DCLS: A Fair and Efficient Scheduling with Bandwidth Guarantee in WiMAX Mesh Networks*

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Striking balance between throughput and fairness is a challenging issue in a wireless mesh network because of interference among links. This work proposed a Dynamic Clique-based Link Scheduling algorithm (DCLS) with minimal bandwidth guarantee for a WiMAX mesh backhaul network. DCLS includes two phases. First, it exploits a novel scheme based on cliques to maximize parallel transmission and ensure minimum bandwidth guarantee. Second, it employs a bandwidth tracking scheduling to enhance fairness among users. Simulation results show that DCLS performs better than existing scheduling schemes in network throughput and fairness.

Keywords: clique set, bandwidth guarantee, dynamic link scheduling, spatial reuse, WiMAX

1. INTRODUCTION

WiMAX Mesh Networks (WMNs) have been considered a good candidate for *Multihop Cellular Networks* (MCNs) [1], which is a potential candidate for the next-generation cellular system architecture. One of the most significant issues in the WMNs is to design an efficient and fair resource scheduling algorithm that exploits well spatial reuse of wireless links in its Time Division Multiple Access/Time Division Duplex (TDMA/TDD) system. Although both centralized and distributed algorithms are applicable to the WMNs, it is agreed that the centralized scheduling algorithm performs more efficient and suits well for MCNs [1]. Thus this work focused on the design of a centralized scheduling algorithm for WMNs.

For improving throughput, spatial reuse of wireless links is a very common technology used in a shared channel multi-hop wireless network such as WMNs. A channel can be reused by scheduling non-interfered links to achieve current transmition. A scheduling algorithm obtains good throughput if it schedules more frequently the transmitting nodes with low interference. However, such a greedy scheme is unfair to nodes with high interference. Thus, it is very challenge to striking the balance between throughput and fairness in the scheduling algorithm design. The issue becomes even more difficult when the scheduler must schedule time slots based on dynamical traffic requests from users.

In the past, the multi-hop transmission issue in the wireless packet network has attracted many studies [11, 12]. Many researchers [13-15] have studied packet scheduling in the wireless networks, but focusing on contention-based MAC (Media Access Control) protocols such as IEEE 802.11. The works [4, 5] propose efficient scheduling algorithms

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for WMNs without considering the fairness problem between transmitting nodes. Some other works [6, 7, 10] propose scheduling algorithms with hard fairness to ensure a user to transmit data in a desired rate. However, they cannot dynamically schedule resource to achieve fairness, and thus, when user demands vary drastically, substantial data loss may occur.

This paper designs a *Dynamic Clique-based Link Scheduling* algorithm (DCLS) to balance the throughput and fairness. Unlike the hard fairness used in the static clique-based scheduling algorithm, DCLS allocates bandwidth according to different user demands and guarantees each node to obtain a minimum bandwidth allocation. Therefore DCLS suits better for a dynamic bandwidth request/grant system such as WMNs. In DCLS, user demands are divided into two categories: the guaranteed traffic and the non-guaranteed traffic. The DCLS algorithm consists of two steps. The first step is the *Minimal Bandwidth Guarantee Scheduling* algorithm (MBGS) which schedules the guaranteed traffic using a novel clique-based scheme. The second step is *Bandwidth Tracking* (BT) that fills up the bandwidth aperture left from the first step to the highly interfered links. Thus, BT can effectively boost fairness among nodes. Simulation results show that DCLS performs better than existing scheduling algorithms in network utili- zation and fairness.

The remainder of the paper is organized as follows. Section 2 overviews the WiMAX architecture. Section 3 states related work. Section 4 introduces the design of DLCS. Section 5 presents the simulation results. Finally, section 6 concludes the paper.

2. WiMAX NETWORK ARCHITECTURE

The MAC functions of the WiMAX network is defined in IEEE 802.16 [2] which contains two types of network configurations: the point-to-multipoint (PMP) mode and the Mesh mode. In the PMP mode, the Subscriber Station (SS) nodes directly connect to the Basic Station (BS) through one hop wireless communication similar to the traditional cellular network such as GSM (Global System for Mobile communications). The BS operates as a coordinator and provides the access to the Internet. In the Mesh mode, the network coverage is extended by SS nodes. It allows SS nodes to communicate with the Mesh BS (*i.e.*, the BS in the Mesh mode) via the multi-hop transmission. The SS nodes are allowed to communicate with each other. An example of a WiMAX network is shown in Fig. 1. The SS node S_1 to S_9 and the Mesh BS form the mesh network configuration, whereas the SS node S_{10} to S_{13} and the BS form the PMP network configuration.

In the Mesh mode with the centralized control, the Mesh BS controls the channel access using TDMA/TDD. The Mesh BS collects the resources requests from SS nodes and schedules each link for both uplink and downlink transmission. Minislots (*i.e.*, time slots in the WiMAX system) in a time frame are assigned to links so that the transmission of data traffic is collision free. The Mesh BS uses the Mesh Centralized Scheduling Configuration (MSH-CSCF) message to establish a scheduling tree rooted at the Mesh BS. The MSH-CSCF message is broadcasted from the Mesh BS to the SS nodes in the network. A SS node estimates its uplink/downlink traffic demand (including its descendant's traffic demand) and sends the Mesh Centralized Scheduling Request (MSH-CSCH: Re-

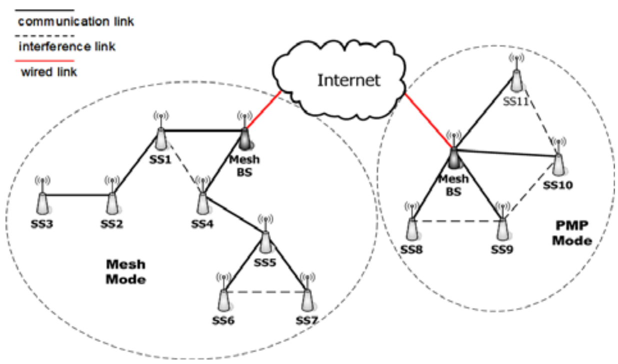

Fig. 1. WiMAX network architecture.

quest) message to the Mesh BS for requesting bandwidth. The Mesh BS allocates the minislots and uses MSH-CSCH: Grant to confirm the bandwidth request during a scheduling period.

The format of signaling messages for the WiMAX system are already defined in the standard, but scheduling algorithms are undefined and open to discussion. Thus, a scheduling algorithm should be investigated to allocate network capacity efficiently and fairly.

3. RELATED WORK

In 1985, Nelson and Kleinrock proposed a collision-free multi-hop channel access protocol called Spatial TDMA (STDMA) [3] to coordinate channel access in the multi-hop packet radio environment. The authors exploit the compatibility matrix to present the interference between wireless links and generate a set of cliques from the matrix. The clique sets provide comprehensive information for scheduling of links. Hence STDMA can achieve high spatial utilization and throughput.

Based on the link interference among SS nodes, Wei *et al*. [4] propose an interference-aware scheduling algorithm for the WiMAX mesh backhaul network. They use a simple algorithm to calculate the blocking value of a SS node to denote the level of interference. The time slot assignment is based on the blocking value of a route between SS nodes and the Mesh BS so that the high throughput is achieved. Then in [5], Tao *et al*. propose another more precise link based interference model differed from [4] and a scheduling algorithm with adjustment of the scheduling tree to improve network throughput. However, both [4] and [5] only propose scheduling algorithms to raise throughput without considering the fairness among SS nodes.

Fairness is a necessary consideration for a scheduling algorithm in the WMNs. The SS nodes must fairly share the resource regardless of their distance to the Mesh BS. In [8], the fairness study in the WiMAX PMP mode is presented, but it cannot be directly applied to the Mesh mode because it does not consider the multi-hop transmission property. A fairness model is proposed by Gambiroza *et al*. [6] to handle fair share problems for the wireless multi-hop network, and then Salem *et al*. extend the model to the users in [7]. However, the fairness model in [6, 7] belongs to the hard fairness which ensures a user to transmit data as its desired rate disregarding the actual traffic demands of different SS nodes. Thus they trade efficiency for fairness and result in poor performance.

The scheme in [7] uses the compatibility matrix of [3] to generate a set of cliques and statically schedules time slot for all SS nodes without concerning the demand variation of SS nodes. However when the traffic demand changes dynamically, the scheme in [7] will under utilize link capacity and become inefficient. The scheduling in [10] considers the fair problem occurred on the per-hop MSH-CSCF broadcast ordering. It arranges the per-hop ordering according to transmission history, *i.e.*, average allocated bandwidth and uses weight to adjust the broadcast ordering to handle the unfair bandwidth allocation. However, it uses a hard fairness which makes it difficult to handle dynamic traffic demands.

4. DCLS DESIGN

4.1 Network Model

Consider a WiMAX mesh network composed of a Mesh BS denoted by S_Ω and n SS nodes denoted by $S_1, \ldots, S_n$. All SS nodes rely on the Mesh BS to relay outside traffic to and from Internet via multi-hop transmission. The mesh network can be represented by an undirected graph $G = (V, E)$, where $V = \{S_\Omega, S_1, S_2, \ldots, S_n\}$, and $E = \{(i, j) \mid$ for all S_i and S_j that can communicate directly$\}$. Without loss of generality, it assumes that all wireless links in the mesh network have the same capacity and share the same frequency band. The interference occurs when multiple links transmit simultaneously within a transmission range. For uplink traffic, a flow labeled by f_i denotes a data stream from S_i to S_Ω. Assume the Mesh BS allocates bandwidth through scheduling minislots and a minislot provides transmission rate r bps. Then, a SS node i demanding bandwidth $r \cdot d_i$ can be translated to a bandwidth request with d_i minislots. Since bandwidth demands vary at each scheduling period, S_Ω should dynamically calculate a new schedule for bandwidth allocation.

Let h_i be the number of hops that S_i is away from S_Ω. If S_i is the parent of S_j, S_i must forward data for S_j after S_Ω grants the bandwidth request of S_i. Thus, a flow f_i with bandwidth demand d_i consumes $h_i \cdot d_i$ minislots in a scheduling period including forwarding bandwidth requirement. Let $|f_i|$ be the number of flows from S_i. Then the total number of flows to S_Ω is equal to $\sum_{i=1}^{n} |f_i|$. Taking data forwarding into account, $\sum_{i=1}^{n} h_i \cdot |f_i| \cdot d_i$ is the total number of minislots required to transport all flows up to S_Ω. Let M be the total number of available minislots per unit time, the demands of all flows can be granted only if $\sum_{i=1}^{n} h_i \cdot |f_i| \cdot d_i \leq M$ without considering the spatial reuse.

4.2 DCLS Scheduling Scheme

Concurrent transmission in the same minislot on non-interfering links is critical in improving overall network throughput in the WiMAX mesh network. In this section, we design a link scheduling algorithm, DCLS, to achieve high performance bandwidth utilization. DCLS is comprised of three main steps: (1) Proper Clique Set (PCS) construction, (2) flow table construction, and (3) link schedule construction, which are given in details in the following subsections.

4.2.1 PCS construction

For a connected network with omni-direction transmission, a node interferes with its adjacent nodes when it starts transmitting. Given a network graph $G = (V, E)$, a compatibility matrix CM is an $m \times m$ matrix, where $m = |E|$, $|E|$ is the number of edges in E, and $x_{p,q} = 1$ in CM indicates that link p and link q can transmit concurrently, and $x_{p,q} = 0$ indicates that link p and link q interfere with each other.

Using the matrix CM, a compatibility graph $G' = (V', E')$ can be generated, where $V' = E$; *i.e.* a node in G' corresponds to a link in G. In G', an edge (i', j') in E' denotes that the two links in G corresponding to i' and j' can be activated in the same time slot without collision. Fig. 2 shows an example of compatibility graph for the mesh mode in Fig. 1. Based on G', a proper clique set $CS = \{C_k\}$ can be generated, in which C_k is a clique of cardinality k, represented by a set of k links $\{(i_1, j_1), (i_2, j_2), \ldots, (i_k, j_k)\}$ and a clique in CS is not covered by any other clique. Table 1 shows the PCS for Fig. 2. All edges (links) in the same clique can transmit data simultaneously without making any collision. Thus we can schedule transmission of the links in a clique at the same time slot, resulting in higher throughput.

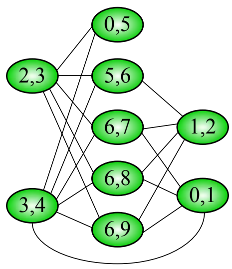

Fig. 2. Compatibility graph G' for WiMAX mesh mode in Fig. 1.

Table 1. Proper clique set for G' in Fig. 2.

C_3	{(0, 1), (3, 4), (6, 7)} {(0, 1), (3, 4), (6, 8)} {(0, 1), (3, 4), (6, 9)}
C_2	{(2, 3), (0, 5)} {(2, 3), (5, 6)} {(2, 3), (6, 7)} {(2, 3), (6, 8)} {(2, 3), (6, 9)} {(3, 4), (0, 5)} {(3, 4), (5, 6)} {(1, 2), (5, 6)} {(1, 2), (6, 7)} {(1, 2), (6, 8)} {(1, 2), (6, 9)}

Since the maximal clique set generation problem is NP-complete [17], it is unrealistic to construct an optimal clique set. Thus, in this study, we assume that a WiMAX mesh network topology is static and hence existing algorithms [17] would be used to generate close to optimal PCS offline.

4.2.2 Flow table construction

To make efficient minislot assignment, DCLS converts large grain bandwidth requests to fine grain per flow request. As shown in Fig. 3, a link scheduling algorithm dealing with a request of large time unit of bandwidth causes bandwidth aperture (*i.e.*, the wastage of bandwidth). On the other hand, scheduling the small time unit of bandwidth makes higher minislot utilization, as illustrated in Fig. 4. Thus, DCLS constructs a flow table by converting each bandwidth request into a number of requests or flows, each with data rate at most d_i. An example is shown in Fig. 5. Note that the conversion is just for the convenience of scheduling and does not incur any extra overhead because it does not involve any change in the frame format.

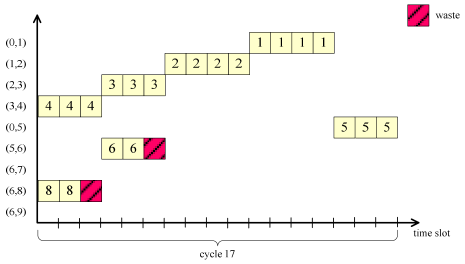

Fig. 3. A schedule generated by algorithm in [7].

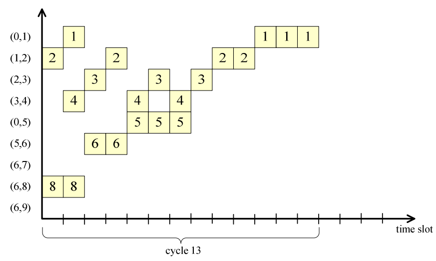

Fig. 4. A schedule arranged by small time unit.

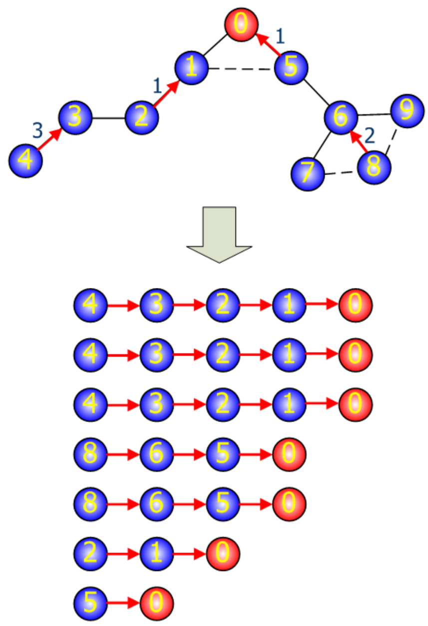
Fig. 5. A flow table conversion.

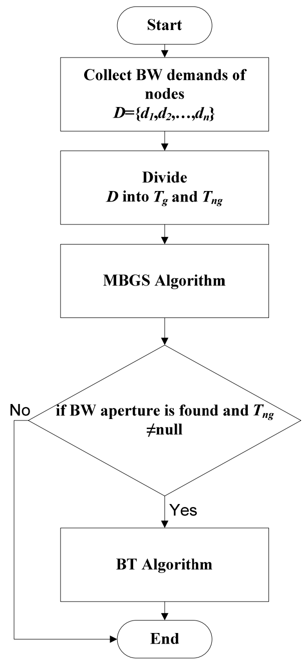

Fig. 6. DCLS flow chart.

4.2.3 Link schedule construction

The design goal of DCLS is to exploit concurrent transmission of links to achieve high throughput with minimal bandwidth guarantee of each node at the same time. For a given mesh network and a minimal bandwidth guarantee g_i for node S_i, DCLS divides bandwidth demand d_i into two categories: the guaranteed flows T_g and the non-uaranteed flows T_{ng}. Next, DCLS is executed by two phases. First, DCLS schedules T_g with a novel clique-based algorithm MBGS. Second, the bandwidth not fully utilized is then scheduled for T_{ng} with the BT algorithm. Fig. 6 shows the flow chart of DCLS.

The two phases in DCLS assign minislots based on PCS presented above. The priority of which clique should be scheduled would cause different results. Using the node demands as shown in Fig. 5 for instance, there are two schedules shown in Figs. 7 and 8, where each link is activated during a minislot if assigned (a square on the link). Obvi-

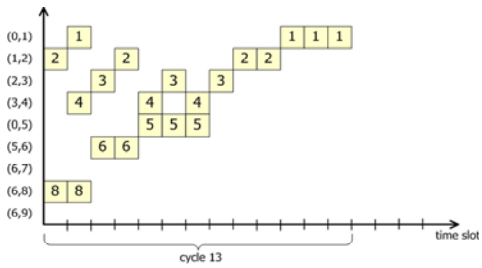

Fig. 7. A schedule based on cliques in a managed order.

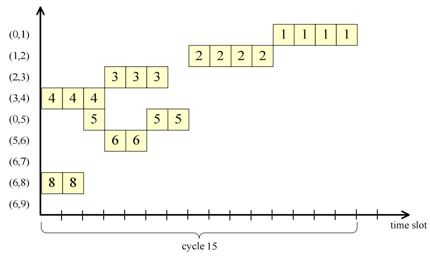

Fig. 8. A schedule without processing cliques in a random order.

ously, the schedule arranged in a managed method as shown in Fig. 7 has a shorter cycle than that in Fig. 8 with a random order, and hence has a higher throughput.

Based on the above observation, DCLS schedules cliques based on a priority index, which balances the spatial reuse degree and clique interference. The spatial reuse degree is defined as the number of concurrent active links; a link is active if it has data to send. The clique utilization, denoted as $u(cl)$, is defined as the ratio of the number of active links to the number of links in the clique cl. Then, $|cl| \cdot u(cl)$ represents the degree of spatial reuse of the clique cl where $|cl|$ is the number links in cl. The clique interference is defined as the average degree of interference incurred over all links in a clique. Let $I_{(i,j)}$ denote the interference of link (i, j), which is defined as

$$I_{(i,j)} = \frac{n_{(i,j)}(I)}{n} \tag{1}$$

where $n_{(i,j)}(I)$ is the size of the collision domain of the link (i, j), *i.e.*, the number of nodes that are interfered when S_i activates link (i, j) and n is the total number of SS nodes in the network. For example, uplink (4, 3) as shown in Fig. 1 has a collision domain $\{S_2, S_3, S_4\}$ and thus $n_{(4,3)}(I) = 3$ and $I_{(4,3)} = 3/10$.

Then, the average link interference value $I(cl)$ of clique cl is calculated as follows.

$$I(cl) = \frac{\sum_{(i,j)\in cl} I_{(i,j)}}{|cl|} \tag{2}$$

Based on the degree of spatial reuse and average interference of a clique, a clique priority function is defined as:

$$priority(cl, L) = |cl| \cdot u(cl) + I(cl) \tag{3}$$

where L is a set of active links in cl for a given time unit (minislot). Note that $|cl| \cdot u(cl)$ is an integer number larger than 1 and $I(cl)$ is a decimal number smaller than 1. Thus, $I(cl)$ affects only when the number of active links is the same between two chosen cliques. If two or more cliques have the same number of active links, we choose the clique with higher average interference first. Given high priority to a clique with a high average interference is to schedule early the data that will be more likely interfered by others or interfere others when transmitting, which contributes effectively to improve fairness because links with high interference degree are scheduled whenever possible.

The output of DCLS is a schedule η which specifies the time slot assigned to all links, and it is defined as an $M \times 1$ matrix, where M is the total number of time slots that can be assigned. η is denoted as

$$\eta = [\eta_x],\ 1 \leq x \leq M \tag{4}$$

where $\eta_x = \{(i, j)|(i, j) \in E\}$ is a set of links that can transmit data simultaneously in mini-slot x.

The working principle of MBGS is to schedule guaranteed flows using the priority of cliques as specified in Eq. (3) and colors bandwidth aperture links as gray. Then, BT schedules non-guaranteed flows with respect to gray links to increase parallel transmission degree and hence increase the throughput. The details of algorithms of MBGS and BT are given in Fig. 9. The MBGS algorithm first creates a bandwidth tracking set B for recording the bandwidth aperture. Second, MBGS starts to schedule the T_g based on the average interference of the clique set PCS. When the T_g is scheduled, it means the minimal bandwidth is guaranteed. After the procedure of MBGS is finished, the BT algorithm is executed to check the tracking of the bandwidth aperture. If the bandwidth aperture exists (*i.e.*, B is not empty), the BT algorithm allocates the remained bandwidth to the gray links in $\bar{\eta}$ which is colored in the progress of executing MGBS. After the two phases, MGBS and then BT, the bandwidth can be allocated fairly for SS nodes with high utilization.

MBGS Algorithm

Input: PCS, and T_g
Output: a schedule η, gray slot set $\bar{\eta}$, a BT set B
$ts \leftarrow 1$; /* the time slot to be assigned */
$B \leftarrow \varnothing$
While $T_g \neq \varnothing$ and $ts < M$
  $L \leftarrow$ the active links in T_g
  $cl \leftarrow \arg\max_{\forall cl \in PCS} priority(cl, L)$
  $L_{cl} \leftarrow \{(i, j)|(i, j) \in cl\}$
  color L_{cl} white
  If $u(cl) \neq 1$ **then**
    add ts to B /* for tracking later */
    color $L_{cl} - (L_{cl} \cap L)$ gray
  End if
  add L_{cl} into η_{ts}
  $ts = ts + 1$;
  $T_g \leftarrow T_g - (L_{cl} \cap T_g)$
End while

BT Algorithm

Input: B, η, $\bar{\eta}$, and T_{ng}
Output: a schedule η
While $B \neq \varnothing$ and $T_{ng} \neq \varnothing$
  $L \leftarrow$ the active links in T_{ng}
  $b \leftarrow$ argmin B
  $L_{gray} \leftarrow$ the gray links in η_b
  While $L_{gray} \neq \varnothing$
    $l \leftarrow (i, j) \in L_{gray}$
    If found l in L **then**
      $T_{ng} - l$
      $L \leftarrow$ the active links in T_{ng}
    End if
    color l white
    $L_{gray} - l$
  End while
  $B - b$
End while

Fig. 9. Algorithms of MBGS and BT.

5. SIMULATION

In this section, we conduct a simulation for the WiMAX mesh network to investigate the performance of the DCLS algorithm. As shown as in Fig. 10, the simulation environ-

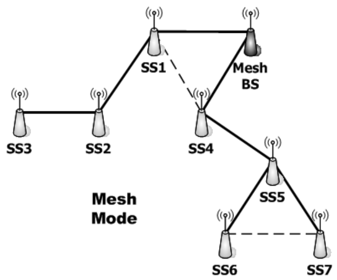

Fig. 10. Mesh topology for the simulation.

Table 2. Simulation parameters.

Parameter	Value
Minislots per frame (M)	256
Bits per minislot (r)	3K
Frame duration (F_d)	10ms
Simulation time	1000s

ment is set up to one Mesh BS and seven SS nodes. In the simulation, only uplink traffic is studied and the uplink traffic is generated by each SS node using uniformly distribution with mean λ and variance v. The parameters used in the simulation are listed in Table 2. It is assumed that the slot assignment is with per-frame scheduling and centralized. All SS nodes share the same guaranteed traffic load g as follows:

$$g = 17 \approx \frac{M}{\sum_{i=1}^{n} h_i} = \frac{256}{15}.$$

For comparison, we implement the following scheduling algorithms:

- **MBGS:** The DCLS algorithm without BT. MBGS only provides a bandwidth guarantee to each node, but the bandwidth aperture is not rechecked.
- **DCLS:** The scheduling algorithm implements both MBGS and BT.
- **Greedy Scheduling:** The scheduling algorithm always chooses links with the lowest interference.
- **Extended Hard Allocation Scheduling with Concurrent Transmission (EHAS with CT):** The EHAS with CT is extended from the Hard Allocation Scheme (HAS) presented in [7]. HAS does not adjust the scheduling scheme based on traffic condition. Here, we extend HAS to accept traffic demands even when d_i is larger than g and allow concurrent transmission. In fact, by our extension, the EHAS with CT can perform reasonably well.
- **Extended Hard Allocation Scheduling without Concurrent Transmission (EHAS without CT):** Use the same scheme as described in the EHAS with CT, but concurrent transmission is not allowed. Thus, it performs poorly in network throughput.
- **Extended Hard Allocation Scheduling with Ordering Adjustment (EHAS with OA):** The EHAS with OA extends HAS to adjust fairness by per-hop ordering as presented in [10].

5.1 Network Throughput

The system throughput is defined as

$$\Gamma_{total} = \sum_{i \in V} \frac{n_i \cdot r}{F_d} \tag{5}$$

where F_d is a frame duration, r is the data rate per minislot, and n_i is the total number of already arranged minislots for S_i in a frame duration. Γ_{total} represents the summation of throughput over all links.

First, compare the total network throughput between six scheduling algorithms presented above. Figs. 11 to 14 illustrate the performance of various schemes with various variances. The result shows that the degree of spatial reuse governs the throughput of the scheduling schemes. The greedy scheme always achieves the highest throughput because it always tries to maximize parallel transmission while the EHAS without CT always performs the worst because it does not exploit spatial reuse. Also, the result illustrates that DCLS can obtain almost the same performance as that of the EHAS with OA which uses the per-hop ordering to adjust the scheduling. However, we will see later, DCLS performs much better than the EHAS with OA in fairness. Furthermore, DCLS can improve throughput over MBGS at any traffic condition, about 16.7% in network throughput. This is because the BT scheme tries to fill up all bandwidth apertures and thus raises network throughput. Note that when traffic variance increases, all scheduling algorithmsperform not so well when traffic variance is small. This is because clique utilization becomes low when traffic variance is large and leads to more bandwidth aperture.

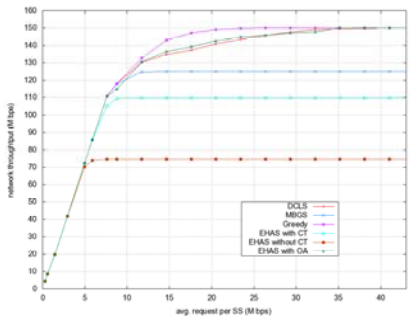

Fig. 11. System throughput with $v = 0.2 \times load$.

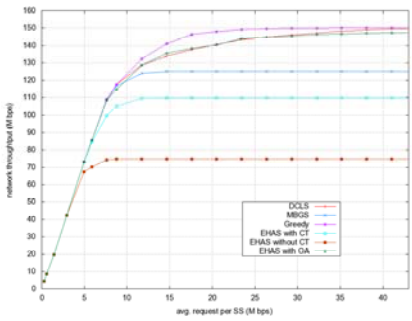

Fig. 12. System throughput with $v = 0.4 \times load$.

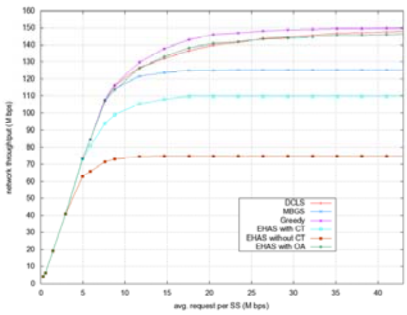

Fig. 13. System throughput with $v = 0.6 \times load$.

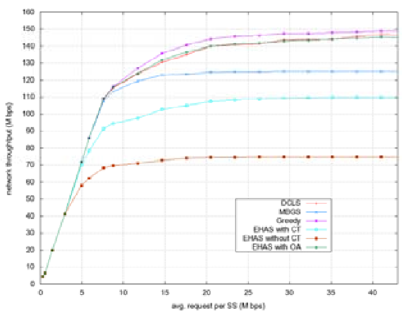

Fig. 14. System throughput with $v = 0.8 \times load$.

5.2 Fairness

In order to measure the fairness in such a bandwidth request/grant system, we adopt the fairness index given in [18] to denote the fair level of a system:

$$FI = \frac{\left(\sum_{i=1}^{n} x_i\right)^2}{n \cdot \sum_{i=1}^{n} (x_i)^2}, \forall i \in V \tag{6}$$

where $x_i = \begin{cases} \dfrac{a_i}{d_i} & \text{if } d_i > g_i \\ 1 & \text{otherwise} \end{cases}.$

a_i is the bandwidth allocated to demand d_i. It is easy to show that $0 < FI \leq 1$. A system is fair if $FI = 1$, and a smaller value of FI indicates the less fair allocation in a system. x_i is equal to a_i/d_i implying that Mesh BS should allocate more bandwidth to S_i when d_i is large. Thus, when FI is close to 1, all nodes can share bandwidth proportional to their bandwidth requests. Figs. 15 to 18 show the performance of various scheduling schemes in fairness. The results illustrate that when the network is not saturated, all algorithms can share bandwidth proportional to traffic demands. However, if the network is saturated, the efficiency and fairness of various scheduling schemes become more obvious. Comparing the fairness among six scheduling algorithms presented above, the result shows that DCLS performs the best in fairness no matter what traffic variance is. DCLS performs better than MBGS. This is because the BT scheme uses the bandwidth aperture to enhance the nodal ratio of a_i to d_i for nodes with high interference degree. The EHAS with CT and without CT scheduling algorithms perform well when traffic variance is low. However, when the variance gets large, the fairness of EHAS with/without CT scheduling algorithm falls and is close to that of MBGS. The result also illustrates that both the Greedy scheduling scheme and the EHAS with OA scheduling algorithm have low fairness although they can achieve high network throughput.

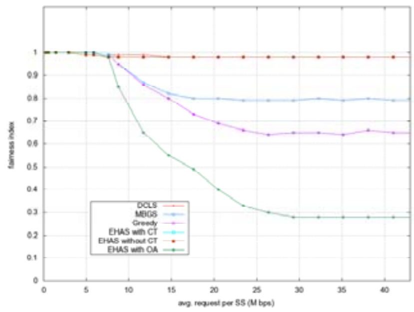

Fig. 15. Fairness with $v = 0.2\lambda$.

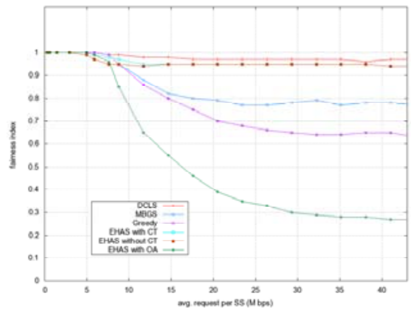

Fig. 16. Fairness with $v = 0.4\lambda$.

5.3 Impact of Clique Interference

The priority function of clique as defined in Eq. (3) gives priority to a clique with the largest average interference when the number of active links is the same among two or more cliques. The simulation results in Figs. 19 and 20 show that scheduling cliques with

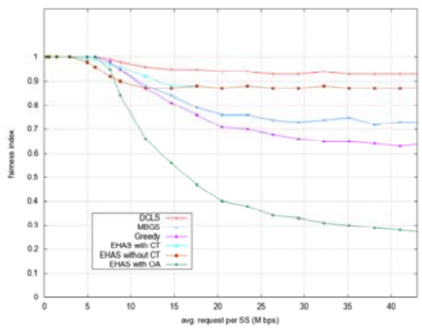

Fig. 17. Fairness with $v = 0.6\lambda$.

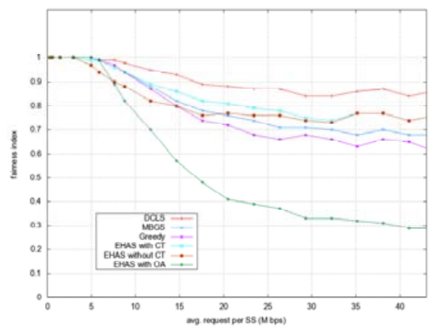

Fig. 18. Fairness with $v = 0.8\lambda$.

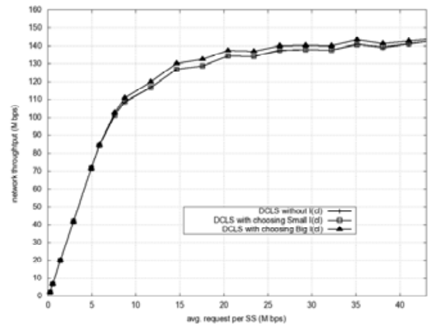

Fig. 19. Effect of $I(cl)$ on network throughput.

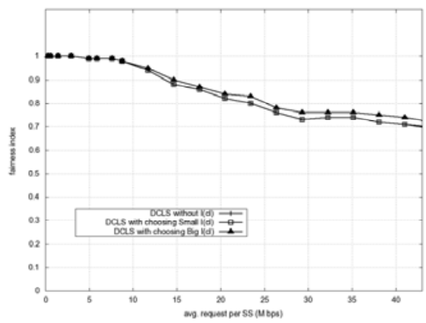

Fig. 20. Effect of $I(cl)$ on fairness.

larger average link interference does have better performance in network throughput and fairness. The result confirms our observation that assigning cliques with high average link interference can not only give higher probability of parallel data transmission later but also give a better chance to nodes with a link of high interference degree to deliver data and hence improving fairness.

6. CONCLUSION

This paper proposes a Dynamic Clique-based Link Scheduling (DCLS) scheme. DCLS guarantees a minimal bandwidth for each SS node in a WiMAX mesh backhaul network. The minimal bandwidth guarantee is used to provide a safeguard in various types of traffic. In addition, DCLS supports dynamic bandwidth allocation according to user bandwidth demands and exploits spatial reuse to schedule data transmission. A novel priority function is defined to select cliques for scheduling. The priority function balances spatial reuse and average clique interference, *i.e.*, throughput and fairness. DCLS consists of two phases, MBGS and BT. MBGS arranges guaranteed flows using the clique priority function and records the bandwidth aperture. The BT scheme then finds active links to fill up bandwidth aperture according to the records from MBGS. The BT scheme also makes good fairness because it tends to schedule high interference links for the bandwidth aperture and hence can compensate those SS nodes with large collision domain size. Extensive simulation results show that DCLS does perform better than existing schemes both in network throughput and fairness, in particular when traffic variance is large.

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