Practical Distributed Scheduling for QoS-aware Small Cell mmWave Mesh Backhaul Network

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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. However, 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 Distributed Maximum QoS-aware (DMQ) scheduling algorithm for the mmWave backhaul network of small cells to maximize the system throughput while satisfying QoS requirements for each flow. Based on CSMA/CA, the proposed algorithm is the first that prioritizes MAC contention window to provide better concurrent transmission support while achieving QoS-aware capability. Simulations in the 73 GHz band are conducted to demonstrate 25%–40% performance boost in terms of system throughput and packet loss ratio against other existing schemes.

Keywords: Wireless Network; QoS; 5G; mmWave; Directional Antenna.

1. Introduction

Some industry and academic experts predict a 1000-fold demand of mobile data increase by 2020 [1]. In order to offer such gigantic demand 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, 4, 5]. Although fiber based backhaul offers large bandwidth, it is costly, inflexible, and time-consuming to connect the densely

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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. Meanwhile, rapid progress in mmWave circuits and antennas has accelerated popularization of wireless products and services in mmWave bands [6]. There are also several standards defined in the mmWave bands, such as ECMA-387 [7], IEEE 802.15.3c [8], and IEEE 802.11ad [9].

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 [10]. 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.

There has been some related work on the transmission scheduling for mmWave communications. Since time division multiple access (TDMA) is adopted in ECMA-387 [7] and IEEE 802.15.3c [8], many existing works are based on TDMA [11, 12, 13, 14, 15, 17]. One influential work is the Exclusive Region (ER) based scheduling which is introduced and derived in [13]. Qiao *et al.* [15] proposed a concurrent transmission scheduling considering QoS for flows. In such work, 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.

Although TDMA-based scheduling has been widely adopted in literature, one of its key disadvantage is that a *centralized* backhaul network controller is needed to coordinate scheduling process. This inevitably increases the system overhead, complicates the system design and limits the scalability of backhaul network. Furthermore, as energy efficiency emerges to be an important metric for next generation wireless networks [16], it also poses a challenge that the increased overhead and complexity would increase the energy cost.

In order to solve the problem and reduce system complexity, there are a few emerging works that propose applying CSMA contention based scheduling on 60GHz mmWave band. CSMA has been widely adopted in various existing 802.11 standards and is a practical distributed scheduling framework that does not need centralized control. Gong *et al.* [21] propose a directional CSMA/CA protocol designed specifically for 60GHz WPANs. It adopts virtual carrier sensing and relies on a central coordinator to distribute network allocation vector (NAV) information. The authors also extended the work to support spatial reuse in [22]. Similar works can also be found in [23]. Another notable work by Zheng *et al.* [20] proposes an optimal scheduling algorithm for contention based network although it does not specifically target on mmWave band. However, all

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

these approaches only target on channel access control and are generally lack of QoS support. Thus they cannot be applied to QoS-aware backhaul networks.

In this paper, we develop a practical CSMA contention based scheduling scheme that is also QoS aware for the small cell backhaul network specifically in mmWave band. The proposed scheme operates in a completely distributed fashion and does not need centralized controller to coordinate flow scheduling. To the best of our knowledge, this is the first CSMA contention based scheduling protocol that prioritizes the MAC contention window to better facilitate both concurrent transmission and QoS support. This greatly reduces the protocol complexity of the network system compared with other existing schemes. Further, we adopt a realistic directional antenna model to evaluate our proposed algorithm for the backhaul network in 73 GHz band. The simulation results demonstrate the superior performance of our algorithm against other existing schemes.

The rest of this paper is structured as follows. Section 2 gives an overview of the system model which includes network model and antenna model. Section 3 formulates the scheduling problem. Section 4 presents in detail our proposed DMQ scheduling algorithm for the mmWave backhaul network. Extensive simulations are conducted and evaluated in Section 5. Finally, Section 6 concludes this paper.

2. System Model

2.1. Network Model

The characteristic of strong line of sight (LOS) at low inter-site distances (ISDs) of 73GHz mmWave band generally requires the small cells be deployed densely. Therefore, we consider the scenario where small cells are densely deployed as illustrated in Fig. 1, where we illustrate 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. Each BS in the network is equipped with an electronically steerable directional antenna, and can direct its beam towards other BSs for directional transmission. The backhaul network is in E-band, which provides high data rates. For the scheduling problem of such backhaul network for small cells, there are two challenges. First, concurrent transmissions need to be fully exploited to maximize the spatial reuse gain. Second, 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.

2.2. Directional Antenna Model

With BSs fixed, since non-line-of-sight (NLOS) transmissions suffer from higher attenuation than line-of-sight (LOS) transmissions [18], we assume the directional LOS transmission between BSs can be achieved with the locations of BSs adjusted appropriately (e.g., on the roof). Suppose there are N flows requesting transmission, 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

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

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 [13, 15]. Due to the half-duplex assumption, adjacent links cannot be scheduled for concurrent transmissions [19]. 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

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

where we consider ρ as the multi-user interference (MUI) factor related to the cross correlation of signals from different links. Thus, the received SINR at r_i can be expressed as

$$SINR_i = \frac{k_0 G_t(i, i) G_r(i, i) d_{ii}^{-n} P_t}{N_0 W + \rho \sum_{j \propto i} k_0 G_t(j, i) G_r(j, i) d_{ji}^{-n} P_t}, \quad (3)$$

where W is the bandwidth, and N_0 is the onesided power spectra density of white Gaussian noise [15]. Then according to Shannon's channel capacity, the

achievable data rate of flow i can be estimated as

$$R_i = \eta W \log_2 \left(1 + \frac{k_0 G_t(i, i) G_r(i, i) d_{ii}^{-n} P_t}{N_0 W + \rho \sum_{j \propto i} k_0 G_t(j, i) G_r(j, i) d_{ji}^{-n} P_t} \right), \quad (4)$$

where $\eta \in (0, 1)$ describes the efficiency of the transceiver design.

For individual antenna, we adopt the reference model described in [26]. First, we define maximum gain of antenna as G_0 , which can be determined by employing the formula of an ideal circular aperture antenna with uniform field distribution:

$$G_0 = (ka)^2 \quad (5)$$

$$ka \cdot \sin(\theta_{-3dB}/2) = 1.6162 \quad (6)$$

where k and a are the wavenumber and radius of the aperture.

Then, the main-lobe function G is defined as

$$G(\theta, \phi) = G_0 \exp(-\alpha \theta^2). \quad (7)$$

where θ is the main-lobe width and α is determined by the half-power beamwidth θ_{-3dB} as:

$$\alpha = \frac{4 \cdot \ln 2}{\theta_{-3dB}^2}. \quad (8)$$

In unit of dB, the main-lobe can be expressed as:

$$G(\theta, \phi)[dB] = G_0[dB] - 3.01 \cdot \left(\frac{2\theta}{\theta_{-3dB}} \right)^2. \quad (9)$$

Considering -20 dB from the maximum gain as a main-lobe, the main-lobe width θ_{ml} can be derived from (9) as:

$$\theta_{ml} = 2.6 \cdot \theta_{-3dB}. \quad (10)$$

Finally, the side-lobe power G_{sl} can be modeled as:

$$G_{sl} = \frac{4\pi - G_0 \int_0^{\theta_{ml}/2} \exp(-\alpha \theta^2) \cdot \sin \theta d\theta \int_0^{2\pi} d\phi}{\int_{\theta_{ml}/2}^{\pi} \sin \theta d\theta \int_0^{2\pi} d\phi}. \quad (11)$$

3. Problem Formulation

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

We assume there is a QoS requirement that represents a minimum throughput requirement for each flow i , and denote it by q_i . We also define a term *grouping*, which represents a group of nodes that are able to schedule transmissions concurrently. We denote a schedule as $\mathcal{S}$, and assume it has K groupings.

In each grouping, 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 k th grouping. If so, $a_i^k = 1$; otherwise, $a_i^k = 0$. We denote the number of time slots of the k th grouping by δ^k .

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

$$R_i^k = \eta W \log_2 \left(1 + \frac{a_i^k k_0 G_t(i, i) G_r(i, i) d_{ii}^{-\alpha} P_t}{N_0 W + \rho \sum_j a_j^k k_0 G_t(j, i) G_r(j, i) d_{ji}^{-\alpha} P_t} \right). \quad (12)$$

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

$$T_i = \frac{\sum_{k=1}^K \delta^k \cdot R_i^k \cdot t_{slot}}{t_{bo} + M \cdot t_{slot}}, \quad (13)$$

where t_{bo} is the time for back-off, and t_{slot} is the time duration of each time slot on transmission. M denotes the total number of time slot available. Then we define a binary variable Q_i to indicate whether the QoS requirement of flow i is satisfied in $\mathcal{S}$. If so, $Q_i = 1$; otherwise, $Q_i = 0$. Given the throughput requirements of flows, with limited number of time slots assigned, the optimal schedule should accommodate as many flows as possible [15]. Therefore, the optimal scheduling problem $\mathbf{P}$ can be formulated as follows.

$$(\mathbf{P}) \max \sum_{i=1}^N Q_i \quad (14)$$

s.t.

$$Q_i = \begin{cases} 1, & \text{if } T_i \geq q_i, \\ 0, & \text{otherwise;} \end{cases} \quad \forall i \quad (15)$$

$$\sum_{k=1}^K \delta^k \leq M; \quad (16)$$

$$a_i^k + a_j^k \leq 1, \text{ if flow } i \text{ and } j \text{ are adjacent; } \forall i, j \quad (17)$$

It is obvious that this is a nonlinear integer programming problem, and is NP-hard. Constraint (15) 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 (16) indicates there are at most M time slots. Constraint (17) 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 [19].

Although it is difficult to solve the problem $\mathbf{P}$ in polynomial time, we propose an efficient and practical distributed scheduling algorithm to achieve a sub-optimal solution instead in the next section.

4. Distributed Scheduling Algorithm

In this section, we propose a practical Distributed Maximum QoS-aware (DMQ) scheduling algorithm to solve the scheduling problem in (14).

4.1. Neighborhood Detection

In order to effectively schedule flows between base stations, each station needs to keep track of how many other stations that can potentially cause interference to the station. One of the advantage of mmWave band is its strong capability for channel reuse. However, interference plays an important role in reducing such channel reuse capability. By detecting information of neighbors, we are able to reduce such interference. One straight-forward way to conduct neighborhood detection could be that every node periodically broadcasts beacon signal to its neighbors. If the other node is able to receive such beacon signal, then it knows it has one neighbor that could possibly in the interference range. However, since interference only occurs when nodes are transmitting, such active signaling mechanism can cause unnecessary overhead over time. The increased overhead will not only impact the performance of the network, but it also increases the energy consumption. We can eliminate such overhead by setting up an overhearing mechanism at each base station.

The neighborhood detection algorithm works as follows. At time slot t , each base station b_i counts the number of distinct sources for flows not destined to b_i by letting the NIC operate in promiscuous mode. Therefore, when a nearby base station $b_j (j \neq i)$ sends a packet, base station b_i is able to detect the signal and effectively count b_j as its neighbor. The detailed procedure is described in Algorithm 1.

Algorithm 1 Neighborhood Detection

Each base station does the following:

Output: the number of interfering neighbors detected.

- 1: Enable promiscuous mode;
 - 2: Define and initialize a neighbor set $\mathbf{N}$;
 - 3: **while** received a packet p **do**
 - 4: src = source address of p ;
 - 5: $dest$ = destination address of p ;
 - 6: **if** $dest$ is *not* a broadcast address **then**
 - 7: Define b_{src} as the base station that sent packet p ;
 - 8: Add b_{src} to neighbor set $\mathbf{N}$;
 - 9: **end if**
 - 10: **end while**
 - 11: **return** size of $\mathbf{N}$;
-

While signal in mmWave band is more concentrated and less likely that it will cause interference in large range, yet it is still not uncommon that interference does happen when several base stations are located in densely deployed small

cells and, in the meantime, the directional antennas' orientation is also set within the interfering sidelobe or mainlobe area. Thus, for a base station b_i , there could be simultaneously several neighbor base stations contending for the same channel. This will cause the degradation of network throughput if we don't take measures to mitigate the problem. Our proposed DMQ is right designed for this task. DMQ scheduler is able to schedule flows according to a base station's *contention level*, which is positively proportional to its number of neighbors.

4.2. Contention Window Prioritization

In order to facilitate both contention avoidance and QoS-aware scheduling between base stations, we define eight priority levels indexed from 0 to 7. For practical concern, DMQ algorithm exploits the Quality of Service (QoS) feature shipped with 802.11e. IEEE 802.11e standard is an amendment to IEEE 802.11 standard family that defines a set of QoS facilitating features, of which the most notable is the Enhanced Distributed Channel Access (EDCA) mechanism. EDCA provides levels of priority which are called Access Categories (ACs). By default, there are 8 distinct ACs indexed from 0 to 7. We follow such settings in order to make our proposed scheme adopt to 802.11e standard. Each AC has a pair of minimum contention window size (CWmin), maximum contention window size (CWmax). These parameters regulate the back-off behavior of current distributed coordination function (DCF). The larger index number represents higher priority level and vice-versa. Each priority level has parameters of minimum contention window size (CWmin) and maximum contention window size (CWmax). The configuration of these parameters are shown in Table 1.

For a specific priority, the CWmin and CWmax regulate the back-off behavior of current contending base station. When contention occurs, similar to CSMA/CA mechanism, the scheduler will initialize a random back-off window of size within CWmin and CWmax. If contention still occurs after back-off, the scheduler will double the size of current back-off window until it reaches CWmax and will keep it at CWmax until reset. The back-off procedure continues. Generally, the *average* size of back-off window determines how contentious current base station is. The larger the size of back-off window, the longer the base station will wait to try to initiate next transmission, thus exhibiting less contentious behavior, and vice-versa.

Therefore, we utilize this fact to configure the CWmin and CWmax parameters with respect to their associated priority levels. For contention resolving purposes, we want the base stations operating in lower priority level to be less contentious. Thus we assign them with relatively larger CWmin and CWmax values. Vice-versa, the base stations with higher priority levels will be assigned with smaller CWmin and CWmax values. Furthermore, we also try to adjust CWmin and CWmax to make each priority level more distinct and dispartate from one another; such that, for a given priority level i , the probability that the randomized back-off window size will overlap with that of priority level j ($j \neq i$) will be reduced to minimum. Table 1 shows the exact configuration of these parameters, where we completely eliminate the possible back-off window size overlapping between different priority levels.

Table 1: Contention Window Prioritization

Priority	0	1	2	3	4	5	6	7
CWmin	512	256	128	64	32	16	8	3
CWmax	1023	511	255	127	63	31	15	7

4.3. Coarse-to-Fine Window Mapping Algorithm

Based upon prioritized contention window configuration in Table 1, we propose a Coarse-to-Fine Window Mapping (CFWM) algorithm. Namely, CFWM is a two-phase process. In the coarse-phase, the algorithm addresses the contention issue while in the fine-phase, QoS requirements are accommodated.

4.3.1. Coarse Phase

Let's first define *contention degree* d_c^i , as the number of neighboring base stations a base station b_i detects. The value of d_c^i will be calculated by Algorithm 1 described in Section 4.1. CFWM works by assigning priority level to current schedule according to its base station b_i 's contention degree d_c^i . We call this *coarse* phase of CFWM, which is illustrated in Algorithm 2.

Algorithm 2 Priority Level Computation (Coarse)

Input: contention degree d_c^i for base station b_i .

Output: the corresponding priority level.

- 1: Define P_i as the priority level to be assigned for base station b_i ;
 - 2: **if** $d_c^i > 7$ **then**
 - 3: $P_i = 0$;
 - 4: **else**
 - 5: $P_i = 7 - d_c^i$;
 - 6: **end if**
 - 7: **return** P_i ;
-

The intuition behind Algorithm 2 is that the scheduler always tries to assign higher priority level to base station b_i that has smaller value of contention degree d_c^i . In such case, since the base station has less number of neighbors contending with it (smaller value of contention degree), it is more likely that this base station is able to fulfill the QoS requirement and increase the overall network throughput of the system. Thus, CFWM will assign it with a higher priority level. On the other hand, if base station b_i has a larger value of contention degree, the CFWM will assign it with a lower priority level which tends to curb the sending rate of base station b_i . In practice, the number of contention neighbors a base station potentially has usually would not exceed 7, thus we believe the linear mapping between contention degree and priority level (line 2–5 in Algorithm 2) is reasonable. For cases where contention degree does exceed 7, CFWM just assigns priority level 0, the lowest, to the corresponding base stations.

In essence, each priority level determines the contention window adjustment strategy. Since the lower the priority level is, the larger CWmin/CWmax will be set, which leads to a less contentious base station. It is also true vise-versa. Our rationale behind this mechanism is that we always want the least contending base station to transmit first, because the less contending a base station is, the higher throughput the base station can potentially create. As will be seen in Section 5, our experimental results also support this rationale.

4.3.2. Fine Phase

So far, the priority level assignment procedure described in Algorithm 2 only considers the contention between base stations. The more neighbors a base station b_i has, the more contending b_i becomes, the lower priority level b_i will be assigned. Another important issue that we need to address is QoS-awareness of the DMQ scheduler. On top of the scheduling scheme in Algorithm 2, we equip DMQ with QoS scheduling capability which is described in Algorithm 3. We call this *fine* phase of CFWM.

Algorithm 3 Contention Window Adjustment (Fine)

Input:

- P_i – current priority level for base station b_i ;
- d_q^f – QoS degree for base station b_i .

Output:

- CW_{min} – the adjusted CWmin value.
 - CW_{max} – the adjusted CWmax value.
 - 1: Retrieve CWmin and CWmax values with respect to P_i ;
 - 2: Let $f(t) = \frac{2}{1+e^{-\alpha t}} - 1$, where α is a constant;
 - 3: $CW_{max} = CWmin + f(d_q^f) \cdot (CWmax - CWmin)$;
 - 4: $CW_{min} = \max(CW_{max} - \beta, CWmin)$, where β is a positive integer;
 - 5: **return** CW_{min} and CW_{max} .
-

For each flow f , define *QoS degree* d_q^f as a positive value that indicates the QoS priority for the flow. The higher the QoS priority is, the larger d_q^f is assigned. In Algorithm 3, CFWM tries to make a finer contention window parameter adjustment based on *QoS degree* d_q^f for current flow f on base station b_i . According to our QoS-aware schedule policy, the higher QoS priority a flow has, the sooner it needs to be scheduled in order to achieve optimal throughput over the network. CFWM achieves this purpose by adjusting the CWmin and CWmax value according to the QoS priority inside current priority level P_i . Recall in Section 4.2, we described that CWmin and CWmax determine the range within which the size of contention window could be. Although not guaranteed, statistically, when CWmin or CWmax increases, the back-off time for current DCF will become longer since the probability to randomize a larger back-off slot number becomes higher. Therefore, when a flow with higher QoS priority needs to be scheduled, Algorithm 3 will return a decreased CWmax and CWmin value (line 3 and line 4 of Algorithm 3) which essentially leads to

a shorter back-off time. This will make the flow be able to have much larger probability to be scheduled earlier than its contending counterparts if there are any.

Algorithm 2 and Algorithm 3 altogether constitute the cornerstone of our proposed CFWM algorithm. They work cooperatively to schedule flows according to both their contention degree and QoS degree. When a base station b_i has a flow to send, CFWM will first retrieve appropriate priority level by referring to Algorithm 2 with contention degree information. Afterwards, CFWM will continue to run Algorithm 3 to set proper CWmin and CWmax values for scheduler's back-off window *inside* current priority level. Results returned from Algorithm 2 only indicates which priority level current flow should be associated with, while Algorithm 3 further deals with the exact values of CWmin and CWmax inside that priority level. Thus Algorithm 2 is called *coarse* phase while Algorithm 3 is called *fine* phase. That is how CFWM deals with both contention issue and QoS-awareness in a unified framework.

5. Simulation Results

In this section, we implemented our proposed DMQ algorithm and compared the performance with existing schemes.

5.1. Development of Simulator

For performance evaluation of DMQ, we consider a backhaul network consisted of 25 base stations (nodes) evenly distributed over a 500 meters $\times$ 500 meters grid area, as illustrated in Figure 2. Each base station is equipped with directional antennas as well as quasi omni-directional antennas. For each node, we implemented the widely adopted directional antenna model as described in [26]. The beamwidth of the directional antennas is set to 30 degrees and the channel is set to work on 73GHz band. On top of directional antenna model, our proposed DMQ scheduling algorithm is implemented. The simulation system is developed under NS-3 [27].

For each base station, it is able to communicate with its 8 adjacent neighbors in one-hop distance. We note that for base stations that are out of one-hop distance, an appropriate routing protocol is needed to route packets through multiple hops. Since routing is not our focus in this work, we believe many existing wireless routing protocols should work with our experiment. For simplicity, we just use Optimized Link State Routing (OLSR) protocol to achieve such purpose.

For performance comparison, we also implemented the optimal Distributed Opportunistic Scheduling (DOS) scheme proposed in [20] and a default 802.11 random access scheme as a baseline. To evaluate our proposed scheme, the following metrics are considered:

- **System throughput:** Needless to say, system throughput is a key performance metric we primarily concern about. By throughput, we mean the overall throughput on the whole backhaul network. We will study

Figure 2: Topology of base stations used in simulation.

the effects of number of flows, effects of number of packets and effects of antenna beamwidth on throughput performance.

- **Packet loss ratio:** Since we also consider QoS as an essential part of our scheduling, packet loss ratio is yet another important indicator that measures the reliability performance of the scheduling system from a packet level perspective. We will study the effects of number of flows on packet loss ratio.

5.2. Performance Evaluation

In this subsection, we design experiments to study the scheduling algorithm performance under different number of flows, under different number of packets in each flow and under different antenna beamwidth. In order to focus on scheduling itself rather than the effect of routing, we use the term “flow” to only refer to the case where the flow is originated at one base station and travels to another in one hop. If there are more than one hop along the path of the flow, e.g. $k(k > 1)$ hops, we regard this as k flows. To reduce random error for each experiment, we repeat the same experiment for 10 times and the average results are calculated and taken.

5.2.1. Effects of Number of Flows on Throughput Performance

First, we set that each flow is consisted of 10 packets and each packet is of size 1000 bytes. Then, we add flows to the system. The number of flows is varied in range of 10 to 100. Once the number of flows is determined, these flows are generated and added randomly among the base stations. For each base station, one packet is scheduled to be generated and sent from transport layer in every 30 milliseconds, i.e., the sending interval. On the MAC layer, we configured each base station and installed scheduling scheme using, respectively, DMQ, DOS as

Figure 3: Number of flows on throughput performance.

well as default 802.11 random access. We recorded the elapsed time between moment when first packet of the whole network was sent at transport layer and moment when last packet of the whole network was *successfully* received at one base station. Then we calculated the overall system throughput for each scheme. We recorded throughput performance of each scheme for different number of flows. Each of the experiment was repeated 10 times and the average results were taken. Finally, we plotted the comparison results shown in Figure 3.

We have the following observations:

- Our proposed DMQ achieves the best result in system throughput performance among all of the three schemes. It achieves an average of 25% throughput gain over DOS and 40% over 802.11. Thanks to the coarse-to-fine hierarchical structure of DMQ, the scheduler is able to make best use of the available contention window values and assigns them to flows according to both their contention and QoS priorities. Thus the contention between different flows with different priorities can be reduced to minimum.
- Our proposed DMQ is better suited for practical environment. From Figure 3, we see that DOS does not achieve the best performance although it is theoretically proved to be optimal. This is due to the fact that DOS relies on highly accurate past channel estimation to determine current scheduling scheme. However, in practical environment, it is difficult to achieve such an accurate channel estimation in real time. This makes DMQ perform much better than DOS.

5.2.2. Effects of Number of Packets in Each Flow on Throughput Performance

In this experiment, we randomly add 50 flows in the system. Then, we vary the number of packets for each flow from 10 to 100. Other setups remain the

Figure 4: Number of packets in each flow on throughput performance.

same as described in Section 5.2.1. As previously, we recorded the elapsed time between moment when first packet of the whole network was sent at transport layer and moment when last packet of the whole network was successfully received at one base station. The performance comparison is shown in Figure 4.

It clearly shows that:

- Our DMQ outperforms both DOS and default 802.11 scheduling schemes in terms of throughput performance. DMQ can achieve more than 20% gain over DOS and 40% gain over 802.11 as the number of packets increases.
- The general trend is that when the number of packets in each flow increases, the overall system throughput also increases.
- As the number of packets increases, the increasing trend of system throughput tends to slow down at the end. This is because the system is more and more approaching its capacity as more and more packets are injected into the system.

5.2.3. Effects of Antenna Beamwidth on Throughput Performance

One of the major difference between omni-directional antenna and directional antenna is the beamwidth. In directional antenna patterns, the beamwidth is the angle between half-power (-3dB) points and the main lobe. Therefore, beamwidth is an important factor that affects the performance of directional antennas. In this experiment, we study the effects of antenna beamwidth on system throughput. We set the number of flows to 50 and randomly assigns them to base station pairs in the system. In each flow, we set the number of packets to 50. Then, we vary the beamwidth from 5° to 50° . As previously, we recorded the elapsed time between moment when first packet of the whole network was sent at transport layer and moment when last packet of the whole

Figure 5: Antenna beamwidth on throughput performance.

network was successfully received at one base station. We collect the experiment data and compare the result in Figure 5.

We observe that:

- Our proposed DMQ achieves the best throughput performance among all the three schemes compared. It can achieve a maximum of 30% gain over DOS and even triple the performance of 802.11.
- The system throughput decreases as the beamwidth increases. This is because smaller beamwidth means a narrower antenna pattern between half-power and main lobe, which would consequently make the wireless signal more concentrated. As a result, the interference between base stations will be reduced, making the whole system less contending. Thus the throughput can be achieved a lot higher.
- When beamwidth keeps increasing, the contention between base stations also increases as more and more base stations become able to detect the signals from neighboring base stations. This leads to the trigger of back-off mechanism, thus reducing the system throughput.

5.2.4. Effects of Number of Flows on Packet Loss Ratio

In this experiment, we focus on the relationship between number of flows in the system and its corresponding packet loss ratio. The experiment setup and methodology are similar to the those described in Section 5.2.1. However, instead of recording throughput, here we record the total number of packets that are successfully received by all receiving base stations. Using such information, we are able to calculate the packet loss ratio (PLR) as:

$$PLR = 1 - \frac{\text{Total number of packets received}}{\text{Total number of packets sent in the network}}. \quad (18)$$

Figure 6: Effects of Number of Flows on Packet Loss Ratio, the less the better.

Again, the experiment was repeated 10 times and the average results were taken. The results of comparison is shown in Figure 6.

We have the following observations:

- Our proposed DMQ achieves the least packet loss ratio which indicates the best performance among the three. It almost can achieve close-to-zero packet loss ratio when the number of flows is small.
- Thanks to CFWM algorithm, DMQ is able to detect and avoid the contention as much as possible, and only loses half of packets DOS has lost and a quarter of packets conventional 802.11 has lost.
- The packet loss ratio of all three schemes tends to increase as the number of flows increases. This is because when number of flows increases, the probability of contention between different flows is also increasing, which leads to the increase of packet loss ratio. Although increasing, the proposed DMQ always keeps packet loss ratio much lower than others.

6. Conclusion

In this paper, we have considered the problem of backhaul scheduling to maximize the system throughput while having flows' QoS requirements satisfied in the mmWave backhaul network. The formulated problem is NP-hard, thus we proposed the DMQ scheduling algorithm, where it is designed to achieve the spatial reuse while reducing interference and channel contention between neighbors in a coarse-to-fine two-phase fashion. The QoS aware priority is exploited in the algorithm to provide better QoS guarantees for flows. We conducted extensive experiments and results have shown that our proposed algorithm is able to achieve much higher system throughput and much lower packet loss ratio than other existing schemes under different criteria.

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