Centralized Scheduling Tree Construction under Multi-channel IEEE 802.16 Mesh Networks

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***Abstract*—This paper focuses on routing tree construction problem and its influence on the performance of utilizing centralized scheduling in IEEE 802.16 mesh networks. We apply three routing tree construction algorithms, namely, Hop Minimization Modulation Maximization (HMMM), Energy/bit Minimization (EbM), and Interference Minimization (IM) routing tree constructions with nodes spaced randomly. Furthermore, a novel multi-channel centralized scheduling algorithm with spatial reuse is proposed and its performance with the three routing tree construction algorithms is evaluated under variance of link capacity induced by co-channel interference. Simulation results show that the routing tree constructed by the EbM algorithm outperforms the two others. Therefore, EbM routing tree construction algorithm with multi-channel scheduling algorithm with spatial reuse is highly efficient for IEEE 802.16 mesh networks.**

Keywords-centralized scheduling; multi-channel scheduling; IEEE 802.16 mesh

I. Introduction

IEEE 802.16-2004, defining the WirelessMAN™ air interface specification, supports both Point-to-MultiPoint (PMP) and Mesh topologies [1]. With characteristics of adaptability, scalability, self-configuring and self-healing, IEEE 802.16 mesh networks greatly benefit wireless communication and have a good prospect of application. In IEEE 802.16 mesh networks, the optimal throughput is achieved by selecting optimal routes and scheduling the links on the routes appropriately. There are two scheduling mechanisms defined for the mesh mode, namely, centralized scheduling and distributed scheduling. IEEE 802.11 mesh is based on a distributed scheduling, in which the route from the source to the destination changes with the traffic and channel conditions varying. The similar distributed scheduling is also defined in IEEE 802.16 mesh [1] and IEEE 802.16a [2]. Such an ad hoc like topology change brings much control overhead to the system, which consumes too much bandwidth resource and decreases the efficiency of scheduling for the 802.16 mesh networks. Therefore, centralized scheduling attracts more attentions.

For centralized scheduling, the first and essential step is to build an optimal routing tree rooted at a known Mesh Base Station (MBS), and then all traffic will be routed along this tree.

Two routing tree construction algorithms called Hop Minimization Modulation Maximization (HMMM) and Energy/bit Minimization (EbM) are proposed in [3], however, throughput has not been investigated under a certain scheduling algorithm. In [4], an interference-aware routing tree construction algorithm (we call it Interference Minimization (IM) algorithm in this paper) for IEEE 802.16 mesh initialization process is proposed to improve the network throughput by selecting routes with minimal interference. Such an interference-aware route construction is only applicable on a known connectivity graph and the capacity of each link has not been carefully considered. For scheduling scheme, a single channel reuse algorithm called interference-aware scheduling is proposed in [4] by introducing concurrent transmission. However, concurrent transmission also introduces co-channel interference that tends to decrease the capacity for the active links. Unfortunately, this problem is not addressed in [4]. Therefore, the throughput performance should be re-evaluated for scheduling with spatial reuse in the presence of co-channel interference. [5], [6] and [7] studied channel assignment and routing algorithms for multi-channel scheduling, but they all focus on IEEE 802.11 networks. In [2], an example is given for centralized scheduling in which two channels are supported in IEEE 802.16 mesh mode. But the example itself is not efficient and the algorithm is not provided. In this paper, we propose a multi-channel centralized scheduling algorithm with spatial reuse, and evaluate the performance of the three routing tree construction algorithms under the scheduling scheme.

The rest of this paper is organized as follows: the routing tree construction for centralized scheduling is provided in Section II. The multi-channel centralized scheduling algorithm with spatial reuse is proposed in Section III. Simulation and comparisons are conducted in Section IV. Section V concludes this paper.

II. Routing Tree Construction

Optimization of routing tree contributes to the overall throughput. We apply the three routing tree construction algorithms mentioned above for centralized scheduling in IEEE 802.16 mesh networks.

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A. Connectivity Graph Construction

For centralized scheduling, the routing tree is rooted at a MBS and constructed on the connectivity graph. We assume every Mesh Subscriber Station (MSS) node would transmit at the maximum power. The signal traveling from the transmitter to the receiver will suffer from path loss attenuation, which is a function of distance *d* between two nodes.

Suppose node n_i wants to transmit to node n_j. The transmission is successful if

$$SNR_{ij} > SNR_{thresh}, \tag{1}$$

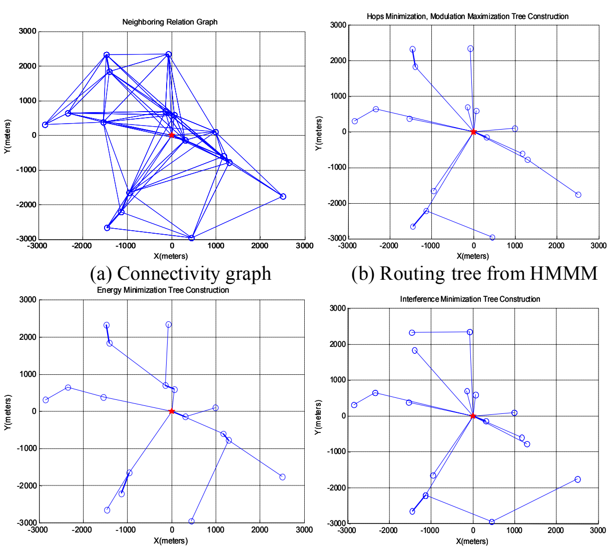
where SNR_{ij} denotes the signal-to-noise ratio at the node n_j for signal received from node n_i, and SNR_{thresh} can be obtained from the Tab.266 of [1], which rests with different modulation and coding schemes and it should be ensured that the Bit-Error-Rate (BER) is less than 10^{-6}.

We calculate SNR_{ij} at the receiver of every link according to the following:

$$SNR_{ij} = P\text{Tx} - 10\log(BW) + G\text{Tx} + G\text{Rx} - \text{pathloss}(d_{ij}) - 10\log(KT0) + N\text{F}, \tag{2}$$

in which,
KT_0 = -144 dBW/MHz = Equipartition Law,
N_F = Receiver noise figure,
P_{Tx} = Mean power at the antenna port,
BW = Occupied bandwidth,
G_{Tx} = Antenna gain for Tx,
G_{Rx} = Antenna gain for Rx,

If SNR is below the threshold of QPSK 1/2, the two nodes are disconnected and the capacity of the link is set to 0. Following the method above, we get a connectivity graph *G (V, E)* with links marked with its capacity. The routing tree will be built based on this graph.



(a) Connectivity graph (b) Routing tree from HMMM

(c) Routing tree from EbM (d) Routing tree from IM

Figure 1. An example of connectivity graph and routing tree. (18 nodes within a radius of 3.2 km)

Fig. 1(a) shows an example of connectivity graph for 18 MSS nodes. MSSs are randomly distributed in a cell of 3.2 km while the MBS is located at the centre of the cell. Other topology plans are also possible, for example, MBS can be in other positions of the network, or MBS only supports one sector in a multi-sector cell.

B. Routing Tree Construction

Routing tree will be constructed after the connectivity graph is obtained. Beginning with the MBS, the MSS nodes are added into the tree one by one. For each time, we define the nodes, which are not yet in the routing tree but have neighbors already in the tree, as the candidate nodes *CN*. And for each *CN* η, the neighbors that are already in the tree are called the candidate parent nodes of node η, namely $CP(\eta)$. Due to the unique path characteristic of the tree topology, for *CN* η with *N* candidate parent nodes, there are *N* potential routes toward the MBS, each of which can be represented as $Path(i),\ i\in CP(\eta)$. The following three routing tree construction algorithms are used to find the parent node $P(\eta)$.

1) HMMM Algorithm

The modulation matrix $m(\eta, P(\eta))$ is given among {0, 1, 2, 3, 4} corresponding to the following modulation type and coding rate {BPSK 1/2, QPSK 1/2, QPSK 3/4, 16-QAM 1/2, 16-QAM 3/4} respectively [1]. Let $\{h(\eta) = h(\eta, P(\eta)) = 5 - m(\eta, P(\eta))\}$ be the link cost along the link $\{\eta, P(\eta)\}$, the weighted hops $H(i)$ from node *i* to MBS is

$$H(i) = \sum_{v\in Path(i)} h(v)\,. \tag{3}$$

For each *CN* η, we choose its parent node $P(\eta)$ (hence the route to MBS) by selecting the one with the minimal hops and maximum modulation order

$$P(\eta) = \arg\min_{i\in CP(\eta)} \{H(i) + h(\eta, i)\}\,. \tag{4}$$

Fig. 1(b) shows an example of the routing tree constructed by HMMM algorithm on the connectivity graph shown in Fig. 1(a). From Fig. 1(b), we can see that this algorithm typically leads to the use of very long links to the MBS with low modulation orders.

2) EbM Algorithm

The energy value $e_b(\eta) = e_b(\eta, P(\eta))$ is defined as the energy value consumed for one byte data while node η is transmitting to its parent node $P(\eta)$. We introduce the energy metric $E_b(i)$ of a given route from node *i* to MBS to evaluate the total energy spent in transmitting one byte along the path

$$E_b(i) = \sum_{v\in Path(i)} e_b(v)\,. \tag{5}$$

For each *CN* η, we choose its parent node $P(\eta)$ (hence the route to MBS) by selecting the one with the minimal energy

$$P(\eta) = \arg\min_{i\in CP(\eta)} \{E_b(i) + e_b(\eta, i)\}\,. \tag{6}$$

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Fig. 1(c) shows an example of the routing tree constructed by EbM algorithm on the connectivity graph shown in Fig. 1(a). From Fig. 1(c), we can see that this algorithm typically leads to the use of short links using very high orders of modulation, but tends to result in a fairly high hop-count to reach the MBS.

3) IM Algorithm

The blocking value $b(\eta)$ is defined as the number of blocked (interfered with) nodes while node η is transmitting. And the blocking metric $B(i)$ of a given route from node i to MBS is introduced to evaluate the interference level of routes in the mesh. We have

$$B(i)=\sum_{v\in Path(i)} b(v)\cdot \tag{7}$$

For each *CN* η, we choose its parent node $P(\eta)$ (hence the route to MBS) by selecting the one with the minimal blocking (see [4] for further details)

$$P(\eta)=\arg\min_{i\in CP(\eta)} B(i)\cdot \tag{8}$$

And the *CN* η with the minimal blocking is chosen to be the next node to be added in the tree, i.e.,

$$n=\arg\min_{\eta\in CN} B(P(\eta))\cdot \tag{9}$$

According to (7), since $B(i)$ is the sum of interfered nodes along the path, this strategy typically leads to the use of less hop-count to reach the MBS with few nodes blocked. Fig. 1(d) shows an example of the routing tree constructed by IM algorithm on the connectivity graph shown in Fig. 1(a).

III. Multi-Channel Centralized Scheduling With Spatial Reuse

A. Assumptions and Definitions

Assumption 1: A node in the mesh network cannot transmit and receive at the same time.

This assumption will be hold for both single channel and multi-channel case. That is, if a node is sending in channel l, it cannot receive in the same channel or other channel.

Assumption 2: A node in the mesh network cannot work in different channel at the same time.

This assumption can ensure the usage of multi-channel does not add extra hardware to the wireless mesh network. So, if a node is sending in channel l, it cannot do the following: 1) send in other channel; 2) receive in other channel.

Let N denote the number of total available channels, the following definitions are made in this paper.

Active node set AN: A node is active if it is transmitting or receiving information. All the active nodes which are working in channel l form AN_l. All working nodes form the active node set AN, that is $AN=AN_1\cup AN_2 ...\cup AN_N$.

Active link set AL: A link is active if it is scheduled to transmit from source to destination in a transmission opportunity.

Transmission block set BT: A node is said to be transmission blocked if its transmission will interfere with the currently receiving nodes. If the active node is transmitting using channel l in a certain interval t, all the transmission blocked nodes form BT_l. BT is composed of all BT_l, namely, $BT=BT_1\cup BT_2 ...\cup BT_N$.

Reception block set BR: A node is said to be reception blocked if its reception will be interfered by the currently transmitting nodes. If the active node is transmitting using channel l in a certain interval t, all the reception blocked nodes form BR_l. BR is composed of all BR_l, that is, $BR=BR_1\cup BR_2 ...\cup BR_N$.

In general, if there is an active link in a transmission opportunity t using channel l, it is concluded in this paper that:

- All neighbors of the source (destination) node except the receiver (sender) in the active link will be reception (transmission) blocked using channel l.
- A link could be active only when it has available channels.

B. Multi-channel Centralized Scheduling Algorithm

The aim of proposed scheduling is to utilize concurrent transmission opportunity to achieve a higher system throughput, which can be realized by maximizing simultaneous transmissions without introducing exceeding interference for other transmissions. Furthermore, spatial channel reuse is adopted in this paper to fulfill this aim.

The capacity request of node k to MBS is denoted by $D(k)$. Along the routing tree, each link k is assumed to be uni-directional from source node S to destination node D. The MBS will grant radio resource according to the capacity request, $D(k)$-s ($0\leq s\leq D(k)$). Let t be the current transmission opportunity in a data sub-frame, link k is the current selected link to be served using channel l. Link demands $Y(j)$ for every link j is derived from $D(k)$ according to the obtained route information of routing tree. The scheduling algorithm iteratively determines active link set at time t, namely, $AL(t)$. Suppose there are M transmission opportunities within a centralized scheduling validity and N frequency channels to be used, the scheduling algorithm is shown in Fig. 2.

```
// Scheduling scheme for multi-channel centralized mesh network
t←1
While t<M+1 AND exist any Y(j)>0 for any link j
    k← argmax_∀j Y(j) ;  //select link k
    l←1;
    While l<N+1
        AN_l←Φ, BT_l←Φ, BR_l←Φ;//Initialize these sets for each channel
        l←l+1;
    End while;
    l←1;
    While l<N+1 //select channel one by one
        While k≠Φ
            Add link k's src node S and dest node D to AN_l;
            Add node S's neighborhood to BR_l;
```


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Add node D's neighborhood to BT_l;
Add link k to $AL(t)$;
$k \leftarrow \arg\max_{j \notin AN \cup BT_l; d \notin AN \cup BR_l; Y(j)>0} Y(j)$;
End while;
$l \leftarrow l+1$;
End while;
$Y(j) \leftarrow Y(j)-1 \quad \forall j \in AL(t)$;
$t \leftarrow t+1$;
End while.

Figure 2. Scheduling scheme for multi-channel centralized mesh network.

In this scheme, in transmission opportunity t, channel l is selected first to serve each transmission until there is no link satisfying the constraint ($k \neq \phi$) using channel l. Then next channel is chosen to do the same operation. This process will be repeated until $k = \phi$ for all possible channels. Thus, this scheduling of this transmission opportunity ends and scheduling in t+1 opportunity will start until all the traffic served.

IV. PERFORMANCE EVALUATION

A. Evaluation Metric

The performance of IEEE 802.16 mesh networks is evaluated with a number of MSS nodes that are randomly scattered physically. First, we generate a link connectivity graph using the method given in Section II.A; then three routing trees are built using the three construction algorithms summarized in Section II.B.

For measuring the simultaneous transmission efficiency with spatial reuse of different scheduling schemes, the concept of concurrence rate is introduced here. Let K denote the total number of transmission opportunity (in slot) consumed to fulfill the overall transmission. Given a frame slot k, $k \in [1, K]$, $AL(k)$ is the number of links that are active for uplink and downlink traffic, $|E'|$ is the number of branches (edges) of the routing tree, the concurrence rate CR for a scheduling scheme is defined as

$$CR = \left(\sum_{k=1}^{K} AL(k) / (K \bullet |E'|) \right). \qquad (10)$$

Given that the number of MSSs in the network is N, and MSS i's uplink and downlink traffic request are $D^+(i)$ and $D^-(i)$ respectively, which have been normalized by $C_{BPSK,1/2}$, link capacity with modulation matrix of {BPSK 1/2}. We denote MSS i's total traffic demand as $D(i)$, which equals the summation of $D^+(i)$ and $D^-(i)$. Then, the overall network demand is D, which equals $\sum_{i=1}^{N} D(i)$. We define the overall normalized network throughput as D/T, where T is the time consumed to accomplish all these transmission. T equals $\tau \times K$, where τ is the duration of a single transmission opportunity. Then, the overall normalized network throughput can be defined as

$$T_r = \left(\sum_{i=1}^{N} D(i) \right) / K. \qquad (11)$$

Suppose that traffic from/to MSS i needs to be relayed $h(i)$ times to reach the destination. Let $C(l)$ be the average link capacity in the branch of l of the routing tree, α be the weighted factor which varies upon simultaneously active link number and link capacity, K can be expressed as

$$K = \sum_{i=1}^{N} \left(D(i) \bullet h(i) \right) / \alpha, \qquad (12)$$

where $\alpha = CR \bullet \sum_{l=1}^{|E'|} C(l) / C_{BPSK,1/2}$.

Thus, the overall normalized throughput will be denoted as

$$T_r = \left(\sum_{i=1}^{N} D(i) \right) \Big/ \left(\sum_{i=1}^{N} \left(D(i) \bullet h(i) \right) / \alpha \right). \qquad (13)$$

Especially, when the applied scheduling scheme has no spatial reuse and constant link capacity of $C_{BPSK,1/2}$, α will equal 1. Thus the throughput can be simplified as:

$$T_r = \left(\sum_{i=1}^{N} D(i) \right) \Big/ \left(\sum_{i=1}^{N} \left(D(i) \bullet h(i) \right) \right) \qquad (14)$$

The network average concurrent rate and overall normalized throughput of the proposed multi-channel centralized scheduling algorithm are evaluated respectively.

B. Performance Evaluation

In the simulation, given a total number of MSS nodes, totally 20 random topologies are generated within a radius of 3.2 km. Co-channel interference is taken into account rather than ignoring the interference signal from nodes beyond several hops. Each node demands traffic following Poisson arrival, (λ =20 bits per scheduling interval) to MBS. The bandwidth demand of the node is mapped into link demand $Y(j)$ based on the topology in the routing tree. Their average active link number in a transmission opportunity is compared by combining the results of these 20 topologies.

Fig. 3 shows the concurrent rate under the routing tree generated by three strategies. With the number of nodes in the network increasing, the concurrent rate tends to decrease. That is because in (10), the increase speed of total number of active link are not as fast as that of links in the routing tree $|E'|$. Obviously, EbM algorithm greatly outperforms the other candidates in concurrent rate while IM algorithm performs slightly better than HMMM algorithm. Concurrent rate under EbM tree using single channel is almost the same as that of HMMM tree using two channels. It is also observed that for EbM algorithm, two channels strategy can have almost twice concurrent rate as that of single channel, while for HMMM and IM algorithms, the concurrent rate improvement is not so obvious. The reason why EbM has a better concurrent rate can be explained as follows: in contrast to HMMM and IM that tends to select fewer hops, EbM tends to choose fairly high hops to reach MBS, which gives concurrent transmission more

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opportunities. Hence, it is very important to select a proper routing tree construction algorithm.

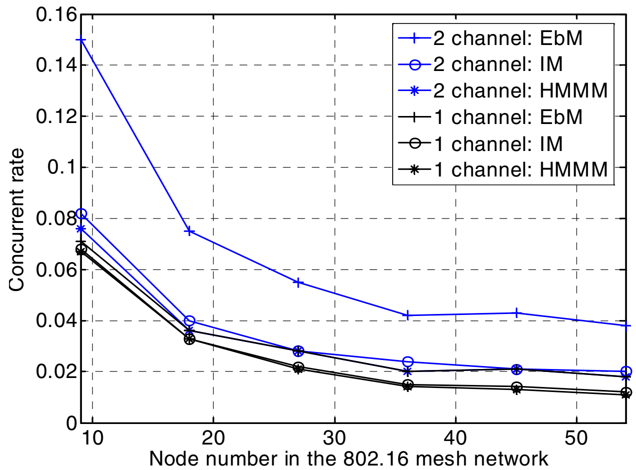

Figure 3. Concurrent rate comparison between single and two channels deployment with spatial reuse.

Fig. 4 shows the normalized throughput for single and two channels deployment with spatial reuse. For spatial reuse, there is a trend that with the nodes increase, the throughput increases almost linearly up to a certain network size and then drops. The reason is that with network size increases and spatial reuse enables, more concurrent transmission is possible and the throughput will increase. But co-channel interference introduced by concurrent transmission is also getting higher, hence signal-to-interference-and-noise ratio (SINR) decreases. The link capacity finally drops to overcome lower SINR by increasing coding rate and decreasing modulation. Thus the throughput also decreases after a certain network size. Heavy traffic and relative low bandwidth also contributes to such a decreasing due to the physical constraint.

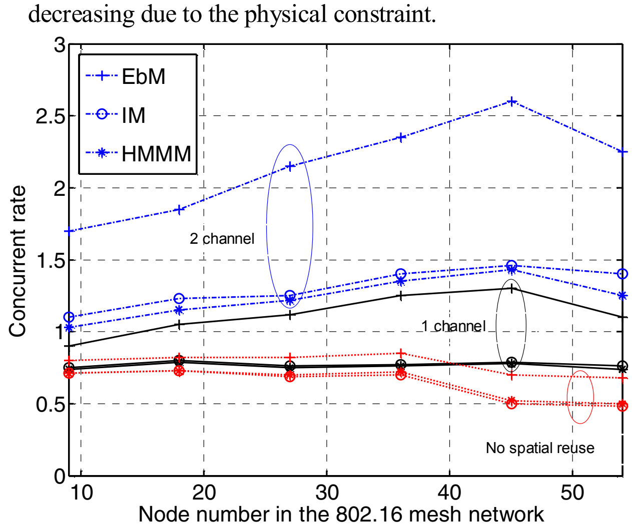

Figure 4. Normalized throughput for one, two channels with spatial reuse and no spatial reuse

However, for single channel applied to the HMMM and IM routing tree, the throughput only shows slight changes while network scale rises. Because with the less concurrent transmission rate in these cases (nearly flat in Fig.3 for more than 25 nodes), the less interference level it induces. And the channel capacity $C(l)$ keeps time-invariant in most cases and the fluctuation of α is very limited.

It is also observed that the throughput performance obtained from EbM routing tree is overwhelming against the other two types because this algorithm trends to transmit with less energy and the interference level is lower than the others. With spatial reuse, the IM algorithm performs slightly better than HMMM algorithm because it also tends to decrease interference induced to other nodes and the SINR level is higher than HMMM in general. While without spatial reuse, the performance of IM algorithm is slightly inferior to that of HMMM algorithm since the non-blocked nodes are also prohibited from transmitting at the same scheduling opportunity.

V. CONCLUSION

Routing tree construction algorithms and a multi-channel centralized scheduling with spatial reuse for IEEE 802.16 mesh networks are proposed in this paper. In contrast to previous research that evaluates a routing tree construction algorithm on a known connectivity graph; three routing tree construction algorithms are investigated under some random spaced nodes for initial deployment, which are applicable for centralized scheduling. Meanwhile, to the best of our knowledge, this is the first work to evaluate a scheduling algorithm under the variance of link capacity in IEEE 802.16 mesh network. Under time variable channel capacity induced by co-channel interference, the scheduling algorithm we propose can improve the throughput compared to no spatial reuse scenario. This paper shows that EbM routing tree construction has the best performance in both concurrent rate and normalized throughput, which should be a favorable approach for coverage and topology planning of IEEE 802.16 mesh network using centralized scheduling. Furthermore, multi-channel and spatial reuse will also contribute to performance improvement of centralized scheduling.

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