Quality of Service in Mesh Mode IEEE 802.16 Networks

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***Abstract*— IEEE 802.16 standard supports two topologies: point-to-multipoint (PMP) and Mesh. In this paper, a QoS mechanism for the Mesh mode of IEEE 802.16 and a BS scheduler for the Mesh mode are proposed. Our QoS mechanism is developed by modifying the QoS mechanism of the PMP mode in IEEE 802.16. We compare our QoS mechanism against the default Mesh QoS mechanism of IEEE 802.16. The performance of both methods are analyzed by providing simulation results based on these two solutions. The results show that the default QoS mechanism introduces a delay of at least 100 ms, which makes it inappropriate for real time and multimedia services.**

I. INTRODUCTION

The initial IEEE 802.16 standard is developed to serve fixed *subscriber stations* (*SSs*) through a central *base station* (*BS*) using a PMP topology. In the current standard, IEEE 802.16-2004 [1], the Mesh mode is introduced as an additional operating mode. Unlike the PMP mode, there exist SSs that are not directly connected to the BS in the Mesh mode. SSs can relay transmissions of second stage SSs that cannot directly communicate with the BS. Thus, a BS can support more SSs in the Mesh mode than the PMP mode. So, in order to minimize the number of BSs that are needed to cover a given area Mesh mode is more appropriate than the traditional PMP mode.

IEEE 802.16e adds mobile user support to IEEE 802.16 networks [2]. Unlike fixed SSs, these *mobile SSs* (*MSs*) have limited battery capacity unlike fixed SSs and they employ mechanisms to reduce power consumption such as the Sleep mode in IEEE 802.16e standard. However additional mechanisms are needed to further increase battery life. Since SSs do not need to be directly connected to the BS in the Mesh mode, MSSs are able to connect to nearby SSs instead of connecting directly to the BS. The reduced transmission distance decreases power consumption of the MS. Thus, with the introduction of IEEE 802.16e, the importance of the Mesh mode is increased considerably.

IEEE 802.16 is developed with QoS in mind. Five different service classes are introduced for different applications and packets from different service classes are handled based on their QoS constraints. However, this mechanism can only be used in the PMP mode. In the Mesh mode, QoS is maintained in a message-by-message basis. It can be argued that the QoS mechanism used in the PMP can also be used in the Mesh mode. In this paper, we have developed a QoS mechanism based on this method. The performance of this method is compared to a generic Mesh mode QoS mechanism. In Section II, the Mesh mode of the IEEE 802.16 standard is explained. Section III, explains our proposed QoS mechanism and the BS scheduler used in this study. The simulation scenarios are explained in Section IV, and the results are presented in Section V. We conclude our paper in Section VI.

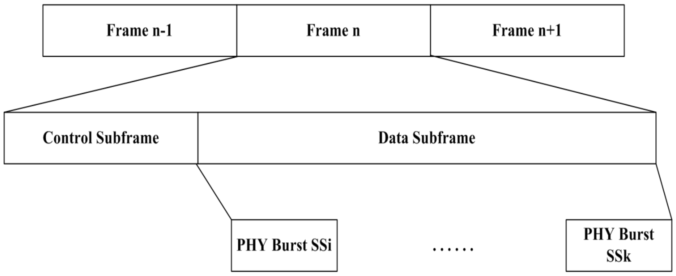


Fig. 1. Frame Structure of the IEEE 802.16 Mesh Mode

II. MESH MODE OF IEEE 802.16

First introduced in the IEEE 802.16a standard, the Mesh mode of IEEE 802.16 is included in the current version of the standard, IEEE 802.16-2004 [1]. SSs are called *mesh SS* (*MSS*) and BS is called *mesh BS* (*MBS*) in this mode. There are several differences between the PMP and Mesh modes of IEEE 802.16. All transmissions between two nodes (either a MSS and the MBS or two MSSs) are carried over one bidirectional link, which is established during the initialization of the new SS. These links are identified by 8-bit link identifiers (Link IDs). Unlike the PMP mode, there is no clear distinction between the downlink and uplink traffic in the frames of the Mesh mode. If a transmission is sent to a node closer to the MBS than the source node, it is uplink traffic, otherwise it is downlink traffic.

A. Frame Structure

The frame is divided into two parts in the Mesh mode (Figure 1). The first part is the control subframe, in which network configuration and scheduling messages are sent. The second part, the data subframe, consists of data bursts to and from MSSs and the MBS. The control subheader can be either a scheduling control subheader or a network control subheader. The requests and grants for transmissions are sent using the

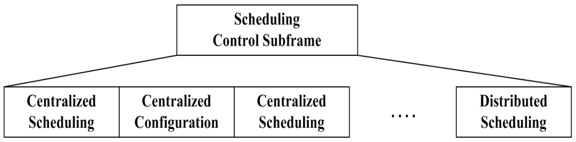


Fig. 2. Scheduling Control Subframe

scheduling control subframe (Figure 2). The second subframe is used less frequently (e.g. 1 network control subheader in 15 frames). If there are topology changes in the network (e.g. a node is down or a new node is introduced), the MBS is informed about these changes in this subframe by the network configuration and entry messages sent by MSSs. Additionally, the MBS informs MSSs about data subframe usage until the frame with the next network control subframe by sending the burst profiles (Figure 3).

B. Scheduling Mechanisms

There are three different scheduling methods in the Mesh mode: coordinated distributed scheduling, uncoordinated distributed scheduling, and centralized scheduling. In the distributed scheduling method, nodes use a three-way handshake scheme for traffic scheduling. Each node transmits its current schedule and its proposed schedule changes (i.e. requests) to its one-hop neighbors. If the destination nodes grant a request, they respond to the source node in one of the slots of the control subframe, which is also described in the request message. Finally, the source re-transmits the grant message to the destination for confirmation. The difference between the two distributed scheduling methods are the use of the control subframe for the scheduling messages. In the coordinated distributed scheduling, scheduling messages are sent in a collision-free manner whereas, the scheduling messages may collide in the uncoordinated distributed scheduling.

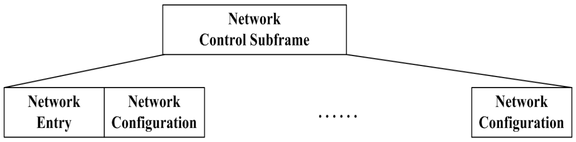


Fig. 3. Network Control Subframe

The centralized scheduling method is similar to the PMP mode. All the traffic in the network is handled by the MBS. Each MSS sends its request and relays the requests from its children to the MBS. The MBS generates a grant package according to these requests and sends it to the MSSs. MSSs receiving the grant packet relay this packet to their children. Thus, all nodes in the network know which node will transmit to which node in which time slot. Similar to the coordinated distributes scheduling, request messages are sent in a collision-free manner. In this paper, we use the centralized scheduling method as the scheduling method.

C. Default Mesh QoS (DMQoS) Mechanism in IEEE 802.16

When a node has packets to send to either other MSSs or the MBS, it sends a request packet in the control subframe using the mesh centralized scheduling message (MSH-CSCH message) to the MBS. The node sends one bandwidth request for each link it has and all requests belonging to that node are sent in one MSH-CSCH message. After receiving requests from all MSSs in the network, the MBS applies its traffic scheduler to these requests, including its own traffic requests. Based on the scheduler used in the MBS, these requests are granted wholly or partially. Then, the MBS broadcasts these grants in a MSH-CSCH message. A grant packet describes the data subframe usage of a frame. This data subframe description belongs to a frame after the frame that the grant is sent. In our model we select this grant delay as two MAC frames. Each MSS forwards this grant message to its children. However, these requests and grants include only the amount of data that a node can transmit. The MBS uses another message, the mesh configuration (MSH-CSCF) message, to specify the modulation, coding scheme, and portion of the frame used to transmit and receive data for each link. The MBS describes the usage of these channels via this broadcast message. The channel usage is summarized using 4-bit burst profiles, which in turn are declared in the network control subframe by the MBS. Based on the grant MSH-CSCH and MSH-CSCF messages, each node computes the usage of the whole data subframe and knows when to transmit and receive data.

The control messages are sent in a collision free manner. The MBS is informed about the topology in the network control subframe during system initialization. When there is a topology change in the network, the nearby nodes inform the MBS about the change in the next network control subframe. Since the MBS knows the topology of the network at a given time, it allocates the slots in the control subframe so that each node sends its requests and receives its grants without any collision.

However, traffic classification and flow regulation are left to upper layers in the Mesh mode of IEEE 802.16. There are no service or QoS parameters associated with a link in the Mesh mode. The MBS sends one grant information to each link in the network based on the requests. All packets originating from this node uses this aggregate grant values regardless of their QoS requirements.

III. PROPOSED QOS MECHANISM

A. QoS Mechanism in IEEE 802.16 PMP Mode

Unlike the Mesh mode of IEEE 802.16, a detailed QoS mechanism is described for the PMP mode. There are five service types specified and the request/grant mechanisms are different for each type. Each connection in the network uses one of these five scheduling services. *Unsolicited Grant Service* (*UGS*) supports real-time T1/E1 services and *Constant Bit Rate* (*CBR*) traffic. *Real Time Polling Service* (*rtPS)* supports real-time *Variable Bit Rate* (*VBR*) traffic. The third service, *non-Real Time Polling Service* (*nrtPS*) is used to carry non-real-time traffic. There is also a service type for *Best Effort* (*BE*) traffic. The fifth scheduling service is included to the standard with IEEE 802.16e. In [3], Lee *et al.* have shown that the former four scheduling services described in the

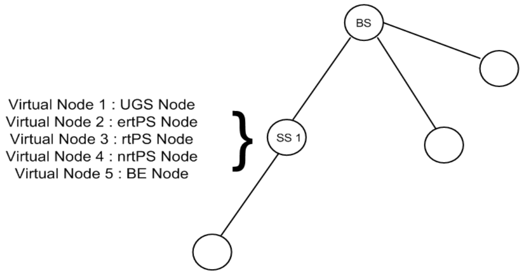


Fig. 4. Virtual Nodes

standard are not appropriate for services like VoIP. Addressing this issue, the latest standard of IEEE 802.16 has introduced the fifth scheduling service, the *Extended Real Time Polling Service* (*ertPS*).

A UGS connection declares its average traffic usage to the BS during connection establishment, and the BS allocates exactly that amount of bandwidth in each frame, even if the bandwidth is not utilized. The second scheduling service, rtPS, uses dedicated periodic slots in the uplink channel for sending its request to the BS. nrtPS connections also use dedicated periodic request slots. However, the period for the allocation of dedicated requests is much longer for nrtPS connections than rtPS connections. nrtPS connections may also use contention based time slots to send their requests to the BS. These contention slots are also used by the BE connections. The ertPS scheduling service uses a request/grant mechanism similar to the one used for UGS connections. The difference is that the allocated bandwidth can be decreased (and increased back again) based on the offered traffic.

B. Service Adaptive QoS (SAQoS)

The QoS mechanism designed for the the PMP mode of IEEE 802.16 can also be used in the Mesh mode. However, since all transmission between two nodes is managed by one link, this method cannot be applied in the Mesh mode directly. In the Mesh mode, each MSS is assigned a *node identifier (node ID)* upon connection establishment. In our solution, *Service Adaptive QoS (SAQoS)*, the MBS assigns five node IDs instead of one node ID to each MSS. These five virtual nodes represent the five scheduling classes explained above (Figure 4). Each one of these virtual nodes requests bandwidth individually, and the MBS handles these requests according to their scheduling services.

The first virtual node is used for UGS scheduling services. This virtual node requests bandwidth once after connection establishment and then MBS allocates the requested amount of bandwidth in each frame. The second virtual node is used for ertPS services. The request/grant mechanism used for this virtual node is similar to the one used for the UGS virtual node. However, unlike the UGS virtual node, the ertPS virtual node may send requests to the MBS after connection establishment to reduce and increase its allocated size up to its maximum sustained allocation limit. The third and fourth virtual nodes are used for rtPS and nrtPS services respectively. While both of them use the default request/grant messaging of the Mesh mode (with the CSCH messages), a nrtPS virtual node cannot send a request message in each frame. It can only send its requests in one frame in a given number of frames (nrtPS Poll Interval). The last virtual node is used for BE services. It can use a special collision-based slots in the scheduling control subheader to send its request messages to the MBS.

C. Fair Adaptive Base Station Scheduler (FABS)

As stated above, the MBS generates a grant message based on the requirements of each link in the request messages. However, the standard does not describe any scheduler for this grant generation process; it is left unstandardized for both the PMP and Mesh mode. There are a variety of BS schedulers in the literature. A *Call Admission Control* (*CAC*) mechanism and a BS scheduler is described in [4]. In this proposal, *Earliest Deadline First* (*EDF*) is used for rtPS connections and *Weighted Fair Queuing* (*WFQ*) is used for nrtPS connections. In [5], Jiang *et al.* developed another BS scheduler using the CAC mechanism proposed in [4]. Token buckets are used in this work to characterize the traffic flows. In [6], a *Weighted Round Robin* (*WRR*) scheduler is used for uplink bandwidth allocation in BS. The schedulers described above are developed for the PMP mode of IEEE 802.16. A comprehensive study about schedulers for the centralized scheduling the Mesh mode is presented in [7].

We have developed a BS scheduler for the centralized scheduling of the Mesh mode. We propose a *Fair Adaptive Base Station Scheduler (FABS)* that makes scheduling decisions based on each SS's current request and the grants given to all SSs in the network. Let r_i denote the current request of link i and tg_i denote the total grant given to the link i since the establishment of the link in bits. We calculate a normalization factor (nF) based on these total grant sizes with the Eq. 1 where n is the number of links in the network. A grant ratio is calculated for each link (gr_i) using Eq. 2. Finally, all links are sorted by their grant ratios in decreasing order. The link that received the least grant so far will be in the top of the list, whereas the link that received the highest grant will be in the end of the list. The BS starts allocating bandwidth to links (g_i) in this sequence, and traverse the list several times (BS pass count). In each pass it allocates bandwidth to links based on the Eq. 3, where $rFsize$ denotes the part of the frame not allocated to any links so far in bits.

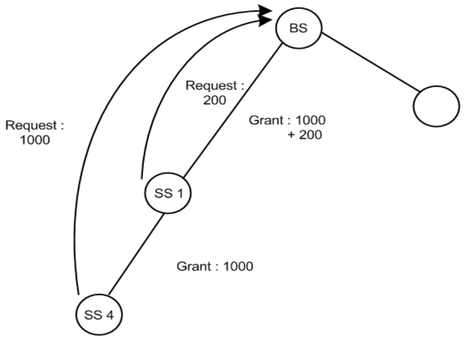


Fig. 5. Bandwidth Allocation to Uplink Traffic

$$nF = \sum_{i=1}^{n} \frac{1}{tg_1} \tag{1}$$

$$gr_i = \frac{\frac{1}{tg_1}}{nF} \tag{2}$$

$$allocBW_i = min(r_i, gr_i \cdot rFsize) \tag{3}$$

In the Mesh mode, nodes request bandwidth on a link basis. Thus, if the source and destination of a traffic has a hop count higher than one, for each hop a separate request must be sent to the MBS. As stated before, there is a few frame delay between the request and grant messages and this delay is multiplied by the number of hops a traffic need to reach its destination. In our model we assume that all MSSs communicate with the MBS. So, when our MBS allocates uplink traffic to a SS with a hop count two or more it also allocates that amount of bandwidth to each link the traffic uses to reach the MBS (Figure 5). The same allocation differentiation is valid for downlink traffic to SSs with hop count more than one. With this hop count addition, bandwidth allocation to links follow the Eq. 4.

$$\begin{aligned} allocBW_i = {} & min(r_i, gr_i \cdot rFsize) \\ & \cdot hopcount[src][dst] \end{aligned} \tag{4}$$

IV. SIMULATION SCENARIO AND PARAMETERS

In the simulations, we have used a topology that consists of seven MSSs: one MSS with three hops to the MBS, three MSSs with two hops, and three MSSs with one hops (Figure 6). We assume error free link conditions. WirelessMAN - OFDM PHY layer of IEEE 802.16 standard is used with a channel bandwidth of 20 MHz. The frame duration is 5 ms and large packets are fragmented with the use of the fragmentation mechanism of IEEE 802.16. ARQ and packing mechanisms are not used. In the simulations, the topology is fixed changes. Other simulations parameters are provided in Table I. The simulations are carried out using OPNET 11.5. Both of the simulations are run for 10 minutes.

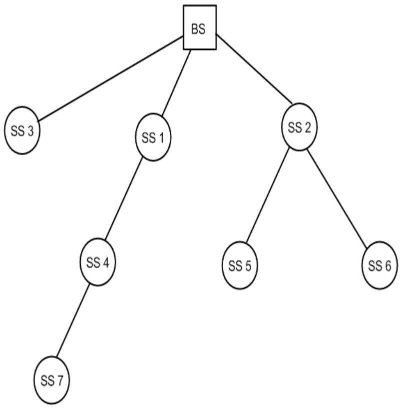


Fig. 6. Simulation Topology

TABLE I

SIMULATION PARAMETERS

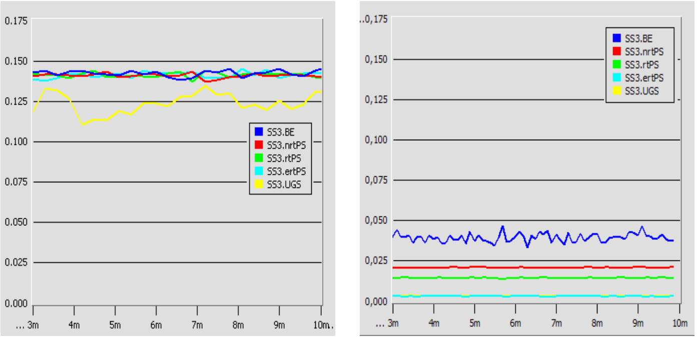
Simulation Parameter	Value
Channel Bandwidth	20 MHz
Frame Duration	5 ms
Modulation Scheme	64-QAM
FEC Rate	7/8
Aggregate Data Rate	74 Mbps
UGS traffic per SS	0.8 Mbps
ertPS traffic per SS	1 Mbps
rtPS traffic per SS	1 Mbps
nrtPS traffic per SS	1 Mbps
BE traffic per SS	1 Mbps
UGS traffic BS	3.75 Mbps
ertPS traffic BS	6 Mbps
rtPS traffic BS	6 Mbps
nrtPS Time traffic BS	6 Mbps
BE traffic BS	6 Mbps

V. SIMULATION RESULTS

To present the results of the simulations one MSS is selected from each hop level. In Figure 7, our SAQoS mechanism is compared against the default Mesh mode QoS mechanism. It is apparent in the figure that SAQoS outperforms the default mechanism in all classes. Especially for the UGS and ertPS services, the delay is improved by a factor of 10.

The case of the two-hop SSs is represented for SS5 in Figure 8. As in one-hop SSs, SAQoS outperforms the default mechanism in the UGS and ertPS services again by a factor of 10. The rtPS and nrtPS services are still better than the default mechanism, though not as good as the one-hop level. However, as a result of the tradeoff SAQoS performs worse then the default mechanism for the BE service.

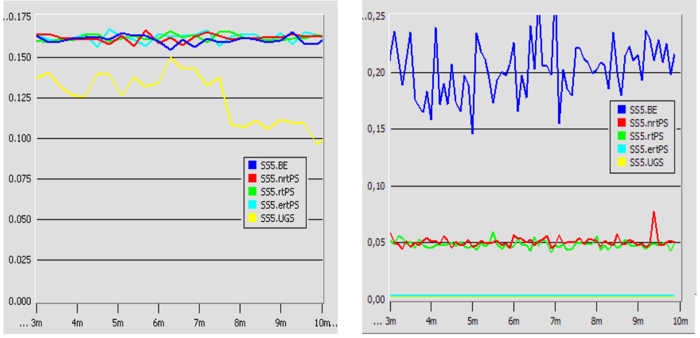
Figure 9 depicts the case of three-hop SSs for SS7. As seen in the figure, SAQoS outperforms DMQoS in the UGS and ertPS, but not in the others. Thus, SAQoS allows the use of real-time and multimedia applications even for three-hop SSs, but low priority services suffer. From this result, we conclude that it is not reasonable to run low priority applications at the SSs beyond the second level in the Mesh mode of IEEE 802.16 if one favors real-time and multimedia applications.



(a) DMQoS

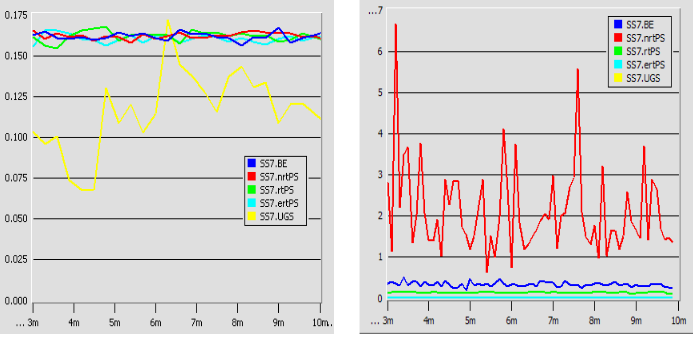
(b) SAQoS

Fig. 7. Service delays of SS3



(a) DMQoS (b) SAQoS

Fig. 8. Service delays of SS5



(a) DMQoS (b) SAQoS

Fig. 9. Service delays of SS7

VI. CONCLUSION & FUTURE WORK

In this paper, we have proposed a QoS mechanism, SAQoS, for the Mesh mode of IEEE 802.16. We have also introduced a simple scheduling algorithm for the BS. Simulation results show that the default mesh QoS mechanism, DMQoS, introduces a delay of at least 100 ms from MSS to MBS for the UGS and ertPS services. Considering also the delay from the MBS to the correspondent node, it is apparent that DMQoS is not suitable for real-time and multimedia services. Using SAQoS, we are able to limit this delay to 5 ms. However, we observe that BE service suffer beyond the second hop level. This is mainly due to the fact that lower level SSs suffer from contention at all levels above.

As a future work, we will also consider direct communication between MSSs in the Mesh mode. We also plan to extend our work to MSs.

ACKNOWLEDGEMENT

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