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Centralized Scheduling and Channel Assignment in Multi-Channel Single-Transceiver WiMax Mesh Network

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Abstract—**The IEEE 802.16a standard defines WiMax mesh network, using the base station (BS) as a coordinator for the centralized scheduling. This paper proposes a centralized scheduling algorithm for WiMax mesh networks. In our scheme, each node has one transceiver and can be tuned between multiple channels, intending to eliminate the secondary interference for reducing the length of scheduling. We first study the problem when sufficient channels are supported, then extend our solution to the case with insufficient number of channels. Both the scheduling algorithm and the channel assignment strategies are included. The simulation results show that the multi-channel single-transceiver MAC can reduce the length of scheduling substantially as compared with the single channel system, and double channel may provide a performance similar to the multiple channels.**

Index Terms—**802.16, WiMax, multi-channel, scheduling, channel assignment.**

I. INTRODUCTION

The IEEE standard 802.16, which is commonly known as WiMax, has been designed to provide wireless last-mile broadband access in the Metropolitan Area Network (MAN). This standard specifies the physical (PHY) layer and the medium access control (MAC) layer. The IEEE standard 802.16a, as an amendment to IEEE 802.16, provides advanced PHY layer and MAC layer specifications. According to this standard, both point-to-multipoint (P2MP) mode and multipoint-to-multipoint (mesh) mode are supported.

In the P2MP mode, nodes are organized into a cellular like structure. All links are among a BS and some subscriber stations (SS). The SSs must be within the transmission range and line-of-sight (LOS) of the BS. Nodes in the mesh mode are organized in an ad-hoc fashion. Within a mesh network, a system that has a direct connection to backhaul services outside the mesh network is termed as a mesh BS and all other systems of a mesh network are termed as mesh SSs [1]. Traffic towards the BS is defined as uplink and traffic away from the BS is termed as downlink. The major difference between P2MP and mesh is that, connections among the BS and SSs can be routed through other SSs in the mesh network.

The IEEE standard 802.16a specifies the network entry, link selection, physical time synchronization and time slot allocation in the mesh mode. The mesh mode uses the time division multiple access (TDMA) technology. One frame is divided into 256 time slots. The first 16 time slots form a control subframe and the others constitute a data subframe. The control subframe takes responsibility for network configuration and time slot allocation, while the data subframe is mainly used for data transmission. The time slot allocation, where transmissions in each time slot of the data subframe are determined, is crucial to the system throughput and Quality of Services (QoS).

The scheduling is another expression of time slot allocation. Both centralized scheduling and distributed scheduling are supported in the IEEE standard 802.16a. The centralized scheduling, which is coordinated by the BS, is best for links supporting persistent traffic streams. During the control subframe, the BS collects bandwidth requests from all SSs through mesh centralized scheduling (MSH-CSCH) request messages. After that the BS decides the transmissions in each time slot using the scheduling algorithm and disseminates the scheduling results to all SSs in a certain hop range through MSH-CSCH grant messages. The most important measure of the performance of a scheduling algorithm is the length of scheduling, which is defined as the number of time slots needed to complete all data transmissions. The length of scheduling might be reduced if more transmissions are selected to be active concurrently in each time slot. All control and data messages between the BS and SSs in the centralized scheduling are along a routing tree which is constructed during the network entry process. In distributed scheduling, each SS gathers information about its 2-hop neighbors during the Mesh Distributed Scheduling (MSH-DSCH) messages exchange. Then the scheduling result is decided in a distributed fashion.

We develop a centralized scheduling algorithm for the IEEE 802.16a mesh mode. In our scheme, the routing tree is constructed in a width-first fashion. To reduce the length of scheduling, a multi-channel MAC is used. A multi-channel MAC can be multi-channel multi-transceiver or multi-channel single-transceiver [2]. In the multi-channel multi-transceiver system, each node has a radio supporting several simultaneous channels and the multiple channels are coordinated in the MAC layer. In the multi-channel single-transceiver system, each node has only one transceiver so one node can not support multiple channels simultaneously. However, more transmissions might be active concurrently when different nodes work on different channels and thus the length of scheduling is reduced.

Multi-channel multi-transceiver may lead to a short length of scheduling. However, it will increase the cost and hardware complexity dramatically. Multi-channel single-transceiver can provide performance better than the single channel system, while it needs only slight modification on the MAC and PHY layer. In our scheme, a multi-channel single-transceiver MAC is used. As only one transceiver is supported on each node, primary interference can not be avoided and that is why we focus on the elimination of secondary interference. This will be illustrated in section III. Since one node might be tuned between different channels, a dynamic channel assignment strategy is used. For simplicity, the switching delay, which is incurred when a transceiver switches between different channels, is ignored.

The rest of the paper is organized as follows. Section II presents the related work. In section III, the scheduling model and the benefit of multi-channel single-transceiver are illustrated. In section IV, we discuss the issues when sufficient channels are supported. The channel assignment and scheduling algorithm for the case in which the number of channels is not large enough to eliminate secondary interference completely are described in section V. Section VI presents the simulation results and we conclude the paper in the final section.

II. Related work

Current research on WiMax mesh centralized scheduling mainly focuses on spectrum reuse. An interference–aware scheduling scheme is presented in [3]. Harish Shetiya and Vinod Sharma developed routing and centralized scheduling algorithms, along with an admission control policy to provide per flow QoS [4]. Researchers in Bell Laboratories design an algorithm using directional antennae to achieve high channel utilization ratio [5], whereas their solution doesn't support omni antenna and is difficult to support a large number of SSs.

A related problem is the scheduling in TDMA based packet radio network. Scheduling strategies must ensure that transmissions in each time slot do not collide. There are two types of scheduling, broadcast and link. In a broadcast schedule, the entities scheduled are the stations themselves while in a link schedule, the links between the stations are scheduled [6]. Many link and broadcast scheduling algorithms have been proposed. The comparison between these two kinds of scheduling can be found in [7]. A node assignment strategy in which a node has multiple reception capacity is presented in [8]. The upper bound of capacity in TDMA based wireless mesh network has been studied. Both arbitrary and random networks are considered [9].

Current research on multi-channel mesh network is mainly based on the IEEE 802.11 MAC, focusing on QoS routing and channel assignment. The concepts of multi-channel multi-interface mesh network are illustrated in [10]. Several channel assignment and routing schemes have been proposed [11] [12]. An advanced AODV routing protocol to support multi-channel single-transceiver is presented in [13]. But the issues are different in the IEEE 802.16a mesh network. First, the QoS routing is difficult because static routing is used and the route is constructed without knowledge of bandwidth request. Another difference is that dynamic channel assignment is available since fine synchronization is provided. To the best of our knowledge, this paper is the first one that discusses the issue using multi-channel on IEEE 802.16a mesh network.

III. Problem definition

In WiMax mesh centralized scheduling, the BS decides the transmission sequence in data subframes. The scheduling algorithm, along with the policy of routing tree construction decides the system performance. We construct the routing tree in a width-first fashion and use a multi-channel single-transceiver MAC to reduce the length of scheduling. We focus on the scheduling algorithm and the channel assignment strategy in the mesh network.

A. Centralized scheduling algorithm

In the centralized scheduling algorithm, the BS gathers the bandwidth requests from all SSs and schedules the order of transmission in data subframes. Scheduling algorithms are used to minimize the length of scheduling. Previous research shows that scheduling downlink and uplink traffic simultaneously only decreases the length of scheduling in a negligible degree. For simplicity we only consider uplink traffic and all links mentioned are for uplinks in the rest of the paper. In the case of downlink traffic, we first assume all downlink bandwidth requests to be uplink and use our proposed scheme to schedule the uplink transmissions. Then we reverse the sequence of scheduled time slots. Finally we change the uplink traffic to downlink traffic in each time slot and the result is for the original downlink bandwidth requests.

In a multi-hop wireless network, depending on the signaling mechanism, transmissions may collide in two ways—these are typically referred to as primary and secondary interference. Primary interference occurs when the schedule is such that a station must do more than one thing in a single time slot.

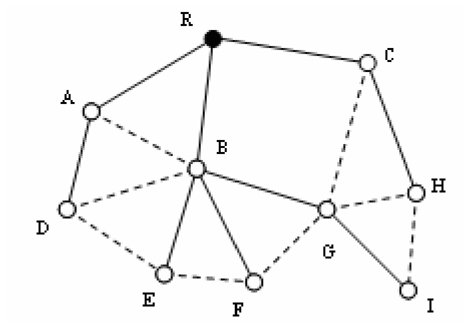

Figure 1. Interference model.

Secondary interference occurs when a node R tuned to an adjacent transmitter T is within the range of another transmitter whose transmissions interfere with the transmissions of T [6]. The interference model is illustrated in Figure 1.

In Figure 1, the black node R stands for the BS and all other nodes are SSs. Solid lines represent edges in the routing tree and dash lines represent the remainders in the mesh network. Suppose F transmits to B in a certain time slot. Then links EB, GB and BR are blocked because of primary interference. Links DA, AR and IG are blocked due to the secondary interference. Another constraint is in the relay model. One link can be active only when the buffer of its transmitter is not empty. In a certain time slot, we consider the link that might be active as "available". In Figure 1, if node C has no uplink bandwidth requests, then link CR is not available until node H finishes at least one time slot uplink transmission. In a real WiMax system, a SS must delay a certain time before relaying a message. We omit this restriction for simplicity. Another assumption is that all nodes have the same capacity.

B. *Benefit of multi-channel single-transceiver*

In a multi-channel single-transceiver system, one node can support only one channel in a certain time slot and adjacent nodes can communicate with each other only when they are tuned to the same channel. Obviously the primary interference is unable to avoid. However, different nodes may operate on different channels to avoid secondary interference. The benefit of multi-channel single-transceiver is illustrated in Figure 1. Suppose all links are available in a certain time slot. If all nodes are switched to the same channel, we may choose links CR, EB to be active concurrently. However, if nodes A, D, I, G are switched to another channel, then links DA and IG may be used at the same time. The number of channels supported is determined by frequency planning in licensed bands or dynamic frequency selection (DFS) in licensed-exempt bands, which is beyond the scope of this paper.

IV. PROBLEMS WITH SUFFICIENT CHANNELS

We use a multi-channel single-transceiver MAC to avoid secondary interference in each time slot, in order to reduce the length of scheduling. If sufficient channels are supported, secondary interference can be eliminated completely. We consider the channel assignment and scheduling model in this case.

A. *Channel assignments*

With sufficient channels, we first assign channels on the edge set of the routing tree before the design of scheduling. This can be expressed as coloring the links of routing tree *T* with minimum number of colors.

Given the mesh topology $G=(V,E)$ and the routing tree $T=(V,E')$, for link $(a,b)\in E'$ and $(c,d)\in E'$, (*a, b*) and (*c, d*) may be colored the same if and only if:

(1) *a,b,c,d* are not mutually distinct, or

(2) $(a,d)\notin E$ and $(c,b)\notin E$

In the first case, link (*a, b*) and (*c, d*) are adjacent. They may be assigned the same channel because the joint node can not be tuned to different channels in one time slot. In the second case, link (*a, b*) and (*c, d*) may be colored the same since they are not interfered with each other.

We use an approximation algorithm to solve this problem. For each link *l* in the uncolored link set L_U, we define *SI(l)* as the set of links that have secondary interference with link *l*. *C* is the color set of all links in *SI(l)*. We color *l* with the minimum color in *N-C* and delete *l* from L_U. This process repeats until L_U is empty. Details of the algorithm are given in Figure 2. *c(l)* stands for the color of link *l* and the function *random_select* is used to select one link randomly.

The result of this algorithm is the color of each link. Suppose the mesh network has *n* nodes. The time complexity will be *O(n)*. If the number of channels is larger than the number of colors used in this algorithm, secondary interference can be eliminated completely. In each time slot, one link should be assigned a channel corresponding to its color. Thus, the transmitter and receiver of this link must be tuned to the same channel.

We use the mesh network in Figure 1 as an example. We select link AR first and color it with color 1. The second link selected is link FB. Since FB and AR have secondary interference, we color it with color 2. Then we select link IG and color it with color 1. This process repeats until all links on the routing tree are colored. The result is shown in Figure 3. The color of each link is marked near the link.

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Coloring Algorithm:
Input:  mesh network  G = (V, E)
        routing tree  T = (V, E')
Output: A coloring c:  E' → N
L_U ← E'
While L_U ≠ φ
    l ← random_select( L_U )
    C ← φ
    C ← C ∪ {c(k)}  for all  k ∈ SI(l) − L_U
    c(l) ← argmin_{i∈N−C} i
    L_U ← L_U -{l}
End While
```

Figure 2. Coloring algorithm to eliminate secondary interference.

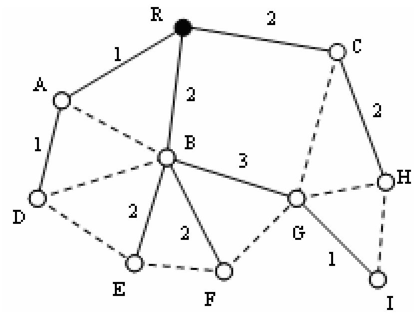

Figure 3. Coloring of routing tree.

B. *Scheduling without secondary interference*

When secondary interference is eliminated, the scheduling problem can be described as a linear programming (LP) problem and many mathematical models can be used to solve it. The details are given in [5].

V. SCHEDULING AND CHANNEL ASSIGNMENT WHEN THE NUMBER OF CHANNELS IS LIMITED

In this case, secondary interference may not be eliminated completely. In the following we will discuss the scheduling and channel assignment under this situation.

A. *Scheduling*

As both primary and secondary interference may exist in each time slot, the linear programming model in [5] is not suitable. We propose an active link selection (ALS) algorithm to solve this problem. Inputs of the ALS algorithm are the mesh topology, routing tree, supported channels and bandwidth request of each node in terms of time slot numbers. As mentioned above, our scheme must follow the interference and relay models.

Initially we assign a token to each node. The token is proportional to the upward traffic demand of this node. In each time slot, a link whose transmitter has a non-zero token is considered as "available". All available links constitute the available link set *A*. We use a nearest select (NS) algorithm to find a group of links to transmit concurrently from *A* and assign channels to them. After that, for each selected link, the token of its transmitter is decreased by 1 and the token of its receiver is increased by 1. This process finishes when the tokens of all SSs are 0. We use *C(t)* to record the active link set in time slot 't'. The ALS algorithm is presented in Figure 4. Details of the NS algorithm are illustrated in part B.

B. *Channel assignment and link selection*

The NS algorithm is used to select a set of active links from the available link set in a nearest first fashion and to assign channels to them. Restriction of this algorithm is that, active links switching to the same channel must not interfere with each other. The algorithm is presented in Figure 5.

Suppose *n* channels are supported, without loss of generality we use a color set C_A=[1,…,*n*] to represent the channels. For each link *l* in the uncolored link set L_U, *PI(l)* and *SI(l)* denote the set of links that have primary and secondary interference with *l* respectively. *C* is the color set of all links in *SI(l)*. If links in *PI(l)* are not active and links in *SI(l)* do not occupy all colors, we color *l* with the minimum color in $C_A - C$ and delete *l* from L_U. The color of link *l* is recorded in *c(l)*. Each time *l* can be selected from L_U according to a certain criterion. Previous research showed that the nearest first criterion, according to which the link whose transmitter has the minimal hop count to the BS be selected first, may lead to a high system performance, and thus in our scheme we use the *nearest_select* function to select *l* from L_U in the nearest first order.

C. *Performance analysis*

Suppose the mesh network has *n* nodes. One link is interfered with *O(1)* links and the available link set in each time slot has at most *n* links. So the NS algorithm can be finished in *O(n)* time. The length of scheduling *L* is no more

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ALS Algorithm:
Input: mesh network G = (V, E)
    routing tree T = (V, E')
    channel set C_A
Output: scheduling result C
Initialize token of each node
t ← 1
While exist any token(j)>0 for any SS j
  A ← φ
  Add k to A for each available link k
  C(t) ← NS(A)
  adjust tokens for each link in C(t)
  t ← t+1
End While
```

Figure 4. ALS scheduling algorithm.

NS Algorithm:
Input: mesh network $G = (V, E)$
  routing tree $T = (V, E')$
  available link set A
  color set C_A =[1,*n*]
Output: active link set $L_A \subset A$,
  channel assignment c: $L_A \to C_A$
$L_U \leftarrow A$
While $L_U \neq \phi$
  $l \leftarrow$ *nearest_select*(L_U)
  $C \leftarrow \phi$
  $C \leftarrow C \cup \{c(k)\}$ for all $k \in SI(l) \cap L_A$
  if $PI(l) \cap L_A = \phi$ and $C_A - C \neq \phi$
    $L_A \leftarrow L_A \cup \{l\}$
    $c(l) \leftarrow \arg\min_{i \in C_A - C} i$
  End if
  $L_U \leftarrow L_U - \{l\}$
End While

Figure 5. NS algorithm.

than *O(n)* and the NS algorithm is executed *L* times. Thus the time complexity of the ALS scheduling algorithm is $O(n^2)$.

VI. SIMULATION

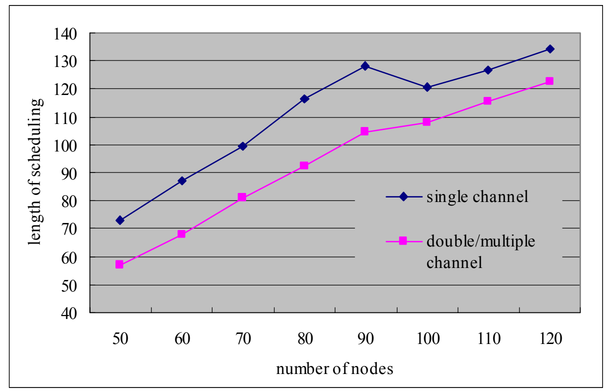
The purpose of scheduling algorithms is to minimize the length of scheduling as the scheduling chain may take a long time for a node to pass. Another purpose is to reduce the average transmission delay, which is defined as the number of time slots between the time slot when a packet is transmitted by the source SS and the time slot when it arrives at the BS. We compare the length of scheduling and the average transmission delay among three schemes. The first one is a single-channel scheduling algorithm using nearest first selection. The second and third schemes are used for multi-channel single-transceiver systems. In the second scheme, two channels are supported and the scheduling algorithm presented in Figure 4 is used. The third scheme is similar to the second one, whereas sufficient channels are supported and the secondary interference is eliminated completely. These algorithms are named “single channel”, “double channel” and “multiple channel” respectively.

We use a java-code custom simulator to evaluate the performance. Nodes are within a 100×100 square area. All nodes have a same transmission range ‘r’ and two nodes are neighbors only if they are in the transmission range of each other. We set the BS at the center of the square. Then we construct the routing tree in a width-first fashion.

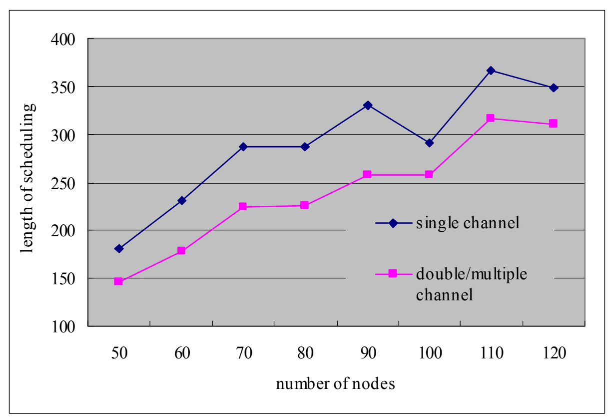
According to the simulation results, “double channel” and “multiple channel” may lead to similar performance so we use one line to represent these two schemes in each line-graph.

The simulation results about the length of scheduling are presented in Figure 6. In Figure 6(a), all nodes have a transmission range of 15 units and the token of each node is set to 1. The number of nodes in the network ranges from 50 to 120 with increment step of 10. In Figure 6(b), the node transmission range is 15. The number of nodes in the network ranges from 50 to 120 and the token of each node is randomly selected from 0 to 5. In Figure 6(c), each node has one token. The number of nodes is set to 50 and the transmission range of each node ranges from 15 to 50 with increment step of 5. From Figure 6 (a) and (b), we find that the length of scheduling rises with the increase of tokens and nodes. Compared with the results of “single channel”, the “double channel” and “multiple channel” schemes decrease the length of scheduling dramatically. In Figure 6(c), the disparity in the length of scheduling between the three schemes decreases with the increase of transmission range, because long transmission range may lead to a low-depth routing tree and thus the influence of secondary interference can be ignored compared with that of primary interference.

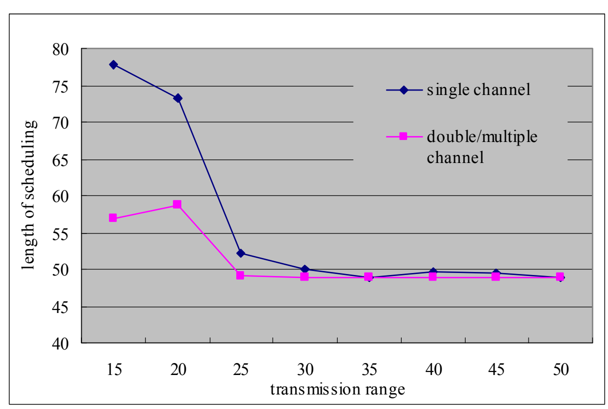
The configuration of Figure 7 is the same as that of Figure 6 whereas Figure 7 depicts the average transmission delay. The transmission delay may be influenced by the buffer management policy of each node. In our solution, the token, whose origin has the minimum depth, has a high priority. When each node has a low transmission range, the use of “double channel” or “multiple channel” may decrease the average transmission delay remarkably. However, when the transmission range is large, the transmission delay in a multi-channel single-transceiver system may be longer than that in a single-channel system. The reason is that, source SSs may be selected earlier when multi-channel is used, while the arrival time is difficult to advance in a low-depth routing tree, and thus the transmission delay is increased.



(a) r=15, token=1, n is from 50 to 120

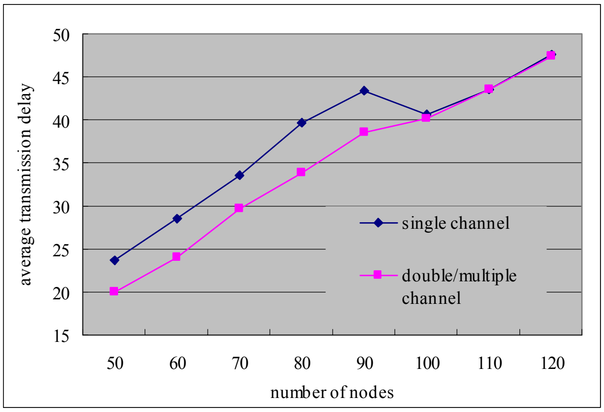


(b) r=15, token∈ [0,5], n is from 50 to 120

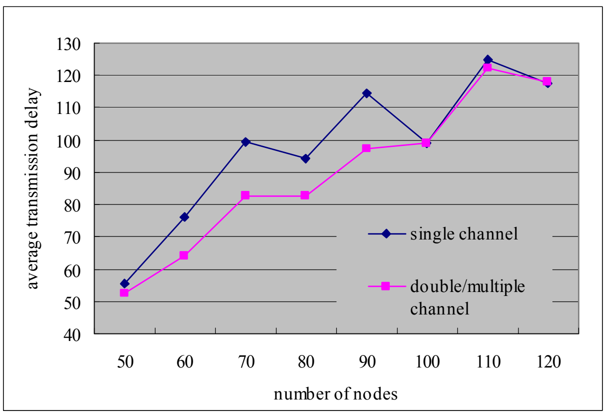


(c) n=50, token=1, r is from 15 to 50

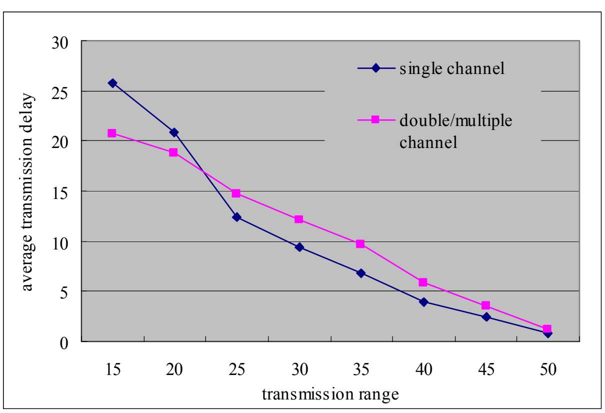
Figure 6. The length of scheduling.



(a) r=15, token=1, n is from 50 to 120



(b) r=15, token∈ [0,5], n is from 50 to 120



(c) n=50, token=1, r is from 15 to 50

Figure 7. Average transmission delay.

VII. CONCLUSION

We have proposed a centralized scheduling algorithm using multi-channel single-transceiver in the IEEE 802.16a mesh network. In our scheme, the channels are assigned to nodes in a dynamic manner and the switching delay is ignored. We presented the channel assignment to eliminate the secondary interference and studied the scheduling model when the secondary interference is avoided. We also presented a scheduling algorithm along with a channel assignment strategy for the case in which a limited number of channels are supported. We compared our proposed scheme with a single-channel scheduling algorithm. According to the simulation results, the multi-channel single-transceiver MAC improves system performance dramatically. An interesting issue is that using the double channel and the multiple channels may lead to a similar length of scheduling with similar transmission delay. Thus, in a multi-channel multi-transceiver WiMax mesh network, the number of channels should be no more than twice the number of the transceivers.

ACKNOWLEDGMENT

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