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Joint Optimization of Routing and Scheduling for Higher Throughput in IEEE 802.16 Mesh Networks

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***Abstract*— Wireless mesh networks are emerging to be a promising technique for the next generation wireless networks. Specifically, the MAC layer in IEEE Standard 802.16-2004 supports mesh mode. In this paper, an optimal scheduling scheme is proposed to increase the network throughput. The problem of finding the maximum network throughput in the optimal scheduling scheme can be formulated as an integer linear problem. Meanwhile, a minimal interference routing algorithm is introduced to improve the network throughput by reducing the interference among the links. Furthermore, the simulation results show that the combination of the optimal scheduling scheme and the minimal interference routing algorithm can achieve significant improvement in the throughput performance.**

I. INTRODUCTION

Broadband wireless access (BWA) systems, e.g. IEEE 802.16 family of standards [1]–[3], have been considered as a promising approach for high-speed wireless access networks. These standards provide high data rates over large areas and offer an attractive alternative to cabled access networks, such as fiber optic links, coaxial systems using cable modems, and digital subscriber line (DSL) links, etc.

In IEEE Standard 802.16-2004 [1], the wireless system in license-exempt frequencies between 2 and 11 GHz provides optional support for mesh topology. In the mesh mode, traffic can be routed through other subscriber stations (SSs) and can occur directly between SSs. Wireless mesh networks, which have started an upsurge in the wireless research area in recent years, have many advantages, such as high reliability, wide coverage, low upfront investments, and easy configuration [4]. Wireless mesh networks are characterized by multi-hop radio broadcast environment and spatial reuse can be used to increase the capacity of the network. The idea of spatial reuse is that several nodes, which are far enough in space, can make transmissions simultaneously in the same channel without a packet collision. However, interference among multiple paths limits the effectiveness [5]. Hence, independent multiple paths, where transmissions along the different links do not interfere with each other, are highly desirable. In IEEE Standard 802.16-2004, the detailed design of the routing algorithm over multiple paths is not specified and has been left for further study [6], [7].

In this paper, we investigate the scheduling and routing algorithms in IEEE 802.16 mesh networks while considering the wireless interference. Specifically, we propose an optimal scheduling scheme and a minimum interference routing algorithm to increase the overall network throughput. In the optimal scheduling scheme, the problem of finding the maximum network throughput can be formulated as an integer linear problem. We also propose the minimum interference routing algorithm to improve the network throughput by reducing the interference among the links.

The rest of the paper is organized as follows: in Section II we describe the details of our interference model. The optimal scheduling scheme in the IEEE 802.16 mesh networks is described in Section III. In Section IV, we propose the minimum interference routing algorithm. Section V presents the simulation results and the discussions. Finally, the conclusions are drawn in Section VI.

II. SYSTEM MODELS

A. The Interference Model

We adopt the protocol model similar to those introduced in [8] and [9] to define our interference model. Consider a wireless network with N nodes arbitrarily located in a disk of unit area in the plane. Let n_i, $1 \leq i \leq N$ denote the nodes, and X_i denote the location of the node n_i. The wireless transmissions in the network are assumed to be homogeneous. Nodes in the network including the SSs and the mesh base station (BS) are assumed to have the same transmission range, which is denoted by r.

A transmission from node n_i is successfully received by node n_j in a single wireless channel if both of the following conditions are satisfied:

(1) Node n_j is in the transmission range of node n_i, i.e.,

$$|X_i - X_j| \leq r$$

where $|X_i - X_j|$ represents the distance between node n_i and node n_j in the plane.

(2) For every other node n_k simultaneously transmitting over the same channel,

$$|X_k - X_j| > (1 + \Delta)r$$

$\Delta \geq 0$ is required. This condition guarantees a protection zone around the receiving node to prevent a neighboring node from transmitting on the same channel at the same time. The parameter Δ defines the size of the protection zone. $(1+\Delta)r$ represents the interference range of the receiving node n_j. Note that the model requires only the receiver to be free of interference.

B. Interference Matrix

According to our interference model, we define the interference matrix T to model the effects of wireless interference. For a network with M links, the interference matrix is an $M \times M$ matrix with elements T_{ij} such that:

$$T_{ij} = \begin{cases} 0, & \text{if link } i \text{ and link } j \text{ can be active simultaneously,} \\ 1, & \text{otherwise.} \end{cases}$$

III. Optimal Scheduling

In IEEE 802.16 mesh networks, all the SSs in the mesh network share a common wireless channel with a combination of TDMA (Time Division Multiple Access) and DAMA (Demand Assigned Multiple Access) mechanisms. The channel is divided into a number of time slots of fixed durations. Communications on all the links in the mesh network can be scheduled by a centralized algorithm, or by a distributed algorithm, or by a combination of both. For better control in the IEEE 802.16 mesh networks, we adopt the centralized scheduling mechanism. In the centralized scheduling, the mesh BS acts as a centralized scheduler for all the mesh SSs. The mesh BS gathers resource requests from all the mesh SSs and determines the amount of granted resources for each link in the network.

Each mesh SS has to transmit relayed traffic as well as its own in the mesh mode. The traffic that has to be forwarded by each link can be computed by each mesh SS. The mesh BS has perfect knowledge of the topology and the traffic loads of all the mesh SSs. So the mesh BS can schedule the transmissions of all the links. We propose an optimal scheduling scheme in which the mesh BS can allocate the same time-slot to the links that do not interfere with each other. Our goal is to maximize the overall network throughput.

In order to analyze the maximum throughput of the optimal scheduling scheme, we first define a maximal independent set (MIS). The links belonging to a maximal independent set can be active simultaneously without interfering with each other. However, if we add another link to the set, there is a packet collision. Given the interference matrix T of the network, one can decide all its maximal independent sets.

For a network with M links and K maximal independent sets $I_1, I_2, \cdots I_K$, we define a matrix R as an $M \times K$ matrix with elements R_{ij} such that:

$$R_{ij} = \begin{cases} 1, & \text{if link } i \text{ is in the maximal independent set } I_j, \\ 0, & \text{otherwise.} \end{cases}$$

Let $F = (F_1, F_2, \cdots, F_M)$ and $u = (u_1, u_2, \cdots, u_K)$, where F_i, $1 \leq i \leq M$ and u_j, $1 \leq j \leq K$ denote the traffic load of link i and the number of time-slots allocated to the maximal independent sets I_j, respectively. The problem of maximizing the network throughput is converted to the problem of minimizing the total time-slots the network needs to transmit all the traffic. It can be formulated as an integer linear programming problem, shown as follows:

$$\begin{array}{lll} min & \sum_{i=1}^{K} u_i & \\ s.t. & Ru^T \geq F^T & \\ & u_i \geq 0 & 1 \leq i \leq K \\ & int. \quad u_i & 1 \leq i \leq K \end{array}$$

IV. Minimal Interference Routing

In IEEE 802.16 mesh networks, a new node entering the network shall first search for the mesh network configuration (MSH-NCFG) messages to acquire coarse synchronization with the network. The new node, which is termed as candidate node in IEEE Standard 802.16, listens to active nodes and accumulates MSH-NCFG messages with Network Descriptor. The candidate node selects one of its neighbors as the candidate sponsoring node by transmitting a mesh network entry (MSH-NENT) message with NetEntryRequest information. Upon reception of the MSH-NENT message, the candidate sponsoring node shall assess the request and either opens the sponsor channel for further initialization procedure or rejects the request. If the candidate sponsoring node accepts the request, the candidate sponsoring node becomes the sponsoring node. Finally, the authorization and the registration processes shall be performed.

The routing algorithm in multi-hop wireless networks is crucial in order to achieve high throughput performance. We propose a new and effective routing algorithm that considers the interference among links in the mesh networks. We define the collision metric $C(i)$ to model the interference level of the ith link. The collision metric $C(i)$ indicates the number of links that interfere with link i. As defined in the interference model, link i is interfered by link j when the receiving node of link i is within the interference range of the transmitting node of link j.

We illustrate our routing algorithm through the simple case depicted in Figure 1. Both SS_6 and SS_7 are in the transmission range of the new SS, which is entering the mesh network. So the new SS has two choices while selecting the sponsoring node. The link between the new SS and SS_6 is denoted as l_a and the link between the new SS and SS_7 is denoted as l_b. According to the interference model, l_a is interfered by links 2,5,6 and 7 and l_b is interfered by links 1,2,4,5,6 and 7. Therefore, $C(l_a)$ is 4 and $C(l_b)$ is 6. Our design approach in the proposed routing scheme is to select the sponsoring node with the least interference. So in the example in Figure 1, we select SS_6 as the sponsoring node and establish a new link between the new SS and SS_6 for transmitting the traffic of the new SS.

The procedures of our routing algorithms begin with a single mesh BS node, and then one SS node is added into the mesh network at a time. Direct communication links are created

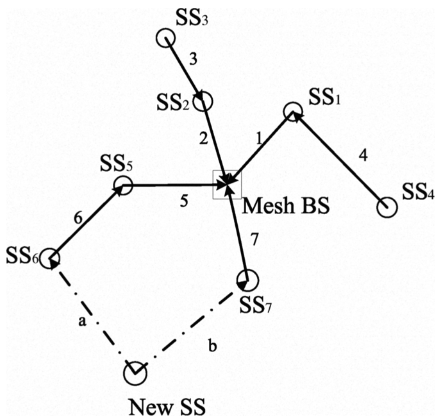

Fig. 1. An illustration of minimal interference routing algorithm

between the mesh BS and the SSs if the SSs are in the transmission range of the mesh BS. For the SSs, which are not in the direct coverage range of the Mesh BS, the connections can be provided via other SSs. For each new SS, among the multiple available paths, the collision metric of each choice is computed and the sponsoring SS with the minimum collision metric value is chosen.

The concept of our routing algorithm is that by using the position information of the SSs and the network topology information, we can select a circuitous but less interference-prone route along the periphery of a network instead of picking a shorter but more interference prone route through the middle of the network in order to reduce the interference among the links hence to improve the network throughput.

V. Simulation and Results

In this section, we give some results on the performance of optimal scheduling scheme and the minimum interference routing algorithm. The proposed schemes are compared to the basic 802.16 schemes defined in IEEE Standard 802.16-2004 [1]. First, we evaluate the performance of minimum interference routing in an arbitrary mesh topology; then we evaluate the throughput performance of taking consideration of both scheduling and routing in a planar topology.

We start with several simplifying assumptions. We assume that there is only one mesh BS in the network and the traffic is unidirectional from the mesh SSs to the mesh BS. We also assume that all SSs generate the same amount of traffic.

A. Routing in Arbitrary Mesh Topology

The SSs are randomly distributed in an area of 1 square kilometer. The mesh BS is set in the center of the plane. We assume that the communication range of each node is 300 meters, while the interference range is 350 meters. The number of SSs varies from 40 to 80.

In our proposed routing scheme, the order of SSs joining the mesh network is arranged by the location of each SS: SS, which is close to the mesh BS, joins into the network first. We start with the mesh BS, SSs within the transmission range of the mesh BS get direct access to the mesh BS. For each new SS that is not in the direct coverage range of the mesh BS, the new node selects the sponsoring SS with the minimum collision metric value.

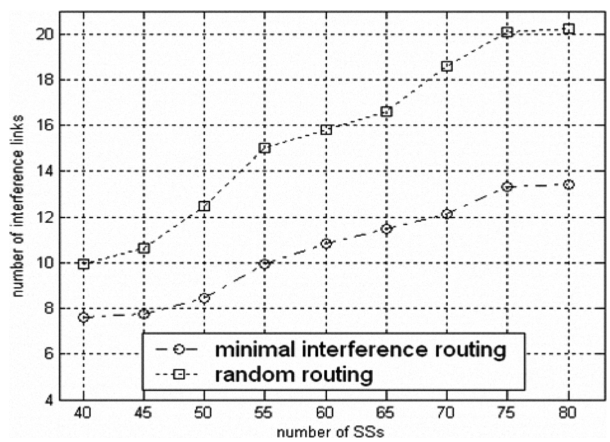

Fig. 2. Collision metric in arbitrary topology

The collision metric in our scheme is compared with the collision metric when the new SS selects a sponsoring node in a random way. Figure 2 shows the results of the average collision metric when the number of SSs varies from 40 to 80 in the two scenarios. As the number of SSs in the plane increases, the number of interference links in our proposed routing scheme increases much slower than that in the random routing algorithm. The improvement is becoming greater as the number of SSs increases.

B. Throughput Performance

We investigate the throughput performance while taking consideration of both scheduling and routing algorithms in the 802.16 mesh networks. In our simulation, the nodes are placed in a 5×5 grid. There are totally 24 mesh SSs and 1 mesh BS. The mesh BS is placed in the center. The horizontal and vertical separation between adjacent nodes is 250 meters. We assume that the communication range is 300 meters and the interference range is 360 meters.

We consider the following four scenarios:

Scenario I: random routing with basic 802.16 MAC scheduling.
Scenario II: minimal interference routing with basic 802.16 MAC scheduling.
Scenario III: random routing with optimal scheduling.
Scenario IV: minimal interference routing with optimal scheduling.

Table I shows the throughput performance of each scenario. The results show that when the networks adopt the same

TABLE I

THROUGHPUT PERFORMANCE

Scenario	Throughput
I	0.4000
II	0.4000
III	0.7500
IV	0.9231

routing algorithm, the overall network throughput in the network with optimal scheduling is greater than the network with basic 802.16 MAC scheduling. It is also clear that minimum interference routing yields better throughput performance than the random routing when optimal scheduling is used in both cases. The network with both the minimal interference routing and the optimal scheduling achieves the highest network throughput.

The network topology with minimum interference routing is shown in Figure 3. By solving the integer linear program in section III, we can find out that in scenario IV, when the mesh BS allocates the time-slots to each maximal independent set in the proportion shown in table II, the maximum network throughput is achieved.

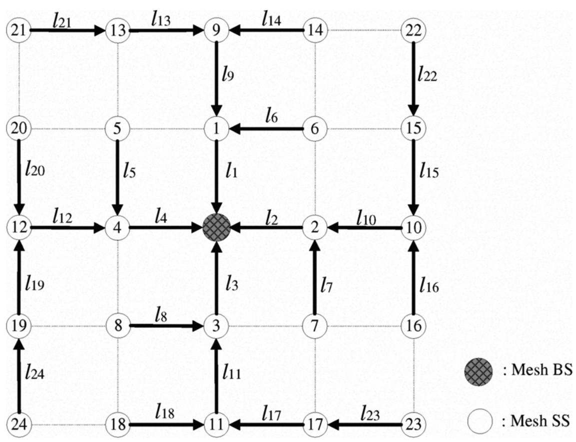

Fig. 3. Network topology with minimal interference routing

VI. CONCLUSION

In this paper, we have proposed the optimal scheduling scheme in which the BS allocates different time-slots to each Maximal Independent Set instead of different links to increase the overall network throughput. We used the concept of collision metric to model the interference level and have proposed a novel routing algorithm to reduce the number of links that interfere with each other. The simulation results demonstrate that our proposed schemes effectively improve the network throughput performance. We can also conclude that jointly optimizing the scheduling and routing can achieve better throughput performance.

TABLE II

THE PROPORTION OF TIME-SLOTS ALLOCATED TO EACH MIS

I_i	links belonging to I_i	the proportion of time-slots allocated to I_i
I_1	$l_1, l_{11}, l_{15}, l_{19}$	3/26
I_2	$l_1, l_{11}, l_{15}, l_{20}, l_{24}$	1/26
I_3	$l_1, l_{11}, l_{16}, l_{19}, l_{22}$	1/26
I_4	$l_1, l_{15}, l_{18}, l_{19}, l_{23}$	1/26
I_5	$l_2, l_{12}, l_{13}, l_{17}$	5/26
I_6	$l_2, l_{12}, l_{14}, l_{17}, l_{21}$	1/26
I_7	l_3, l_9, l_{15}, l_{19}	6/26
I_8	$l_4, l_{10}, l_{13}, l_{17}$	6/26
I_9	l_5, l_7, l_{22}, l_{24}	1/26
I_{10}	l_6, l_8, l_{21}, l_{23}	1/26

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REFERENCES

[1] IEEE Std 802.16-2004, “IEEE Standard for Local and Metropolitan Area Networks—Part 16: Air Interface for Fixed Broadband Wireless Access Systems,” October 2004.

[2] IEEE Std 802.16-2001, “IEEE Standard for Local and Metropolitan Area Networks—Part 16: Air Interface for Fixed Broadband Wireless Access Systems,” April 2002.

[3] IEEE Std 802.16a-2003, “IEEE Standard for Local and Metropolitan Area Networks—Part 16: Air Interface for Fixed Broadband Wireless Access Systems—Amendment 2: Medium Access Control Modifications and Additional Physical Layer Specifications for 2–11 GHz,” April 2003.

[4] Ian F. Akyildiz and Xudong Wang, “Wireless mesh networks: a survey,” *Computer Networks*, vol. 47, no. 4, pp. 445-487

[5] Kamal Jain, Jitendra Padhye, Venkata N. Padmanabhan and Lili Qiu, “Impact of Interference on Multi-hop Wireless Network Performance,” *in Proc. ACM Annual International Conference on Mobile Computing and Networking (MOBICOM)*, Sep. 2003

[6] Liqun Fu, Zhigang Cao and Pingyi Fan, “Spatial Reuse in IEEE 802.16 Based Wireless Mesh Networks,” *in Proc. IEEE International Symposium on Communications and Information Technology*, 2005

[7] Hungyu Wei, Samrat Ganguly, Rauf Izmailov and Zygmunt J. Haas, “Interference-Aware IEEE 802.16 WiMax Mesh Networks,” *in Proc. IEEE VTC*, Spring 2005.

[8] Piyush Gupta and P.R. Kumar, “The Capacity of Wireless Networks,” *IEEE Trans. Information Theory*, vol. 46, no. 2, pp. 388-404, March 2000.

[9] Benyuan Liu, Zhen Liu and Don Towsley, “On the Capacity of Hybrid Wireless Networks,” *in Proc. IEEE INFOCOM*, April 2003.