A Study on Distributed/Centralized Scheduling for Wireless Mesh Network

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ABSTRACT

The IEEE 802.16 standard proposes the *Media Access Control* (MAC) protocol for the *Wireless Metropolitan Area Network* (WMAN). Two transmission modes are defined in the IEEE 802.16, including *Point-to-Multipoint* (PMP) mode and mesh mode. In the 802.16 mesh mode, allocation of minislots can be handled by the centralized and distributed scheduling mechanisms. This paper proposes the *Combined Distributed and Centralized* (CDC) scheme to combine the distributed scheduling and centralized scheduling mechanisms so that the minislot allocation can be more flexible, and the utilization is increased. Two scheduling algorithms, Round Robin (RR) and Greedy, are proposed as the baseline algorithms for the centralized scheduling mechanism. We conduct simulation experiments to investigate the performance of the CDC scheme with the RR and Greedy algorithms. Our study indicates that with CDC scheme, the minislot utilization can be significantly increased.

Categories and Subject Descriptors

C.2.1 [**Computer-Communication Networks**]: Network Architecture and Design—*centralized networks, distributed networks, wireless communication*; D.2.8 [**Software Engineering**]: Metrics—*performance measures*

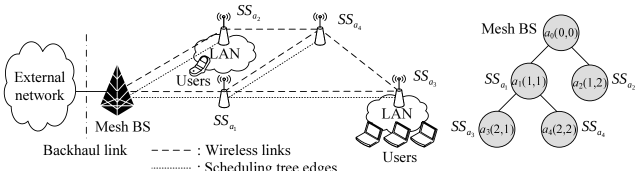
General Terms

Experimentation, Measurement, Performance

Keywords

802.16, mesh, performance, scheduling, wireless

IWCMC'06, July 3–6, 2006, Vancouver, British Columbia, Canada.



(a) Network topology

(b) Scheduling tree with index numbers

Figure 1: The IEEE 802.16 mesh network architecture

1. INTRODUCTION

The IEEE 802.16 standard [1] (also known as WiMax) defines the *Media Access Control* (MAC) protocol for the *Wireless Metropolitan Area Network* (WMAN). It provides fixed broadband wireless access with the same level of QoS as the traditional cabled access network. Compared with the traditional cabled access network (where high deployment and maintenance costs are required), IEEE 802.16 provides a cheaper and more ubiquitous solution to connect home and business to Internet.

IEEE 802.16 operates at 10-66 GHz for *Line-Of-Sight* (LOS) and 2-11 GHz for non-LOS. Typically, channel bandwidth is 25 MHz or 28 MHz. The data transmission rate is up to 134.4 Mbits/s. An IEEE 802.16 network consists of *Base Station* (BS) and *Subscriber Station* (SS). The BS serves as a gateway between the IEEE 802.16 network and the external network. The SS acts like a client-side terminal, through which mobile users can access the network through air interface. IEEE 802.16 defines two wireless transmission modes between SSs and BS, including *Point-to-Multipoint* (PMP) mode and mesh mode. The PMP mode is designed for high data rate transmission service with support of various QoS. It requires all SSs to be within clear LOS transmission range of the BS. On the other hand, in the mesh mode, the SSs can communicate with each other within non-LOS transmission range of the SSs. In this paper, we converge our study on the mesh mode. To simplify our description, hereafter, IEEE 802.16 with the mesh mode is called as the wireless mesh network [2].

Figure 1 (a) depicts the architecture of a wireless mesh network. The mesh BS interfaces the external network with

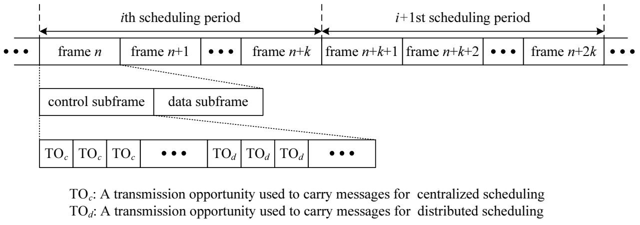


Figure 2: The frame structure of the IEEE 802.16 mesh network

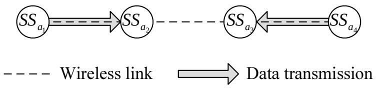


Figure 3: An example for the minislot reuse property

backhaul links. Any SS pair without direct links can relay the data to each other through other SSs. The users connect to the SS by adopting various existing *local area network* (LAN) technologies, e.g., IEEE 802.3 (Ethernet) or IEEE 802.11 (WiFi). In this paper, we focus on the MAC protocol between SSs and between the SS and mesh BS.

The wireless mesh network adopts the *Time Division Multiplexing* (TDM) radio access technology between SSs and between the SS and the mesh BS, where a radio channel is divided into *physical slots* (PSs) using time sharing, and multiple PSs are grouped as a frame. Figure 2 shows the frame structure. A frame is divided into a control subframe and a data subframe. The control subframe consists of Transmission Opportunities (TOs) used to carry signaling messages for centralized scheduling[1] and distributed scheduling, which are denoted as TO$_c$ and TO$_d$, respectively. The numbers of TO$_c$s and TO$_d$s in a control subframe are configured by the operator. The data subframe carries the user data and is further divided into 256 minislots. The transmission rate r bits/sec (that a minislot can provide) depends on several factors (e.g., channel coding, modulation, frequency band, and so on). Due to the page limitation, we do not include the discussion for these factors in this paper, and readers may refer to [1] for more details. A minislot can be reused by multiple SSs (i.e., multiple SSs may be allowed to transmit in the same minislot) as long as the SSs are geographically separated (i.e., they do not interfere each other) [11][7]. For example, in Figure 3, SS_{a_1} and SS_{a_4} can transmit data to SS_{a_2} and SS_{a_3} in the same minislot, respectively. This property is called as "*minislot reuse*" in TDM.

The data traffics in the wireless mesh network can be divided into two categories: intranet traffic and Internet traffic, which are the traffic between two SSs in the same wireless mesh network and the traffic between the SS and the application server in Internet, respectively. A data subframe can simultaneously carry the intranet traffic data and the Internet traffic data. The IEEE 802.16 proposes the distributed scheduling mechanism for minislot allocation for the intranet traffic and the centralized scheduling mechanism for the Internet traffic. The details of the two mechanisms are given in Section 2. The distributed scheduling targets on data delivery between two SSs in the same wireless mesh network, while the centralized scheduling enables the communication between the mesh BS and the SS. It is important to carefully schedule the minislots in a data subframe for both kinds of traffics to optimize minislot utilization.

IEEE 802.16 suggests to partition a data subframe into two parts for the two scheduling mechanism which is known as the "Partition" scheme. However, this may not be the best solution due to the fact that the partitioned boundary may not precisely capture the traffic patten, and the minslots may not be fully utilized. This paper proposes the *Combined Distributed and Centralized* (CDC) scheme to combine the distributed scheduling and centralized scheduling mechanisms so that the minislot allocation can be more flexible, and the minislot utilization is increased. We conduct simulation experiments to investigate the performance for the Partition and CDC schemes.

2. CENTRALIZED AND DISTRIBUTED SCHEDULING MECHANISMS

This section first illustrates the distributed and centralized scheduling in the wireless mesh network. Then, we propose the CDC scheme to combine the two scheduling mechanisms.

2.1 Distributed Scheduling

Before two neighboring SSs start to exchange data, they exercise a three-way handshaking procedure to select the minislots for data transmission, which is known as the distributed scheduling. In this scheduling, the SSs use the control subframe to transmit control messages. The SSs compete for control message transmission based on a pseudo-random election algorithm. The details of the algorithm can be found in [1]. When an SS joins the wireless mesh network, the SS obtains a node ID by exercising the registration procedure, whose details can be found in [1]. In this paper, to simplify our description, we denote an SS with the node ID a_i as SS_{a_i}. Figure 4 illustrates the message flow for the distributed scheduling, where SS_{a_s} has data to be transmitted with transmission rate R to its neighbor, SS_{a_r}. Let n_{f,a_s} denote the number of SS_{a_s}'s free minislots. The SS_{a_s} first checks whether n_{f,a_s} is smaller than $\lceil \frac{R}{r} \rceil$. If so, SS_{a_s} quits the distributing scheduling. Otherwise, the following three steps are executed to reserve minislots for data transmission.

Step D1. SS_{a_s} sends a Mesh Distributed Scheduling (MSH-DSCH) Request message to SS_{a_r}, which is carried in the control subframe and contains the transmission rate R and the IDs of all free minislots.

Step D2. Upon receipt of the message, SS_{a_r} determines if the number n_{f,a_r} of its free minislots is smaller than $\lceil \frac{R}{r} \rceil$. If so, SS_{a_r} quits this procedure without sending additional messages. Otherwise, SS_{a_r} compares the IDs of its free minislots with the IDs carried in MSH-DSCH Request message. If the number of matched IDs is larger than or equal to $\lceil \frac{R}{r} \rceil$, then SS_{a_r} selects $\lceil \frac{R}{r} \rceil$ matched minislots, sets the states of these minislots as **busy**, and sends the IDs of the selected minislots to SS_{a_s} through the MSH-DSCH Grant message. Otherwise, SS_{a_r} exits the distributed scheduling.

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[1] The scheduling is to schedule minislots to serve different SSs.

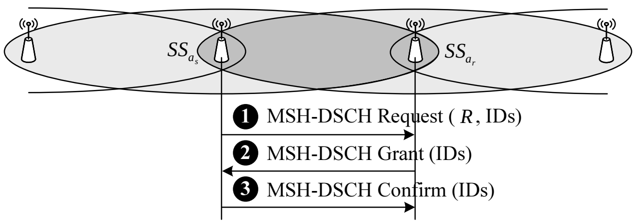

Figure 4: Message flow for the distributed scheduling

Step D3. The SS_{a_s} confirms the minislot reservation by sending SS_{a_r} the MSH-DSCH Confirm message.

After the execution of the distributed scheduling, SS_{a_s} can transmit data to SS_{a_r} in the reserved minislots in the data subframe without collision.

2.2 Centralized Scheduling

IEEE 802.16 specifies the centralized scheduling for the communication between the mesh BS to SSs, where the mesh BS acts as a scheduler and determines transmission and reception minislots for each SS. A scheduling tree rooted at the mesh BS is established for the routing path between each SS and the mesh BS. Denote a scheduling tree as $T = \{a_0(k_{a_0}, n_{a_0}), a_1(k_{a_1}, n_{a_1}), a_2(k_{a_2}, n_{a_2}), ..., a_i(k_{a_i}, n_{a_i}), ...\}$, where k_{a_i} is the layer number, n_{a_i} is the position number in layer k_{a_i}, and (k_{a_i}, n_{a_i}) is the index number of the SS. Without loss of generality, the index number of the mesh BS is (0,0). Figure 1 (b) shows an example of the scheduling tree for Figure 1 (a). Before an SS executes the registration procedure to join the wireless mesh network, it selects a network node with smallest layer number from all neighboring network nodes as the *candidate node*. Then the SS sends the registration message to the mesh BS through the candidate node. Upon receipt of the registration message, the mesh BS sets the SS as the child of the candidate node in the scheduling tree, updates the scheduling tree, and then broadcasts the scheduling tree to all SSs. Readers may refer to [1] for more details of the registration procedure. The SSs negotiate with the mesh BS for bandwidth request and grant by routing signaling messages according to the scheduling tree. The centralized scheduling reserves bandwidth for an SS all the way to the mesh BS.

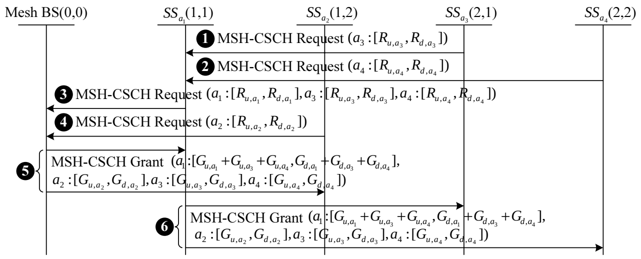

Figure 5: Message flow for the centralized scheduling

The centralized scheduling consists of two stages. In the first stage, the mesh BS collects bandwidth requests from all SSs. In the second stage, the mesh BS calculates and then distributes the transmission and reception schedule to all SSs. The time period for exercising the two stages is called as *scheduling period*. The schedule assigned in the ith scheduling period is referenced in the $i+1$st scheduling period as shown in Figure 2. Take Figure 1 as an example, where SS_{a_i} $(i = 1, 2, 3, 4)$ requests transmission rates, R_{u,a_i} and R_{d,a_i} for data transmission to and data receipt from the mesh BS, respectively. The SS_{a_i} first checks whether the number n_{f,a_i} of free minislots is smaller than $\left\lceil \frac{R_{u,a_i}}{r} \right\rceil + \left\lceil \frac{R_{d,a_i}}{r} \right\rceil$. If so, SS_{a_i} quits the centralized scheduling. Otherwise, the centralized scheduling exercises as follows: Based on the scheduling tree, the SS with larger k_{a_i} and smaller n_{a_i} transmits the uplink signaling messages first, while the SS with smaller k_{a_i} and smaller n_{a_i} relays the downlink signaling message first. Figure 5 illustrates the message flow for the centralized scheduling mechanism with the following steps, where we consider the example in Figure 1 (a).

Step C1. SS_{a_3} sends a Mesh Centralized Scheduling (MSH-CSCH) Request message to SS_{a_1} where R_{u,a_3}, R_{d,a_3}, and its node ID, a_3, are carried in this message.

Step C2. SS_{a_4} sends SS_{a_1} an MSH-CSCH Request message carrying R_{u,a_4}, R_{d,a_4}, and its node ID, a_4.

Step C3. SS_{a_1} sends the mesh BS an MSH-CSCH Request message containing R_{u,a_1}, R_{d,a_1}, and its node ID, a_1, and the parameters obtained in Steps C1 and C2, i.e., $a_3 : [R_{u,a_3}, R_{d,a_3}]$ and $a_4 : [R_{u,a_4}, R_{d,a_4}]$.

Step C4. SS_{a_2} sends an MSH-CSCH Request message to the mesh BS, where R_{u,a_2}, R_{d,a_2}, its node ID, a_2, are carried in the message.

Step C5. Upon receptions of the MSH-CSCH Request messages from all SSs, the mesh BS obtains the requested bandwidth of all SSs. The mesh BS exercises a scheduling algorithm to allocate the transmission and reception minislots for each SS. Depending on the execution result of the algorithm, the mesh BS replies an MSH-CSCH Grant message to its children. Let G_{u,a_i} and G_{d,a_i} denote the granted data transmission rate and receipt rate for SS_{a_i}, respectively. The grant message carries the parameters $a_1 : [G_{u,a_1} + G_{u,a_3} + G_{u,a_4}, G_{d,a_1} + G_{d,a_3} + G_{d,a_4}]$, $a_2 : [G_{u,a_2}, G_{d,a_2}]$, $a_3 : [G_{u,a_3}, G_{d,a_3}]$, $a_4 : [G_{u,a_4}, G_{d,a_4}]$. Based on these parameters, SS_{a_i} determines the minislots allocated for it to transmit/receive data, whose details are not described in this paper, and can be found in [1].

Step C6. Upon receipt of the MSH-CSCH Grant message, SS_{a_1} forwards the MSH-CSCH Grant message to its children.

After the execution of the centralized scheduling, SS_{a_1}, SS_{a_2}, SS_{a_3}, and SS_{a_4} can transmit and receive data in the reserved minislots during the next scheduling period.

Note that in Step C5, the scheduling algorithm may affect the minislot utilization. Several previous studies [6][5][8] have been contributed for this issue. It has been shown that scheduling algorithm is an *NP-hard* problem, that is, we may not find the optimal solution for it when the number of SSs in a wireless mesh network is sufficiently large. In this study, we use two algorithms, Round Robin (RR) and Greedy, as the baseline algorithms to investigate the performance of the centralized scheduling. The two algorithms will be described in Section 3.

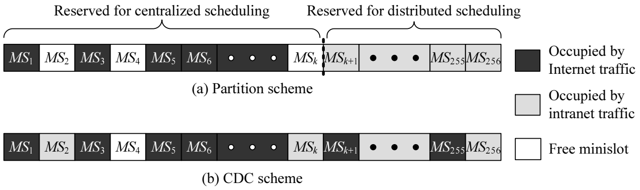

Figure 6: The examples for minislot allocation for Partition and CDC schemes

2.3 The CDC Scheme

The distributed scheduling is designed for data delivery between two SSs in the same wireless mesh network, while the centralized scheduling is designed for communication between the mesh BS and the SS. For the Internet traffic, the packets must be routed to the external network through the mesh BS. On the other hand, intranet traffic occurs between two SSs. Thus, in [1], it is suggested to adopt the centralized scheduling and distributed scheduling to allocate minislots for the Internet traffic and intranet traffic, respectively.

The IEEE 802.16 standard proposes a Partition scheme that partitions the minislots in a data subframe into two parts. The minislots in one part are scheduled by the centralized scheduling, and the minislots in the other part are scheduled by the distributed scheduling. When the wireless mesh network is initially configured, the Partition scheme broadcasts the maximum percentage of minslots (in a data subframe) for the centralized scheduling through the Mesh Network Configuration (MSH-NCFG) message delivery. Figure 6 (a) shows an example for the partition result with the Partition scheme, where the minslots in a data subframe are labeled as MS_1, MS_2, ..., MS_{256}. In the Partition scheme, once the wireless mesh network is configured, the minislots can not be flexibly reserved for the centralized scheduling and distributed scheduling until the next configuration. We propose the *Combined Distributed and Centralized* (CDC) scheme to release the above limitation, whose details are given below.

The CDC scheme utilizes the MSH-CSCH Grant message in Step C5 of the centralized scheduling to notify all SSs the minislots reserved for the centralized scheduling. When an SS receives the MSH-CSCH Grant message, it calculates minislots scheduled by the centralized scheduling for transmitting/receiving data for Internet traffic in the next scheduling period. In the next scheduling period, the SS can determine the free minislots that can be scheduled by the distributed scheduling. Figure 6 (b) shows an example for minislot allocation with the CDC scheme.

3. THE RR AND GREEDY ALGORITHMS

This section describes the scheduling algorithms, RR and Greedy, adopted in Step C5 for centralized scheduling. Let (a_u, a_v) denote the wireless link between the two nodes with node IDs a_u and a_v, respectively, and E be the set of wireless links among SSs and mesh BS. For the jth minislot in a data subframe, the variable s_j is maintained to indicate the status of the minislot. $s_j =$ `F` indicates that the minislot is free, $s_j =$ `TX` indicates that the minislot serves for data transmission, and $s_j =$ `RX` indicates that the minislot serves for data reception. For each SS, SS_{a_i}, an array $\mathbf{S}_{a_i} = \{s_1, s_2, s_3, ..., s_{256}\}$ is maintained to store the status of each minislot in a data subframe. The operation $\textsc{Get}(a_i, j)$ is used to get the status of the jth minislot from $\mathbf{S}_{a_i}$, and $\textsc{Set}(a_i, j, \{$`TX`, `RX`, `F`$\})$ sets the status of the jth minislot serving for SS_{a_i}. When "*collision*" occurs, the transmission between network nodes (the mesh BS or SS) fails [5], which is lead by one of the following two conditions: Consider the three nodes with node IDs, a_u, a_v, and a_w where (a_u, a_v) and $(a_v, a_w) \in E$.

```
Algorithm 1 Round Robin
generate the ordered list $L$ as $\langle a'_1, a'_2, ..., a'_N \rangle$
$j \leftarrow 1$
for $i \leftarrow 1$ to $N$ do
  if $N_{d,a'_i} > 0$ then
    for $p \leftarrow 1$ to $k_{a'_i}$ do
      for $q \leftarrow 1$ to $N_{d,a'_i}$ do
        Set($A_{a'_i}[p], j + q - 1$, RX)
        if $A_{a'_i}[x] \neq a'_i$ then
          Set($A_{a'_i}[p], j + N_{d,a'_i} + q - 1$, TX)
      $j \leftarrow j + N_{d,a'_i} - 1$
      if $j > 256$ then
        return fail
  if $N_{u,a'_i} > 0$ then
    for $p \leftarrow k_{a'_i}$ downto 1 do
      for $q \leftarrow 1$ to $N_{u,a'_i}$ do
        Set($A_{a'_i}[x], j + q - 1$, TX)
        if $A_{a'_i}[x] \neq a'_i$ then
          Set($A_{a'_i}[x], j - N_{u,a'_i} + q - 1$, RX)
      $j \leftarrow j + N_{u,a'_i} - 1$
      if $j > 256$ then
        return fail
return success
```

Figure 7: The pseudo code for the RR algorithm

Condition 1. If there exists the kth minislot such that $\textsc{Get}(a_u, k) =$ `TX` and $\textsc{Get}(a_u, k) =$ `RX`, then the collision occurs. In this condition, SS_{a_u} can not transmit and receive data in the same minislot.

Condition 2. If there exists the kth minislot such that $\textsc{Get}(a_u, k) = \textsc{Get}(a_w, k) =$ `TX`, then the collision occurs. In this condition, SS_{a_u} and SS_{a_w} send data to SS_{a_v} in the same minislot, and the collision occurs.

The scheduling algorithms schedule each minislot to guarantee the requested transmission data rate and reception data rate without collision.

Suppose that the wireless mesh network consists of N SSs with the scheduling tree $T = \{a_0(k_{a_0}, n_{a_0}), a_1(k_{a_1}, n_{a_1}), a_2(k_{a_2}, n_{a_2}), ..., a_N(k_{a_N}, n_{a_N})\}$. In the two algorithms, we maintain an array A_{a_i} for each SS, SS_{a_i}, to store the node IDs of the mesh BS and SSs along the routing path from the mesh BS to SS_{a_i} in the increasing order of their layer numbers. Assume that SS_{a_i} requests the data transmission rate R_{u,a_i} and the data reception rate R_{d,a_i}. Then the numbers of minislots required by SS_{a_i} for data transmission and data reception are $N_{u,a_i} = \left\lceil \frac{R_{u,a_i}}{r} \right\rceil$ and $N_{d,a_i} = \left\lceil \frac{R_{d,a_i}}{r} \right\rceil$, respectively. Initially, the status of all minislots are set as `F`. The RR and Greedy algorithms exercise as follows.

Algorithm RR. Figure 7 shows the pseudo code for the RR algorithm. The RR algorithm does not use the minislot reuse property in TDM, and each minislot is allocated to at most one SS. Due to the page limitation, the description for the RR algorithm is not shown in this paper.

```
Algorithm 2 GREEDY
generate the ordered list $L$ as $\langle a'_1, a'_2, ..., a'_N \rangle$
$j \leftarrow 1$
for $i \leftarrow 1$ to $N$ do
  if $N_{d,a'_i} > 0$ then
    for $p \leftarrow 1$ to $k_{a'_i}$ do
      for $q \leftarrow 1$ to $N_{d,a'_i}$ do
        for $j \leftarrow 1$ to $257$ do
          if $j > 256$ then
            return fail
          if COLLISION($A_{a'_i}[p-1], A_{a'_i}[p], j$) = FALSE then
            SET($A_{a'_i}[p], j$, RX)
            if $k_{A_{a'_i}[p]} \neq 1$ then
              SET($A_{a'_i}[p-1], j$, TX)
            break
  if $N_{u,a'_i} > 0$ then
    for $p \leftarrow k_{a'_i}$ downto 1 do
      for $q \leftarrow 1$ to $N_{u,a'_i}$ do
        for $j \leftarrow 1$ to $257$ do
          if $j > 256$ then
            return fail
          if COLLISION($A_{a'_i}[p], A_{a'_i}[p-1], j$) = FALSE then
            SET($A_{a'_i}[p], j$, TX)
            if $k_{A_{a'_i}[p]} \neq 1$ then
              SET($A_{a'_i}[p-1], j$, RX)
            break
return success
```

Figure 8: The pseudo code for the Greedy algorithm

Algorithm Greedy. Figure 8 illustrates the pseudo code for the Greedy algorithm. In the Greedy algorithm, we adopt the minislot reuse technology. In this algorithm, we implement the COLLISION to determine whether allocation of the jth minislot to SS_{a_u} for transmitting data to its neighbor SS_{a_v} will cause collision, which is shown below:

```
COLLISION($a_u, a_v, j$)
if GET($a_u, j$) $\neq$ F or GET($a_v, j$) $\neq$ F then
  return TRUE
end if
for $i \leftarrow 1$ to $N$ do
  if (($a_i, a_u$) $\in E$ and GET($a_i, j$) = RX) or (($a_i, a_v$) $\in E$ and GET($a_i, j$) = TX) then
    return TRUE
  end if
end for
return FALSE
```

4. PERFORMANCE EVALUATION

This section conducts simulation experiments to investigate the performance for the Partition and CDC schemes with the RR and Greedy algorithms. To simplify our description, we use Partition_RR and Partition_Greedy to denote the Partition scheme with the RR and Greedy algorithms and CDC_RR and CDC_Greedy to denote the CDC scheme with the RR and Greedy algorithms, respectively. We adopt the event-driven based simulation technique [9], which has been widely adopted to simulate the wireless networks [10][3]. The details are not presented here. In the simulation model, we assume that the SSs are identical. A wireless mesh network is modeled as a regular hexagonal topology as show in Figure 9, which is the same as that in IEEE 802.16 standard [1]. In this configuration, the SS node is located on each corner of each hexagon. Following the registration mentioned in Section 2, in this topology, if an SS is k hops way from the mesh BS, then the SS is in the layer k of the scheduling tree. There are $3k$ SSs in layer k. An l-layer wireless mesh network covers one mesh BS and SSs from layer 1 to layer l. Our simulation model has been validated by an analytical model. Due to page limitation, the details of the analytical model are not shown in this paper, and we will treat it in the extended version of this paper [4].

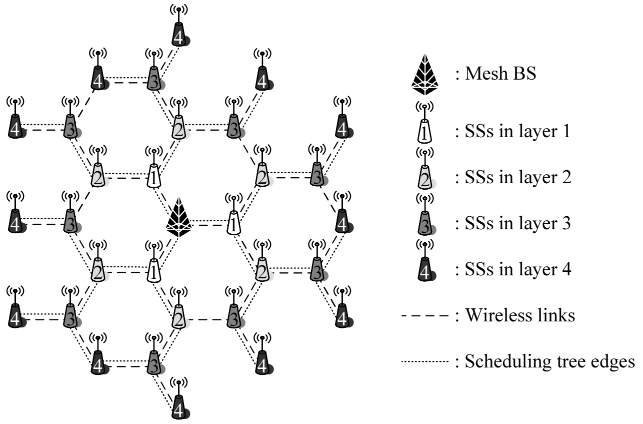

Figure 9: A 4-layer wireless mesh network layout structure

Suppose that the arrivals of Internet session requests in an SS form a Poisson process with rate λ_I, and the elapse times of the Internet sessions are exponentially distributed with the mean $\frac{1}{\mu_I}$. Define $\rho = \frac{\lambda_I}{\mu_I}$ as the traffic load to an SS. To simplify our discussion, we assume that the number of minislots requested by an Internet session for data transmission or reception is one. Let α be the maximum percentage of minislots (that can be allocated for Internet sessions) in a data subframe, M be the number of minislots in a data subframe ($M = 256$ in our study), and t_s be the scheduling period. In each experiment, we simulate $N_I = 10^7$ Internet sessions to ensure the convergence of our simulation. Let $N_{d,I}$ be the number of the dropped Internet session requests in a each experiment. Then, the blocking probability $P_{b,I}$ for the Internet sessions (i.e., the probability that the Internet session request is dropped due to no available minislot) is obtained by using

$$P_{b,I} = \frac{N_{d,I}}{N_I}$$

Let U_{i,a_i} be the minislot utilization in SS_{a_i} for the intranet sessions. For the Partition scheme, since the minislots in a data subframe are partitioned into two groups to serve Internet sessions and intranet sessions, respectively, we have

$$U_{i,a_i}(\text{Partition}) = 1 - \alpha \tag{1}$$

Let M_{I,a_i} be the number of minislots in a data subframe in SS_{a_i} occupied by the Internet sessions, and M_{r,a_i} be the number of minislots in SS_{a_i} that can not be reused due to occurrence of collision between SS_{a_i} and its neighboring SS. Then U_{i,a_i} for the CDC scheme can be obtained by using

$$U_{i,a_i}(\text{CDC}) = \frac{M - M_{I,a_i} - M_{r,a_i}}{M} \tag{2}$$

Then by using (1) and (2), the mean of the U_{i,a_i} for the

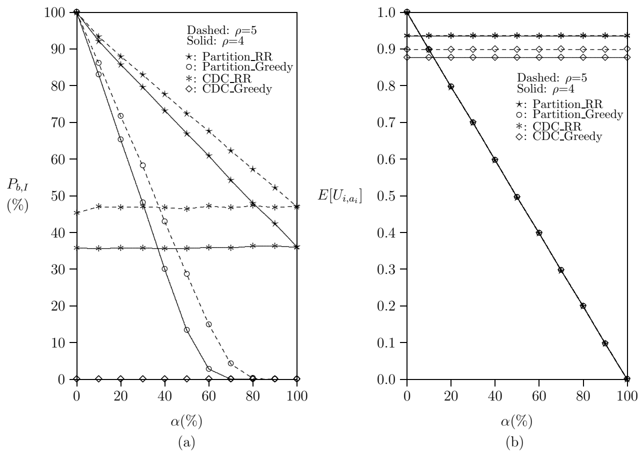

Figure 10: Effects of α and ρ on $P_{b,I}$ and $E[U_{i,a_i}]$ ($t_s = \frac{1}{\lambda_I}$)

Partition scheme and the CDC scheme can be calculated by

$$E[U_{i,a_i}](\text{Partition}) = 1 - \alpha$$

and

$$E[U_{i,a_i}](\text{CDC}) = \frac{\sum_{i=1}^{N} U_{i,a_i}(\text{CDC})}{N}$$

where N is the total number of SSs in the wireless mesh network.

In this study, we use $P_{b,I}$ and $E[U_{i,a_i}]$ to measure the QoS of the wireless mesh network for the Internet sessions and the intranet sessions. A smaller $P_{b,I}$ value implies that the Internet sessions have better chance to be served. On the other hand, a larger $E[U_{i,a_i}]$ value indicates that there are more minislots that can be allocated to the intranet sessions. In the following, we study the effects of α and ρ on the $P_{b,I}$ and $E[U_{i,a_i}]$ performances for the the Partition_RR, Partition_Greedy, CDC_RR, and CDC_Greedy schemes, where we consider a 4-layer wireless mesh network.

Effects of α and ρ on $P_{b,I}$: Figure 10 (a) plots $P_{b,I}$ against M with various ρ setups for the four schemes. This figure indicates that as for the Partition_RR and Partition_Greedy schemes, $P_{b,I}$ decreases as M increases. For the CDC_RR and CDC_Greedy schemes, M does not affect the $P_{b,I}$ performance. The figure also shows that as the Internet traffic load (i.e., ρ) increases, the $P_{b,I}$ performance for the four schemes become worse. Moreover, we observe that the CDC_Greedy scheme outperforms other three schemes in terms of the $P_{b,I}$ performance in all cases. The $P_{b,I}$ values for CDC_Greedy scheme approach to 0%. When $\alpha < 40\%$, CDC_RR has better $P_{b,I}$ performance than that for Partition_Greedy. On the other hand, $\alpha > 40\%$, Partition_Greedy outperforms CDC_RR.

Effects of α and ρ on $E[U_{i,a_i}]$: Figure 10 (b) plots $E[U_{i,a_i}]$ as functions of α for the four schemes. The figure indicates that for Partition_RR and Partition_Greedy, $E[U_{i,a_i}]$ decreases as α increases. On the other hand, for CDC_RR and CDC_Greedy, α has no effect on the $E[U_{i,a_i}]$ performance. This figure also shows that the Internet traffic load ρ only affects the $E[U_{i,a_i}]$ performance for the CDC_Greedy scheme. For other three schemes, the effect of ρ is insignificant. The CDC_RR has the best $E[U_{i,a_i}]$ performance among the four schemes.

5. CONCLUSION

This paper proposed the *Combined Distributed and Centralized* (CDC) scheme to combine the distributed scheduling and centralized scheduling mechanisms in the IEEE 802.16 to more flexibly allocate the minislots in a data subframe to serve Internet sessions and intranet sessions in the wireless mesh network, while IEEE 802.16 proposed the Partition scheme for minislot allocation for two kinds of traffic. We conducted simulation experiments to compare the performance of the CDC and Partition schemes, where we used the Round Robin (RR) and Greedy algorithms as baseline algorithms for the centralized scheduling mechanism. Our study indicate that the CDC scheme outperforms the Partition scheme in most of cases.

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