Exploiting Spectral Reuse in Resource Allocation, Scheduling, and Routing for IEEE 802.16 Mesh Networks

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***Abstract*—The IEEE 802.16 standard for wireless metropolitan area networks (WMAN) has been created to meet the need of wide-range broadband wireless access at low cost. The objective of this paper is to study how to exploit spectral reuse in an IEEE 802.16 mesh network through timeslot allocation, bandwidth adaptation, hierarchical scheduling, and routing. To the best of our knowledge, this is the first work which formally quantifies spectral reuse in IEEE 802.16 mesh networks and which exploits spectral efficiency under an integrated framework. Simulation results show that the proposed spectral reuse scheduling and load-aware routing significantly enhance the network throughput performance in IEEE 802.16 mesh networks.**

Keywords: IEEE 802.16, WiMax, Mesh Network, Resource Allocation, Routing, Wireless Network.

I. Introduction

The IEEE 802.16 standard for wireless metropolitan area networks (WMAN) is designed for wide-range broadband wireless access at low cost. It is based on a common medium access control (MAC) protocol with different physical layer specifications. The PHY layer can employ the orthogonal frequency division multiplexing (OFDM) below 11GHz or the single carrier (SC) scheme between 10GHz and 66GHz.

The MAC layer of IEEE 802.16 [4] can support the point-to-multipoint (PMP) mode and the mesh mode. In the PMP mode, subscriber stations (SSs) are directly connected to base stations (BSs). So all SSs associated to a BS must be within the transmission range of the BS. On the other hand, in the mesh mode, each SS can act as an end point or a router to relay traffics for its neighbors. So there is no need to have a direct link from each SS to its associated BS, and SSs may transmit at higher rates to their parent SSs/BS. Also, a BS can serve wider network coverage with lower deployment cost and higher robustness and flexibility [3]. However, intelligent routing and scheduling protocols are needed to fully exploit such benefits. For IEEE 802.16 mesh networks, efforts have been dedicated to topology design [10], packet scheduling [8], and QoS support [1].

This paper studies the spectral reuse issue in an IEEE 802.16 mesh network through multi-hop routing and scheduling. The proposed framework includes a load-aware routing algorithm and a centralized two-level scheduling scheme, which consider both traffic demands and interference among SSs. Given traffic patterns of SSs, we show how to achieve better spatial reuse and thus higher spectral efficiency. Table I compares our work against previous works. Reference [2] proposes an interference-aware route construction and a scheduling algorithms. However, the algorithm does not fully exploit spectral reuse and it is not load-aware (in the sense that the routing tree is a fixed one). How to attach a new SS to a mesh tree is discussed in [6], but scheduling is not addressed in that work. As pointed out in [5], the network performance highly depends on the order that SSs join the routing tree. Although [5] has taken routing tree reconstruction into account, the traffic demands of SSs are still not considered. Thus, the real traffic bottleneck of the network is not reflected. Compared to existing works, our work is most complete in exploiting spectral reuse in IEEE 802.16 mesh networks in the sense that it takes dynamic traffic loads of SSs into account and integrates not only a hierarchical bandwidth scheduling scheme for bandwidth adaptation and timeslot allocation, but also a routing algorithm with a tree optimization scheme.

TABLE I
Comparison of existing schemes and our results

	Scheduling		Routing	
Features	Reuse Quantification	Slot Assignment	Route Reconstruction	Load Awareness
Wei et al. [2]	N/A	Yes	N/A	N/A
Tao et al. [5]	N/A	Yes	Yes	N/A
Fu et al. [6]	N/A	N/A	N/A	N/A
Our work	Yes	Yes	Yes	Yes

The rest of the paper is organized as follows. Section II briefly reviews the IEEE 802.16 mesh mode and then formally defines our problem. Section III develops our resource allocation and scheduling framework, followed by our routing and tree construction algorithms. Performance evaluation is given in Section IV. Finally, Section V concludes this paper.

II. Backgrounds and Problem Definition

In an IEEE 802.16 mesh network, transmission schedules of SSs can be determined in a distributed manner by individual SSs, or in a centralized manner by the BS. In this work,

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to better exploit spectral reuse, we will focus on centralized scheduling, which is also most commonly used in the standard for Internet access.

In centralized scheduling, there are two control messages, MSH-CSCF (Mesh Centralized Scheduling Configuration) and MSH-CSCH (Mesh Centralized Scheduling). The BS can specify the current routing tree by using the last MSH-CSCF message and modify the tree by the last MSH-CSCH update. The BS will broadcast MSH-CSCF to all its neighbors, and all the BS neighbors rebroadcast this message to all their neighbors until all SSs have received the MSH-CSCF message. As a result, all SSs maintain a routing tree whose root is the BS and child nodes are SSs. On the other hand, SSs can transmit MSH-CSCH:Request messages to the BS for their traffic demands, which the transmission order is that the SS with the largest hop count transmits first, and retain the order to join the network for SSs with the same hop count. After collecting requests from all SS, the BS can broadcast its flow assignment for all SSs by the MSH-CSCH:Grant message. Since all SS know the current routing tree, they can determine the actual schedule from these flow assignments by dividing the frame proportionally.

In this work, we consider a mesh network with a gateway BS and a number of SSs for Internet access. For centralized scheduling, given the routing tree, the bandwidth demand requested by each SS, and the uplink and downlink data rates of each SS, a two-level scheduling scheme is designed for the following purposes: (1) dynamically adapt the bandwidths between uplink and downlink subchannels; (2) proportionally allocate frame timeslots among SSs; (3) obtain higher gateway throughput based on the above two manners. On the other hand, for routing tree construction, given the traffic demand generated by each SS and the data rate of each link between SSs, a load-aware routing algorithm is developed for constructing a load-balancing routing tree that can distribute evenly the forwarding data of all SSs and increase concurrent transmissions among SSs so as to get higher timeslot reuse ratio.

III. The Proposed Spectral Reuse Framework

A. System Model

We propose an integrated spectral reuse framework for IEEE 802.16 mesh networks, as illustrated in Fig. 1. There are a routing and a scheduling modules. The routing module collects the channel conditions and bandwidth requests of all SSs from MSH-CSCH:Request messages and computes a routing tree T for the mesh network. Next, the scheduling module conducts resource allocation, which contains *channel-level scheduling* (for bandwidth adaptation between uplink and downlink subchannels) and *link-level scheduling* (for timeslot allocation among SSs). Finally, the BS broadcasts the scheduling information to all SSs via MSH-CSCH:Grant messages. Below, we will focus on uplink traffic scheduling, since downlink traffic scheduling can be obtained similarly.

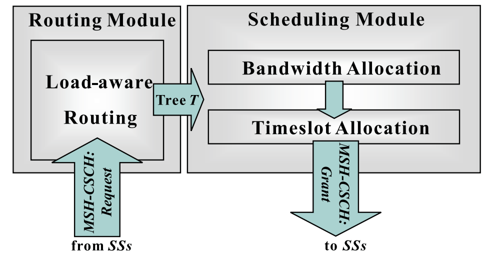

Fig. 1. The system model at BS

B. Resource Allocation and Scheduling Schemes

Below, we assume that the routing tree T is known (refer to Sec. 3-3 for the construction of T). We will derive our resource allocation schemes. Let the uplink data rate and uplink traffic demands of SS i be r_i^u and b_i^u, respectively. From T, we can calculate the aggregated uplink traffic demand $d_i^u = b_i^u + \sum_{j \in child(i)} b_j^u$ for SS i, where $child(i)$ is the set of children of i in T. Thus the demand of transmission time for the uplink of SS i is $T_i^u = d_i^u / r_i^u$. Let $C_{total}^u = \sum_{\forall i} T_i^u$ be the total uplink transmission time of the network, and $C_i^u = \sum_{j \in E_i} T_j^u$ be the total uplink transmission time of extended neighborhood of SS i, which contains SS i and its one-hop and two-hop neighbors. In the IEEE 802.16 standard, only a portion of T_i^u / C_{total}^u is allocated to the uplink transmission time of SS i. Clearly, SS i can detect busy carriers only in C_i^u / C_{total}^u portion of time. In the remaining $(1 - C_i^u / C_{total}^u)$ portion of time, SS i sees idle carriers. Our scheme is designed to exploit this portion of idle time for additional transmissions by raising the same ratio of allocated transmission time for all SSs.

For the fairness of all SSs in E_i, the portion of idle time should be divided proportionally by their transmission time demands. Thus the additional transmission time SS i can obtain is $(1 - C_i^u / C_{total}^u) \times T_i^u / C_i^u$. So the maximal transmission time with spatial reuse for SS i in the mesh network is $T_i^u / C_{total}^u + (1 - C_i^u / C_{total}^u) \times T_i^u / C_i^u = T_i^u / C_i^u$. Let $C_{max}^u = max\{C_i^u, \forall i\}$. For any SS i such that $C_i^u = C_{max}^u$, the SS could be the bottleneck of the network. Therefore, we propose to assign T_i^u / C_{max}^u portion of uplink transmission time to each SS i. It is clear that after assigning T_i^u / C_{max}^u portion of time to each SS i, the bottleneck SS will see 100% busy carriers, whereas other SSs such that $C_i^u < C_{max}^u$ can see some idle carriers. On the other word, we raise the same ratio of uplink transmission time for each SS i from T_i^u / C_{total}^u to T_i^u / C_{max}^u until the bottleneck SS sees 100% busy carriers.

As a result, the smaller C_{max}^u the mesh network can route, the larger transmission time each SS can get. Note that although the maximum of C_i^u among all SS i is used in the mesh network so that T_i^u / C_{max}^u is the lower bound of spectral reuse, actually the lower bound is also an upper bound when C_{max}^u is occurred at the one-hop neighborhood of the BS in most regular mesh networks since all the BS neighbors can not transmit or relay more data for themselves or other child SSs. Continuously, our two-level scheduling scheme with spectral reuse quantified above will be described in the following

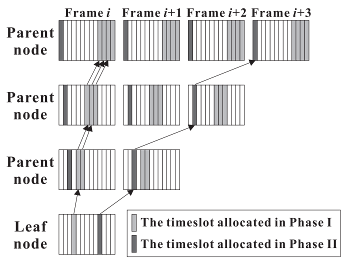

Fig. 2. The timeslots allocated in phase I and phase II

subsections.

1) Channel-Level Scheduling: The mesh mode supports only Time Division Duplex (TDD) to share the channel between downlink and uplink. The TDD framing is adaptive in that the bandwidth allocated to the downlink versus the uplink can vary. The split between uplink and downlink is a system parameter and is controlled at higher layers within the system. In our channel-level scheduling scheme, the ratio of downlink to uplink subchannel will be set to C^d_{max}/C^u_{max} that fits the traffic load distribution. Therefore, the first $F \times C^d_{max}/(C^d_{max} + C^u_{max})$ timeslots in each frame are assigned to downlink subchannel and the rest timeslots are assigned to uplink subchannel, where F is the number of timeslots in a frame. The well-arranged subchannel bandwidth for uplink and downlink could result in that the overall network throughput is increased significantly, which has been validated by simulation results in Section IV.

2) Link-Level Scheduling: In IEEE 802.16 mesh networks, SSs notify the BS their data transfer requirements and the quality of their links to their neighbors. The BS uses the topology information along with the requirements of each SS to decide the routing and the scheduling without spectral reuse. The frame fraction assigned to each SS i is T^u_i/C^u_{total} for uplink traffic in the IEEE 802.16 mesh mode specification, whereas the fraction is T^u_i/C^u_{max} in our scheduling with spectral reuse as mentioned at the beginning of Section III-B. Note that C^u_{max} is much smaller than C^u_{total} in a large IEEE 802.16 mesh network, which implies each SS can obtain much larger frame fraction from our scheduling algorithm.

For timeslot assignment, assume that there are N timeslots in a frame for uplink subchannel. We first allocate $N \times (T^u_i/C^u_{total})$ timeslots in phase I and then assign $N \times (T^u_i/C^u_{max} - T^u_i/C^u_{total})$ timeslots in phase II, which the total allocated timeslots to SS i is $N \times (T^u_i/C^u_{max})$. The allocated timeslots in phase I are assigned to each SS i in the mesh network according to its hop count from the BS, and retain the order to join the network for SSs with the same hop count. The allocated timeslots in phase II are inserted to the remaining space of frame allocation list for all SS j in E_i . As illustrated in Fig. 2, since the forwarding order for all SSs in the mesh network can be hold in phase I and thus the end-to-end delay between the BS and SSs can be minimized, SSs can utilize it by transmitting real-time traffic in order to reduce the packet delay. On the other hand, SSs can use the allocated timeslots in phase II without forwarding order to transmit non-real-time or best effort traffic since the packet delay is not crucial even though the end-to-end delay may be the duration of several frames. Note that the sum of the allocated timeslots for the SSs in the extended neighborhood with C^u_{max} equals to N exactly. Therefore, there are sufficient free timeslots in a frame to insert the allocated timeslots in phase I and phase II for those SSs in the extended neighborhood with C^u_i that is smaller than C^u_{max}. The link-level scheduling algorithm is described as follows.

Link-level scheduling algorithm

Phase I:

Allocate $N \times (T^u_i/C^u_{total})$ timeslots to each SS i according to the transmission order of MSH-CSCH:Request until all SSs have been allocated.

Phase II:

(1) Construct the frame allocation list L_i of E_i for each SS i in the network.

(2) According to the transmission order of MSH-CSCH:Request, assign the first $N \times (T^u_i/C^u_{max} - T^u_i/C^u_{total})$ free timeslots in L_i to SS i.

(3) Update all frame allocation lists L_j that E_j includes SS i.

(4) Repeat steps (2) and (3) until all SSs have been assigned.

C. Routing Tree Construction

The routing tree construction problem investigated in this section is to find a routing tree with the minimum C^u_{max} in a directed mesh network graph $G = (V, E)$ according to the traffic demand b_i requested by vertex $i \in V$ and the uplink data rate r^u_j of edge $j \in E$. We first prove that the routing tree construction problem is a NP-complete problem, and then propose a load-aware routing algorithm to reduce C^u_{max} for spectral efficiency. Below, we show the routing tree construction is NP-complete by proving that its decision problem is NP-complete.

The Problem

Given a directed mesh network graph $G = (V, E)$, the traffic demand b_i requested by vertex $i \in V$, the uplink data rate r^u_j of edge $j \in E$, and a real number R, determine whether G has a routing tree such that its $C^u_{max} \leq R$.

□ **Theorem 1**

The routing tree construction problem is NP-complete.

Proof: The routing tree construction belongs to NP, since we can guess a routing tree and check whether its $C^u_{max} \leq R$ easily in polynomial time. To prove that the routing tree construction problem is NP-complete, we have to reduce an NP-complete problem to it. We use the partition problem: the input is a set X such that each element $x \in X$ has an associated size $s(x)$. The problem is to determine whether it is possible to partition the set into two subsets with exactly the same total size. [7]

Consider a special case of mesh networks in Fig. 3. Assume that E_a and E_b are not overlapped, all uplink data rates in E_a and E_b are the same and low enough such that C^u_{max} is $max\{C^u_a, C^u_b\}$, and there are n SSs $(x_1, x_2, \ldots, x_n)$ be neighbors of SS c and SS d. Let the traffic demands of all SSs in the mesh network except x_1, x_2, ... , and x_n be zero.

Now we start to reduce the partition problem to the special case of the routing tree construction problem. Let $X = \{x_1, x_2, \ldots, x_n\}$, $s(x_k)$ be the traffic demand of x_k for $k = 1, 2, \ldots, n$, and $R = 5/2 \cdot \sum_{\forall k} s(x_k)/r_{slow}$, where r_{slow} is the data rate of slow link in Fig. 3. The parent node of x_k is either vertex c or vertex d. Thus, we can get the smallest C^u_{max} by partitioning $X(x_1, x_2, \ldots, x_n)$ into two subsets (SS c and SS d) with exactly the same total size. Therefore, if there is a routing tree such that $C^u_{max} = R$ in G, then there is a partition to divide X into two subsets with exactly the same total size. This reduction can obviously be performed in polynomial time. Since the special case of the routing tree construction problem is NP-complete, the general case is also NP-complete. □

To achieve efficient spectral reuse and high throughput in IEEE 802.16 mesh networks, we propose a load-aware routing algorithm to reduce C^u_{max} for uplink traffic. In our algorithm, we assume the initial value of C^u_i is $\sum_{j \in E_i} d^u_j / r^u_j(max)$ for each SS i in the mesh network, where $d^u_j = b^u_j$ and $r^u_j(max)$ is the highest data rate among links of SS j to its neighbors with less or equal hop count. The tree construction uses a bottom-up fashion that each SS i with the largest hop count to the BS will be first attached to its neighbors k which have less or equal hop count to estimate each new C^u_k, and then the SS which has minimum C^u_k will be chosen as the parent node of SS i. If there are several SSs with the same minimum C^u_k, the SS with smaller hop count has the higher priority. Once each SS with largest hop count has been attached to its parent node, the remaining SSs without a parent node repeat the above procedure until each SS in the mesh network has a parent node. Note that the step (2) in load-aware routing algorithm is to build the subtree with the minimum C^u_k first, which can balance the distribution of forwarding traffic and further reduce C^u_{max}.

Load-aware routing algorithm

(1) Let A be the set of SSs without a parent node that have the largest hop count, and B the empty set

(2) Estimate each C^u_k for all neighbors k with less or equal hop count when SS i in A becomes the child of SS k, and the SS with the smallest C^u_k will be chosen as the parent node of SS i

(3) Remove SS i from A, add SS i into B, and update C^u_l for all SS $l \in E_i \cup E_k$

(4) Repeat steps (2) and (3) until there is no SS in A

(5) Repeat steps (1) $\sim$ (4) until each SS has a parent node

The analysis of time complexity is as follows. Since each SS only has a parent node, steps (2) and (3) just repeat n times, where n is the number of SSs in the network. The dominant part of steps (2) and (3) is the step (2) that selects the smallest one from at most $m \times d$ estimated C^u_k values, where m is the maximum number of SSs with the same hop count, and d is the maximum degree of SSs. Therefore, the algorithm takes $O(nmd)$ time to build the routing tree.

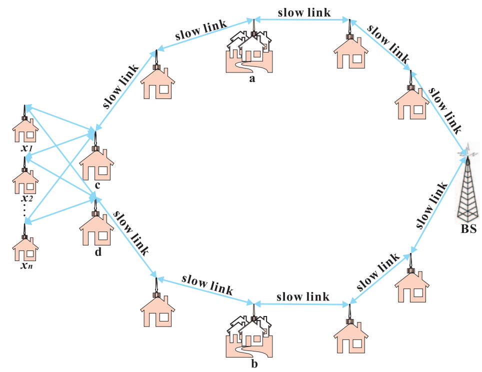

Fig. 3. The special case of the routing tree construction problem

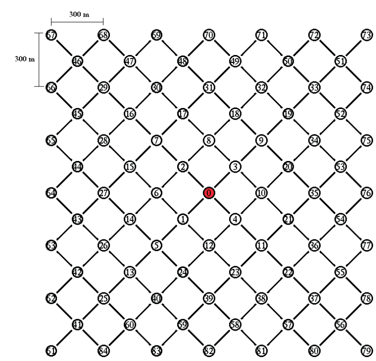

Fig. 4. The node placement in the regular mesh topology

IV. Performance Evaluation

In this section, we provide ns-2 [9] simulation results for the spectral reuse framework and compare it with the basic 802.16 mesh operation in [4] as well as the concurrent transmission with route adjustment in [5]. The typical TCP/IP/LL/MAC/PHY stack is used in our study. In addition, we adopt a single channel OFDM PHY and two-ray ground reflection model for radio propagation, and all the SSs are stationary and working in half duplex. In our work, we extend the TDMA MAC module in ns-2 for timeslot reuse in a multi-hop environment and use it to study the system performance.

In our simulation, the node placement in the regular mesh topology is shown in Fig. 4. There are totally at most 85 nodes which consist of a single BS (node 0) and 84 SSs (node 1 $\sim$ 84), and the one-hop neighbors are connected by lines. The channel bandwidth is set to 50 Mb/s and the data rates of all links are the same for simplicity. The extended neighborhood of each SS includes one-hop and two-hop neighbors. The random routing tree is used in the basic 802.16 mesh mode and our link-level scheduling except that the load-aware routing is marked on the figures. Note that the overall network throughput has been normalized by the performance of basic 802.16 mesh operation so that the scalability and improvement of our proposed framework are clearly demonstrated in the simulation results.

Fig. 5 shows the normalized gateway throughput with different scheduling and routing methods, respectively. The

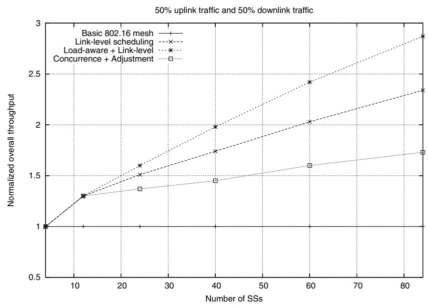

Fig. 5. The performance comparison for link-level scheduling

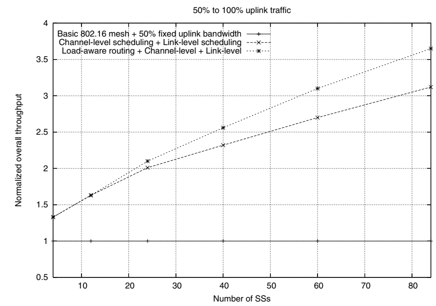

Fig. 6. The performance comparison for channel-level scheduling

number of SSs increases from 4, 12, 24, 40, 60, to 84 and all SSs request the same bandwidth for uplink and downlink. The throughput values are the average of simulation in 100 times with random load distribution among SSs. As shown in Fig. 5, the proposed link-level scheduling scheme outperforms the basic mesh mode significantly. Also, the routing tree generated by the load-aware routing algorithm further improves the throughput. It is because that in the basic 802.16 mesh scheme, the network throughput drops significantly as the number of SSs increases due to the fact that a packet needs to be forwarded several times since the length of relay route increases with the number of SSs in the network, whereas the proposed link-level scheduling is much more scalable than the basic scheme since the degree of spectral reuse increases with the network size. In addition, the load-aware routing algorithm produces better routing paths to distribute the traffic more evenly in the mesh network. Therefore, the scheme with both the load-aware routing and link-level scheduling achieves the highest network throughput. The scheme only using link-level scheduling still has the second best performance. On the other hand, since there is no scheduling algorithm provided in [6] and the concurrent transmission scheme in [5] outperforms that without route adjustment in [2], we also compare the performance of concurrent transmission with route adjustment in the simulation. The non-load-aware routing method constructs a routing tree according to the SS positions, which can not release the traffic bottleneck in the network efficiently. Thus, the benefit of route adjustment has been limited in the nature unless every SS generates the same traffic load under the same link data rate. In addition, the concurrent transmission algorithm forces SSs can not transmit data earlier than their child SSs so that the utilization of spectral reuse is reduced significantly. Therefore, its throughput improvement is much lower than our integrated spectral reuse framework.

Fig. 6 shows the normalized overall throughput with channel-level and link-level scheduling schemes. The configuration of simulation is as same as in Fig. 5. However, every SS requests 50% to 100% uplink bandwidth randomly, and thus the downlink bandwidth requested is 0% to 50% which depends on the uplink bandwidth requested. Note that the basic 802.16 mesh mode allocate the bandwidth equally for uplink and downlink subchannels. As shown in Fig. 6, the proposed channel-level and link-level scheduling scheme outperforms the basic mesh mode more significantly. Again, the combined routing and scheduling scheme gets the highest system throughput. This is because that channel-level can adapt dynamically the bandwidth between uplink and downlink subchannels based on the traffic load distribution in the mesh network. Using load-aware routing, the network throughput can be enhanced as the number of SSs increases. As a result, the combination of channel-level and link-level scheduling as well as load-aware routing can fit more traffic patterns so as to keep high network performance.

V. Conclusions

In this paper, we have formally quantified spectral reuse in IEEE 802.16 mesh networks. Also, an integrated spectral reuse framework for centralized scheduling scheme and routing tree construction is developed. Compared to existing works, our work is most complete in exploiting spectral reuse in IEEE 802.16 mesh networks in the sense that it takes dynamic traffic loads of SSs into account and integrates bandwidth adaptation, timeslot allocation, as well as routing tree construction under a framework. Simulation results indicate that the spectral reuse scheduling and load-aware routing significantly increase the overall throughput in IEEE 802.16 mesh networks.

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