Spatial Reuse in IEEE 802.16 Based Wireless Mesh Networks

Liqun Fu, Zhigang Cao and Pingyi Fan
State Key Laboratory on Microwave and Digital Communications
Department of Electronic Engineering
Tsinghua University, Beijing, China, 100084
E-mail: flq03@mails.tsinghua.edu.cn

[1]***Abstract*— The IEEE Standard 802.16 supports for creating wireless mesh networks. The primary advantage of mesh networks is an improvement of capacity by concurrent transmission in the wireless environment. Therefore, the degree of spatial reuse is very crucial to realize the full potential of such wireless mesh networks. In this paper, we investigate the spatial reuse in IEEE 802.16 mesh networks. We propose a scheduling mechanism and a routing algorithm taking into account the interference in wireless environment to achieve maximum spatial reuse hence to increase the overall network throughput. The simulation results show that the proposed schemes achieve significant improvement and are more effective.**

***Key words*—IEEE 802.16, wireless mesh networks, spatial reuse, multi-hop, interference**

I. Introduction

IEEE Standard 802.16-2004[1] defines the air interface, including the MAC (Medium Access Control) layer and physical layer specifications of fixed broadband wireless access (FBWA) systems that support multimedia services. It provides high data rates up to 70 Mbps over large areas and offers an alternative to cabled access networks, such as fiber optic links, coaxial systems using cable modems, and Digital Subscriber Line (DSL) links, etc..

In the first version of IEEE Standard 802.16, the MAC layer only supports point-to-multipoint (PMP) topology, on which traffic only occurs between the Base Station (BS) and Subscriber Stations (SSs). In addition to the PMP mode, The MAC layer in IEEE Standard 802.16a[2], which was integrated into IEEE Standard 802.16-2004, defines the control mechanisms and management messages to establish connections in mesh network architectures. In the mesh mode, traffic can be routed through other 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 good reliability, high coverage, low upfront investments, and easy configuration.

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 collision. Both the bandwidth allocation algorithms in MAC layer and the routing strategies in network layer have significant effects on the performance of spatial reuse.

Many existing routing protocols use minimum hop-count as a performance metric to select the routing path. However, this has been demonstrated not being a sufficient one [3]. The reason is that the link on the minimum hop-count path between two nodes may have bad quality. Flow contention graph is used in [4] to capture interference in wireless networks. But the purpose of this paper is to study MAC fairness issues. The notion of interference-aware scheduling and routing are introduced in [5] to achieve higher spectral efficiency. However, the interference is just defined by the number of intermediate nodes along the route, which does not reflect the actual interference in wireless networks.

In this paper, we investigate the spatial reuse in IEEE 802.16 mesh networks while considering the wireless interference. We develop a scheduling mechanism and a routing algorithm to maximize the spatial reuse in the wireless mesh networks and thus to achieve better overall network throughput and higher spectral efficiency.

The rest of the paper is organized as follows: in Section II we give a brief introduction to the IEEE 802.16 mesh networks. Section III presents the details of our Interference Model and algorithm for maximizing the spatial reuse in IEEE 802.16 mesh networks. In Section IV we provide simulation results of our method. Finally, the conclusions are drawn in Section V.

II. IEEE 802.16 Mesh Networks

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 IEEE

This research was supported by the NSF of China (No.60472027)

802.16 mesh network, a node that has a direct connection to backhaul services outside the mesh network is termed as a Mesh BS. All other nodes in the mesh network are termed as Mesh SSs.

Five kinds of MAC management messages are defined in the standard for mesh mode operation. Mesh Network Configuration (MSH-NCFG) messages provide the basic information of the network configuration. Mesh Network Entry (MSH-NENT) messages provide the means for a new node to gain synchronization and initial network entry into a mesh network. Mesh Centralized Scheduling (MSH-CSCH) and Mesh Centralized Scheduling Configuration (MSH-CSCF) messages shall be used when the mesh network adopts the centralized scheme for bandwidth requests and grants. While using the distributed scheme, Mesh Distributed Scheduling (MSH-DSCH) messages shall be involved.

All the SSs in the mesh network share the 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. The time slot is termed as a minislot, which is the smallest unit in bandwidth allocation process. Communication on all the links in the Mesh network shall be scheduled by a centralized algorithm, or by a distributed algorithm, or by a combination of both. For better spatial reuse in the IEEE 802.16 mesh networks, we adopt the centralized scheduling mechanism. In centralized scheduling, the Mesh BS acts as a centralized scheduler for all the Mesh SSs. The Mesh BS shall gather resource requests from all the Mesh SSs and determine amount of granted resources for each link in the network.

A new node that enters the mesh network shall first search for 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 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.

In wireless mesh networks, multiple paths are available between the source and destination. The use of the multiple paths not only can provide high fault tolerance, but also can increase the network capacity. However, interference between multiple paths limits the effectiveness. 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 detail design of the routing algorithm over multiple paths is not specified and has been left for further study. We propose a new routing strategy to maximize the degree of spatial reuse achievable in the mesh network hence to increase the overall throughput.

III. SPATIAL REUSE IN 802.16 MESH NETWORKS

A. *Interference Model*

We adopt the Protocol Model to define our interference model. These models are similar to those introduced in [6] and [7]. Consider a wireless network with N nodes arbitrarily located in a disk of unit area in the plane. Let n_i, $1 \le i \le N$ denote the nodes, and X_i denote the location of the node n_i. Nodes in the network 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.,

$$|X_i - X_j| \le r$$

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,

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

$\Delta \ge 0$ is required. $(1+\Delta)r$ represents the interference range of the receiving node n_j. Note that the model requires only the receiver to be free of interference.

B. *Spatial Reuse in Chain Topology*

Let us consider the chain topology first. In Figure 1, each SS generates traffic to be forwarded to the Mesh BS. It assumes that all nodes use the same channel for the transmissions and they have the same transmission range just enough to reach their neighbors, so each node can only receive packets from its immediate neighbor nodes. It also assumes that the interference range is equal to the communication range.

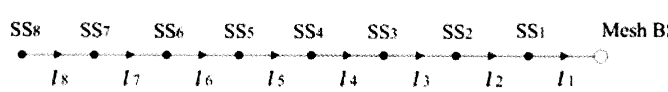

Fig. 1. A linear-chain topology n=8

In mesh networks, we consider the issue of fairness. An SS has to transmit relayed traffic as well as its own.

Besides contention with other SSs, there is inevitable contention between its own and relayed traffic. A detailed illustration is presented in [8]. So we assume that all SSs generate the same amount of traffic and there exists a mechanism for enforcing absolute fairness for all SSs.

Due to the Interference Model and the assumptions, when link 3 is active, links 1, 2, 4, 5 ought to be silent, otherwise the transmissions will result in collision. The Mesh BS has perfect knowledge such as the topology and the traffic loads of all SSs. So the Mesh BS can schedule transmissions at all links to maximize spatial reuse. The Mesh BS can allocate the same timeslot to the links, which do not interfere with each other. The maximum spatial reuse is achieved when all links at 3-hop distance from each other are active simultaneously. That means links 1, 4 and 7 can be active simultaneously without interfere with each other, then links 2, 5 and 8, and so on.

C. *Spatial Reuse in Arbitrary Topology*

The routing algorithm in multi-hop wireless networks is crucial in order to achieve high spatial reuse. 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 *i*th link. The *collision metric C(i)* indicates the number of links that are interfered with link *i*. As defined in the Interference Model, link *i* is interfered with link *j* when the receiving node of link *i* is within the interference range of the transmitting node of link *j*.

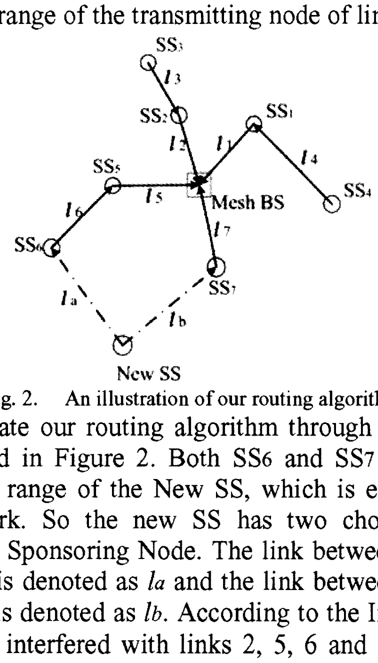

Fig. 2. An illustration of our routing algorithm

We illustrate our routing algorithm through the simple case depicted in Figure 2. Both SS6 and SS7 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 SS6 is denoted as *la* and the link between the new SS and SS7 is denoted as *lb*. According to the Interference Model, *la* is interfered with links 2, 5, 6 and 7 and *lb* is interfered with links 1, 2, 4, 5, 6 and 7. Therefore, *C(la)* is 4 and *C(lb)* 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 2, we select SS6 as the Sponsoring Node and establish a new link between the New SS and SS6 for transmitting the traffic of the New SS.

The procedures of our routing algorithms are described as follows. Beginning with a single Mesh BS node, we add one SS into the mesh network at a time. We create direct communication links 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 we compute the collision metric of each choice and choose the Sponsoring SS with the minimum collision metric value.

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 achieve better spatial reuse hence to improve the throughput.

IV. Simulation and Results

In this section, we evaluate the performance of our proposed scheme for IEEE 802.16 mesh networks, using Matlab tool. Two scenarios were considered: a linear chain topology and an arbitrary mesh topology.

A. *Chain Topology*

In the chain topology, we assume that the traffic is unidirectional from the SSs to the Mesh BS. By enforcing absolute fairness here, each SS receives an equal share of the bandwidth available in the network. We also assume that the transmission range of each SS is equal to the interference range and is just enough to reach its lateral neighbors.

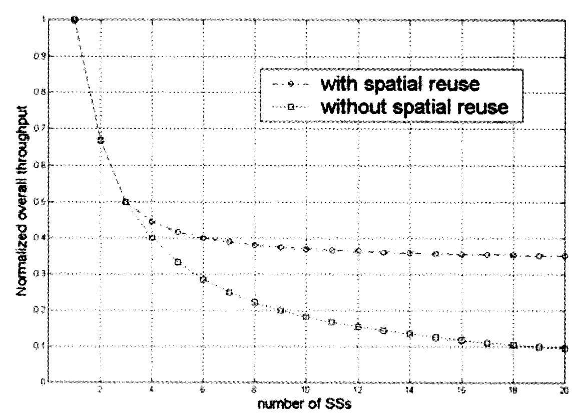

Fig. 3. Normalized overall throughput in chain topology

The throughput of the basic IEEE 802.16 mesh networks without spatial reuse is compared with that of our proposed scheme.

Figure 3 shows the result of the simulation. As the number of SSs increases, the overall network throughput drops significantly in the basic IEEE 802.16 mesh network.

In our proposed scheme with maximum spatial reuse the overall network throughput degrades gracefully. The throughput decreases due to the fact that before the traffic reaches the Mesh BS it has to be relayed several times by other SSs. As the number of SSs in the chain increases, the traffic needs to be forwarded many more times.

In the proposed scheme described in Section III, when the maximum spatial reuse is achieved, links at 3-hop distance from each other can be active simultaneously. Therefore as the length of the chain increases, the number of links that can be active at the same time also increases. This will effectively compensate the reduction in the throughput in the multi-hop wireless networks.

B. Spatial Reuse in Arbitrary Mesh Topology

The SSs were randomly distributed in an area of 1 square kilometer. The Mesh BS is set in the centre 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 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.

Table 1. The collision metric of each link N=40

link	l_{12}	l_{13}	l_{14}	l_{15}	l_{16}	l_{17}	l_{18}	l_{19}	l_{20}	l_{21}	l_{22}
min	7	7	7	7	6	6	8	9	5	6	6
rand	8	7	9	10	12	9	9	10	10	12	10
link	l_{23}	l_{24}	l_{25}	l_{26}	l_{27}	l_{28}	l_{29}	l_{30}	l_{31}	l_{32}	l_{33}
min	12	8	5	7	8	8	5	6	6	7	12
rand	12	8	9	7	9	10	10	11	11	8	14
link	l_{34}	l_{35}	l_{36}	l_{37}	l_{38}	l_{39}	l_{40}	sum		average	
min	8	10	13	10	7	3	11	220		7.6	
rand	8	14	15	10	7	8	11	288		10	

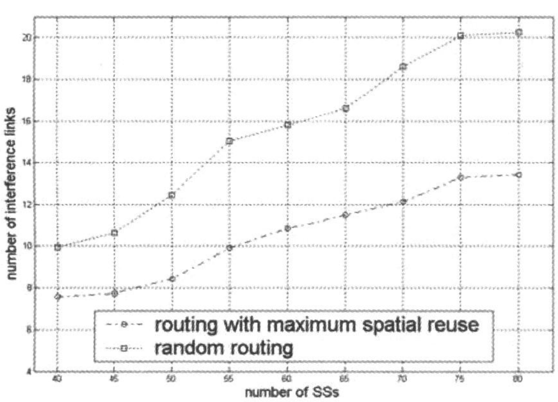

Fig. 4. Collision metric in arbitrary topology

The degree of spatial reuse in our scheme is compared with the degree of spatial reuse while the new SS selects a Sponsoring Node in a random way. Table 1 shows the collision metric of the candidate link of each new SS that joins into the network in the mesh mode. There are total 40 SSs in the network. The results illustrate that the degree of spatial reuse increases by 24% by adopting our routing algorithm. Figure 4 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 SS increases.

V. CONCLUSIONS

Spatial reuse, which allows concurrent transmissions, is very important in wireless mesh networks. We introduce the wireless interference model and investigate the maximum spatial reuse in chain topology. We use the concept of collision metric to model the interference level and propose a novel routing algorithm to increase the degree of spatial reuse in wireless mesh networks. Both the scheduling and routing schemes are based on IEEE 802.16 mesh mode. The simulation results demonstrate that our proposed schemes are more effective than the previous one.

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," Oct. 1, 2004.

[2] 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," Apr.1, 2003.

[3] Couto D.S.J.D., Aguayo D., Chambers B.A. and Morris R. "Performance of Multi-hop Wireless Networks: Shortest Path is not Enough." *1st Workshop on Hot Topics in Networks*, Oct.2002.

[4] Nandagopa T., Kim T., Gao X. and Bharghavan V., "Achieving MAC Layer Fairness in Wireless Packet Networks." *ACM MOBICOM*, Aug. 2000.

[5] Hungyu Wei, Samrat Ganguly, Rauf Izmailov and Zygmunt J. Haas, "Interference-Aware IEEE 802.16 WiMax Mesh Networks." *IEEE VTC*, Spring 2005. in press.

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

[7] Benyuan Liu, Zhen Liu and Don Towsley, "On the Capacity of Hybrid Wireless Networks," *Proc. IEEE INFOCOM*, 2003.

[8] J. Jun, M. L. Sichitiu, "The Nominal Capacity of Wireless Mesh Networks," *IEEE Wireless Communications*, vol.10, pp.8-14, Oct.2003