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AN ENHANCED SCHEDULE ALGORITHM FOR IEEE 802.16 WIMAX MESH NETWORKS FOR NEXT-GENERATION MOBILE SERVICES

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ABSTRACT

The WiMAX mesh networks based on IEEE 802.16 standard is being implemented with the goal of establishing open, easily extensible and manageable networks for a variety of people-centric 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 and administration. Multimedia networking requires quality-of-service (QoS) support, which demands promising and potential mechanisms in addition to the four service types defined in the specification. In this paper, we design a general algorithm for subscriber stations (SSs) to achieve concurrent transmission in both uplink and downlink streams. Mechanisms for constructing and making adjustment of routing trees are also given in this paper. 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. Simulation results show that overall end-to-end throughput is greatly improved when using our algorithm for concurrency and that the algorithm performs better when the routing tree is adjusted. The average delay as well as the delay jitters per hop in the proposed scheme is lower than that of the distributed scheme and much lower than that of the centralized scheme. Furthermore, proposed mechanisms can also achieve higher throughput and generate much lesser signaling overhead, making our framework a promising one for multimedia support.

Keywords: *IEEE 802.16. WiMAX Mesh, QOS, Scheduling, Throughput, Concurrent Transmission*

1. INTRODUCTION

The WiMAX (World Interoperability for Microwave Access) technology based on the pioneering IEEE 802.16 standards addresses the last-mile broadband wireless access (BWA) problem in metropolitan areas and underserved rural areas. In order to gain the distinct advantages of fast and cost-effective deployment, WiMAX is considered as one of the most promising technologies in the ever-green wireless communication domain. As various kinds of wireless networks evolve to provide a spectrum of new-generation services, a key technology, wireless mesh network (WMN), has emerged recently and is on the faster evolution mode [1]. There are real-time and real-world applications out of this emerging technology.

IEEE 802.16 MAC protocol is mainly designed for point-to-multipoint (PMP) access in wireless broadband application. To accommodate the more demanding physical environment and different service requirements of the frequencies ranging between 2 and 11 GHz, the 802.16a project upgrades the MAC to provide automatic repeat request (ARQ) and support for mesh [2]. The Mesh mode is the critical extension to the PMP mode with the unique advantage of less coverage path loss. The coverage and robustness have improved exponentially as subscribers are being added and the larger user throughput over multiple-hop paths is being realized [3, 4]. Capacity enhancement in mesh networks is another feather in the case of mesh networks. One way to increase the capacity of the multi-hop systems is to allow concurrency among the multi-hop transmissions. For example, Wei et al. [5] has proposed an interference-aware route construction algorithm and centralized scheduling scheme, which achieves high utilization of the WiMAX Mesh network. However, that algorithm may result non-minimized interference along the path because of the entry order. Further on, it is more constrained by the format of centralized scheduling messages as the scheduling information generated by the algorithm has to be concurrently transmitted to every SS. This clearly paves the way for deeper exploration and calls for extensive work on sufficiently improving the capacity of mesh networks.

There are two basic mechanisms to schedule data transmission in the IEEE 802.16 mesh network [6]: centralized and distributed scheduling. In centralized scheduling, the base station (BS) works like the cluster head and determines time slot allocation of each SS. In order to transmit data packets, the SS is required to submit the request packet (Layer 2 frame namely BW_REQ) to the BS via the control channel. The BS grants the access request by sending the slot allocation schedule called UL_MAP (uplink map for slot access) to all SS nodes. Since all the control and data packets need to go through the BS, the scheduling procedure happens to be very simple; however a longer path in the mesh network is inevitable. On the other hand, in distributed scheduling, every node competes for channel access using an election algorithm based on the scheduling information of the two-hop neighbors. Distributed scheduling is more flexible in terms of route selection (e.g. shortest path route can be used) at the cost of higher signaling overhead for the exchange of scheduling information. Some research works [7]-[9] have designed for routing and transmission tree construction in centralized scheduling. In light of Wei et al's work, in this paper we have proposed a general algorithm for SSs to achieve concurrent transmission in both uplink and downlink streams based on IEEE 802.16 centralized scheduling. In addition, we have compared the performance of the algorithm with different routing trees and this shows that the end-to-end throughput of our algorithm is significantly enhanced. Also, we focus on the combined scheduling with QoS support and propose a new cut-though mechanism for lower end-to-end delay in the 802.16 mesh network.

2. RELATED WORK

The IEEE 802.16 standard specifies both PMP and mesh technologies. The main difference between PMP and mesh modes is that in PMP mode, traffic only occurs between the BS and SSs where as in mesh mode, traffic can be routed through other SSs. As shown in Fig. 1, the overall area is divided into meshes and managed by a single node, which we refer to as Mesh BS (MBS). It serves as the interface for WiMAX-based mesh to the external network. A transmission can take place between two SSs within a mesh or within two different meshes. The transmission between two SSs within a mesh can occur via other SSs within the mesh which may or may not involve the MBS. Transmission between two SSs in two different meshes involves transmission from SS to MBS (possibly via other SSs within the mesh), from MBS to BS, from BS to MBS of receiver mesh and finally from that MBS to the receiver SS.

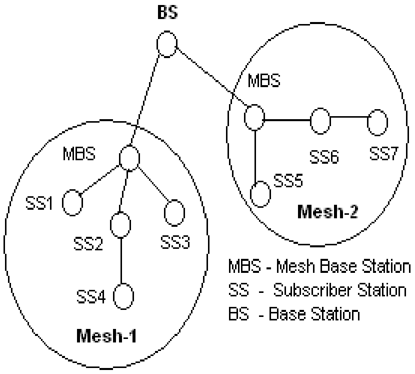

Fig. 1: A typical Mesh Network

Mesh Mode Frame Structure: The IEEE 802.16 Mesh mode MAC supports both centralized scheduling and distributed scheduling. Most of the algorithms discussed here focus on the centralized mesh scheme to establish high-speed broadband mesh connections, in which MBS coordinates the radio resource allocation within the mesh network. Contrary to the basic PMP mode, there are no separate downlink and uplink subframes in the mesh mode. The mesh mode only supports Time Division Duplex (TDD) to share the channel between the uplink and the downlink. A mesh frame consists of a control and a data subframe. The control subframe serves two functions: network control and schedule control. The data frame is shared between centralized and distributed scheduling.

In a network control subframe, mesh network configuration (MSH-NCFG) and mesh network entry (MSH-NENT) packets provide some basic level of communication for nodes to exchange network configuration information. In a schedule control subframe, the mesh centralized scheduling (MSHCSCH) and mesh centralized scheduling configuration (MSHCSCF) packets are used for transmission bursts corresponding to centralized messages, and rest is allocated to transmission bursts containing mesh distributed scheduling (MSH-DSCH) packets for distributed scheduling. The data subframe consists of minislots. Each minislot, except the last minislot, consists of [d(OFDM symbols/frame − MSH-CTRL-LEN ×7)/256e] symbols, where MSH-CTRL-LEN in the length of the 802.16 mesh control plane. A scheduled allocation consists of one or more minislots.

A). Minimizing Interference

Motivation: Multiple-access interference is a major limiting factor for wireless communication systems. Interference in wireless systems is one of the most significant factors that limit the network capacity and scalability. The motivation of the paper [10] is to design an efficient multi-hop routing and scheduling scheme that is interference-aware and hence maximizes parallel transmission, providing high throughput and scalability.

The scheme proposed in [11] includes a novel interference-aware route construction algorithm and an enhanced centralized mesh scheduling scheme, which takes both traffic load demand and interference conditions into consideration. This provides better spatial reuse and hence higher spectral efficiency. The scheme is based on a tree-based routing framework. The paper considers WiMAX-based mesh which is managed by Mesh BS. The metric considered for routing is blocking metric B(k). The Blocking Metric B(k) of a multihop route indicates the number of blocked/interfered nodes by all the intermediate nodes along the route from the root node towards the destination node k. The paper defines blocking value b(η) of a node η, as the number of blocked/interfered nodes when η is transmitting. Thus blocking metric of a route is summation of the blocking values of nodes that transmits or forwards packets along the route.

Algorithm: The algorithm consists of two parts:

1) Interference-Aware Route Construction: The scheme selects routes with less interference. To do so, the blocking metric for the different routes to the destination from the source are computed. Then the route with the least value of the blocking metric is selected as it will cause least interference as compared to other routes. The example for the computation of blocking metric is shown in Fig. 2. In this example, the first path is selected.

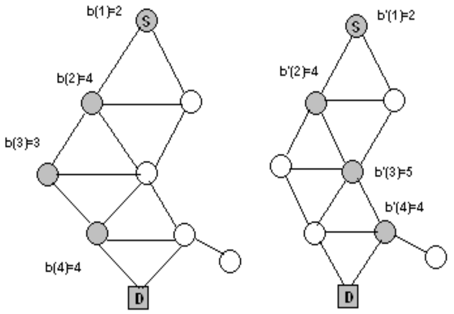

Fig. 2: Example of Blocking metric B (K) = 2+4+3+4=13; B' (K) =2+4+5+4=15

The new node chooses the potential sponsoring nodes based on the blocking metric information. It selects a sponsoring node with least blocking value.

2) Interference-Aware Scheduling: The design goal of interference-aware scheduling is to exploit concurrent transmission to achieve high system throughput. Let D(k) denotes the capacity request of an SS node from k. D(k) can also be represented in terms of Y(j) for every link j. In each allocation iteration t, the scheduling algorithm determines a set of active links. Then the link with highest unallocated traffic demand is selected for next allocation of unit traffic. The interfering links are excluded. The iterative allocation continues until there is no unallocated capacity request. The algorithm is shown in Table 1.

Table 1: Interference-Aware Scheduling Algorithm

```
//t = 1; -> time
//k = link  (arg max Y(j) )
//b = set of blocked links is this iteration
//a = set of selected active links in this iteration
//maxN -> Initialize parent node for node 1, 2,…n
//argmaxY = maximum value of link
//demandY = Demands for any link
//aL = Active Links of Time t
//bN = clocked Neighbor link of k
while(demandY > 0)
{
 k = argmaxY;
 a = maxN;
 b = maxN;

  while(k != maxN)
  {
   k = k + a;
   k = bN + b;
   k = argmaxY;
  }
 aL = a;
 t = t + 1;
 demandY = demandY – 1;}
```

Advantages: The algorithm is compared to the basic random scheduling described in the IEEE 802.16 standards. They have also compared it with the theoretical upper bound obtained by linear programming. In chain topology, the throughput achieved outperforms basic scheme and it approaches the upper bound. While in case of random mesh topology, the throughput is better than basic scheme but it is less than the upper bound obtained by linear programming. The algorithm leads to better spatial reuse and thus higher spectral efficiency.

Limitations: The given routing scheme in the paper suffers from the limitation that they consider the number of blocking nodes as routing metric. Even if a blocked node does not have any packet to send, it is considered for calculation. The number of blocked nodes does not give you the real picture of interference in the network. The better metric is to consider number of packets in the blocked nodes.

B). Throughput Enhancement in WiMAX Mesh

There are two control messages, MSH-CSCF (Mesh centralized scheduling Configuration) and MSH-CSCH (Mesh centralized scheduling), in centralized scheduling. MSH-CSCF message delivers the information of channel configuration and routing tree, while MSH-CSCH message delivers the information of bandwidth request and grant and updating of routing tree.

The BS generates MSH-CSCF and broadcasts it to all its neighbors, and all the BS neighbors shall forward (rebroadcast) this message according to its index number specified in the message. This process repeats until all SS nodes have broadcasted the MSH-CSCF message. According to the routing tree in MSH-CSCF message, all the SSs maintain a routing tree whose root is BS and children are SSs. All SSs are eligible to transmit MSH-CSCH: Request message. The transmission order is determined with regard to the hop-count - the one with the largest hop-count is transmitted first, but retains the transmission order as listed in the routing tree for nodes with the same hop-count. Before transmitting a MSH-CSCH: Request message, an SS puts the requests from its children into its own MSH-CSCH: Request and transmits it to father node. Thus, the BS can gather bandwidth requests from all the SSs, and assign spatial resource for SSs. These assignments (grants) are put in MSHCSCH: Grant message and broadcasted by BS. Then the BS's children node which has no less than one child, ordered by their appearance in the routing tree, rebroadcast the MSHCSCH: Grant message. This process repeat until all the SSs receive MSH-CSCH: Grant. After receiving a MSH-CSCH: Grant message, the SSs determine its actual uplink and downlink transmission time from MSH-CSCH: Grant by a common algorithm which divides the frame proportionally. In the next section, we will discuss a concurrent transmission algorithm in detail to enhance the overall throughput for centralized scheduling.

C). Achieving Concurrent Transmission

Link Interference: The wireless network inherently uses a shared medium to communicate with neighboring nodes. In a single-channel Time Division Duplex (TDD) network, any unicast transmission follows the principle that there must be only one receiver among the neighborhood of a transmitter and there must be only one transmitter among the neighborhood of a receiver. As we can see in Fig. 3, the solid lines with arrow denote directional links in the routing tree. The dashed lines connect the neighboring nodes in one-hop. And the curves with arrow denote the interference by an active link. Let L(x,y) represent the link from x to y, then the interfered links by L(4,6) are L(6,4), L(2,4), L(5,2), L(4,2), L(BS,2), L(BS,1), L(3,1), i.e. when node 4 is transmitting data to node 6, the 7 links above can't be active to avoid collision. The number of Interfered links by L(x,y) is given by I(x,y), so I(4,6)=7 for example.

Constructing Routing Tree - The performance of centralized scheduling method sharply goes up due to the application of a well-structured routing tree mechanism. To reduce the interference between links, balance traffic load, and shorten the period of request and grant, the structure of the routing tree plays a key role. In this section, we propose a construction algorithm based on interference to achieve the following concurrent algorithm, and to improve network performance.

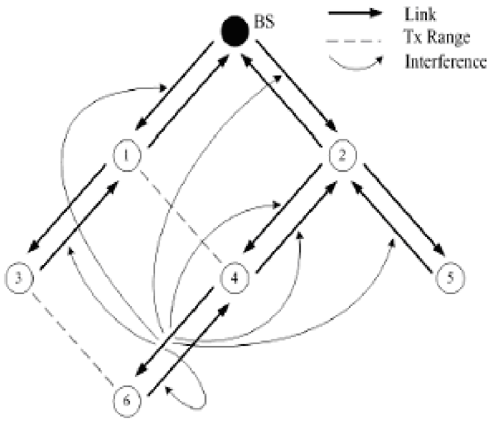

Fig. 3: Link Interference in routing tree

Assume BS-z-y-x is a path in the routing tree, and Py(x) is the sum of uplink and downlink interference through the path from node x whose father node is y to BS. So Py(x) is calculated by

$$P_y(x) = I(x,y) + I(y,x) + P_z(y) \quad \ldots$$
(1)

In Fig. 1, for example,

$$P_4(6) = I(4,6) + I(6,4) + P_z(4)$$

We suppose network begins with only one BS, and all the SSs enter the network one by one. When an SS is entering, all its neighbor nodes are eligible to be the father node of the entering SS. In order to minimize interference, the entering SS should select a father node with minimal interference. So father node is

$$F_x = \arg \min_{i \in Neighbor\ (x)} P_i(x) \quad \ldots \ (2)$$

Where Neighbor(x) is a set of x's neighbor nodes

So far we have considered the minimal interference along the path, but after an SS entering the network, the interference value on the path of other SSs in the network might be changed. Therefore, the entry order impacts the construction of routing tree. A better method to construct routing tree is to make the impacted SSs select the father node once more. Fig. 4 represents the process of entering and adjustment, where SS5 is the entry node. After SS5 entered the network, P2(4)=46,P5(4)=30, so the father node of SS4 is adjusted from SS2 to SS5.

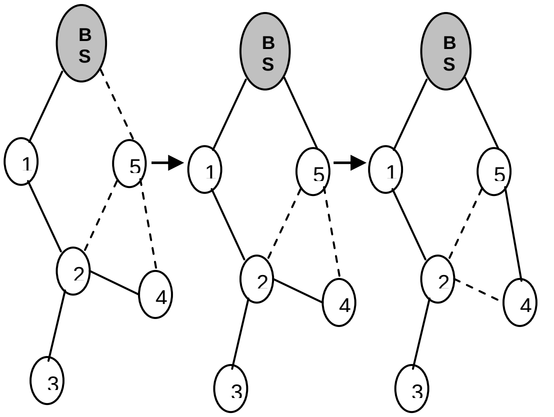

Fig. 4: Construction and adjustment of routing tree

Concurrent Transmission Algorithm: Achieving spatial reuse with concurrency is an effectual method to improve the throughput in multi-hop systems. After analyzing the scheduling and construction of routing tree in WiMax Mesh networks, we propose a concurrent transmission algorithm with no collision to improve the overall end-to-end throughput.

The idea of the algorithm in uplink is described as follows. The order of transmission time determination in uplink is the same as transmission order of MSH-CSCH: Request, i.e., nodes with the biggest hop-count first, and remain the order in the routing tree for nodes with the same hop-count. The transmission time should be as early as possible on condition that no collision would happen. Considering the delay of relaying data, the transmission time of an SS should not be earlier than any of its children's. The algorithm is described as following.

Table 2: Concurrent Transmission Algorithm

```
// x = neighbor node
// fx = father node
// t = time
// Tx = Time assigned to node
// A = Tx (Nodes Assigned Tx time)
// B = {1,2,..n} (Nodes Assigned upto infinity)
// Rx = Assigned x node to record time
// Rxfx = father node record time

while(B != Tx)
{
        x = i;              // i = Maximum hopcount
        C = Tx;             // interference time

        For (int j = 1; j <= x; j++)  //  for all j ε
neighbor(x)
```

```
        {
          C = C + (Rx[j] + t[j])
        }
        for(int k = 1; k <= fx; k++)    // for all k ε neighbor($father_x$)
        {
          C = C + (Tx[k] + t[k])
        }
        Tx = C;          // assign x's Tx time
        Rxfx = Tx;       // record Rx time of x's father

        A = A + x;       // Add x to A
        B = B - x;       // Remove x from B
}
```

Note that the algorithm in downlink is similar to that in uplink.

D). QoS Framework and Mechanisms for WiMAX Mesh

QoS Framework: There are both pros and cons 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, which increases the consumption of link capacity. On the other hand, the distributed scheduling has the advantage of using shortest-path route but suffers from the larger signaling cost due to 2- hop neighbor's 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.

Fig. 5 displays the architecture of the proposed QoS framework at the BS and SS nodes. The main idea behind the framework is that we take advantage of the centralized control for scheduling and route selection. However, we avoid the longer transmission path by adopting the flow setup phase and maintaining routing information at each SS for QoS flows to provide more efficient route control. Novel features of the QoS framework are listed as follows:

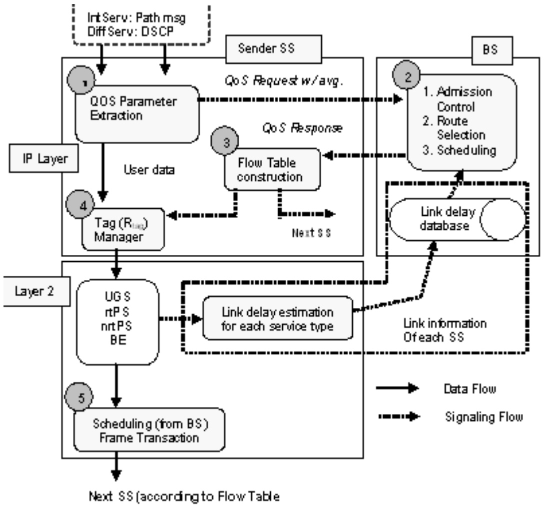

Fig. 5: QoS Framework

(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)**), admission control and route selection according to current load of the network (item **(2)**), flow table setup for routing in the Mesh network (item **(3)**), etc.

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

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

(4) Subscriber stations access the data channel in the allocated time slots according to the instruction (*UL-MAP*) from the BS, and transmits data packets to the next hop according to the value of *Rtag* added in the header of the data frame and the flow table (item **(5)**). Note that using *Rtag* in 802.16 data frame header for fast packet routing is similar to the idea of *Multi-Protocol Label Switching* (*MPLS*) [11]. Moreover, each SS estimates its current link delay (the system time of each QoS queue in the SS) and reports its link state to the BS on a regular basis.

E). QoS Scheduling and Mechanisms

The IEEE 802.16 provides the QoS to achieve the multimedia service in BWA. There are five service types in the 802.16, *Unsolicited Grant Service (UGS), extend real-time Polling Service (ertPS), real-time Polling Service (rtPS), non-real-time Polling Service (nrtPS), and Best Effort (BE).* Since real time multimedia traffic needs sufficient bandwidth and low delay, the UGS service type designed to support the appropriate service.

A specific scheduling algorithm is not described for PMP or for mesh modes in the IEEE 802.16 standard [12]-[13], because it is not included among the mandatory modules required for the standardized operation of system. On the other hand, the operation of the scheduler is important for the performance of the whole system. In the literature so far, a limited number of papers can be found proposing scheduling algorithms for 802.16. Those proposals are based mostly on extensions and combinations of ideas already applied in systems prior to IEEE 802.16, such as the IEEE 802.11 wireless local-area network, and they focus mainly on the PMP mode.

To achieve the requirement for each service type, we focus on two parts, designing the special bandwidth request for highest priority of UGS, adding the weight of delay for different SSs with the same service type and using appropriate scheme of slot allocation. The detail is showed as follows.

Expedited Queue: In the PMP (Point to Multipoint) mode, the BS and a couple of SSs that connect to the BS via high-speed wireless link and the BS according to the initiation UGS request to allocate the fixed bandwidth for the CBR traffic session. However, the ertPS, rtPS and nrtPS are polling services, they should perform dynamic request to BS in each frame. Therefore, those services are designed for VBR-rt traffic or lower priority non-real time traffic. On the other hand, the other mode of 802.16 Mesh has different situation, the traffic flow transmission might be divided into multi-hop according to the flow path, so the traditional bandwidth requests (BW_REQ) is sending by each intermediate SS. The QoS service types only apply different priorities like polling service. Since the UGS flow is the highest priority and fixed bandwidth requirement, it is unnecessary to be allocated per time frame, so the UGS traffic can be granted in initiation request with one time request like PMP mode. To support UGS traffic with initiation bandwidth request (BW_REQ), we should adopt the idea of cut-through in ATM network. In our proposed *Expedited Queue (EQ)* scheduling scheme, when the traffic flow passed the admission control policy and belonged to UGS service, the resource allocation function should consider both per hop BW_REQ and end-to-end route path. Our *EQ* scheme provides absolute QoS guarantee for UGS service type with highest priority. We have added a special queue in each SS for supporting UGS flow and there is no need to be scheduled. When sender SS of UGS flow requests BW_REQ, the BS allocated the slots based on its request slots and number hop of route path (*request slots * hop count*). The *EQ* scheme can reduce a fewer signal overheads and apply lower end-to-end delay.

Delay-based Weight Design: The scheduling algorithm in this 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 ertPS (Extended real-time Polling Service) flows, ertPS flows are also higher than rtPS (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, ertPS and rtPS to reduce the access delay by giving higher priority to those data frames that have been waiting a longer time in the queue. More specifically, the data frames with 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 *SSi*, i.e. *DUGS,i*, *DertPS,i*, *DrtPS,i*, *DnrtPS,i*, and *DBE,i*. For delay-constrained service types such as UGS, ertPS and rtPS, one more parameter (denoted by *WUGS,I*, *WertPS,i* and *WrtPS,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, ertPS and rtPS data frames higher priorities in scheduling, we define a delay compensation factor (denoted by *DC* and *DC*=5 is used in our simulation) for *WUGS,i*, *WertPS,i* and *WrtPS,i*. The weighting functions for UGS, ertPS and rtPS queues are therefore defined respectively as follows:

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

$$XMT_{rtPS,i} = W_{rtPS,i} * DC + (D_{rtPS,i} - W_{rtPS,i})$$

Note that the values of *XMT* for nrtPS and BS queues are simply *DnrtPS,i* and *DBE,i.*

3. PERFORMANCE EVALUATION

A). Simulation Scenario for Achieving concurrent Transmission

Random topology is generated in an L*L square. And $L = d\sqrt{n/2}$, where n is the number of SSs, d is the maximal transmission range between two nodes. We also insure that any SS can communicate with BS through one or multiple hops. We assume a single channel network with no bit errors, and all the SSs are immobile and working in half duplex. Since we only care the performance of our algorithm, it is nearly optimal to transmit at the highest available rate (set to 50Mbps here) regardless of the channel state. Every SS request 0.5Mbps bandwidth for both uplink and downlink.

Results and Analysis: Fig. 6 and Fig. 7 show the overall end-to-end throughput with different routing trees. The number of SSs increases from 20 to 120 with a step of 10. The throughput values are the average of simulations in 500 times.

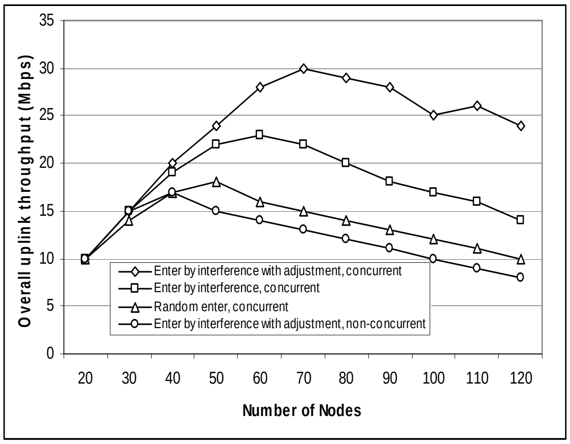

Fig. 6: Throughput vs. number of nodes in uplinks

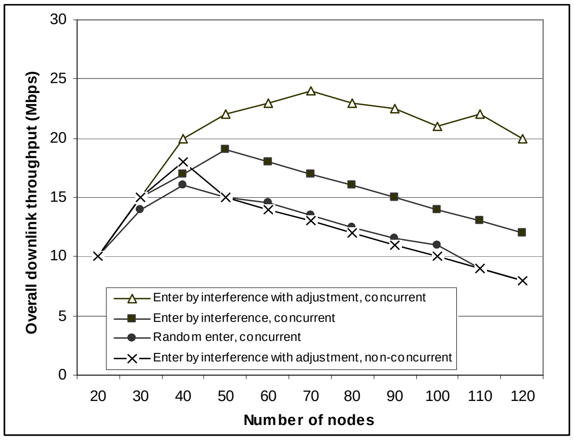

Fig. 7: Throughput vs. number of nodes in downlinks

As we can see in the two figures, the overall end-to-end throughput is increased greatly using concurrency, and the routing trees generated by different means impact the throughput. When concurrency is adopted, the throughput with interference-based routing tree is greater than that with random routing tree, and the throughput with adjusted interference based routing tree is higher than that with non-adjusted interference-based routing tree. Therefore, our concurrency algorithm performs best when using an adjusted and interference-base routing tree.

B). Simulation for QoS Scheduling and Mechanisms

Simulation Environment and Parameter: 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 5Mbps. A time frame structure with size 10 ms is defined for slot allocation. Other parameters used in the simulation are displayed in Table 3. 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

Table 3: Simulations parameters

Simulation parameters	**Value**
Network Size	5x5 mesh
Link Capacity	5 mbps
Time frame duration	10 ms
# of slots per time frame	10
# of flows per service type	5
Average data rate of all flows	0.5 – 5 mbps
Variation of data rate per non-UGS flow	25%
Link State report interval	50 ms
Flow arrival rate	1 flow /sec
Flow departure rate	1 flow /sec

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).

Simulation results: As shown in Fig.8 and 9, the average delay and delay variation per hop for different service types under flow data rate 2.5Mbps in the proposed scheme are smaller than those of the distributed scheme (Fig.9) and much smaller than those of the centralized scheme (Fig. 8). For more investigation of delay behavior, Fig.10–13 display the results of the average delay per hop for different service type of flows under flow data rate ranging from 500 kbps to 5Mbps. Some observations and interpretations can be made from the figures as follows:

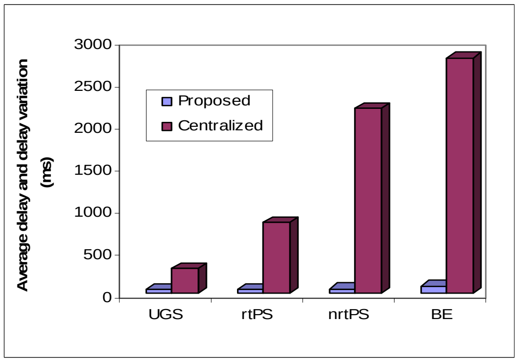

Fig. 8: Delay and delay variation with flow data rate 2.5 Mbps: proposed vs. centralized.

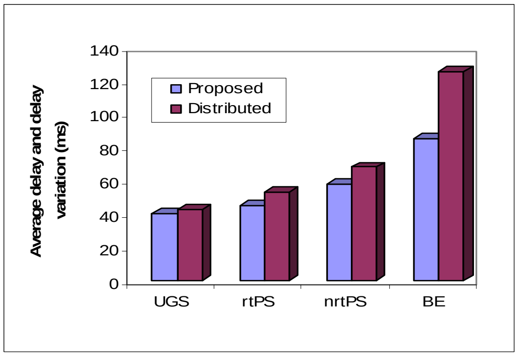

Fig. 9: Delay and delay variation with flow data rate 2.5 Mbps: proposed vs. distributed.

(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 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.

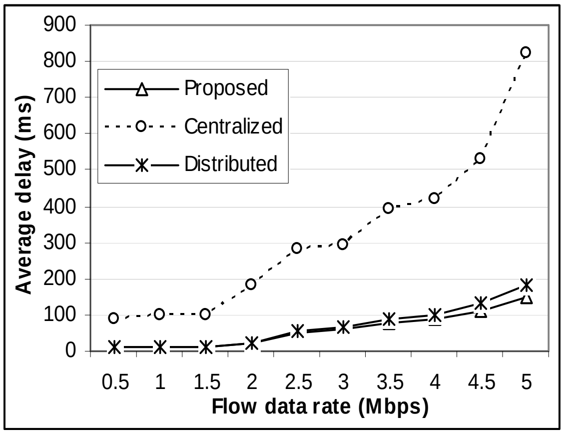

Fig. 10: Average delay of UGS flows.

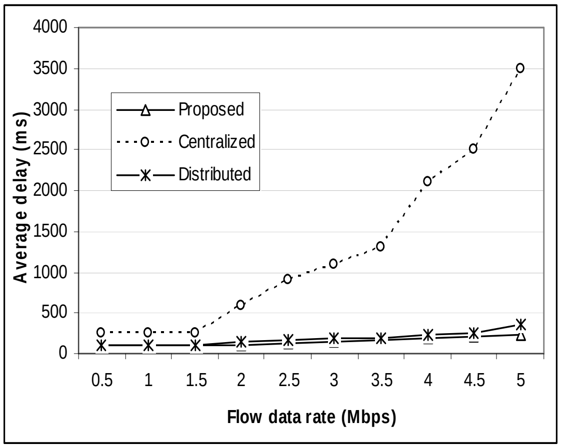

Fig. 11: Average delay of rtPS flows.

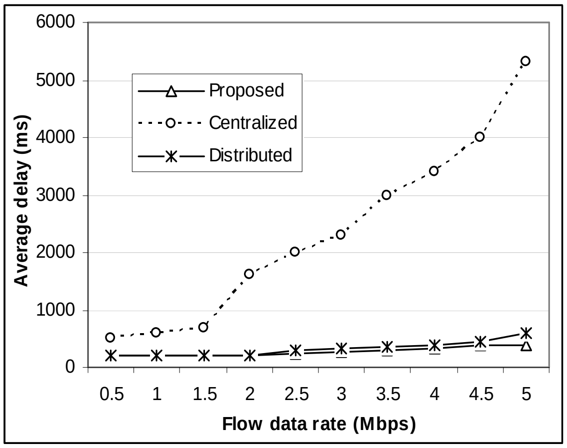

Fig. 12: Average delay of nrtPS flows

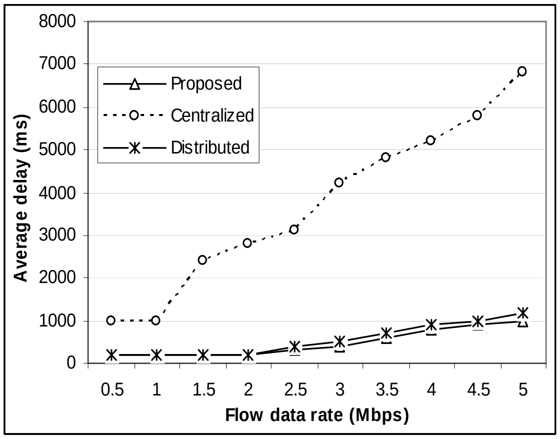

Fig. 13: Average delay of BE flows.

(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) Fig.14-17 displays 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.

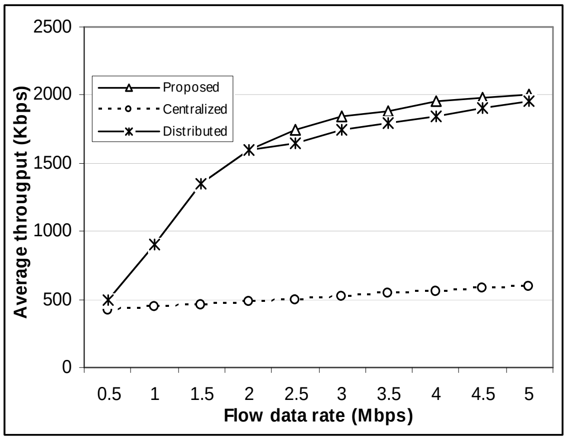

Fig. 14: Average throughput of UGS flows.

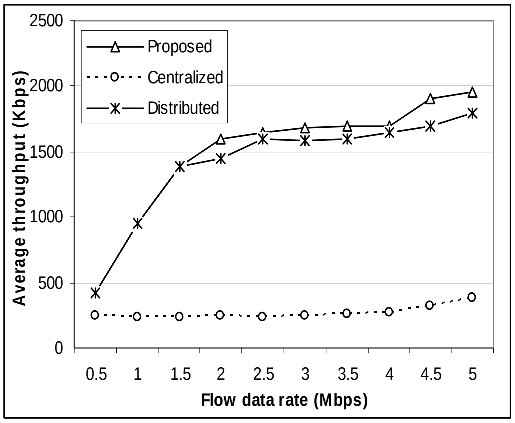

Fig. 15: Average throughput of rtPS flows.

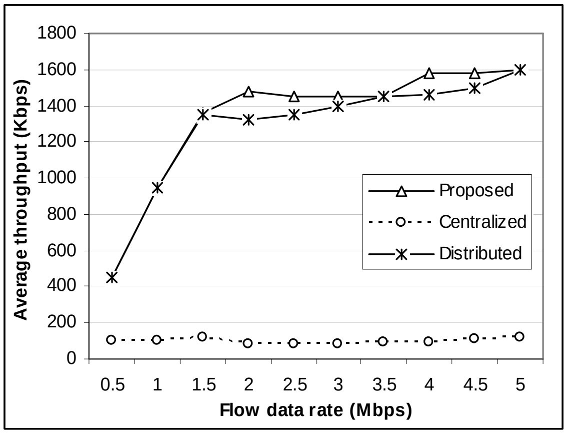

Fig. 16: Average throughput of nrtPS flows.

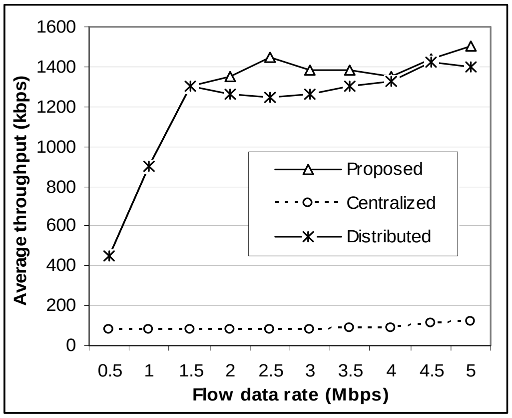

Fig. 17: Average throughput of BE flows.

(5) The average signaling cost of the schemes is shown in Fig.18, 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 MSHCSCH 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. Fig. 19 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.

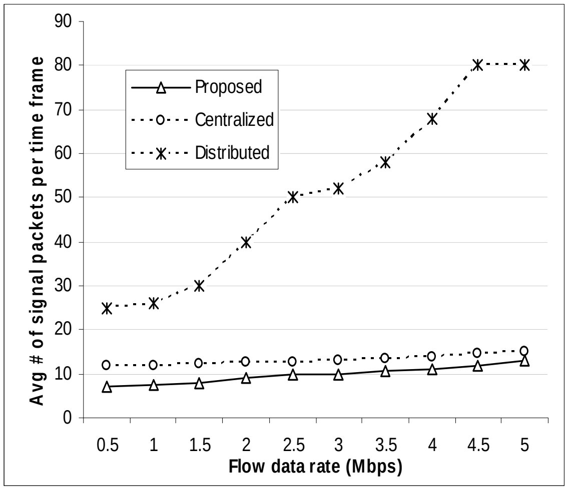

Fig. 18: Average Signaling cost.

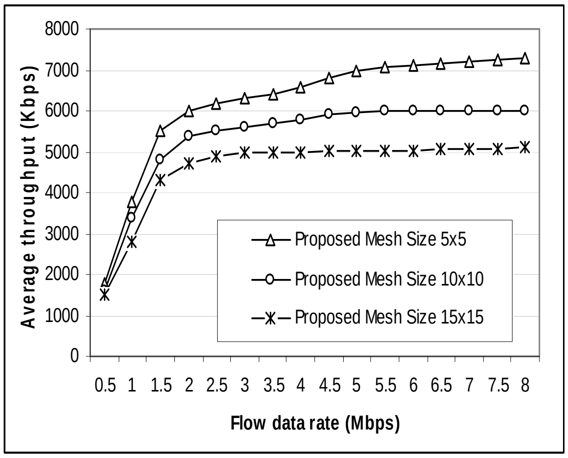

Fig. 19: Average throughput of all flows with different mesh sizes.

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, 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 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 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.

4. CONCLUSION

WiMax Mesh networking is a promising technology for wireless broadband access. In WiMAX Mesh mode, there is no need to have direct link from SSs to the BS, which provides a more flexible approach for network deployment. Data frames in the 802.16 Mesh modes can be transmitted directly between two neighboring SS nodes and sent to the destination node in the hop-by-hop manner. This paper proposes a concurrent transmission algorithm to promote spatial resource reuse, which increases the overall end-to-end throughput. 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 investigated the performance problems in each of the basic schemes and proposed more efficient scheduling mechanisms. Simulation results indicate that different constructions of routing tree impact the performance of the concurrent algorithm. Simulation results have demonstrated that the proposed framework and the associated mechanisms can achieve a better performance in terms of delay, throughput, and signaling cost over the basic centralized and distributed scheduling schemes. On the other hand, our proposed EQ mechanism can reduce larger transmission time than traditional mechanism.

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