QoS-aware Scheduling for Small Cell Millimeter Wave Mesh Backhaul

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***Abstract*—With the explosive growth of mobile data demand, small cells densely deployed underlying the homogeneous macrocells are emerging as a promising candidate for the fifth generation (5G) mobile network. The backhaul communication for small cells poses a significant challenge, and with huge bandwidth available in the mmWave band, the wireless backhaul at mmWave frequencies can be a promising backhaul solution for small cells. In this paper, we propose the Maximum QoS-aware Independent Set (MQIS) based scheduling algorithm for the mmWave backhaul network of small cells to maximize the number of flows with their QoS requirements satisfied. In the algorithm, concurrent transmissions and the QoS aware priority are exploited to achieve more successfully scheduled flows and higher network throughput. Simulations in the 73 GHz band are conducted to demonstrate the superior performance of our algorithm in terms of the number of successfully scheduled flows and the system throughput compared with other existing schemes.**

I. Introduction

Mobile data demand is growing explosively. Some industry and academic experts predict a 1000-fold demand increase by 2020 [1]. In order to offer the 1000x increase in data rates and throughput, small cells densely deployed underlying the conventional homogeneous macrocells are emerging as a promising candidate for the fifth generation (5G) mobile broadband [2]. This new network deployment is usually referred to as heterogeneous cellular networks (HCNs). However, with the increase of the number of small cells deployed, the backhaul for small cells becomes a significant challenge [2], [3]. Although fiber based backhaul offers large bandwidth, it is costly, inflexible, and time-consuming to connect the densely deployed small cells. In contrast, wireless backhaul is more cost-effective, flexible, and easier to deploy [3]. With huge bandwidth available, wireless backhaul in mmWave bands, such as the 60 GHz band and E-band (71–76 GHz and 81–86 GHz), provides several-Gbps data rates and can be a promising backhaul solution for small cells.

On the other hand, unlike existing communication systems using lower carrier frequencies (e.g., from 900 MHz to 5 GHz), mmWave communications suffer from high propagation loss. To combat severe channel attenuation, directional antennas are utilized at both the transmitter and receiver for high antenna gain. With the beamforming technique, the transmitter and the receiver are able to direct their beams towards each other for the directional communication [4]. The directional communication reduces the interference between links, and concurrent transmissions (spatial reuse) can be exploited to greatly improve network capacity. In a scenario where small cells are densely deployed, effective and efficient backhaul scheduling schemes need to be designed with the characteristics of mmWave communications taken into account.

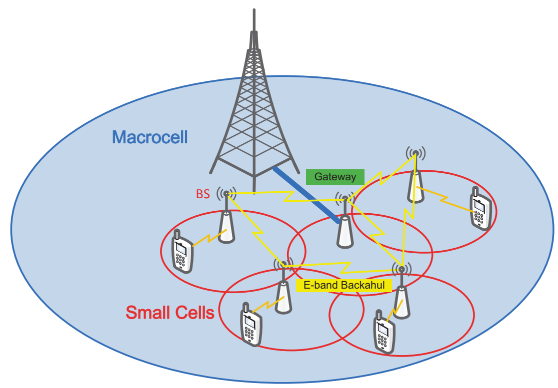

Fig. 1. The mesh backhaul network in the small cells densely deployed scenario.

In Fig. 1, we present a typical scenario of densely deployed small cells underlying the macrocell cellular network. In the small cells, mobile users are associated with the base stations (BSs), and the BSs are connected via backhaul links with the mesh topology. There are one or more BSs connected to the backbone network via the macrocell site, which are called gateways. In this targeted small cells system, the backhaul network is in the E-band, which provides high data rates. For the scheduling problem of the backhaul network for small cells densely deployed, there are two aspects of challenges. In the first aspect, concurrent transmissions need to be fully exploited to maximize the spatial reuse gain. In the second aspect, the scheduling scheme should provide the quality of service (QoS) guarantee for flows in the backhaul network. To ensure fairness, the scheduling scheme should maximize the scheduled flows in the network with the QoS requirement of each flow satisfied.

In this paper, we develop a QoS aware scheduling scheme for the small cell backhaul network in the mmWave band. The contributions of this paper are summarized as follows.

- We formulate the problem of optimal scheduling to maximize the number of flows with their QoS requirements satisfied in the mmWave backhaul network as a nonlinear

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integer programming. Concurrent transmissions (spatial reuse) are explicitly considered in this problem.
- We propose a heuristic scheduling algorithm to solve the formulated problem with low complexity. The interference between flows is modeled by the contention graph. Based on the contention graph, we propose the Maximum QoS-aware Independent Set (MQIS) based backhaul scheduling algorithm to achieve more successfully scheduled flows and higher total network throughput.
- We evaluate our algorithm for the backhaul network in the 73 GHz band, and the realistic antenna model is adopted in the simulation. The simulation results demonstrate the superior performance of our algorithm in terms of the number of successfully scheduled flows and the system throughput compared with other existing schemes.

The structure of this paper is as follows. Section II describes the related work. Section III gives an overview of the system model. Mathematical analysis and problem formulation are presented in Section IV. Section V presents the MQIS based scheduling algorithm for the mmWave backhaul network. Extensive simulations are conducted and evaluated in Section VI. Section VII concludes this paper.

II. Related Work

Time division multiple access (TDMA) has been a prominent solution for mmWave backhaul [5], [6]. Taori *et al.* [5] proposed a time-division multiplexing (TDM) based scheduling scheme to support point-to-multipoint, non-line-of-sight, mmWave backhaul. Islam *et al.* [3] performed the joint cost optimal aggregator node placement, power allocation, channel scheduling and routing to optimize the wireless backhaul network in mmWave bands. In [7], the scheduling for the radio access and backhaul networks were jointedly designed. To the best of our knowledge, none of the previous works are devoted to address the balance between the QoS requirement and the contention between links in the mmWave backhaul network. On the other hand, similar problems have also been investigated in WPANs [8], [9], [10]. One influential work is the Exclusive Region (ER) based scheduling which is introduced and derived in [8]. It ensures that concurrent transmissions always outperform the serial TDMA by co-scheduling flows in the exclusive region. Qiao *et al.* [10] proposed a concurrent transmission scheduling with the QoS requirements of flows considered. In Ref. [10] , the set of concurrent flows are chosen in a greedy manner to maximize the overall system throughput, through which the number of flows successfully scheduled is maximized. However, existing scheduling approaches have not fully utilized the global information of the contentions residing in the network. And a more QoS-favorable strategy is desired. In this paper, for the first time we introduce the concept of QoS-aware independent set to the scheduling problem under mmWave bands, and the proposed protocol achieves better performance in terms of system throughput and the number of scheduled flows in the mmWave backhaul network.

III. System Model and Assumption

A. Link Level QoS

In the backhaul network, a end-to-end flow with QoS requirement may go through multiple hops with a proper routing protocol in place. Once the routing path is fixed, all the single-hop flows along the path will share the same QoS constraint as the end-to-end traffic. Accordingly, for every single hop link in the backhaul network, its QoS is defined as the sum of QoS requirements of all the end-to-end traffic going through it. To this end, the scheduling can only focus on the single hop links with QoS requirements, and the designing of routing protocol will be left for our future work. In following paper, the word “flow” only means the single-hop link.

B. TDMA Structure

We consider the scenario where small cells are densely deployed, and assume there is a backhaul network controller (BNC) residing on one of the gateways. Each BS in the network is equipped with an electronically steerable directional antenna, and can direct its beam towards other BSs for directional transmission. In our investigated system, time is partitioned into superframes, and each superframe consists of M time slots called channel time allocation (CTA). We further assume the transmission requests and signaling information for mmWave backhauling are collected by the 4G BS by its reliable transmission [6]. Thus the BNC is able to obtain the transmission requests and the location information of other BSs. In our scheme, with directional transmission, multiple links can be scheduled concurrently in the same time slot, which is also referred to as the spatial-time division multiple access (STDMA) [10].

C. Physical Model

Since non-line-of-sight (NLOS) transmissions suffer from higher attenuation than line-of-sight (LOS) transmissions [11], we assume the directional LOS transmission between BSs can be achieved with the locations of BSs adjusted appropriately (e.g., on the roof). We assume there are N flows requesting transmission slots in the superframe, and each flow represents one backhaul link. We denote the distance between the transmitter s_i of flow i and the receiver r_j of flow j by d_{ij}. We also denote the antenna gain of s_i in the direction of from s_i to r_j by $G_t(i,j)$, and the antenna gain of r_i in the direction of from s_j to r_i by $G_r(j,i)$. Then considering the path loss and signal dispersion over distance, the received power at the receiver r_i from s_i can be calculated as

$$P_r(i,i) = k_0 G_t(i,i) G_r(i,i) d_{ii}^{-n} P_t, \tag{1}$$

where k_0 is a constant coefficient and proportional to $(\frac{\lambda}{4\pi})^2$ (λ denotes the wavelength), n denotes the path loss exponent, and P_t denotes the transmission power [10]. Due to the half-duplex assumption, adjacent links cannot be scheduled for concurrent transmissions. If flow i and flow j are not adjacent, we denote it by $i \propto j$. Then under concurrent transmissions, the received interference at r_i from s_j can be calculated as

$$P_r(j,i) = \rho k_0 G_t(j,i) G_r(j,i) d_{ji}^{-n} P_t. \tag{2}$$

where ρ is the multi-user interference (MUI) factor related to the cross correlation of signals from different links.

According to the Shannon's channel capacity, the achievable data rate of flow i can be estimated as

$$R_i = \eta W \log_2(1 + \frac{P_r(i,i)}{N_0 W + \sum_{j \propto i} P_r(j,i)}), \tag{3}$$

where W is the bandwidth, and N_0 is the onesided power spectra density of white Gaussian noise [10]. $\eta \in (0,1)$ describes the efficiency of the transceiver design.

IV. Problem Formulation And Analysis

In this section, we formulate the optimal scheduling problem into a nonlinear integer programming problem.

We assume there is a minimum throughput requirement for each flow i, and denote it by q_i. We denote a schedule as $\mathbf{S}$, and assume it has K stages. In each stage, multiple links are scheduled for concurrent transmissions. For each flow i, we define a binary variable a_i^k to indicate whether flow i is scheduled in the kth stage. If so, $a_i^k = 1$; otherwise, $a_i^k = 0$. We denote the number of time slots of the kth stage by δ^k.

Since there are different links in different stages, we denote the transmission rate of flow i in the kth stage by R_i^k. Then we can obtain R_i^k as

$$R_i^k = \eta W \log_2(1 + \frac{a_i^k k_0 G_t(i,i) G_r(i,i) d_{ii}^{-n} P_t}{N_0 W + \rho \sum_j a_j^k k_0 G_t(j,i) G_r(j,i) d_{ji}^{-n} P_t}). \tag{4}$$

Then we can obtain the throughput of flow i based on $\mathbf{S}$ as

$$T_i = \frac{\sum_{k=1}^{K} \delta^k \cdot R_i^k \cdot t_{slot}}{t_0 + M \cdot t_{slot}}, \tag{5}$$

where t_0 is the time duration of collecting transmission requests and signaling information, and t_{slot} is the time duration of each time slot in the CTA period (CTAP). Then we define a binary variable Q_i to indicate whether the QoS requirement of flow i is satisfied in $\mathbf{S}$. If so, $Q_i = 1$; otherwise, $Q_i = 0$. Given the throughput requirements of flows, with the limited number of time slots in the CTAP, the optimal schedule should accommodate as many flows as possible. Therefore, the optimal scheduling problem $\mathbf{P1}$ can be formulated as follows.

$$(\mathbf{P1}) \ \max \sum_{i=1}^{N} Q_i \tag{6}$$

s.t.

$$Q_i = \begin{cases} 1, & \text{if } T_i \geq q_i, \\ 0, & \text{otherwise;} \end{cases} \quad \forall\, i \tag{7}$$

$$\sum_{k=1}^{K} \delta^k \leq M; \tag{8}$$

$$a_i^k + a_j^k \leq 1, \text{ if flow } i \text{ and } j \text{ are adjacent; } \forall\, i,j \tag{9}$$

This is a nonlinear integer programming problem, and is NP-hard. Constraint (7) indicates if the throughput of flow i in the schedule is larger than or equal to its throughput requirement, $Q_i = 1$; otherwise, $Q_i = 0$. Constraint (8) indicates there are at most M time slots in the CTAP. Constraint (9) indicates due to the half-duplex operation of BSs, adjacent links cannot be scheduled for concurrent transmissions since there is at most one connection for each node.

Since it is difficult to solve the problem of $\mathbf{P1}$ in polynomial time, we propose an efficient and practical scheduling algorithm instead in the next section.

V. Scheduling Algorithm Design

In this section, we propose the Maximum QoS-aware Independent Set (MQIS) based scheduling algorithm for problem $\mathbf{P1}$. As the name suggests, the Maximum QoS-aware Independent Set is a combination of flows that has minimal internal interference and is beneficial for QoS achievement. In our algorithm, flows in this set are scheduled concurrently. To present the scheduling algorithm, we first introduce the contention graph under directional antennas, which captures the global knowledge of interference; Then we define the QoS-aware priority for each flow and present how to find a MQIS with the contention graph and the priority value; Finally, we give the overall MQIS based backhaul scheduling algorithm.

A. Contention Graph

The MQIS based scheduling summarizes the global interference information in the contention graph, in which a node represents a real flow and an edge between a pair of nodes marks the contention. We judge the existence of contention between every pair of flows based on two principles: 1) the half duplex nature where a single BS can not receive and transmit packets at the same time. In other words, if two flows share the same source or destination, there will be a contention edge between them; 2) the impact that one flow has on another. For every flow pair, we define the relative-interference (RI) as follows:

$$RI_{j,i} = \frac{P_r(j,i)}{P_r(i,i)} \tag{10}$$

where $P_r(j,i)$ and $P_r(i,i)$ is defined by (2) and (1) respectively. We insert an edge between flow i and flow j if $\max(RI_{i,j}, RI_{j,i}) > \sigma$, where σ is a threshold.

B. QoS-aware Priority

We assign a priority value to each flow out of QoS considerations. Flows that can achieve requested throughput more quickly are preferred in our scheduling because they can soon stop transmission and leave time slots for others to use. To give more weight to those flows, we define the priority as the inverse of the number of slots that a flow needs in CTAP to achieve its QoS requirement. Based on previous definitions, the priority of flow i can be expressed as follows:

$$\mathbf{priority}(i) == \frac{R_i \cdot t_{slot}}{q_i * (t_0 + M \cdot t_{slot})} \tag{11}$$

Note that the data rate R_i here is computed without any interference in (3), so the numerator represents how many bits flow i can transmit in a single slot. The denominator in (11) is the total amount of bits that need to be transmitted in one super frame.

C. Find MQIS

In the MQIS based backhaul scheduling, the set of flows scheduled at any slot should be a MQIS. Obviously when some flows achieve QoS requirement and are removed from current scheduling, this condition may no longer be satisfied. When this happens, we will select flows from contention graph $\mathbf{G}$ to add to the current scheduling set to generate a new MQIS.

To begin with, the "unqualified" flows which we will not select from should be removed from $\mathbf{G}$. A flow is "unqualified" if it satisfies one of the following conditions: 1) It has already achieved QoS requirement so there is no need to consider it; 2) It has been scheduled and thus ongoing now; 3) It is a neighbor of one of the ongoing flows. The third condition comes from the fact that neighbors in $\mathbf{G}$ should never appear together in the MQIS.

Then, we iteratively select the best node (or flow) from the remaining graph and add it to the scheduling set. First, we hope the chosen node has few contented neighbors and thus a more number of flows may be co-transmitted at the same time slot. Recall that in the contention graph, for any node, the larger degree means more contented neighbors, so we simply choose the node that has minimal degree. However if there are multiple nodes satisfying this criterion, we evaluate the other aspect of those flows: the ability to achieve QoS requirement quickly. We refer to the $\mathbf{priority}$ computed from (11) and select the node with maximum priority value to add to the scheduling set. After that, we remove the chosen node as well as its neighbors in G and begin to select the next one as long as the remaining contention graph is not empty.

The detailed algorithm is summarized in Algorithm 1. We use an array $\mathbf{schedule}$ to denote the scheduling set, where $\mathbf{schedule}(i) = 1$ means the flow i is scheduled and $\mathbf{schedule}(i) = 0$ means it is unscheduled yet. Moreover, if flow i has already achieved QoS requirement, we denote $\mathbf{schedule}(i) = -1$. In this algorithm, we use the existing scheduling array as the input and generate a new one, which is a MQIS. In line 5, we find the minimal degree set $\mathbb{MD}$. If there are more than one elements in $\mathbb{MD}$, we select the flow with maximum priority value in line 7. In line 12-14 we remove the newly scheduled flows and its neighbors in $\mathbf{G}$ before starting the next round.

Algorithm 1 findMQIS

Input:

contention graph $\mathbf{G}$
existing schedule array $\mathbf{schedule}$
priority array $\mathbf{priority}$

Output:

new scheduling array , $\mathbf{schedule}$;

1: remove unqualified flows from $\mathbf{G}$
2: **while** $\mathbf{G} \neq \emptyset$ **do**
3: $\mathbb{P}$ = the remaining set of flows in G
4: calculate $\mathbf{degree}$ for flows in $\mathbb{P}$
5: $\mathbb{MD} = \{p \mid \min_{p \in \mathbb{P}} \mathbf{degree}(p)\}$
6: **if** $|\mathbb{MD}| > 1$ **then**
7: $i = \max_{i \in \mathbb{MD}}(\mathbf{priority}(i))$
8: **else**
9: choose $i \in \mathbb{MD}$
10: **end if**
11: $\mathbf{schedule}(i) = 1$
12: find neighbor set $\mathbb{N}$ of i
13: $\mathbb{D} = \{i\} \cup \mathbb{N}$
14: remove flows in $\mathbb{D}$ from $\mathbf{G}$
15: **end while**
16: **return** $\mathbf{schedule}$

D. MQIS based Backhaul Scheduling

Now we summarize the overall scheduling algorithm for the backhaul network. After the BNC receives QoS requests from BSs, it will construct the contention graph G and make scheduling decisions. According to (4) (5), the slots can be divided into a number of stages during which the same scheduling is kept. In MQIS backhaul scheduling, the end of one stage is the slot in which some scheduling flows have achieved QoS requirement. We call those flows "finished". In other words, we should check at every slot if there are some newly finished flows, and if so, a new MQIS should be found using Algorithm 1.

For N flows and M slots in CTAP, we use a $N * M$ binary matrix $\mathbf{B}$ to denote the final scheduling $\mathbf{S}$, where $\mathbf{B}(i, j) = 1$ means the flow i at slot j is scheduled. The detailed process is shown in Algorithm 2. The initialization steps are among line 1-5. In line 8-11, we denote the newly finished flows in array $\mathbf{schedule}$ as -1. Then, we will call Algorithm 1 to generate the new scheduling array, as indicated by line 12.

VI. Performance Evaluation

In this section, we evaluate the performance of the proposed scheduling algorithm in the 73GHz band, and compare it with existing schemes.

A. Simulation Setup

We consider a backhaul network with 10 base stations which has at most 90 flows. Since the scheduling performance is

Algorithm 2 MQIS Backhaul Scheduling Algorithm

```
BNC receives transmission request r_i(i = 1,2,...N) requiring minimum throughput R^i_min
construct contention graph G
initialize N * M scheduling matrix B = 0
initialize schedule = (0,0,...0) with length N
compute priority for flows
for slot k(1 ≤ k ≤ M) do
    if k = 1 or some flows newly finished then
        denote the set of the newly finished flows as FIN
        for f ∈ FIN do
            schedule(f) = −1
        end for

            schedule = findMQIS(G, schedule, priority)
        B(:, k) = schedule
    else
        B(:, k) = B(:, k − 1)
        continue
    end if
end for
return B
```

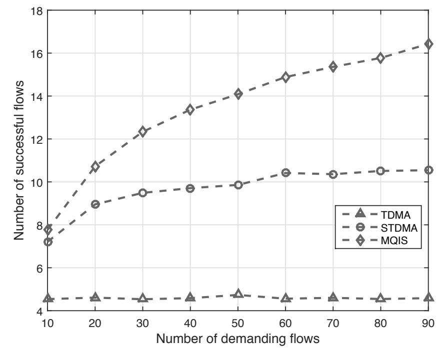
dependent on the location of stations, we randomly generate a position for each BS within a 1000 square meters area. Meanwhile, for every flow, we randomly choose its source and destination. And the requested throughput for this flow is uniformly distributed between 1 Gbps and 3 Gpbs. For the path loss, we use the channel model in Ref [12]. Besides, we adopt the widely used realistic directional antenna model in Ref [13]. All the BSs in the system use the same transmission power level. Some other parameters are shown in Table I.

TABLE I
SIMULATION PARAMETERS

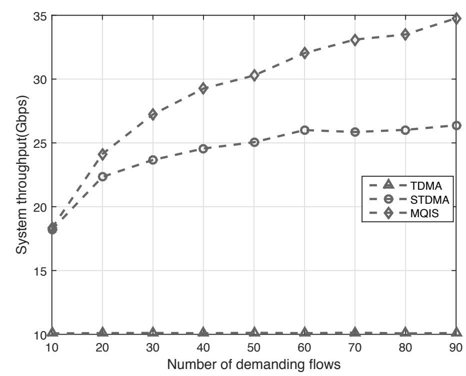
system bandwidth	W	1.2 GHz
transmission power	P_t	30 dBm
background noise	N_0	-134 dBm/MHz
slot time	t_{slot}	18 μs
beacon period	t_0	850 μs
Number of slots in transmission period	M	2000

We implemented the serial TDMA, and the state-of-the-art protocol STDMA [10] for comparison. To evaluate our proposed protocol, the following metrics are considered:

- **Number of successful flows**: the number of flows that achieve the required QoS. Note that if a flow has been scheduled during the scheduling phase but can not satisfy the QoS during the transmission phase, it will not be counted as a successful flow.
- **System throughput**: the achieved total throughput of the backhual network. In other words, this metric is the average of sum of the throughputs of all flows.



(a) Number of successful flows



(b) System throughput

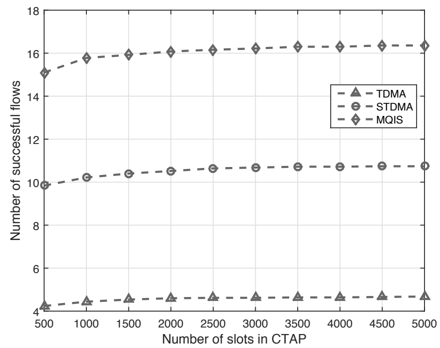
Fig. 2. Performance under different number of flows

B. Comparison with Other Schemes

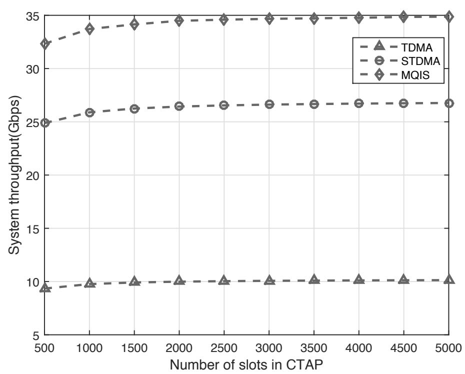
1) Under different number of flows: In this case, we choose the number of slots in CTAP as 2000, and set $\sigma = 10^{-4}$. We vary the number of flows in the backhaul network from 10 to 90. With the increasing number of demanding flows, we evaluate the two metrics and plot the results in Fig 2.

From the results, we can observe the trend of the performance of the MQIS based scheduling algorithm under the increasing number of demanding flows. The more demanding flows there are, the more chances for the spatial reuse, and thus both the number of successful flows and the system throughput keep increasing. Due to the system capacity constraint, they gradually become flat and reaches the capacity.

Compared with TDMA and STDMA, the MQIS based scheduling has obvious advantages. TDMA has no spatial reuse at all so it can only schedule limited flows. When only a few flows are to be scheduled, the difference between STDMA and MQIS is trivial because both schemes can almost accommodate all the demanding flows. But as the number of demanding flows increases, the MQIS based scheduling can achieve better performance in two aspects. First of all, when the number of demanding flows is around 10 to 20, the performance of STDMA has already entered the flattened phase where more number of flows will not bring obvious better performance; However, the proposed scheme keeps increasing dramatically until the number of demanding flows



(a) Number of successful flows



(b) System throughput

Fig. 3. Performance under different number of slots

reaches 80. Moreover, when the traffic demand is large, the MQIS based scheduling can achieve around 60% more number of successful flows and about 40% more system throughput than STDMA.

The better performance of MQIS based scheduling algorithm comes from two facts. First, it uses global contention knowledge to make scheduling. For STDMA, a new flow will be added to scheduling set as long as it can increase the total throughput. This method may get stuck to bad local optimal, where highly contented flows are co-scheduled. While in MQIS scheduling, we always schedule the flows that are relatively independent with each other, and thus more close to the global optimal. Secondly, the QoS of a flow is considered as an priority in MQIS based scheduling algorithm, and contributes to the overall performance.

2) Under different number of slots: In this case, we aim to compare the performance of different protocols under different number of slots in CTAP. The number of demanding flows is kept to be 90. We change the number of slots in CTAP from 500 to 5000, and evaluate the two metrics as before. The results are shown in Fig 3. As we can observe, the number of successful flows and system throughput only slightly increase as the number of slots in CTAP changes. With enough time slots, the MQIS based algorithm can achieve 17 successful flows while STDMA can only schedule around 11 flows. Besides, the system throughput of the MQIS based algorithm is 10 Gbps higher than that of STDMA.

VII. Conclusion

In this paper, we consider the problem of optimal scheduling to maximize the number of flows with their QoS requirements satisfied in the mmWave backhaul network. We have proposed the MQIS based backhaul scheduling algorithm, where the spatial reuse is fully exploited based on the contention graph. The QoS aware priority is also exploited in the algorithm to provide better QoS guarantees for flows. Extensive simulations show our algorithm is able to achieve more successfully scheduled flows as well as higher network throughput than other schemes.

Acknowledgment

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