		
Option (Uplink or downlink burst profile)					

Figure 4. MSH-CSCH message format.

A response is sent back to the corresponding SS after the BS applies the admission control mechanism as explained in the following. A new flow is accepted if the remaining capacity of the channel can support the required bandwidth 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 advantage of mesh networks is an improvement of capacity by concurrent transmission in the wireless environment. Therefore, the degree of spatial reuse is very crucial to realize the full potential of 802.16 mesh networks. So, our 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. In order to model (measure) the effect of the spatial reuse in slot allocation, the *spatial reuse factor* (denoted by SRF) is defined in the paper. The effective channel capacity is therefore affected by SRF. For example, if there are always more than two SS nodes that can access the channel at the same time, the value of SRF will be not less than 2, and the effective channel capacity will be at least double of the original link capacity.

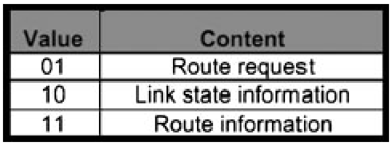
In summary, the BS will accept the new flow if LinkCapacity $*$ SRF - CurrentLoad $>$ (AvgRate of the flow) $*$ (hop count of the minimal-hop-count route), in which the value of SRF is dynamically calculated at the run-time, CurrentLoad is calculated according to the link state report from SS nodes,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

4.3. 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 minimal-hop-count route. The delay information (the system time) for each QoS type at every SS is estimated and reported to the BS periodically. The estimation of system time at each SS in the framework is similar to RTT (Round-trip time) in TCP. Note that as the lower priority service type of non-real time traffic, nrtPS (Non-real-time Polling Service), BE (Best-Effort) flows use the minimal-hop-count route.

It is worth mentioning that the minimal-delay-first route selection has the advantage of load distribution over its minimal-hop-count counterpart, since the delay-based cost also reflects the load at the SS, which means the minimal-delay-first mechanism tends to select a route with minimal end-to-end load in the mesh network, and furthermore it is likely to increase the value of SRF.

In order to support proper signaling for route selection, the reserved bits (2 bits) in the header of the MSH-CSCH message are used to indicate extended payload types for proper information exchange. New payload types used in the proposed scheme are displayed in Figure 5. For route selection, the sender SS sends to the BS an MSH-CSCH message with the value of the reserved bits set as '01' indicating the QoS route request, and the BS selects a minimal-delay path for the requested flow according to the link state database. The link state database maintained by the BS includes the topological information as well as the average delay of each link in the mesh network. For the example mesh network shown in Figure 6, the link database maintained by the BS could be as shown in Figure 7. Moreover, the BS also maintains the route information for each flow as displayed in Figure 8.



Value	Content
01	Route request
10	Link state information
11	Route information

Figure 5. Designed message with reserved bits.

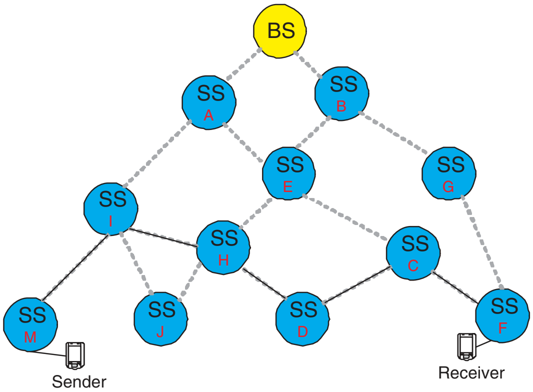
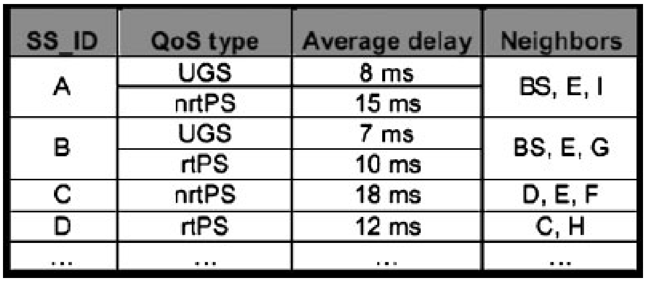
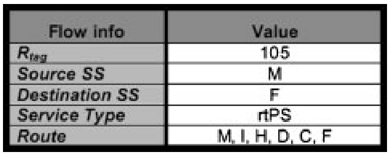


Figure 6. An example mesh network.



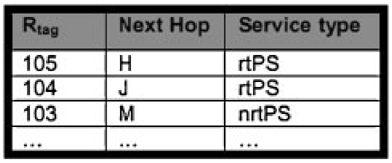
SS_ID	QoS type	Average delay	Neighbors
A	UGS	8 ms	BS, E, I
	nrtPS	15 ms	
B	UGS	7 ms	BS, E, G
	rtPS	10 ms	
C	nrtPS	18 ms	D, E, F
D	rtPS	12 ms	C, H
...	...	...	...

Figure 7. Link state database at the BS.



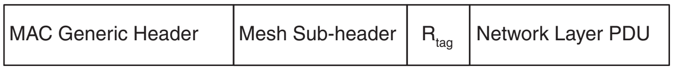
Flow info	Value
R_{tag}	105
Source SS	M
Destination SS	F
Service Type	rtPS
Route	M, I, H, D, C, F

Figure 8. Route information for a flow.



R_{tag}	Next Hop	Service type
105	H	rtPS
104	J	rtPS
103	M	nrtPS
...	...	...

Figure 9. Flow table in SS_I.



MAC Generic Header	Mesh Sub-header	R_{tag}	Network Layer PDU

Figure 10. Addition of the R_{tag} field in the MAC frame.

4.4. *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 value of R_{tag} for the flow is assigned by the BS for fast routing in the mesh network. Route information of the new flow is sent to all SS nodes by a broadcast MSH-CSCH message with the reserved bits set as ‘11’. On receiving the route information of the new flow, the intermediate SS adds a corresponding flow entry in its flow table as shown in Figure 9. Moreover, a new field (as shown in Figure 10) indicating the value of Rtag for a flow is added in the header of the 802.16 MAC frame to support R_{tag}-based fast routing.

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4.5. 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 proposed scheduling algorithm include: (1) UGS (unsolicited grant service) flows have higher priorities than rtPS (real-time polling service) flows, rtPS flows higher than nrtPS (non-real-time polling service), etc. (2) Within the same service type, the SS with higher load has a higher priority. (3) Moreover, an additional mechanism is adopted for 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. An elaborate weighting function integrating the above rules is designed for determining the access sequence that tries to minimize the access delay of real-time data packets as explained in the following.

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. $D_{\mathrm{UGS},i}$, $D_{\mathrm{rtPS},i}$, $D_{\mathrm{nrtPS},i}$ and $D_{\mathrm{BE},i}$. For delay-constrained service types such as UGS and rtPS, one more parameter (denoted by $W_{\mathrm{UGS},i}$ and $W_{\mathrm{rtPS},i}$) of the number of data frames in the queue of which their queuing time exceeding their delay bound is also collected. In order to give delayed UGS and rtPS data frames higher priorities in scheduling, we define a delay compensation factor (denoted by DC and $\mathrm{DC}=5$ is used in our simulation) for $W_{\mathrm{UGS},i}$ and $W_{\mathrm{rtPS},i}$. The weighting functions for UGS and rtPS queues are therefore defined, respectively, as follows:

$$\mathrm{XMT}_{\mathrm{UGS},i} = W_{\mathrm{UGS},i} * \mathrm{DC} + (D_{\mathrm{UGS},i} - W_{\mathrm{UGS},i})$$

$$\mathrm{XMT}_{\mathrm{rtPS},i} = W_{\mathrm{rtPS},i} * \mathrm{DC} + (D_{\mathrm{rtPS},i} - W_{\mathrm{rtPS},i})$$

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

4.6. Discussion

As will be shown in the simulation study, the proposed framework is expected to outperform the centralized scheduling and the distributed scheduling counterparts, but the proposed mechanisms also bring overhead in processing, cache size and signaling as explained in the following:

1. Processing overhead: The BS in the proposed framework has to handle the process of admission control, route selection and scheduling assignment. The operations in admission control and route selection do not impose too much computational overhead, since these operations are only performed whenever a new flow request arrives. On the other hand, in order to provide necessary information for the BS, each SS is required to monitor its link state for each service type.
2. Cache size: A couple of cache databases are required to support the proposed framework. Cache databases at the BS include a link state database and a routing information database. The database for flow table is required at each SS. The size of the cache at the BS is estimated as follows. First of all, 16 bytes is fairly enough for each entry in the link state database at the BS. With the number of mesh nodes not more than 100 (which can construct a very large mesh network), the size of the link state database is only 6.4 kbytes. An entry

in the routing information database is estimated to be fewer than 100 bytes. The total size of the routing information database also depends on the maximum number of flows in the network. In order to support up to 10 k flows in the network, the cache size for the routing information database can be up to 1 Mbytes, which does not impose much memory cost on modern communication systems. At the SS, the entry in the flow table includes Rtag, Next Hop and Service type as shown in Figure 9, and 4 bytes should be enough for an entry. Therefore, for 10 k flows that potentially may pass through an SS, a flow table of 40 kbytes is fairly enough.

(3) Control signaling: a couple of new signaling packets are defined in the proposed framework to support proper operations. First of all, the flow request packet is required for requesting a new flow. Information about the routing path of a new flow is sent to all SS nodes by the BS using broadcast MSH-CSCH messages. Finally, the SS reports it link state to the BS by piggybacking the link state information in the BW_REQ messages.

Last but not least, a larger mesh size potentially implies a longer path for a flow, which will significantly increase the bandwidth consumption in the mesh network. Therefore, the performance of IEEE 802.16 mesh networks degrades seriously as the mesh size goes up such that the scalability problem is the major performance factor that limits the size of the mesh network. Note that the idea of spatial reuse presents some merit to lessen the scalability problem.

5. PERFORMANCE EVALUATION

5.1. Simulation parameters and performance criteria

We have designed the simulation environment of 802.16 Mesh network as well as the three scheduling by using Microsoft Visual C++ 6.0 on Windows XP. Simulation study has been conducted to evaluate the proposed routing and scheduling scheme. Two contrasts are compared with the proposed scheme: centralized scheduling with routing via BS and distributed scheduling with minimal-hop-count routing. The mesh network in the simulation is a 5×5 mesh and the BS is located at the corner. Link capacity of the network is 5 Mbps. A time frame structure with size 10 ms is defined for slot allocation. Other parameters used in the simulation are displayed in Table I. 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. The source SS and destination SS of each flow are randomly selected from the mesh network. Three performance criteria are defined for comparison: (1) average delay (ms) of data frames per hop (SS), (2) average throughput (kbps) and (3) average signaling cost (average number of signaling packets per time frame).

5.2. Simulation results

As shown in Figures 11 and 12, the average delay and delay variation per hop for different service types under flow data rate 2.5 Mbps in the proposed scheme are smaller than those of the distributed scheme (Figure 12) and much smaller than those of the centralized scheme (Figure 11). For more investigation of delay behavior, Figures 13–16 display the results of the average delay

Table I. Simulations parameters.

Description	Value
Network size	5 × 5 mesh
Link capacity	5 Mbps
Time frame duration	10 ms
# of slots per time frame	10
# of flows per service type	5
Average date rate of all flows	0.5–5 Mbps
Variation of data rate per non-UGS flow	25%
State report interval	50 ms

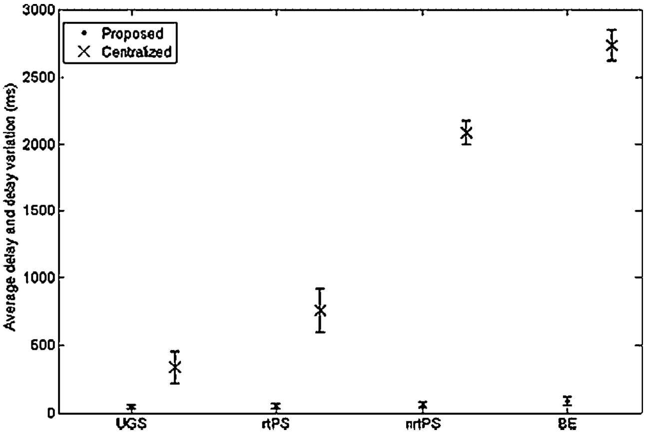

Figure 11. Delay and delay variation with flow data rate 2.5 Mbps: proposed vs centralized.

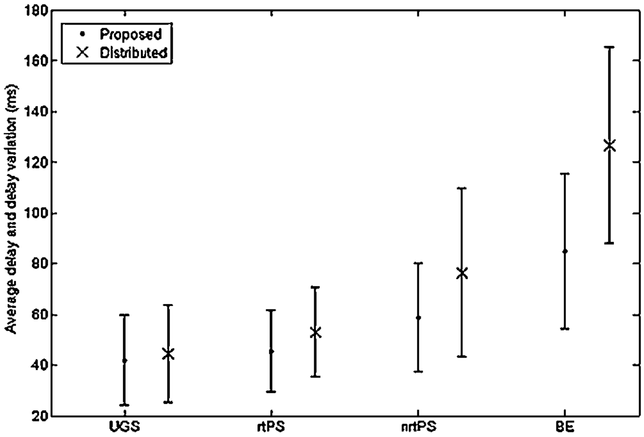

Figure 12. Delay and delay variation with flow data rate 2.5 Mbps: proposed vs distributed.

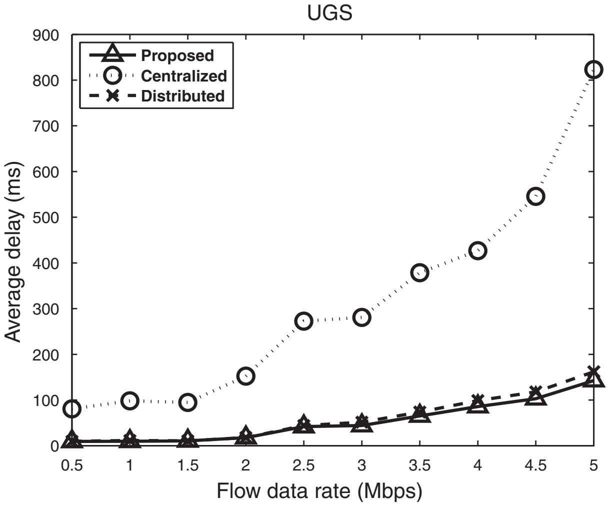

Figure 13. Average delay of UGS flows.

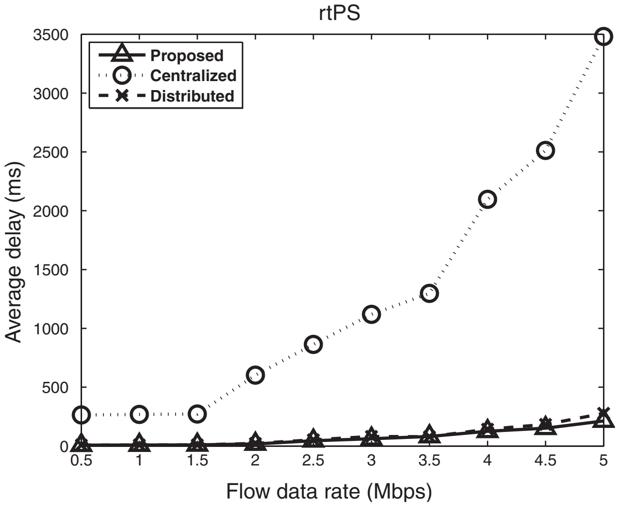

Figure 14. Average delay of rtPS flows.

per hop for different service type of flows under flow data rate ranging from 500 kbps to 5 Mbps. Some observations and interpretations can be made from the figures as follows:

(1) Delay performance of the proposed scheme is better than that of the distributed scheme and much better than that of the centralized scheme. The reason behind the poor delay performance of the centralized scheme is twofold: First, the longer path increases the consumption of the link capacity that is similar to the effect of input load increase. Second, no spatial reuse in the scheduling makes the effective capacity in the network smaller than

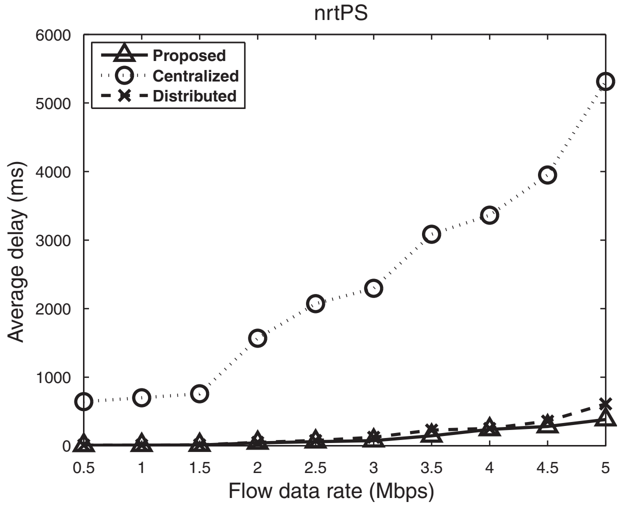

Figure 15. Average delay of nrtPS flows.

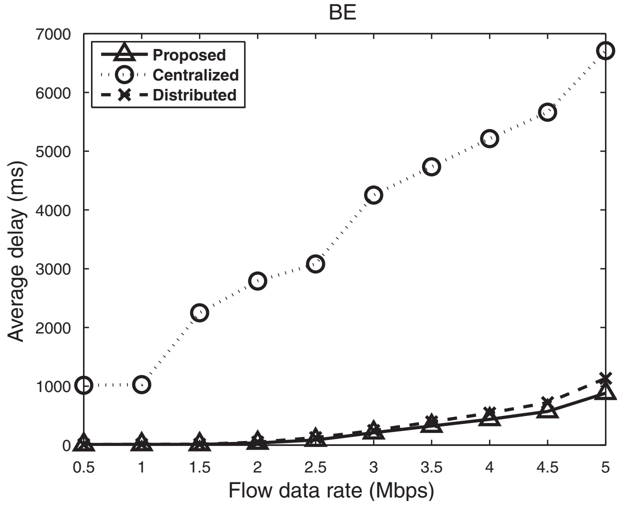

Figure 16. Average delay of BE flows.

that of the proposed scheme. Both factors put together worsen the delay performance in the centralized scheme. On the other hand, the proposed scheme does not beat the distributed scheme too much since the minimal-hop-count route is used in the distributed scheme. However, some gain (decrease of 20% in average delay at the best cases of nrtPS and BE flows) is still achieved by the minimal-delay-first route selection as well as delay-based scheduling in the proposed scheme over the distributed scheme.

(2) The average delay for all the three schemes goes up while the flow data rate increases. However, the significant increase in delay of the centralized scheme reflects that the scheme reaches the saturation point of the queuing system at the SS much earlier than the other two schemes. The major reason is again due to the routing mechanism used in the centralized scheme. Moreover, the proposed scheme presents more effect of load distribution when the flow data rate increases. Therefore, the gain of delay performance in the proposed scheme over the distributed scheme is getting larger under heavy loads.

(3) Since the scheduling algorithms in all the three schemes adopt priorities for different service types, the average delay of UGS flows is always smaller than that of rtPS flows, rtPS delay smaller than nrtPS delay and nrtPS delay smaller than BE delay.

(4) Figures 17–20 display the average throughput of the schemes. As expected, the centralized scheme suffers from poor throughput performance due to the same reasons of poor delay performance. The proposed scheme outperforms slightly the distributed scheme in average throughput because of the effect of load distribution of the delay-based route selection and QoS scheduling mechanism.

(5) The average signaling cost of the schemes is shown in Figure 21, in which the distributed scheme presents the most signaling cost due to 2-hop information exchange in competition of channel access. Moreover, as the input load increases, the contention of channel access among SS nodes in the distributed scheme becomes more intensive resulting in the drastic increase of the signaling cost. On the other hand, the only difference of the signaling overhead between the proposed scheme and the centralized scheme is the number of MSH-CSCH messages. As presented in Section 3, the proposed scheme requires the exchange of MSH-CSCH messages for route setup and link state update, which is not the case in the centralized scheme. However, the number of MSH-CSCH messages for BW_REQ composes a much larger amount of the signaling cost in both schemes. Since the longer transmission path in the centralized scheme increases a larger number of the BW_REQ messages, the proposed scheme outperforms the centralized scheme in terms of the average signaling cost. In summary, reduction ratio of the signaling cost of the proposed scheme over the other two schemes according to the simulation can be up to 37% (over the centralized scheme) and 78% (over the distributed scheme).

(6) The issue of scalability plays an important role on the deployment of the IEEE mesh network. Figure 22 displays the throughput of the proposed scheme under different mesh sizes. As shown in the figure, the throughput of the network degrades seriously as the mesh size increases. For example, the maximum throughput for mesh size 15×15 degrades to only 70% of the throughput for mesh size 5×5. It is the consequence of link sharing in the IEEE 802.16 mesh network. More specifically, the path of the flows in a larger mesh network tends to be longer and consumes more network bandwidth resulting in poorer performance in throughput.

6. CONCLUSION

As the most promising Wireless-MAN technology, IEEE 802.16 provides broadband, wide coverage and QoS support to meet the demand of the next generation BWA network. Two configuration modes for IEEE 802.16 were introduced in the standard: PMP and mesh. In the mesh mode,

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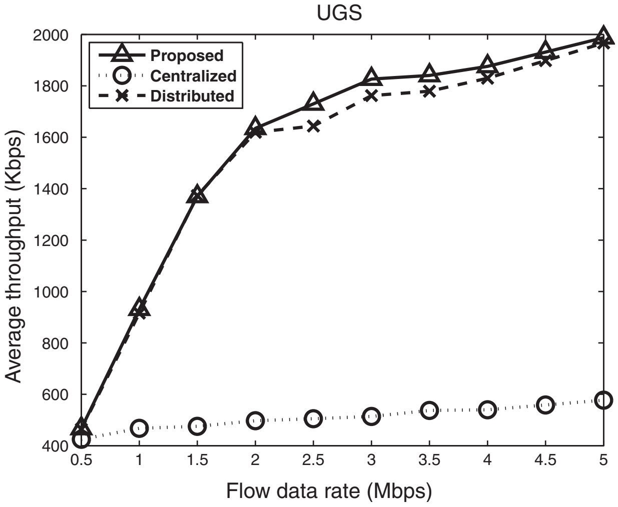

Figure 17. Average throughput of UGS flows.

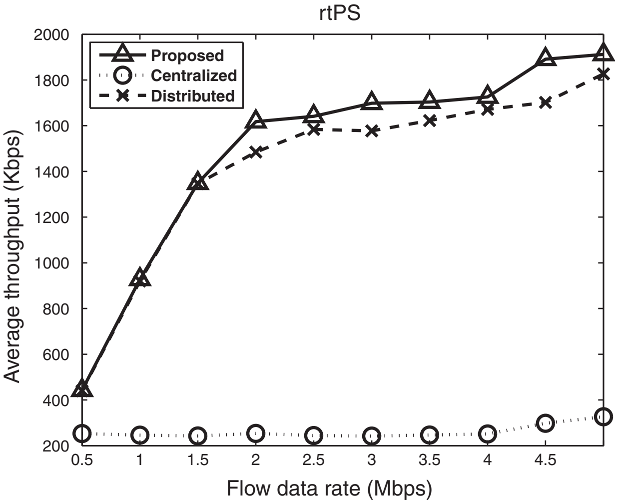

Figure 18. Average throughput of rtPS flows.

there is no need to have direct link from subscriber stations (SSs) to the base station (BS), which provides 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 with QoS support are important issues in the IEEE 802.16 mesh network. Two basic scheduling schemes, the centralized scheme and the distributed scheme, associated with their corresponding routing mechanisms were defined in the 802.16 standard. In this paper, we have pointed out the performance problems in each

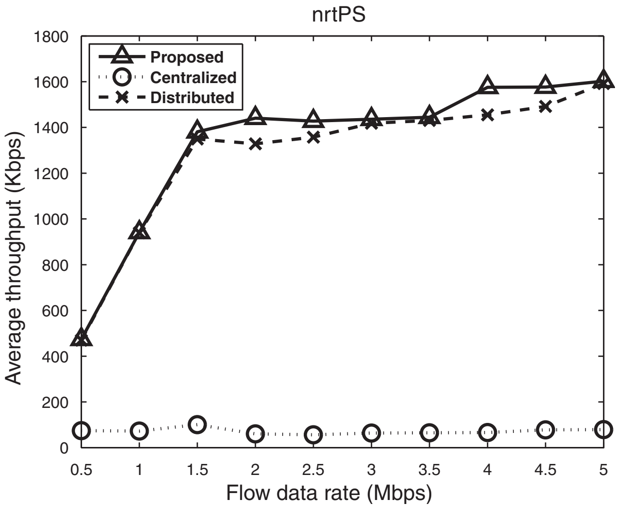

Figure 19. Average throughput of nrtPS flows.

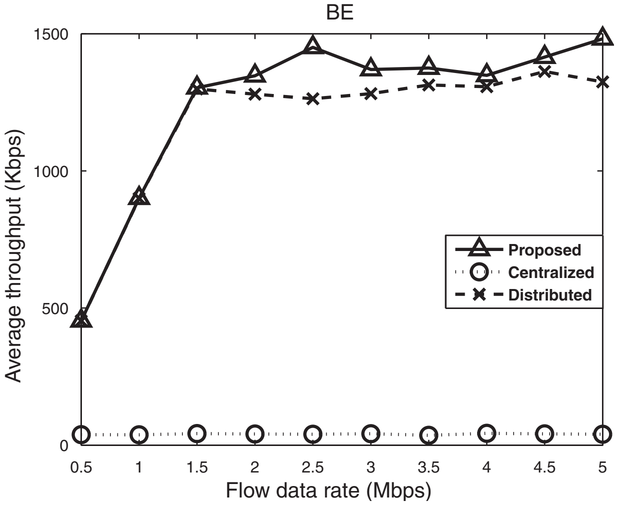

Figure 20. Average throughput of BE flows.

of the standard schemes for QoS support, and proposed more efficient routing and scheduling mechanisms. Companion mechanisms, such as QoS flow setup, link state monitoring, mapping of IP classes to IEEE 802.16 service types, and admission control were also presented. Moreover, a cross-layer QoS framework integrating the proposed mechanisms was presented. Simulation results have demonstrated that the proposed mechanisms can achieve a better performance in terms

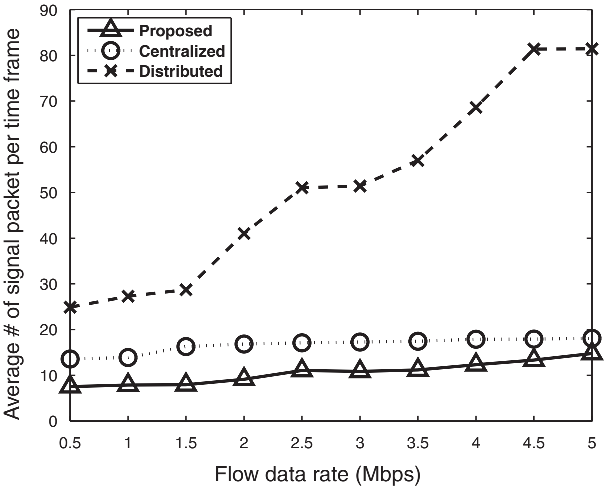

Figure 21. Average signaling cost.

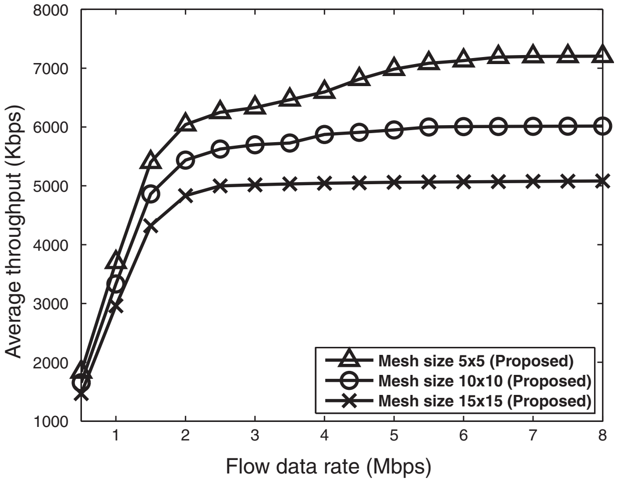

Figure 22. Average throughput of all flows with different mesh sizes.

of delay, throughput and signaling cost over the standard centralized and distributed scheduling schemes making the framework a good solution for multimedia transmission in the IEEE 802.16 mesh network.

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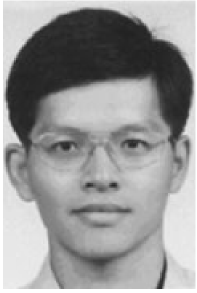

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