A Bandwidth Allocation Model with High Concurrence Rate in IEEE802.16 Mesh Mode

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Abstract- **In this paper, a bandwidth allocation model is proposed for multi-hop Wireless Mesh Network (WMN) with a goal of achieving high traffic throughput in minimal scheduling time slots. Scheduling scheme based on the optimization model serves the centralized scheduling first and compresses the scheduling time to minimum by enhancing concurrence rate among links, thus more time slots can be saved for distributed scheduling. Simulation results show that this model has higher concurrence rate and reduces nearly 50% centralized time slots than FIFO serving mode.**

I Introduction

Multi-hop wireless mesh network is a promising wireless network to provide ubiquitous high-speed wireless access to customers, such as broadband home networking, community and neighborhood networks, enterprise networking [1]. Original IEEE 802.16 standard addressed applications in licensed bands in the 10 to 66 GHz frequency range under point-to-multipoint (PMP) mode [2]. Subsequent amendments have extended the 802.16 air interface standard to cover non-line of sight (NLOS) applications in licensed and unlicensed bands in the sub 11 GHz range and added the Mesh mode [3]. Comparing with the bandwidth scheduling in point to multipoint(PMP) mode, the mesh mode has its characters including:1) Traffic can occur directly between subscriber stations (SSs). 2)Traffic may be relayed by internal node (both uplink and downlink), so the bandwidth allocation may cover more than one frame time slot. 3) The topology of mesh network may change more dynamically than that in PMP mode.

Some research results have shown that throughput capacity can be increased by deploying relaying nodes [4] [5], and the biggest challenge in building a WMN is how to design scheduling schemes to achieve guaranteed performance(throughput and delay). Centralized scheduling, coordinated and non-coordinated distributed scheduling are mentioned in IEEE802.16-2004, but no detailed definitions are described. Algorithms deployed in PMP mode [6][7] are not suitable for Mesh mode because they all deal with centralized scheduling in one hop range; and the algorithms deployed in ad-hoc network [8][9] are applied in distributed network, which lack of the central control .

In this paper, we explore the problem of bandwidth allocation in WMN. An optimization model is proposed to analyze the lower bound of the centralized scheduling in Mesh mode. Traffic for centralized transmission are processed at first and multiple links in the network can send and receive data concurrently such that the transmission delay for centralized scheduling can be compressed to the least. Then the remaining free frame slot can be saved for distributed scheduling through a three-way handshake.

This paper is organized as follows. Section 2 describes the physical layer assumption in this work. Definitions and mathematical model based on these assumptions are presented in Section 3. Section 4 gives the experiment results and the paper concludes in Section 5.

II Preliminaries

In this paper we focus on the scenario in which only one Mesh BS is in the network to provide the function of centralized scheduling and connect the sub network to the back haul links. SSs communicate with BS via wireless links to send or receive data from the Internet.

To simplify the scheduling and routing over mesh network, we assume that the mesh topology broadcasted in Mesh Centralized Schedule Configuration (MSH-CSCF) message has been partitioned into a tree, where the tree is rooted at BS. In this tree, typically there will be traffic in the downlink direction from the BS to the SS, as well as traffic in the uplink direction from the SS to the BS. Our centralized algorithm only considers these two kinds of traffic, while the direct data exchange between SSs is transmitted during the frame slots that remains for distributed scheduling. The additional problem of scheduling over multiple access trees is beyond the scope of this paper. However, if we assume that different access trees operate in separated frequency bands, or disjoint time slots, the problem can be reduced to scheduling over each access tree separately.

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II-A Physical layer

As mentioned in IEEE 802.16-2004 Standard, only time division mode (TDD) is supported in Mesh mode. Furthermore, the MAC layer is assumed to schedule data to multiple access (TDMA) through single carrier channel. Thus, as long as the bandwidth allocation result is calculated, the frame in each link can be built following this result in a simple way of mapping.

We have the following rules defined in this paper: Rule 1: A node can't transmit and receive at the same time. Rule 2: The relaying data traffic received by one SS can't be transferred immediately to its neighbor in the same frame slot. That is because the SS usually has performance constrain in buffer writing and reading. Rule 3: Nodes within the transmission range of an active node are blocked to avoid the interference. Rule 4: Any two traffic that are not interfering with each other can potentially transmit data packets over the physical channel simultaneously.

It is believed that interference between concurrent transmissions from neighboring nodes is one of the most significant factors that limit the system throughput and scalability of wireless multi-hop network. Directional antennae at the transmitters as well as the receivers to minimize transmission range of the nodes. According to the Rule 4 the throughput of the mesh work can be improved.

As mentioned above, all nodes share a wireless channel and communicate on that shared channel. Each node is assumed to be equipped with multiple directional antennas[10]. A directional antenna can transmit (receive) over a small angle (e.g., 45 degrees), centered on the receiver (transmitter), and several directional antennas may be used together to cover all directions. We also assume that there is no interference at angles beyond this beam width, or at distances beyond 10% of the transmitter receiver link length (see Fig.1).

Directional transmissions over two different links will interfere at the two receiving access points if the access points are located within the beam of other link, and transmissions by two or more links will interfere at the same receive node even if different directional antennas at the node receive these transmissions. This assumption is justified, for instance, in the case where signals received by all antennas are combined before sending to the receiving circuitry. We also assume that simultaneous transmissions by the same node to different directions are not allowed.

In Fig.1(a), the dotted region denotes the transmission range. It shows when H transmits to G, G will see interference if it were to receive from E. In the figure the highlighted arrow shows the interference. The Fig.1(b) also shows a condition where node G can safely transmit to node H, since it will not interfere with node E's communication to F.

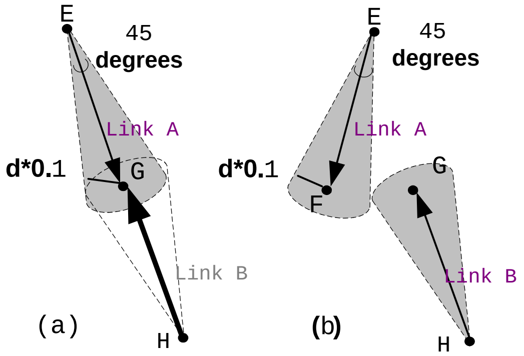

Figure 1: Region of Interference

III Mathematical Model

Centralized scheduler provides bandwidth allocation scheme for each node such that traffic can reach its destination in the scheduling period. Usually, the longer scheduling period the lower bandwidth efficiency, so minimizing the scheduling period becomes an important object in scheduling algorithm design. In the following, we build an optimization model to study the minimal scheduling period that can be provided by an centralized scheduler with specified topology and traffic distribution.

Given an access tree $T = (V, E)$, where the nodes V are access points, and the links E are bidirectional wireless links between neighboring pairs of access points, $|V| = N$. All nodes in V are labelled with an integer and the root node is labelled with 0. The root node 0 is BS, and the other nodes $i \in V - \{0\}$ are SS. Each node $i \in V$ has a specified capacity P which is the data rate it can support.
$F_i, F_i = \{j|(j,i) \in E\}$, is the neighboring parent nodes of node i. With T being an access tree, each node has at most one neighboring parent node, that is, $|F_i| = 1$.
$N_i = \{j|(i,j) \in E\}$ be the neighboring children of node i. Each $j \in N_i$ is given a label $l, l = 1..|N_i|$, and N_i^l is the lth neighboring child of node i. N_i^l and all its children form the lth branch of node i which is denoted as B_i^l.
$C(i)$ represents all the children of node i, and $C(i) = \bigcup_{l=1}^{|N_i|} B_i^l$.
$h(i)$ is the number of hops from root R to node i.
d_i is the uplink traffic request of node i and d_{0i} is the downlink traffic from root 0 to node i.
With all the inputs to the scheduling problem, we need to decide the uplink and downlink traffic of node i in frame k. Set $x_{i,k}$ be the uplink traffic of node i at frame k, and $y_{i,k}^l$ the downlink traffic of node i to branch l at frame k. Fig.2 gives an example access tree, and the explanation of above notions is shown in the figure.

Let K represent the number of frame slots to carry all the requests to its destination, and the scheduling problem, is to

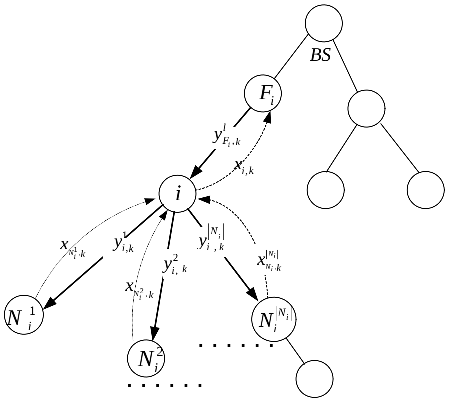

Figure 2: Access Tree and its Notions

find a scheme to minimize K. This problem can be formulated in a linear programme problem as follows:

$$\min K \tag{1}$$

$s.t.$

$$\sum_{k=1}^{K+1-h(i)} x_{i,k} = d_i + \sum_{j \in C(i)} d_j, i = 1, \cdots, N. \tag{2}$$

$$\sum_{k=1}^{K} y^l_{F_i,k-1} = d_{0i} + \sum_{j \in C(i)} d_{0j}$$

$$i = 1, \cdots, N. \; i = N^l_{F_i}, l = 1 \cdots |N_{F_i}|. \tag{3}$$

$$x_{i,k} + \sum_{l=1}^{|N_i|} y^l_{i,k} + y^l_{F_i,k} + \sum_{l=1}^{|N_i|} x_{N_i^l,k} \leq P$$

$$i = 0, \cdots, N, \; i = N^l_{F_i}, \; l = 1, \cdots, |N_i|. \tag{4}$$

$$\sum_{t=1}^{k} x_{i,t} - \sum_{t=1}^{k-1} \sum_{l=1}^{|N_i|} x_{N_i^l,t} \leq d_i$$

$$k = 2, \cdots, K, \; i = 1, \cdots, N. \tag{5}$$

$$\sum_{t=1}^{k} \sum_{l=1}^{|N_i|} y^l_{i,t} \leq \sum_{t=1}^{k-1} y^l_{F_i,t}$$

$$k = 2, \cdots, K, i = 1, \cdots, N, i = N^l_{F_i} \tag{6}$$

$$y^l_{i,k} = 0, k \leq h(i)$$

$$i = 1, \cdots, N. \; l = 1, \cdots, |N_i| \tag{7}$$

$$x_{i,k} = 0, k \geq K + 2 - h(i), \; i = 1, \cdots, N. \tag{8}$$

$$x_{0,k} = 0, \; k = 1, \cdots, K \tag{9}$$

Constraint (2) represents that the uplink traffic via node i to root node 0 must be transmitted out before the $(K+1-h(i))th$ frame such that these traffic can reach root node after $h(i)$ hops. The uplink traffic via node i includes both the traffic originated at node i and the traffic originated by children of i and relayed by i to root node.

Equation (3) means that the downlink traffic from root node to node i should reach node i inside the scheduling period K.

Constraint (4) requires that the total traffic to and from node i can not exceed the total capacity P of node i.

Constraint (5) means that the uplink traffic sent by node i during $k, k = 1, \cdots, K$ frame slots should not be more than what it has received from its neighboring children and its own originated traffic during the k frames. And constraint (6) requires that the downlink traffic sent by node i during $k, k = 1, \cdots, K$ frames should not be more than what it has received from its neighboring parent node.

For root node 0, it has no uplink traffic and it also has no parent node. So $x_{0,k} = 0, k = 1, \cdots, K$. For any SS node i, $i \neq 0$, there is no downlink traffic unless the SS node has received some traffic from its parent nodes, and all uplink traffic should be sent before $K + 2 - h(i)$ frame to guarantee the traffic to reach root node before frame K.

III-A Scheduling Algorithm

The linear programme problem can be solved by many commercial tools and solution to the mathematical model can provide uplink traffic $x_{i,k}$ and downlink traffic $y^l_{i,k}$ of node i in each frame $k, k = 1, \cdots, K$. The solution does not specify that during the P mini-slots for each frame slot, how to arrange the $x_{i,k}$ uplink traffic and $\sum_{l=1}^{|N_i|} y^l_{i,k}$ downlink traffic such that no interference occurs. In the following, we propose an algorithm to allocate the traffic of each node to its mini-slots based on above principle. In the algorithm, $z^t_{i,k}$ represents the tthmini-slot of node i at frame slot k. $z^t_{i,k} = NULL$ means that node i is free in min-slot t in k frame slot. $z^t_{i,k} = r(j)$ represents that node i sends traffic to node j in mini-slot k, and $z^t_{i,k} = s(j)$ represents that node i receives traffic from node j in mini-slot k.

Algorithm 1: Time Slot Allocation Algorithm
Input: $G = (V, E), x_{i,k}, y_{i,k}, P, i \in V, k = 1, \cdots, K$
Output: Mini slots assignment $z^t_{i,k}, t = 1, \cdots, P$ for each i, k.

```
begin
1.   For each $k, k = 1, \cdots, K$, get $x_{i,k}, y^l_{i,k}$,
     $i \in V, \; l = 1, \cdots, |N_i|$. $z^t_{i,k} = NULL, \forall t \leq P$.
     $T_i = \{t | z^t_{i,k} = NULL, t = 1, \cdots, P\}$
2.   $i := 0, V_0 := V, l = 1$.
     /*Begin from BS node.*/
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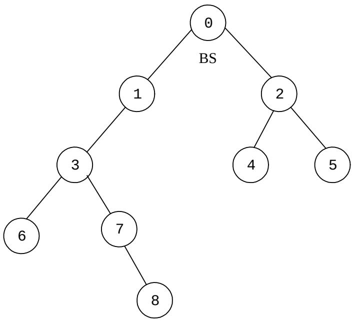

Figure 3: Simulation Topology

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3.  Select $t \in T_i$, if $y^l_{i,k} > 0$,
    $z^t_{i,k} = s(N^l_i)$, $y^l_{i,k} = y^l_{i,k} - 1, T_i := T_i - \{t\}$,
    $j = N^l_i$, $z^t_{j,k} = r(i), T_j = T_j - \{t\}$.
    If $y^l_{i,k} > 0$, go to step 3, otherwise $l++$,
    if $l \leq |N_i|$, go to step 3.
4.  For $j = N^l_i, l = 1, \cdots, |N_i|$, $t \in T_i \cap T_j$,
    if $x_{j,k} > 0$, $z^t_{j,k} = s(i)$, $z^t_{i,k} = r(j)$, $x_{j,k} = x_{j,k} - 1$,
    $T_j = T_j - \{t\}, T_i = T_i - \{t\}$, go to step 4.
5.  $V_0 := V - \{i\}$. If $V_0 \neq NULL$, select $i \in V_0$, and
    $F_i \notin V_0$, set $l = 1$, go to step 3.
end
```

IV Experiment Result

In this section, we use the network shown as Fig.3 as an example to compare the scheduling scheme based on the proposed model with FIFO queue. FIFO queue serves the request according to the sequence of each node defined in Mesh Centralized Schedule (MSH-CSCH) message. We add some optimization in FIFO mode, that is, if an active node's Uplink/Downlink traffic is less than 1 unit, the remaining bandwidth can be allocated to its neighbor father node. The bandwidth for data subframe in each frame slot is taken as 1 unit. We compare the performance of our scheduling model with FIFO queue from the aspect of number of frame slots, concurrence rate and delay boundary in the centralized scheduling.

Fig.4 shows the bandwidth allocation method get from the optimization model when BS has the same downlink traffic as the total uplink traffic generated by SSs. Total traffic is 8 units in each direction on the network shown in Fig.3.

White blocks in Fig.4 represent uplink traffic through the link, and black blocks represent downlink traffic. Total scheduling frame slots is 18, which means that all data traffic can be transmitted to its destination inside 18 frame slots. Generally speaking, the delay upper bound in each direction is 18 frame slots. While in FIFO serving mode, 36 frame slots are needed for the data transmission of 8 units in each direction. And if the uplink data is transmitted first, the delay boundary for downlink data will be enlarged to 36 frame slots (Refer to

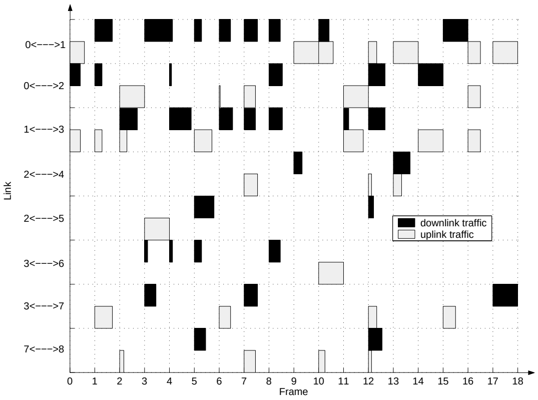

Figure 4: Bandwidth Allocation

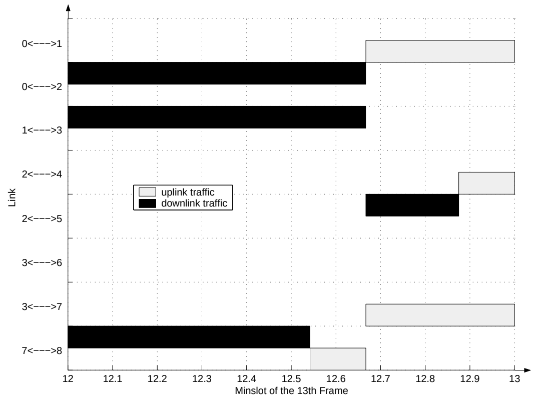

Figure 5: Sample of Mini-Slot Allocation

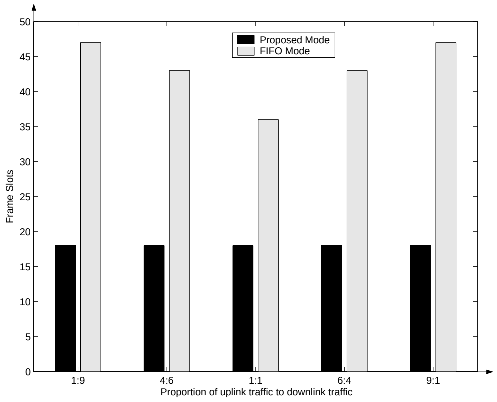

Figure 6: Frame Slots v.s. Traffic Proportion

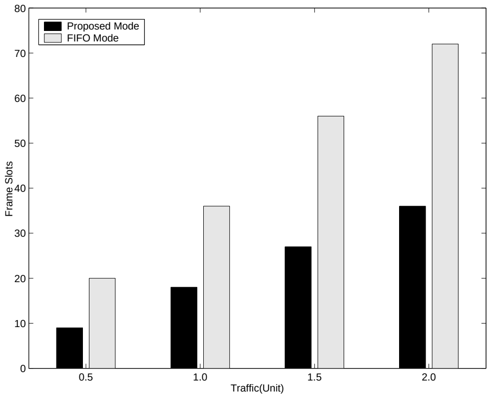

Figure 7: Frame Slots v.s. Traffic Load

1:1 column in Fig.6). Fig.4 shows that many links are active simultaneously in the same frame slot. But in FIFO mode, only one link is active in most of the scheduling time for it serves each node in sequence. In the following, we define the concept of Concurrence Rate, such that the concurrency degree of different scheduling schemes can be measured.

Given a frame slot $k, k = 1, \cdots, K$, A_k is the number of links that are active for downlink or uplink traffic. Then the Concurrence Rate for a scheduling scheme is defined as: $\sum_{k=1}^{K} A_k/(K|E|)$.

Based on the definition, the average Concurrence Rate in Fig.4 is 43%. Use frame slot 13 as an example, the frame structure of each link is shown in Fig. 5. Totally, 7 links($0 \longleftrightarrow 1, 0 \longleftrightarrow 2, 1 \longleftrightarrow 3, 2 \longleftrightarrow 4, 2 \longleftrightarrow 5, 3 \longleftrightarrow 7, 7 \longleftrightarrow 8$) are simultaneously active and collision-free in this slot. While the concurrence rate of FIFO mode is only around 12.5%.

We also compare the performance of frame slots in various traffic proportion. Five different traffic proportion of uplink and downlink are considered: $5:5, 4:6$, 6:4, $1:9$ and $9:1$. Fig.7 shows that scheduling method based on our model only need half of the centralized scheduling time needed by FIFO mode. Moreover, the number of scheduling time slots does not change when traffic proportion varies. However, in FIFO mode, when proportion changes from $5:5$ to $4:6$ or $6:4$, 7 more time slots are needed and when the proportion is $1:9$ or $9:1$, 11 more time slots are needed.

The final comparison we do is scheduling time variety when traffic grows from 0.5 unit per node to 1.5 unit per node. Fig.6 shows both modes need more scheduling time when traffic increasing. Our model always need nearly 50% of time slots what are required by FIFO mode.

V Conclusion

We have presented a scheduling model in IEEE802.16 Mesh mode, which provides high concurrence transmission rate under centralized scheduling in minimal time slots and saves time zone for distributed scheduling as much as possible. Comparing with FIFO serving mode, the scheduling scheme based on our proposed model can save half of the time slots under different traffic load and Concurrence Rate is 3 times better. Simulation results also show that our model has better compatibility for various traffic distributions.

Priority difference between the traffic generated by each node is not considered in this paper. Though Best Effort is the only service type supported by Mesh Mode defined in protocol, it is still possible to classify different service priorities in priority/class field in the Mesh Connection Identifier (CID) construction. Enhancement of the optimization model to support multi-priority traffic and local scheduling policy of SSs is our future work.

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