Improving the Data Scheduling Efficiency of the IEEE 802.16(d) Mesh Network

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***Abstract*—In an IEEE 802.16(d) (WiMAX) mesh network, network bandwidth can be managed by either the centralized scheduling (CS) mode or the distributed scheduling (DS) mode. Compared with the CS mode, the DS mode provides a larger bandwidth capacity and is more scalable. However, because the DS mode uses an on-demand three-way handshake procedure to establish data schedules, the network quality experienced by application programs may fluctuate drastically.**

To address this problem, in this paper we propose three schemes to improve the data scheduling efficiency of the DS mode of the IEEE 802.16(d) mesh network. Our simulation results show that network performances and qualities experienced by application programs are significantly improved under our schemes.

I. INTRODUCTION

In recent years, wireless mesh networks have become increasingly important and obtained much attention. Compared with wired networks, wireless mesh networks provide the following advantages: low-cost deployment, easy maintenance, and high scalability. Among the standards proposed for next-generation wireless mesh networks, the IEEE 802.16(d) mesh-mode standard [1] is a promising technology that aims to provide broadband wireless access in metropolitan areas.

The IEEE 802.16(d) mesh network employs a Time-Division-Multiple-Access (TDMA) based MAC-layer protocol to manage network bandwidth. In an IEEE 802.16(d) mesh network, link bandwidth is partitioned into mesh frames, each of which comprises a control and a data sub-frames. The control sub-frame is divided into transmission opportunities (TxOpps), while the data sub-frame is divided into mini-slots. Each network node broadcasts control messages over TxOpps and transmits data packets over mini-slots.

To schedule data transmission, the IEEE 802.16(d) mesh network defines two scheduling modes to allocate mini-slots. One is the centralized scheduling (CS) mode and the other is the distributed scheduling (DS) mode. In this paper, we focus on the study of the DS mode. The details of the CS mode can be referred to [1]. In the DS mode, network bandwidth is managed in a distributed manner. In this mode, each node has an equal role and employs a three-way handshake procedure (THP) to allocate mini-slots for data transmission and reception. The details of THP are explained in Section III.

The DS mode has two operational modes: the coordinated mode (referred to as the CDS mode) and the uncoordinated mode (referred to as the UDS mode). Both of these modes use THP to schedule data transmission. They differ only in the transmission timing of control messages. Control message transmissions in the CDS mode are scheduled by the pseudo-random election algorithm defined in [1]. However, in the UDS mode, control message are transmitted in a random-contention-based manner on TxOpps left by the CS and the CDS modes.

Due to the nature of distributed scheduling, in the DS mode the time required for negotiating a data schedule in a THP can vary greatly [3]. (A data schedule is defined as a mini-slot allocation for transmitting data packets.) As such, the throughputs and packet delay times experienced by application programs can also vary drastically. In such a condition, the performances of delay-sensitive protocols (e.g., TCP) and applications (e.g., VoIP) are significantly degraded.

In this paper, we first point out the drawbacks of the THP design used in the IEEE 802.16(d) mesh CDS mode and then propose three schemes to address them. Our simulation results show that the proposed schemes can effectively improve the data scheduling efficiency of the IEEE 802.16(d) mesh DS mode and thus improve the network quality experienced by application programs. In addition, our proposed schemes are generic and allow advanced scheduling algorithms to operate on top of them to support better Quality-of-Service (QoS).

The rest of the paper is organized as follows. In Section II, we discuss related work. In Section III, we explain the operation of the THP used in the DS mode and discuss its drawbacks. We then present the proposed scheduling schemes in Section IV and evaluate their performances in Section V. Finally, we conclude this paper in Section VI.

II. RELATED WORK

In [2], the authors build a stochastic model to analyze the scheduling performance of the IEEE 802.16(d) mesh DS mode. Using the built model, the authors study the scheduling performances of the DS mode under different system parameter values. In [3], the authors study the transmission intervals of control messages and the round trip times (RTT) of data packets under different system parameter values. Differing from the previous work, to the best of the authors' knowledge,

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our work is the first paper that improves the data scheduling efficiency of the IEEE 802.16(d) mesh DS mode.

III. THE THP OF THE IEEE 802.16(D) MESH DS MODE

A. Procedure Description

The THP of the DS mode uses the Mesh Distributed Scheduling (MSH-DSCH) messages to exchange the information elements (IEs) required for establishing a data schedule. The detailed steps are explained here: To request a data schedule, the requesting node first transmits a request IE and the corresponding availability IEs to its intended receiving node (referred to as the granting node) using an MSH-DSCH message. A request IE specifies the number of mini-slots demanded by the requesting node, while an availability IE specifies a set of consecutive mini-slots from which the granting node is allowed to choose.

Upon receiving the MSH-DSCH message, the granting node should allocate mini-slots to service the requesting node's request within the mini-slot set specified by the received availability IEs. If the granting node cannot satisfy this request, it can either ignore this request or allocate fewer mini-slots than those specified in the request IE. After finishing the mini-slot allocation process, the granting node sends the requesting node a grant IE describing the allocated mini-slots for the request IE. Finally, on receiving the grant IE, the requesting node broadcasts a confirm IE, which is simply a copy of the grant IE, to acknowledge this mini-slot allocation. During this THP, nodes neighboring to the requesting and granting nodes can overhear the exchanged IEs. As such, they know when this data schedule will take place and will suspend their data transmissions at that duration to avoid packet collisions.

B. The Formats of the Three IEs used in the THP

The detailed formats of the three IEs used in a THP are presented here. A request IE is represented by a 3-tuple (LinkID, DL, DP), where LinkID denotes the ID of the link over which the requesting node is requesting bandwidth. DL and DP denote the number of consecutive mini-slots per frame demanded by the requesting node and the number of consecutive frames demanded by the requesting node, respectively.

A grant (confirm) IE is represented by a 7-tuple (LinkID, M_Start, M_Range, SFN, D, P, CH), where LinkID has been explained previously. The M_Start field denotes the starting mini-slot number of a mini-slot allocation in a frame and the M_Range field denotes how many consecutive mini-slots in a frame are allocated to a request IE. The SFN field denotes the starting frame number of a mini-slot allocation and the P field indicates in how many consecutive frames this mini-slot allocation will remain valid. The D field specifies whether this IE is a grant IE or a confirm IE, and the CH field specifies the ID of the channel that the granting node uses.

C. Disadvantages of the THP

The THP defined by the mesh DS mode has two disadvantages. First, during a THP, the requesting and granting nodes are only allowed to allocate a "continuous" mini-slot allocation. Recall the grant IE format explained in Section III-B. The 4-tuple (M_Start, M_Range, SFN, P) only can specify a continuous mini-slot allocation. As such, the granting node is only allowed to allocate a mini-slot allocation for serving the requesting node's bandwidth need. Such a restriction significantly decreases the flexibility of mini-slot scheduling of the mesh DS mode.

Second, in the mesh mode, traffic flows are classified into connections, each of which can have a different QoS requirement. According to [1], the identifier of a connection is composed of a *"LinkID"* field and a set of QoS parameters. The former specifies the ID of the link that is used to service this connection, while the latter describes the QoS requirements of a connection. Outgoing packets of a connection should be transmitted over the mini-slots allocated to the link serving this connection because the THP establishes a data schedule for a link rather than for a connection.

However, one sees that the format of the request IE does not specify the connection and the QoS requirements associated to this bandwidth request. This means that, when a granting node is serving a request IE, it does not know which connections this request IE serves and the QoS needs of these connections. Lacking such information, the granting node cannot employ advanced QoS-aware scheduling algorithms to efficiently utilize link bandwidth and serve traffic flows.

To solve these two problems, in this paper we propose three schemes to improve the data scheduling efficiency of the THP. The first is the multi-grant (MG) scheme, which allows nodes to allocate multiple mini-slot allocations during a THP; the second is the multi-request (MR) scheme, which allows the granting node to schedule link bandwidth using the QoS requirements associated to each request IE; and, the final one is the "multi-request-multi-grant" (MRMG) scheme, which combines the MR and the MG schemes. The details of these schemes are explained in Section IV.

IV. THE PROPOSED SCHEDULING SCHEMES

In this section, we explain the three proposed scheduling schemes and a basic scheduling scheme in details. The basic scheme is used to generate baseline performances, which are compared with those of the proposed schemes. The details of these schemes are presented below.

A. The Basic Scheme

Using the basic scheme, a network node establishes a link to each of its neighboring nodes. Packets destined to the same node are served by the same link and transmitted in the first-come-first-serve order. As such, the basic scheme cannot provide QoS guarantee for specific traffic flows. In the basic scheme, a node can negotiate only a single data schedule during a THP.

B. The MG Scheme

Due to the restriction of continuous mini-slot allocation, the basic scheme cannot efficiently utilize network bandwidth. As shown in Fig. 1(a), suppose that node A is requesting node B for a mini-slot allocation that occupies four mini-slots per frame and lasts eight frames (in total 32 mini-slots). In the basic scheme, because node B is only allowed to transmit a data schedule during a THP, the best it can do is to allocate a mini-slot allocation occupying the most mini-slots among all continuous mini-slot blocks that are still available. In this example, node B can only choose a mini-slot allocation that occupies 4 mini-slots per frame and lasts 4 frames for node A. As a result, node A just obtains 16 mini-slots, which is only a half of the mini-slots that it needs. To address this problem, we propose the MG scheme that can satisfy a bandwidth request with multiple separated mini-slot allocations.

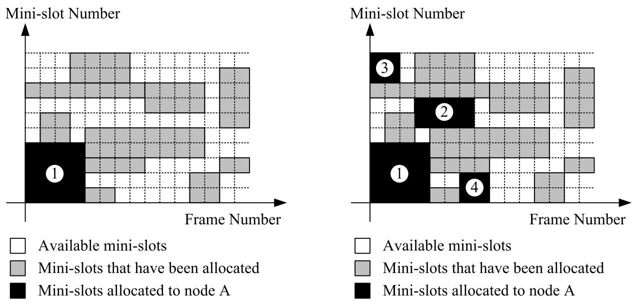
In the MG scheme, on receiving a request IE, a granting node repeatedly allocates multiple mini-slot allocations to serve the request IE until one of the following three conditions holds: 1) the bandwidth need of this request IE has been fulfilled; 2) the granting node has no available bandwidth to allocate data schedules; and 3) the number of generated grant IEs has been equal to a pre-specified G_{Thres} value. The G_{Thres} parameter defines the maximum times that a granting node is allowed to perform the mini-slot allocation process for a request IE. The value of G_{Thres} should be properly set based on network load to prevent a network node from monopolizing network bandwidth.

Fig. 1(b) shows the advantage of the MG scheme. Consider the same example discussed above. In the MG scheme, node B can collect several smaller fragmented mini-slot blocks to satisfy node A's bandwidth need. In this example, it allocates 4 mini-slot allocations (in total 32 mini-slots) to node A during a THP. The MG scheme outperforms the basic scheme on bandwidth utilization and application throughputs because in this scheme a requesting node can obtain as many mini-slot allocations as possible to meet its needs using only one THP. Besides, the MG scheme also reduces the packet delay time experienced by application programs, as compared with the basic scheme. This is because, using the MG scheme, a node can reduce the number of THPs required to meet its bandwidth needs.

C. The MR Scheme

Compared with the basic scheme, the MG scheme greatly improves the scheduling efficiency for a bandwidth request. Under these two schemes, however, a requesting node can only use one mini-slot allocation to represent its bandwidth needs during a THP. Such a design results in long scheduling latencies when multiple connections are active, because nodes using this design are only allowed to process a bandwidth request in a THP. As the number of active connections increases, each connection needs to wait a longer time to establish its data schedule. To solve this problem, we propose the MR scheme that is capable of servicing multiple bandwidth requests of active connections during a THP.

The MR scheme exploits a multi-link design to serve connections. Each link is used to service a group of connections. The main idea of the MR scheme is explained below. On initiating a THP, the requesting node can transmit multiple bandwidth requests (represented by request IEs) for different connection groups to the granting node. As such, the granting node can receive multiple bandwidth requests issued by the requesting node at the same time and then *batch-process* these requests during a THP. Thus, the MR scheme can reduce the number of THPs required to serve the active connections of a requesting node and decrease the time required to establish data schedules.



(a) The basic scheme

(b) The MG scheme

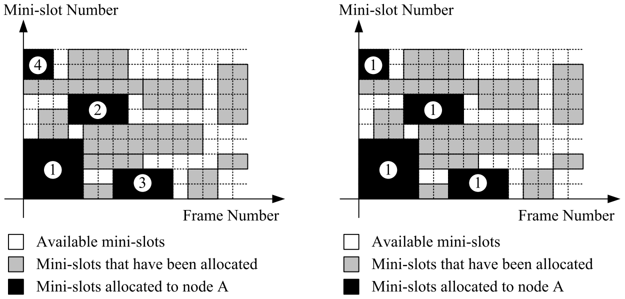
Fig. 1. Examples of mini-slot allocations scheduled by the basic and MG schemes

Besides, to solve the second problem of THP discussed in Section III-C, the MR scheme defines a new type of information element (QoS IE) to enhance the QoS support for the THP. A QoS IE is used to notify a granting node of the priority and the QoS requirements of a link, which serves a connection group in the MR scheme. On initiating a THP, in addition to request and availability IEs, a requesting node should transmit to its granting node the QoS IEs associated to links that it requests. As such, on receiving multiple request IEs at the same time, the granting node can more efficiently serve these bandwidth requests based on the links' priorities and QoS requirements indicated by the received QoS IEs.

The following is an example explaining the advantage of the MR scheme. Assume that node A has established four links to node B. Each link is serving a specific connection group. Each connection group requires 16, 8, 8, and 4 mini-slots, respectively. As shown in Fig. 2(a), when using the basic or MG scheme, node A needs to launch four THPs to request these mini-slot allocations. However, using the MR scheme node A can simultaneously transmit the request IEs for these connections during a THP. As Fig. 2(b) shows, these mini-slot allocations can be scheduled together and transmitted together during a THP. Moreover, since under the MR scheme multiple request IEs of links (and their associated QoS IEs) can simultaneously arrive at the granting node, the granting node has more scheduling flexibility to optimize the use of its link bandwidth.

D. The MRMG Scheme

The MRMG scheme combines the designs of the MR and MG schemes. Therefore, using the MRMG scheme the requesting node can issue multiple request IEs for different



(a) The basic scheme (b) The MR scheme

Fig. 2. Examples of mini-slot allocations scheduled by the basic and MR schemes

TABLE I
THE PARAMETER SETTING USED IN SIMULATIONS

Parameter Name	**Value**
MSH-CTRL-LEN	8
MSH-DSCH-NUM	8
Scheduling Frames	2
Requested Mini-slot Size	30
Requested Frame Length	32
Modulation/Coding Scheme	64QAM-3/4
Maximum Transmission Range	500 meter
Frame Duration	10 ms
Number of Mini-slots per Frame	220
G_{Thres}	63

connection groups during a THP. In addition, upon receiving request IEs, the granting node can allocate multiple data schedules for each request IE to optimally satisfy the bandwidth requirements of these request IEs.

V. PERFORMANCE EVALUATION

In this section, we evaluate the performances of the proposed schemes using the NCTUns network simulator [4]. In the following, we first explain the simulation setting in Section V-A and then explain the used performance metrics in Section V-B. Finally, we present the simulation results in Section V-C.

A. Simulation Setting

The main parameters used in our simulations are listed in Table I. We use a 21-node chain network topology as our simulation topology. From the left to the right, nodes in this chain network are named SS(1), SS(2), SS(3),..., and SS(21), respectively. Each node is spaced 450 meters away from its neighboring nodes. The maximum transmission range of each node is set to 500 meters. Nodes SS($2 + i * 3$), for $0 \leq i \leq 6$, are selected to generate traffic to their left and right 1-hop neighboring nodes. During simulation, each traffic source node generates four types of traffic: TCP, greedy UDP, UDP with constant-bit-rate (CBR) of 100 KB/sec, and UDP with CBR of 10 KB/sec.

For each evaluated scheme, we run simulations three times, each time using a different random number seed. Each presented performance result is the average of these simulation runs. The total simulated time of each run is set to 200 seconds.

B. Performance Metrics

Four performance metrics are used to evaluate the proposed schemes. The first is the number of mini-slots obtained by a network node per frame averaged across all nodes (denoted as M_O). M_O represents the scheduling efficiency of a scheme from the perspective of a network node. A larger value of M_O indicates that a node can obtain more mini-slots during a THP.

The second metric is the sum of the mini-slot utilization of all nodes in a node's two-hop neighborhood, averaged across all nodes in a network (denoted as M_U). The mini-slot utilization of a node is defined as the ratio of the number of mini-slots used by the node to the number of total mini-slots available during the interval that its traffic flows are active. In the mesh DS mode, the two-hop neighborhood of a network node is defined as the set composed of the node's one-hop and two-hop neighboring nodes and the node itself. A network node should coordinate its packet transmissions among its two-hop neighborhood to avoid the *hidden-terminal* problem. A high value of M_U represents that network bandwidth can be utilized efficiently, while a low value of M_U represents that network bandwidth is under-utilized due to too conservative scheduling.

In addition to MAC-layer performances, the average application throughput and packet delay time are also used to evaluate the network quality experienced by application programs. The former is defined as the average of the aggregate throughputs obtained by all traffic flows, while the latter is defined as the average of the times required for packets to travel from their source nodes to their destination nodes.

C. Simulation Results

As shown in Table II, the three proposed schemes outperform the basic scheme on MAC-layer performances. The MRMG scheme on average can obtain 2.88 times mini-slots for served flows in a THP, as compared with the basic scheme. One notices that the MR scheme on average can outperform the MG scheme. The reason is explained below. Using the MR scheme the MAC layer is allowed to allocate only one data schedule for a request IE; however, it can issue up to four request IEs (each for a specific connection group) during a THP. As such, the bandwidth needs of the four connection groups can be processed and satisfied using only one THP. In contrast, although using the MG scheme the MAC layer can allocate more than one data schedules for a request IE, only a request IE can be transmitted and served during a THP. Thus, using the MG scheme the MAC layer should perform four THPs to service the four connection groups, resulting in inefficient use of link bandwidth and larger data scheduling latencies for the four connection groups.

One sees that the MRMG and MR schemes can greatly reduce the packet delay times experienced by traffic flows, as compared with the MG and basic schemes. These results show that the multi-request design can more efficiently serve traffic flows belonging to different connection groups during a THP. Also, the MRMG scheme on average can result in shorter packet delay time than the MR scheme because the

TABLE II
THE PERFORMANCES OF THE FOUR SCHEMES

	MAC		Application	
	M_O	M_U	Throughput (KB/s)	Packet Delay Time (ms)
MRMG	44.18	57.00%	1504.53	80.160
MR	29.79	38.36%	1235.90	116.034
MG	26.65	34.58%	947.54	181.578
Basic	15.36	19.86%	654.70	382.504

TABLE III
THE AVERAGE BANDWIDTH SATISFACTION INDEX RESULTS

	RT CBR-25KB		RT CBR-3KB		TCP		UDP	
	Throughput (KB/s)	ABSI (%)	Throughput (KB/s)	ABSI (%)	Throughput (KB/s)	ABSI (%)	Throughput (KB/s)	ABSI (%)
MRMG	20.20	80.80	2.60	86.67	97.52	97.52	396.28	99.07
MR	23.34	93.36	2.99	99.67	95.79	95.79	373.25	93.31
MG	9.34	37.36	1.69	56.33	79.38	79.38	225.84	56.46
Basic	6.63	26.52	1.77	59.00	69.75	69.75	142.09	35.52

former exploits the multi-grant design to satisfy each request IE's bandwidth need as much as possible. As such, nodes using the MRMG scheme on average can reduce the queuing delay of a data packet because a data packet can be transmitted sooner after being inserted into the link transmission queue.

The simulation results show that the MRMG scheme on average can increase application throughputs by a factor of 2.298 and reduce the packet delay time by a factor of 4.772, as compared with the basic scheme. The reason is that the multi-grant design can maximally satisfy the bandwidth need of a request IE while the multi-request design can efficiently satisfy the bandwidth needs of multiple request IEs simultaneously. As such, the MRMG scheme, which exploits these two designs, in general can achieve the best performances among all the evaluated schemes.

Regarding the capability of QoS support, we define the average bandwidth satisfaction index (ABSI) to evaluate how well the bandwidth need of each flow is satisfied under a scheduling scheme. The ABSI of a scheduling scheme is computed as follows. We first compute the bandwidth satisfaction index (BSI) per second for each flow using the following equation:

$$\text{BSI}(i) = \frac{\text{the amount of the granted BW in } i\text{'th sec}}{\text{the amount of the requested BW in } i\text{'th sec}}. \quad (1)$$

We then compute the average BSI value of each flow (denoted as BSIF) as follows:

$$\text{BSIF}_j = \frac{\sum_{i=1}^{n} \text{BSI}(i)}{n}, \quad (2)$$

where n is the number of seconds of flow j's active duration. The ABSI of a simulation run is calculated as the average of all flows' BSIF values. The ABSI result of a scheme is the average of the ABSI results of all simulation runs. We conducted a series of simulations using the previous settings except the traffic pattern. In these simulations, each traffic source node generates four types of traffic: Real-time UDP with CBR of 25 KB/sec, Real-time UDP with CBR of 3 KB/sec, TCP, and greedy UDP, respectively.

Table III shows the ABSI results of the evaluated schemes. As one sees, the MRMG and MR schemes can serve traffic flows much better than non-MR schemes (such as the MG and the basic schemes). Due to the use of the multi-request design, the MRMG and MR schemes can serve multiple connections well based on their priorities and QoS requirements in a THP. As such, under these two schemes each connection can obtain a bandwidth more close to what it requires. It is worthy to note that the ABSI values of real-time traffic under the MRMG scheme are a bit less than those under the MR scheme. These results show that the MRMG scheme sometimes exhausts link bandwidth to serve greedy traffic (TCP and greedy UDP). As such, upon receiving the bandwidth requests from real-time CBR connections, granting nodes using the MRMG scheme may have less link bandwidth to service these requests than those using the MR scheme. One solution is to employ a collaborative bandwidth sharing algorithm on top of the MRMG scheme to guarantee proportional sharing of link bandwidth among different connections. Such an extension, however, is out of the scope of this paper and is left as future work.

VI. CONCLUSION

In this paper, we propose three schemes to improve the data scheduling performances of the IEEE 802.16(d) mesh DS mode. The proposed MR, MG, and MRMG schemes are presented in detail in this paper. Our simulation results show that the data scheduling efficiency of the IEEE 802.16(d) mesh DS mode and the network quality experienced by application programs are significantly improved under these schemes.

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