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A NOVEL QOS GUARANTEE MECHANISM IN IEEE 802.16 MESH NETWORKS

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Abstract. IEEE 802.16 defines perfect QoS (Quality of Service) guarantee mechanism in PMP (Point to Multi-Point) mode and denotes mesh mode cannot provide this capability. To resolve this problem of WiMAX Mesh network, a novel QoS guarantee mechanism including protocol process and minislot allocation algorithm is proposed. This mechanism uses existing service classes in original standard. Protocol processes that manage dynamic service flow are defined. WiMAX MAC layer is re-designed to support service classification in mesh mode. Using extended distributed scheduling messages, the delivery method of dynamic service management messages in WiMAX mesh networks is implemented. Minislot allocation algorithm is given to support data scheduling of various services. Service establishment time is analyzed in this paper. The simulation result shows that the mechanism can provide QoS in WiMAX mesh networks effectively.

Keywords: Worldwide interoperability for microwave access, wireless mesh networks, quality of service, IEEE 802.16

Mathematics Subject Classification 2000: 68M11

1 INTRODUCTION

WiMAX (Worldwide Interoperability for Microwave Access) system provides high-speed, wide area broadband wireless access service. Compared to the IEEE 802.11 system, IEEE 802.16 standard defines the perfect QoS (Quality of Service) guarantee mechanism. IEEE 802.16-2004 standard gives the definition of four types of services, UGS (Unsolicited Grant Service), rtPS (Real-Time Polling Service), Non-Real-Time Polling Service (nrtPS) and BE (Best Effort) [1]. These services are supported by dynamic services management messages, such as DSA (Dynamic Service Addition), DSC (Dynamic Service Change), DSD (Dynamic Service Deletion).

IEEE 802.16-2004 defines two types of network topology, PMP (Point to Multi-Point) and mesh [2]. IEEE 802.16m defines the multi-hop relay mode which has some similar characters with mesh mode. The WiMAX system under mesh mode has better throughput and greater coverage [3-6]. Unfortunately, IEEE 802.16-2004 standard denotes explicitly that WiMAX system under mesh mode cannot provide QoS guarantee though WiMAX system under PMP mode has perfect QoS guarantee capability; but the capability on QoS guarantee is necessary for WiMAX mesh network when the WiMAX system is employed in practice. For this purpose we develop a novel QoS guarantee mechanism for WiMAX mesh networks.

Though the IEEE 802.16 standard defines perfect QoS guarantee mechanism under PMP mode at MAC layer, the scheduler and admission control mechanisms are still left to researchers and manufacturers [7-10]. Most of these researches focus on the QoS guanantee in PMP mode.

With the development of WiMAX network, network topologies became one of important research areas. The earlier research achievement on the performance of WiMAX mesh network is given by Min Cao [11]. His paper points out that WiMAX mesh networks cannot provide effective QoS guarantee. Schwingenschlogl [12] analyzed the WiMAX mesh network's performance of real-time capabilities of coordinated centralized scheduling and found a similar conclusion in the original IEEE 802.16 standard.

Many scholars are making efforts to solve QoS problem in WiMAX mesh networks. A proposal submitted to IEEE 802.16 workgroup gives a QoS strategy for centralized control in 802.16 mesh network [13]. This strategy uses the original dynamic service management messages in IEEE 802.16-2004 and constructs a QoS guarantee framework for centralized management; but the proposal does not give the performance verification. Reference [14] tried to set the thresholds for the different service priorities based on network congestion statement. When the network is under heavy load, high-priority service can achieve more resources to ensure that high-priority service gains more network bandwidth and lower delay. However, the author does not give the method how the threshold is set. Moreover, this method does not take into account the specific needs of network resources for service level parameters. Reference [15] gives a comprehensive QoS control framework used in mesh mode and PMP mode. Through the use of the resources reservation, the method can establish a rapid and effective QoS flow. However, frame structure and data transmission mechanism are completely different between PMP mode and mesh mode in IEEE 802.16-2004 standard. QoS architecture should be designed and implemented carefully for the special need of mesh mode. Najah investigates IEEE 802.16 mesh schedulers and points out that WiMAX mesh schedulers lack the capability to provide fair, efficient and QoS-guaranteed operation currently [16].

2 OVERVIEW OF IEEE 802.16 MESH NETWORK

IEEE 802.16 Mesh mode supports centralized and distributed scheduling. Both the coordinated and uncoordinated distributed scheduling employ a three-way handshaking using MSH-DSCH (Mesh Mode Schedule with Distributed Scheduling) message.

MSH-DSCH message is always broadcasted to the neighborhood. Each MSS can get the scheduling information of its neighborhood. The collision may occur among MSH-DSCH messages from different MSSs while uncoordinated distributed scheduling is employed. There is no collision among MSH-DSCH from different MSSs using coordinated distributed scheduling. MSS which sends request message should wait enough minislots for grant message from the receiver so that the collision can be avoided. When the requester receives the grant messages, it replies with another grant message as confirmation message. In this process the requester's neighbors know the allocated minislots and will determine which minislots they will employ in the future. There are two important parameters using distributed scheduling, the next MSH-NCFG/MSH-DSCH eligibility interval *Next_Xmt_MX* and the holdoff exponent *Xmt_Holdoff_Exponent*. The two parameters will be described as follows:

- *Xmt_Holdoff_Exponent*: The transmit holdoff time *Xmt_Holdoff_Time* is the number of MSH-NCFG/MSH-DSCH transmission opportunities after next transmit time that this MSS is not eligible to transmit MSH-NCFG/MSH-DSCH packets.
$$Xmt\_Holdoff\_Time = 2^{(Xmt\_Holdoff\_Exponent+4)}$$
- *Xmt_Holdoff_Time* is defined as:
$$2^{(Xmt\_Holdoff\_Exponent)} \times Next\_Xmt\_MX < Next\_Xmt\_Time \\ \leq 2^{(Xmt\_Holdoff\_Exponent)} \times (Next\_Xmt\_MX + 1).$$

Each MSS should select its *Xmt_Holdoff_Time* using election algorithm defined by the standard. According to election algorithm, the next slot after *Xmt_Holdoff_Time* should be set to the first competing slot of the next transmission opportunity.

3 ARCHITECTURE OF IEEE 802.16 MESH NETWORKS WITH QOS GUARANTEE

We pay attention to IEEE 802.16-2004 distributed scheduling mechanism for providing QoS support. Our scheme uses the existing service classes and dynamic service management messages. Relevant protocol processes are shown in Figure 1.

3.1 Protocol Processes

When source node needs to send data, it will send DSx-REQ to the next hop node (MSS n) first according to their own service requirements to initialize QoS request.

QoS Authentication Module (AM) of Node N will determine its own QoS ability to accept or refuse the request. In Figure 1 a), the source node initiates the service management request by sending DSx-REQ. MSS n receives DSx-REQ request from the source node, and judges whether its own ability meets the request. If local resource can satisfy the request, it shall send DSx-RVD to source node to confirm this operation and to reserve resources. At the same time, QoS request should be sent to the next hop by MSS n. After the destination node receives DSx-REQ from its neighboring nodes finally, it should verify whether it can meet the request. If local resource in the destination node satisfies the demand, the destination node should send DSx-RSP to the adjacent node to respond to the request of the data flow. DSx-RSP is relayed to the source node hop by hop. DSx-ACK is corresponded by the source node to the destination node. While nodes receive DSx-ACK, the service flow is established. If the intermediate nodes or destination node refuse the DSx-REQ, DSx-RSP should be sent back to the source node and service flow failures (Figure 1 b)). Of course, after the nodes send request, timers for DSx-REQ and DSx-RSP are necessary. If the source node does not receive DSx-RVD in a certain time after DSx-REQ is sent, DSx-REQ timer overtimes. If the source node does not receive DSx-RSP in a certain time after receiving DSx-RVD, DSx-RSP timer overtimes. When timers overtime, service flow will be degraded or closed (Figure 1 c)). If the source node wants to stop service flow, it should initiate a delete process to its next hop node and DSD-REQ is be relayed to the destination node hop by hop. Each node in the route should reply a DSD-RVD to inform the last node that DSD-REQ is received correctly and release resource (Figure 1 d)).

After expanding the reserved field of DSCH message in control sub-frame, we can send DSx in control sub-frame. Extended DSCH message is shown in Figure 2. In the original standards, reserved field is set to "00". When DSCH message includes QoS management information, the "reserved" field is set to "11".

Admission control mechanism can refer to these solutions used in PMP mode. The schemes are given in [17–18].

3.2 Minislot Allocation Algorithm

In the IEEE 802.16-2004 distributed coordination mechanism, each packet's transmission needs nodes competition, including the transmission opportunity of control subframe and competition of data minislot resource. The mesh mode in the original standard is not connection-oriented and is unable to provide effective QoS guarantee to service flow. The proposed QoS structure can provide connection-oriented service quality guarantee. Transmission of data packets is based on different priorities to implement different management plans such as UGS, rtPS. nrtPS and BE. According to the characteristics of each type of service, MAC frame can be divided into reserved and competitive minislots (as shown in Figure 3). Reserved minislots are used for UGS, nrtPS and rtPS. This part of minislots is reserved at the beginning of service flow establishment. The reserved minislots do not participate in the competition during the data packet transmission process. When the service flows are

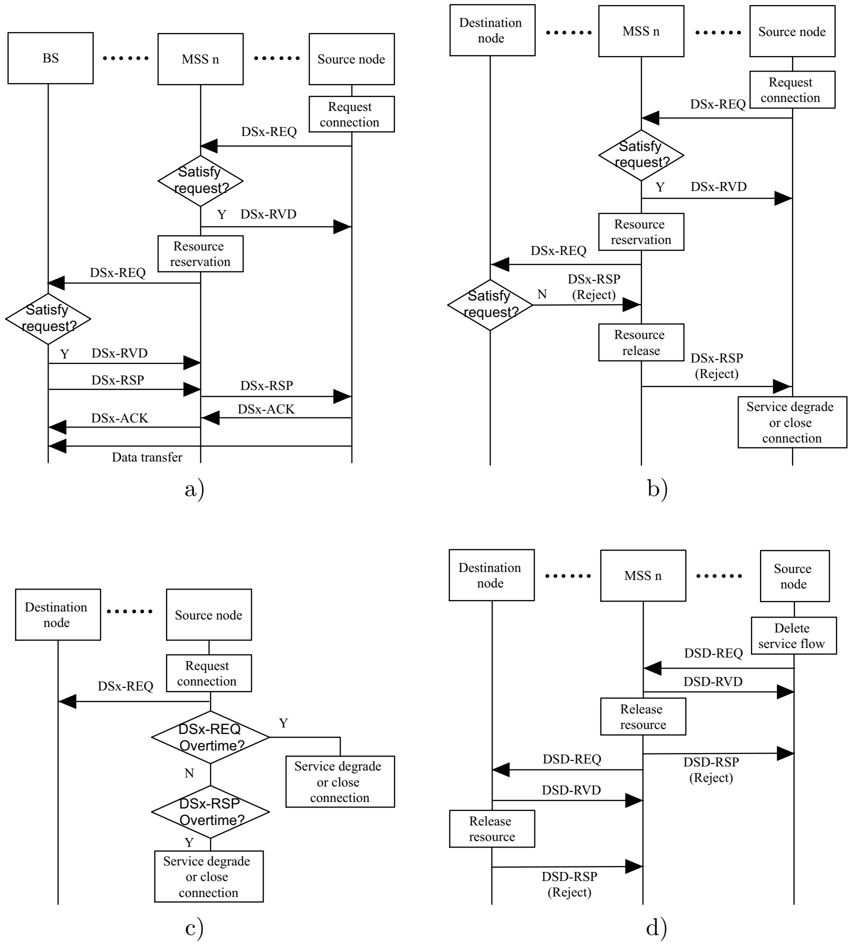


Fig. 1. Service flow management process; a) Succeed in establishing service flow, b) Fail to establish service flow (not enough QoS resource in the route), c) Fail to establish service flow (request overtime), d) Delete service flow

deleted or fail in establishing, the resource can be released for re-allocation. BE and nrtPS use the normal request/authorize mechanism to compete opportunities.

3.2.1 Scheduling for UGS

Fixed amount of bandwidth is assigned to UGS. Bandwidth request message is no longer sent before data transmission. The UGS is designed to support real-time data streams consisting of fixed-size data packets at periodic intervals, such as T1/E1 and Voice over IP without silence suppression. The mandatory QoS service flow parameters for this scheduling service are Maximum Sustained Traffic Rate

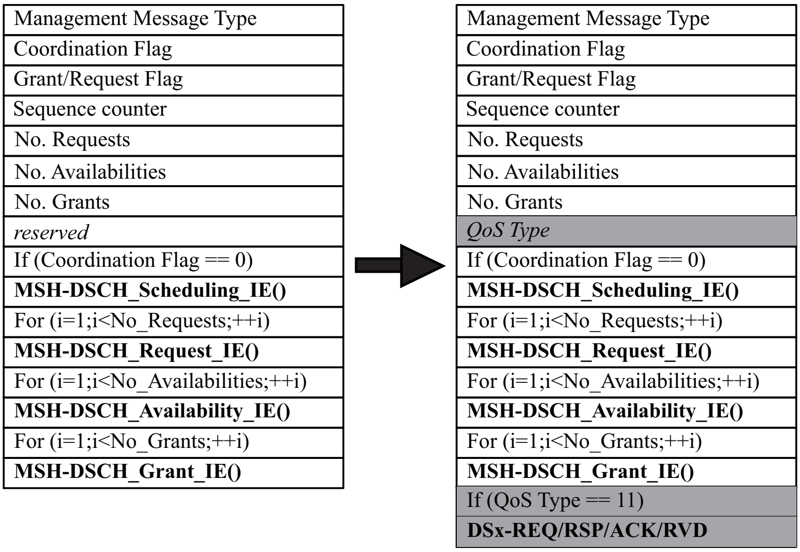


Fig. 2. Extended MSH-DSCH message

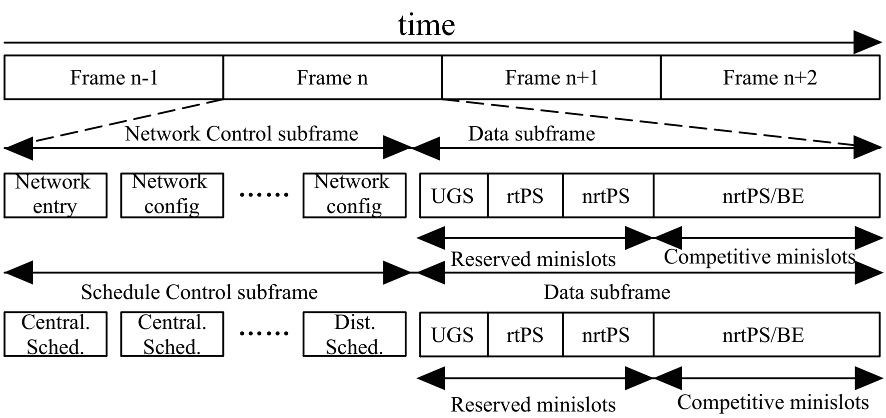


Fig. 3. IEEE 802.16 Mesh frame structure with differentiated service function

$R_{\max}$ (bps), Maximum Latency $D_{\max}$ (second), Tolerated Jitter J (second), and Request/Transmission Policy. Assume that MAC frame length T (second), size of each minislot is L (bytes). There are 256 minislots in a frame. After the node receives DSx-REQ, the reserved minislot number is calculated as follows:

$$N_{\text{minislot}}^{UGS} = \text{ceil}\left(\frac{R_{\max} \times T}{8L}\right). \quad (1)$$

UGS is the highest level service and has the highest priority. The reserved minislots do not participate in the competition of distributed scheduling.

3.2.2 Scheduling for rtPS

The rtPS is designed to support real-time data streams consisting of variable size data packets that are issued at periodic intervals, such as moving pictures experts group (MPEG) video. The mandatory QoS service flow parameters for this scheduling service are Minimum Reserved Traffic Rate $R_{\min}$ (bps), Maximum Sustained Traffic Rate $R_{\max}$ (bps). Maximum Latency $D_{\max}$ (second), and Request/Transmission Policy. Assume that average data rate of VBR service is $R_i(bps)$; then the reserved minislot number is

$$N_{\text{minislot}}^{rtPS} = \text{ceil}\left(\frac{R_i \times T}{8L}\right). \tag{2}$$

3.2.3 Scheduling for nrtPS

The nrtPS is designed to support delay-tolerant data streams consisting of variable size data packets for which a minimum data rate is required, such as FTP. The mandatory QoS service flow parameters for this scheduling service are Minimum Reserved Traffic Rate $R_{\min}$ (bps). Maximum Sustained Traffic Rate $R_{\max}$ (bps), Traffic Priority, and Request/Transmission Policy. The reserved minislot number is

$$N_{\text{minislot}}^{nrtPS} = \text{ceil}\left(\frac{R_{\min} \times T}{8L}\right). \tag{3}$$

The scheduler in MAC layer can assure the minimum reserved traffic rate. The redundant data rate ($R_{\max} - R_{\min}$) of this service flow can adopt the competition mechanism in the original standard to gain the reserved minislots.

3.2.4 Scheduling for BE

The BE service is designed to support data streams for which no minimum service level is required and therefore may be handled on a space-available basis. For this type of service, the competition mechanism in the original standard can be used.

In reserved minislots, packet aggregation and fragment technology are adopted. Packet aggregation makes several packets to a larger packet and fragment makes larger packet to smaller packets whose size is suitable for minislot transmission.

3.3 Service Classification Design

IEEE 802.16 system under mesh mode should provide service classification capability first so that the different service can achieve different QoS guarantee mechanism. Here we carry out a service classification solution in our simulation platform similar to that in reference [19]. The classifier in IEEE 802.16 MAC layer is re-designed.

When a MSS receives the MSH-DSCH including grant IE (Information Element), request IE and available IE from its neighbor, it will differentiate the bandwidth request(s) and memorize it (them) in the corresponding neighbor node information. The neighbor node information contains mainly the neighbor's request and its next transmit time. The receiver should count the reserved and competitive minislots, produce a new grant IE and broadcast to its neighborhood.

4 ANALYSIS AND SIMULATION

4.1 Service Flow Establish Time Analysis

The scheduling mechanism of control subframe and data subframe is individual. The scheduling mechanism of control subframe is specified by IEEE 802.16 standard and that of data subframe should be solved by manufacturer. The model of IEEE 802.16 mesh network is described as follows.

- Assume the number of MSSs in the network is N.
- Let M_k be the set of the neighbor nodes two hops around node k and N_k the node number of M_k.
$$N_k = |M_k|$$
- M_k^{unknown} denotes the set of nodes whose scheduling information is unknown in M_k. Correspondingly, M_k^{known} denotes the set of nodes whose scheduling information is known in M_k.

$$N_k^{\text{unknown}} = \left|\mathrm{M}_k^{\text{unknown}}\right|$$

$$\mathrm{M}_k^{\text{known}} = \mathrm{M}_k - \mathrm{M}_k^{\text{unknown}}$$
$$N_k^{\text{unknown}} = \left|\mathrm{M}_k^{\text{unknown}}\right|$$

- $k = 1, 2, 3, \ldots, N$ denotes the holdoff exponent of node k. $H_k = 2^{x_k+4}$ is transmit holdoff time, $V_k = 2^{x_k}$ is the eligibility interval length.
- S_k denotes the number of slots in which node k fails the competition before it wins, which is a random variable.

The interval between successive transmission opportunities is $\tau_k = H_k + S_k$.

We can give the following conclusions from reference [11]:

Conclusion 1. Assume all the nodes are 1-hop away from each other, holdoff exponents of nodes are the same, $x_1 = x_2 = \ldots = x_N = x$.

$$E(S_1) = E(S_2) = \cdots = E(S_N) = E(S)$$

$$E(S) = (N-1)\frac{2^x + E(S)}{2^{x+4} + E(S)} + 1$$

Then we can give the interval between successive transmission opportunities,

$$\tau_k = H_k + E(S) = 2^{x+4} + E(S).$$

Conclusion 2. If holdoff exponents of nodes are different, assume all the nodes are 1-hop away from each other,

$$E(S_k) = \sum_{j=1, j\neq k, x_j \geq x_k}^{N} \frac{2^{x_j} + E(S_k)}{2^{x_j+4} + E(S_j)} + (\sum_{j=1, j\neq k, x_j < x_k}^{N} 1) + 1, \quad k = 1, 2, \ldots, N.$$

Conclusion 3. If holdoff exponents of nodes are different, all the nodes are not 1-hop away from each other which means some scheduling information of some nodes are unknown:

$$E(S_k) = \sum_{j=1, j\neq k, x_j \geq x_k}^{N_k^{\text{known}}} \frac{2^{x_j} + E(S_k)}{2^{x_j+4} + E(S_j)} + \left(\sum_{j=1, j\neq k, x_j < x_k}^{N_k^{\text{known}}} 1 \right) + N_k^{\text{unknown}} + 1, k = 1, 2, \ldots, N.$$

Collision domain exists in IEEE 802.16 mesh network just like in IEEE 802.11 mesh network [20].The i^{th} link's collision domain given by Jangeun Jun is that the set of the i^{th} link and links which keep silence to ensure the transmission to succeed. The maxium number of minislots is 256 in a collision domain. The maxium throughput of node is determined by the scale of collision domain and by the data rate of data subframe.

Assume the node n_0 wants to establish service flow which may be UGS, rtPS or nrtPS and the distance between node n_0 and the destination is h hops. The nodes along the route are $n_1, n_2, \cdots, n_h$. The service flow establish time includes DSx-REQ transmission time $T_{REQ}^{i,i+1}(i = 0, 1, \ldots, h-1$ and DSx-RSP transmission time $T_{RSP}^{i,i+1}(i = 0, 1, \ldots, h-1$ between node i to node$(i+1)$. Thus, the service flow establish time is

$$T_{\text{delay}} = \sum_{i=0}^{h} T_{REQ}^{i,i+1} + \sum_{i=0}^{h} T_{RSP}^{i+1,i}. \tag{4}$$

To estimate T_{delay}, we calculate the service flow establish time from Mesh SS 5 to Mesh BS shown in Figure 4.

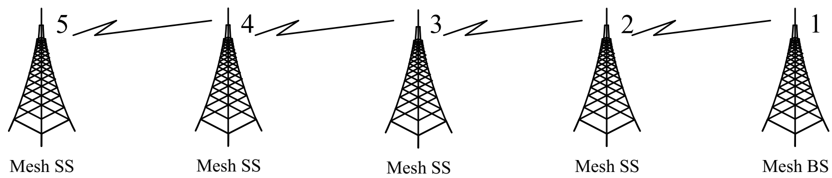


Fig. 4. IEEE 802.16 mesh network (Chain topology)

Assume the holdoff exponent of these mesh node in Figure 4 is the same, $x_5 = x_4 = x_3 = x_2 = x_1 = x$. If $x = 0$,

$$
\begin{aligned}
E(S_5) &= \frac{2^0+E(S_5)}{2^{0+4}+E(S_4)} + \frac{2^0+E(S_5)}{2^{0+4}+E(S_3)} + 1\\
E(S_4) &= \frac{2^0+E(S_4)}{2^{0+4}+E(S_5)} + \frac{2^0+E(S_4)}{2^{0+4}+E(S_3)} + \frac{2^0+E(S_4)}{2^{0+4}+E(S_2)} + 1\\
E(S_3) &= \frac{2^0+E(S_3)}{2^{0+4}+E(S_5)} + \frac{2^0+E(S_3)}{2^{0+4}+E(S_4)} + \frac{2^0+E(S_3)}{2^{0+4}+E(S_2)} + \frac{2^0+E(S_3)}{2^{0+4}+E(S_1)} + 1\\
E(S_2) &= \frac{2^0+E(S_2)}{2^{0+4}+E(S_4)} + \frac{2^0+E(S_2)}{2^{0+4}+E(S_3)} + \frac{2^0+E(S_2)}{2^{0+4}+E(S_1)} + 1\\
E(S_1) &= \frac{2^0+E(S_1)}{2^{0+4}+E(S_3)} + \frac{2^0+E(S_1)}{2^{0+4}+E(S_2)} + 1
\end{aligned}
$$

Similarly we can get the values of $E(S_k)(k = 1,2,3,4,5)$ while $x = 1,2,3,4$. The service flow establish time is

$$T_{\text{delay}} = 2\sum_{j=1}^{5}(E(S_j)+H_j) = 2\sum_{j=1}^{5}\Big(E(S_j)+2^{(x+4)}\Big).$$

Detailed results are shown in Table 1. Service flow establish time depends on the value of holdoff exponent. The larger the value of holdoff exponent, the more time the process will consume. While the holdoff exponent is zero, the process is the fastest.

	$x=0$	$x=1$	$x=2$	$x=3$	$x=4$
$E(S_1)$	1.19	1.14	1.10	1.07	1.07
$E(S_2)$	1.42	1.30	1.24	1.21	1.20
$E(S_3)$	1.61	1.41	1.33	1.29	1.27
$E(S_4)$	1.42	1.30	1.24	1.21	1.20
$E(S_5)$	1.19	1.14	1.10	1.07	1.07
H	16	32	64	128	256
$T_delay)$	173.64	332.58	652.01	1291.72	2571.61

Table 1. Service flow establish time analysis result (minislot)

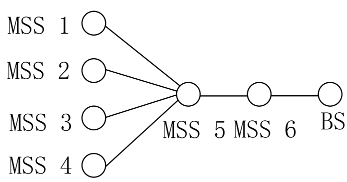


Fig. 5. The simulation network topology

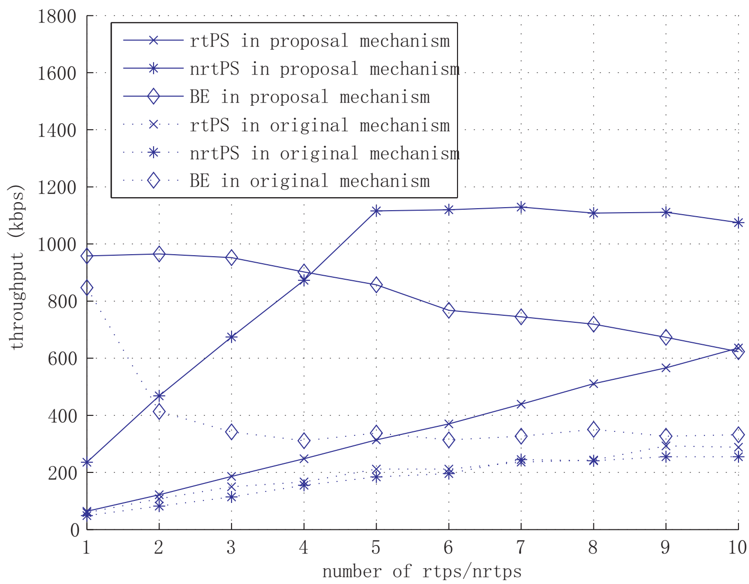
Simulation parameters	Value
Frame Time	20 ms
XmtHoldExponent	0, 2, 4
L	125 bytes
$R_{\max}$ (UGS)	2 Mbps
R_i (rtPS)	64 kbps
$R_{\min}$ (nrtPS)	50 kbps
$R_{\max}$ (nrtPS)	250 kbps
Simulation Time	60 s

Table 2. Simulation parameters

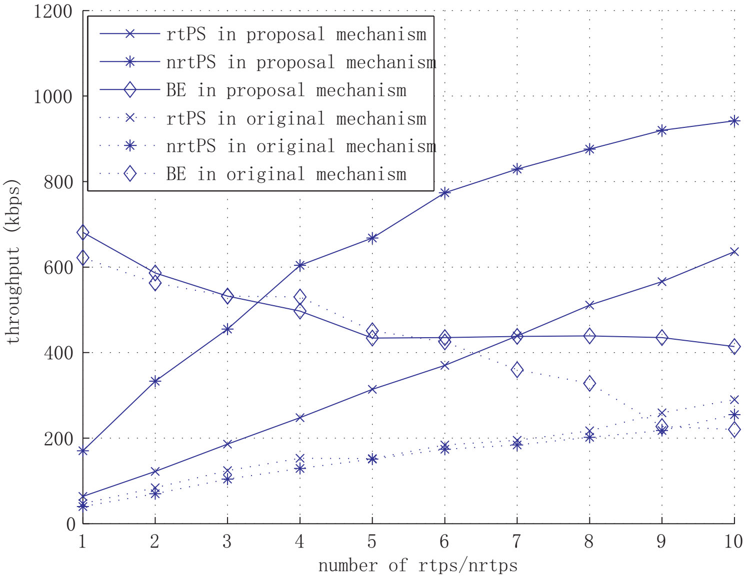
4.2 Throughput Analysis

We developed a simulation platform for WiMAX mesh network based NS2 simulator [21]. The platform implements coordinated scheduling algorithm and dynamic service management under the Mesh mode of IEEE 802.16-2004.

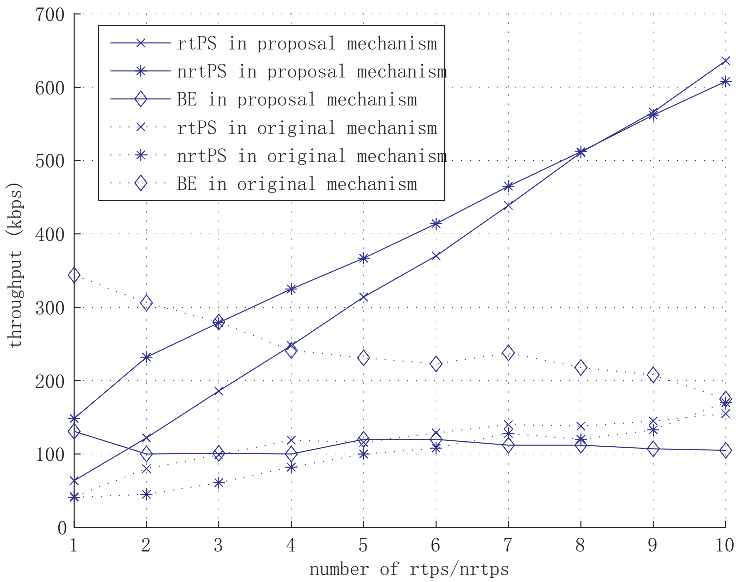
The simulation network topology is shown in Figure 5. MSS 1/2/3/4 have different priority service including T1/E1 (UGS), VoIP (rtPS), FTP (nrtPS) and HTTP (BE) which will be sent to BS. MSS 5 and MSS 6 act as relay stations. The maximum data transmission rate over air link is 20 Mbps. Furthermore, $R_{\max}$ (bps) of UGS in MSS 1 is 2 Mbps and reserved minislots per UGS flow are 40. $R_{\min}$ (bps)



a)



b)



c)

Fig. 6. Throughput of different priority service; a) Holdoff exponent is 0, b) Holdoff exponent is 2, c) Holdoff exponent is 4

of rtPS in MSS 2 is 64 kbps and reserved minislots per rtPS flow are 2. The $R_{\min}$ (bps) of nrtPS in MSS 3 is 50 kbps, $R_{\max}$ (bps) of rtPS in MSS 3 is 250 kbps and reserved minislots per rtPS flow are 1. MSS 4 originates BE service.

The simulation parameters are shown in Table 2. Holdoff exponents are set to 0, 2, 4, respectively.

Assume that BE originated from MSS 4 is 1Mbps. The number of rtPS from MSS 2 and nrtPS from MSS 3 increase from 1 to 10. Figure 6 gives throughput which BS received from MSS 2, MSS 3 and MSS 4. To compare the proposal mechanism to the mechanism in the original standard, we give the simulation results using original WiMAX mesh mechanism. From these figures, we can find that throughput of rtPS which have higher priority can increase linearly. When the network is under heavy load, throughput of nrtPS can keep a higher value and throughput of BE decreases quickly. Throughput of different services including high priority and low priority service cannot achieve guarantee. Original standard does not differentiate service class and all the service data competes the minislots fairly. It should be noted that the throughput using original WiMAX mesh network is much lower than the proposed mechanism because holdoff exponent and minislot scheduling are important factors of throughput performance [10, 16, 22–24]. How to improve the throughput of 802.16 mesh network is out of the scope of this paper. In spite of the network throughput being different using different holdoff exponents, the high priority services can keep its QoS guarantee.

5 CONCLUSION

IEEE 802.16-2004 standard Mesh mode lacks QoS guarantee mechanisms. This hinders the development and promotion of the technology. We investigate the IEEE 802.16 protocol stack and distributed scheduling algorithms to provide QoS support. A new mechanism including protocol process, minislot allocation and service classifier is proposed. The experiment based on NS2 simulation platform shows the validity of the proposed mechanism.

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REFERENCES

[1] Cicconetti, C.—Lenzini, L.—Mingozzi, E. et al.: Quality of Service Support in IEEE 802.16 Networks. IEEE Network, Vol. 20, 2006, No. 2, pp. 50–55.

[2] PedroFrancisco, R. R.: Investigation of IEEE Standard 802.16 Medium Access Control (MAC) layer in Distributed Mesh Networks and comparison with IEEE 802.11 Ad-Hoc Networks. Sweden, Linkoping Institute of Technology, 2006.

[3] Fu, I. K.–Sheen, W. H.—Hsiao, C. L.–Tseng, C. C.: Throughput Improvement with Relay-augmented Cellular Architecture. Contribution of IEEE 802.16 Broadband Wireless Access Working Group: IEEE C80216mmr-05/008, availaible on: `http://ieee802.org/16/`.

[4] Fu, I.-K.–Sheen, W.-H.–Hsiao, C.-L. et al.: System Performance of Relay-based Cellular Systems in Manhattan-like Scenario. Contribution of IEEE 802.16 Broadband Wireless Access Working Group: IEEE C80216mmr-05/041, availaible on: `http://ieee802.org/16/`.

[5] Fu, I.-K.—Sheen, W.-H.—Hsiao, C.-L.—Tseng, C. C.: Reverse Link Performance of Relay-based Cellular Systems in Manhattan-like Scenario. Contribution of IEEE 802.16 Broadband Wireless Access Working Group: IEEE C80216mmr-06/004, availaible on: `http://ieee802.org/16/`.

[6] Tao, J.—Liu, F.—Zeng, Z.—Lin, Z.: Throughput Enhancement in WiMax Mesh Networks Using Concurrent Transmission. Wireless Communications, Networking and Mobile Computing 2005, Wuhan, China, September 2005, Proceedings, Vol. 2, pp. 871–874.

[7] Alavi, H. S.—Mojdeh, M.—Yazdani, N. A.: Quality of Service Architecture for IEEE 802.16 Standards. Asia-Pacific Conference on Communications 2005, Perth, Western Australia, 03–05 October 2005, pp. 249–253.

[8] Wongthavarawat, K.—Ganz, A.: Packet Scheduling for QoS Support in IEEE 802.16 Broadband Wireless Access Systems. International Journal of Communication Systems, 2003, pp. 81–96.

[9] Sun, J.–Yao, Y.—Zhu, H.: Quality of Service Scheduling for 802.16 Broadband Wireless Access Systems. IEEE 63rd Vehicular Technology Conference, 2006, VTC 2006-Spring, Melbourne, Australia, Vol. 3, 7–10 May 2006, pp. 1221–1225.

[10] Chakchai, S.-I.—Jain, R.—Tamimi, A.-K.: Scheduling in IEEE 802.16e Mobile WiMAX Networks: Key Issues and a Survey. IEEE Journal on Selected Areas in Communications, Vol. 27, 2009, No. 2, pp. 156–171.

[11] Cao, M.—Ma, W.—Zhang, Q.—Wang, X.—Zhu, W.: Modelling and Performance Analysis of the Distributed Scheduler in IEEE 802.16 Mesh Mode. Proceedings of the 6th ACM International Symposium on Mobile Ad Hoc Networking and Computing, USA, May 2005, pp. 78–89.

[12] Schwingenschlogl, C.—Dastis, V.—Mogre, P. S. et al.: Performance Analysis of the Realtime Capabilities of Coordinated Centralized Scheduling in 802.16 Mesh Mode. IEEE 63rd Vehicular Technology Conference, 2006, VTC 2006-Spring, Melbourne, Australia, 7–10 May 2006, Vol. 3, pp. 1241–1245.

[13] Rath, K.—Kotecha, L. et al.: Scalable Connection Oriented Mesh Proposal. IEEE 802.16 Broadband Wireless Access Working Group: IEEE C80216d-03/18, availaible on: `http://ieee802.org/16/`.

[14] Liu, F.—Zeng, Z.—Tao, J. et al.: Achieving QoS for IEEE 802.16 in Mesh Mode. 8^{th} International Conference on Computer Science and Informatics, Salt Lake City, Utah, USA, July, 2005.

[15] Chen, J.—Jiao, W.—Guo, Q.: An Integrated QoS Control Architecture for IEEE 802.16 Broadband Wireless Access Systems. Global Telecommunications Conference 2005, St. Louis, Missouri, 28 November–2 December 2005, Vol. 6, 6 pp.

[16] Abu Ali, N. A.—Taha, A.-E. M.—Hassanein, H. S.—Mouftah, H. T.: IEEE 802.16 Mesh Schedulers Issues and Design Challenges. IEEE Network, Vol. 22, 2008, No. 1, pp. 58–65.

[17] Wang, H.—He, B.—Agrawal, D. P.: Admission Control and Bandwidth Allocation above Packet Level for IEEE 802.16 Wireless MAN. Proceedings of 12^{th} International Conference on, Parallel and Distributed Systems, 2006, Minneapolis, Minnesota, USA, 12–15 July 2006, Vol. 1, 6 pp.

[18] Wang, H.—Li, W.—Agrawal, D. P.: Dynamic Admission Control and QoS for 802.16 Wireless MAN. 2005 Wireless Telecommunications Symposium, Pomona, California, April 28–30, 2005, pp. 60–66.

[19] Mao, A.—Zhang, Y.—Wang, Y.: Bandwidth Allocation Mechanism to Provide QoS Guarantee in IEEE 802.16 Mesh Mode. Future Telecommunication Conference 2007, Beijing, China, October 11–12, 2007, pp. 266–269.

[20] Jun, J.—Sichitiu, M. L.: The Nominal Capacity of Wireless Mesh Networks. IEEE Wireless Communications, Vol. 10, 2003, No. 5, pp. 8–14.

[21] You, L.—Wang, Y.—Zhang, Y.—Mao, A.—Cai, J.—Song, J.: Functional Model and Simulation of IEEE 802. 16 Mesh mode based on NS2, Vol. 25, 2008, No. 8, pp. 2505–2508.

[22] Bayer, N.—Xu, B.—Rakocevic, V. et al: Improving the Performance of the Distributed Scheduler in IEEE 802.16 Mesh Networks. Vehicular Technology Conference 2007, VTC2007-Spring, IEEE 65^{th}, April 2007, pp. 1193–1197.

[23] Loscri, V.: A New Distributed Scheduling Scheme for Wireless Mesh Networks. IEEE 18^{th} International Symposium on Personal, Indoor and Mobile Radio Communications, 2007, September 2007, pp. 1–5.

[24] Guizani, M.—Lin, P.—Cheng, S. M.—Huang, D.-W.—Fu, H. L.: Performance Evaluation for Minislot Allocation for Wireless Mesh Network. IEEE Transactions on Vehicular Technology, Vol. 57, 2008, No. 6, pp. 3732–3745.

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