

Throughput Enhancement with Bidirectional Concurrent Transmission in IEEE 802.16 Mesh Networks

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Abstract—Performance of wireless mesh networks can be greatly improved by spatial reuse with concurrent transmissions. However, most current research works on WiMAX mesh networks are based on a unidirectional concurrent transmission scheme to perform link and packet scheduling. In this paper, we analyze the interference model of IEEE 802.16 TDMA mesh networks and propose a bidirectional concurrent transmission model. We formulate the model into an ILP problem and provide the solution. Simulation results show that our bidirectional transmission mechanism can effectively improve the network performance. Further study reveals that the throughput enhancement varies with different network topologies and distinct location of BS.

Index Terms—wireless mesh networks, IEEE 802.16, multi-hop, spatial reuse, interference

I. INTRODUCTION

The IEEE 802.16 standard entitled “Air Interface for Fixed Broad Wireless Access Systems”, commonly known as WiMAX (Worldwide Inter-operability for Microwave Access), was published to construct the last-mile wireless broadband access (WBA) in metropolitan area networks and provide performance comparable to traditional cable, DSL, or T1 networks [1]. With the advantages of low cost, high speed, and easy deployment, WiMAX is considered one of the most promising technologies in the future.

Two basic operational modes, point-to-multipoint (PMP) and mesh, are defined in the IEEE 802.16d standard. In the PMP mode, the nodes in the network are organized into a cellular like structure consisting of a base station (BS) and some subscriber stations (SSs). All the SSs are within the transmission range of the BS and traffic only occurs between the BS and SSs. The channels are divided into uplink (from SS to BS) and downlink (from BS to SS). On the other hand, in the multi-hop mesh mode, the nodes are organized in an ad-hoc fashion. Traffics between BS and SSs can be relayed by other SSs. Unlike the PMP mode, there are no clearly separate downlink and uplink subframes in the mesh mode [1]. Each SS is able to create direct communication links to a number of other SSs in the network instead of only communicating directly with the BS.

Comparing with the PMP mode, the mesh mode can provide better coverage, flexibility and scalability, thus a great deal of research works have been done focusing on WiMAX mesh networks to improve the performance. Much of the works concentrated on construction of routing tree and link or packet scheduling, aiming to maximize the throughput, maximize the number of concurrently activated links without collision, minimize the end to end delay, and provide fairness to all stations, etc. According to the literatures, most works are based on a unidirectional mode, i.e., only uplink (or downlink) traffics are considered at a given time.

In this paper, we study the asymmetric collision features in IEEE 802.16 TDMA mesh networks, and propose a bidirectional transmission model utilizing spatial reuse mechanism [2] to increase the number of concurrently activated links, therefore potentially improve the maximum throughput. Simulations are made in three different topologies (chain, lattice, and random mesh) to evaluate the model. The results reveal that bidirectional concurrent transmission can improve the performance, but to some degree it depends on not only the topology of the network but also the location of the BS. To the best of our knowledge, this paper is the first to study the throughput enhancement using bidirectional concurrent transmission in WiMAX mesh networks.

The rest of this paper is organized as follows. In Section II, we briefly review the related works on wireless mesh networks, especially on routing and scheduling in WiMAX mesh networks. In Section III we present the interference model adopted in this paper and propose our bidirectional concurrent transmission model. The problem formulation and an ILP (Integer Linear Programming) solution are presented in Section IV. In Section V, the methodology is introduced and performance of the bidirectional concurrent transmission model is evaluated through simulations in various topologies with different location of the BS. Finally, we conclude this paper and give a brief introduction to the future work.

II. RELATED WORKS

It has been shown that interference can make significantly impact the performance of wireless networks. Jain et al. [3]

studied the influence of interference and modeled it by using the conflict graph. They presented methods to compute the upper and lower bounds on the optimal throughput. In [3] a protocol model and a physical model were considered to define the conditions for a successful wireless transmission. In [4] the similar protocol model was considered and it was classified into a symmetric scheme and an asymmetric scheme. Since wireless mesh networks work in a multi-hop radio broadcast environment, spatial reuse can be used to increase the capacity of the networks. The idea of spatial reuse is that several nodes can make transmissions concurrently in the same channel without collisions [2].

Recently a great deal of research works on WiMAX mesh networks focused on constructing routing trees and performing effective link or packet scheduling to improve performance. In [5], the authors discussed the criteria that a good routing algorithm should follow. In [6] an interference-aware cross-layer design was proposed to increase the throughput of WiMAX mesh network. In [7] the authors provided a stochastic model for the distributed scheduler of the IEEE 802.16 mesh mode. Lim et al. [8] considered the problem of mitigating interference and improving network capacity in wireless mesh networks from the angle of temporal-spatial diversity. Similarly, in [9] Fu et al. proposed 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. In [10] several algorithms for constructing routing tree and link scheduling are introduced and evaluated. In [11] the problem of maximizing the system throughput in IEEE 802.16 mesh networks was considered in a packet scheduling scheme.

In addition to maximizing the network throughput, other network performance metrics were also taken into account. In [4] the fairness for all relaying nodes were considered. In [12] the authors studied the scheduling delay and interpreted it as a cost collected over a cycle on the conflict graph. Heuristics were designed to select appropriate transmission orders for finding effective min-max delay schedules.

However, most of these algorithms considered the transmissions of uplinks and downlinks separately, i.e., bidirectional concurrent transmissions were not activated simultaneously at any given time slot. But, bidirectional concurrent transmissions can actually improve the network throughput. Moreover, some other mechanisms, e.g., network coding [13], [14], can be introduced to the WiMAX mesh networks if bidirectional concurrent transmissions are enabled.

III. SYSTEM MODEL

A. Interference Model

In this paper we employ the protocol model presented in [3] to be our interference model. Consider that there are N nodes arbitrarily located in a wireless network. Let n_i , $1 \leq i \leq N$, denote the i th nodes, X_i denote the location of the node n_i , and $L_{i,j} = (n_i, n_j)$ denote the directional link from n_i to n_j . Assume that there is only one channel in the network, and all the nodes have the same transmission range, denoted as r .

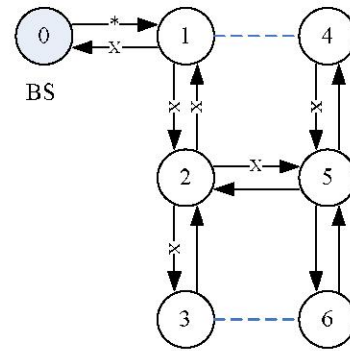


Fig. 1. Link constraint model. If link marked with “*” is transmitting, links marked with “X” should not be activated for collision avoidance.

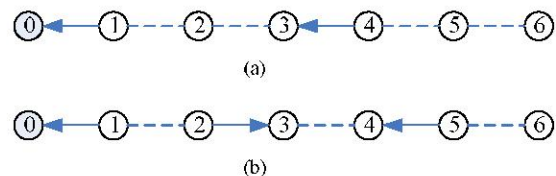


Fig. 2. Comparison of (a) uplink transmissions and (b) bidirectional transmissions in a chain topology.

In a TDMA IEEE 802.16 mesh network, there is no RTS/CTS mechanism being applied. So if node n_j can successfully receive a transmission from node n_i , the following conditions should be satisfied:

$$|X_i - X_j| \leq r \quad (1)$$

$$|X_k - X_j| > r (k \neq i) \quad (2)$$

where $|X_i - X_j|$ denotes the distance between node n_i and n_j . Equation 1 indicates that n_j is in the transmission range of n_i . Equation 2 requires that there should be no other node n_k than n_i whose transmission can be received by n_j while n_i is transmitting to it.

An example of the interference model is clearly depicted in Fig. 1, where solid lines with arrows denote the directional links in routing tree. Dotted lines indicate the connected couple of nodes are within each other’s transmission range. If link $L_{0,1}$ (marked with “*”) is activated, i.e. n_0 is transmitting to n_1 , the links marked with “X” should not be activated simultaneously, otherwise n_1 will be interfered.

B. Bidirectional Concurrent Transmission

Based on the interference model presented in Section III-A, we illustrated the performance improvement of bidirectional concurrent transmission comparing with that of current unidirectional transmission. For simplicity, the comparison is made in a chain topology, as depicted in Fig. 2.

In this figure, there are 7 nodes in each scenario. Neighboring nodes are within the transmission range of each other (denoted as dotted lines). Since there is only one path from the BS (node numbered 0) to each of the other nodes, no

algorithm for routing construction is needed. In Fig. 2(a), only uplink transmissions being permitted, the number of maximal concurrent transmissions is 2; while in Fig. 2(b), bidirectional transmissions are enabled, so the number of maximal concurrent transmissions is 3.

Generally, we observe that for a given chain topology consisting of N nodes with the BS at one end, the maximal number of concurrent transmissions in the unidirectional scheme can be formulated as $K_1 = \lfloor \frac{N-2}{3} \rfloor + 1$, and the maximal number of concurrent transmissions in the bidirectional scheme is $K_2 = \lfloor \frac{N}{2} \rfloor$. With N increasing, the throughput gain of bidirectional transmission approaches to $(1/2 - 1/3)/(1/3) = 50\%$.

The demonstration in Fig. 2 is very simple, but it indicates that bidirectional transmission can greatly improve the throughput performance of the network. Detailed studies reveal that in lattice topology and arbitrary topology, bidirectional transmission can also enhance the throughput, which will be presented in Section V.

IV. PROBLEM FORMULATION

Assume that a network consists of N nodes (including the BS), and the routing tree is constructed. Thus the network can be presented as

$$S = \{V, E, T\} \quad (3)$$

In Equation 3, V denotes the set of all nodes where $|V| = N$ and $n_i \in V$. The set of neighborhoods of all nodes is denoted by E . Each unidirectional edge $e_{i,j}$ or $e_{j,i}$ means that node n_i and node n_j are within the transmission range of each other. $B(n_i)$ denotes the set of all nodes neighboring to node n_i . The set of directional links in the routing tree is denoted by T . Obviously $|T| = 2(N - 1)$, since there are N nodes in the network. For any link $L_{i,j} \in T$, its value can be assigned either 1 or 0. $L_{i,j} = 1$ indicates that node n_i can successfully transmit to node n_j .

The model of maximizing the concurrent transmission for a IEEE 802.16 mesh network with given routing tree can be formulated as an Integer Linear Programming (ILP) problem. The objective function of the ILP problem is:

$$\text{maximize } \sum_{L_{i,j} \in T} L_{i,j} \quad (4)$$

In the rest of this section, we discuss the constraint conditions of the ILP problem. Assume that each station is equipped with only one radio. For any successful transmission, the following conditions should be satisfied:

- 1) A node cannot send and receive simultaneously.
- 2) There may be only one transmitter in the neighborhood of a receiver.
- 3) There may be only one receiver in the neighborhood of a transmitter.

Condition 1) indicates that for each node $n_k \in V$, among all the links whose sink or source node being n_k , at most 1

Chain topology BS in center	Lattice topology BS in center	Random mesh BS in center
Chain topology BS at end	Lattice topology BS in corner	Random mesh BS in corner

Fig. 3. Experiment scenarios: different topologies with BS locating in different places.

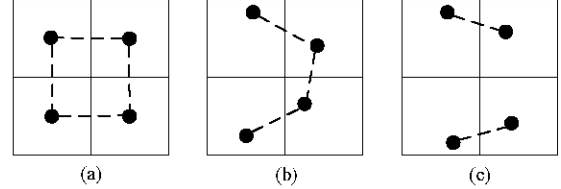


Fig. 4. Demonstration for topology generation. (a) lattice (b) random mesh (c) disconnected random mesh, should be discarded

link can be activated at any time. It can be interpreted as the following constraint expression:

$$\sum_{L_{i,k} \in T} L_{i,k} + \sum_{L_{k,j} \in T} L_{k,j} \leq 1, n_k \in V \quad (5)$$

Condition 2) and 3) actually have the same meaning: for each node $n_k \in V$, no more than one of its neighbors $n_i \in B(n_k)$ can transmit at a given time. In other words, among all the links whose source node being $n_i \in B(n_k)$, at most one of them can be activated at any time. It is presented in the form of constraints as follows:

$$\sum_{n_i \in B(n_k)} \sum_{L_{i,j} \in T} L_{i,j} \leq 1, n_k \in V \quad (6)$$

Notice that among all the constraints provided in Equation 5 and 6, some of them may be redundant, thus better to be eliminated.

V. SIMULATION AND EVALUATION

A. Methodology

In this section, we evaluate the performance of our bidirectional concurrent transmission model and compare it with the currently being used unidirectional scheme. The ILP method presented in Section IV is employed to get the optimal results. The performance is evaluated in three different network topologies: chain topology, lattice topology, and random topology.

Illuminated by the experiments in [14], we think that location of the BS in the mesh network may affect the performance of the bidirectional concurrent transmission. We make simulations in three topologies with BS locating in different places, as depicted in Fig. 3.

B. Implementation and Metrics

The simulations are implemented in Java. We adopt and modify the data structures and topology generating algorithms presented in [15] to create the connected random topologies applicable to wireless environment. To ensure that all nodes

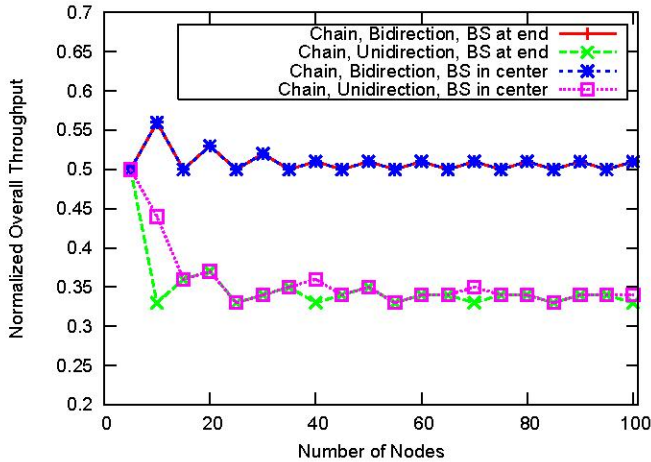


Fig. 5. Performance comparison of bidirectional and unidirectional concurrent transmissions in the chain topology, with the BS locating at the end and in the center of the chains.

are widely distributed in the whole area, we divide the scenario into $n \times n$ grids. A demonstration for 2×2 grids is shown in Fig. 4. For the lattice topology, nodes are planted exactly in the center of each grid; while for the random mesh topology, nodes are planted randomly at any place in each grid. If the topology is disconnected, it should be discarded and new topology should be recreated.

For generality, the routing tree is constructed in a BFS (Breadth First Search) mode, starting from the BS. If more than one nodes can be selected as the parent node for an SS, random selection is used to break the tie. The interference constraints are analyzed according to the problem formulation presented in Section IV. The ILP codes are generated in Java and then executed in LINDO [16].

The normalized overall throughput is employed to evaluate the performance. It is defined as the ratio of the number of actually transmitting physical links to the number of total physical links in the routing tree.

C. Results and Analysis

Fig. 5 depicts the performance comparison of bidirectional and unidirectional concurrent transmission in the chain topology. It reveals that the bidirectional concurrent transmission can greatly improve the throughput. Notice that the location of the BS does not affect the performance in bidirectional transmission, while slightly improves the performance in unidirectional transmission with BS locating in the center.

Fig. 6 and Fig. 7 demonstrate performance of the two transmission schemes in lattice topology, with BS in the corner and in the center respectively. The results show that bidirectional transmission enhances the throughput comparing with unidirectional transmission, and it performs better when the BS locates in the corner.

Similar results are obtained in random mesh topologies through Fig. 8 and Fig. 9, which indicate that bidirectional transmission works better than unidirectional transmission, and

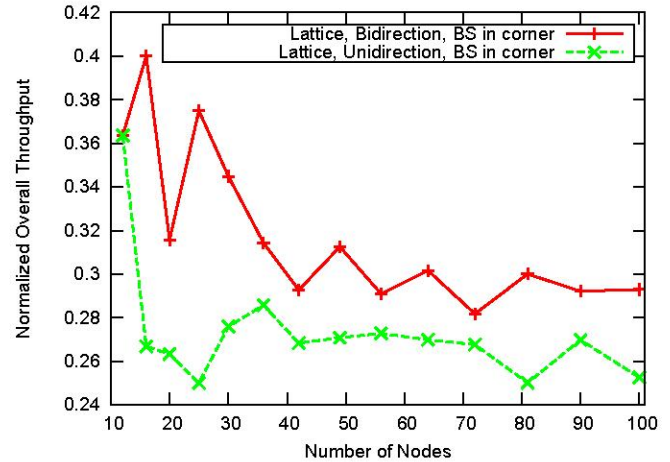


Fig. 6. Performance comparison of bidirectional and unidirectional concurrent transmissions in the lattice topology, with the BS locating in the corner of the networks.

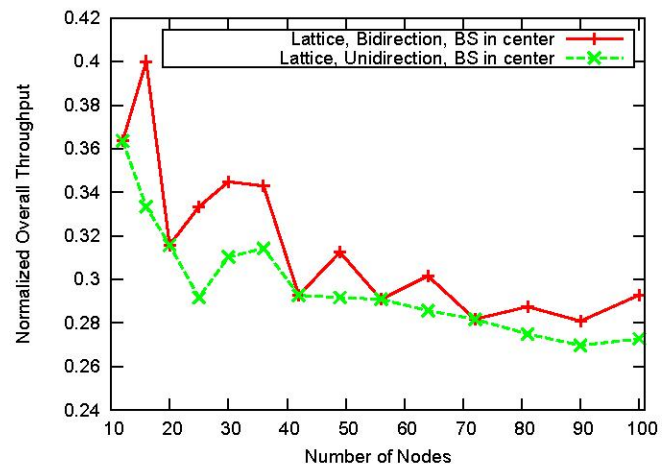


Fig. 7. Performance comparison of bidirectional and unidirectional concurrent transmissions in the lattice topology, with the BS locating in the center of the networks.

the enhancement is more obvious when the BS locates in the corner than in the center.

Moreover, three conclusions can be drawn by combining the four figures from Fig. 6 to Fig. 9.

- As the number of nodes increases, the overall network throughput drops significantly, regardless of the transmission scheme and location of the BS. This is because more nodes bring with more interference, thus the number of concurrent transmission links reduces relatively.
- Among the three topologies, concurrent transmission in chain topology performs the best, with the normalized overall throughput range $0.33 \sim 0.55$; it performs worse in lattice topology ($0.25 \sim 0.4$), and the worst in random mesh ($0.22 \sim 0.36$). The reason is that in the chain topology, each node is interfered by much less neighboring nodes.

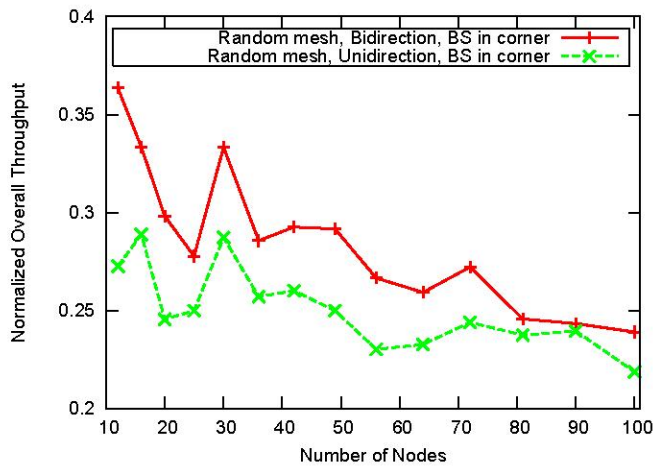


Fig. 8. Performance comparison of bidirectional and unidirectional concurrent transmissions in the random mesh topology, with the BS locating in the corner of the networks.

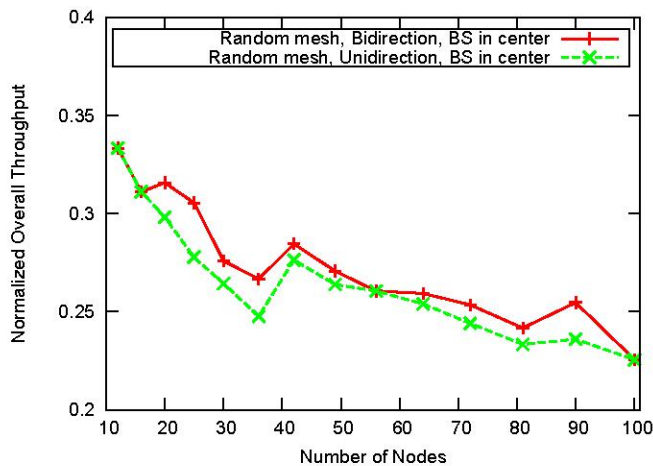


Fig. 9. Performance comparison of bidirectional and unidirectional concurrent transmissions in the random mesh topology, with the BS locating in the center of the networks.

- The throughput enhancement of bidirectional transmission is larger when the BS locates in the corner than in the center. This is because the BS plays an important role in a WiMAX mesh network, and it suffers less interference when locating in the corner than in the center.

VI. CONCLUSION AND FUTURE WORK

Spatial reuse is very important in wireless mesh networks for allowing concurrent transmissions. Performance of WiMAX mesh networks can also be improved by using spatial reuse. Most current research works on WiMAX mesh networks employ unidirectional concurrent transmission to perform link and packet scheduling. In this paper, we analyze the interference model of IEEE 802.16 TDMA mesh networks and propose a bidirectional concurrent transmission model. The problem is formulated and an ILP solution is provided. We make experiments in three different topologies with various

location of BS. Simulation results show that our bidirectional transmission mechanism can effectively improve the network performance. Further studies reveal that the throughput enhancement varies with network topologies and location of BS.

Based on the bidirectional concurrent transmission, we will design a model combining the network coding mechanism with WiMAX mesh networks and work out corresponding scheduling algorithms in the future.

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