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QoS-Aware Bandwidth Allocation and Concurrent Scheduling for Terahertz Wireless Backhaul Networks

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ABSTRACT In recent years, with the spectrum resources in low frequency bands becoming increasingly insufficient, the carrier frequency of wireless communication has started its evolution to the Terahertz (THz) frequency band, and meanwhile the THz communication system has become one of the research hot spots. In this paper, we investigate the problem of concurrent transmission scheduling for THz wireless backhaul network. To increase the weighted sum of completed flows with their quality of service (QoS) requirements satisfied in THz wireless backhaul network, we propose an algorithm of QoS-aware bandwidth allocation and concurrent scheduling (IHQB). Considering the priority of the flow, the reciprocal of the priority is taken as the weight of the flow. In this algorithm, QoS awareness and bandwidth allocation are exploited to achieve more successfully scheduled flows and higher network throughput. The concurrent scheduling with the maximum independent set (MIS) is allocated to different frequency bands. And the mentioned MIS is obtained from the conflict graph which has been established under the conditions of half-duplex and interference threshold. Simulation results show that IHQB performs better than other algorithms in terms of the weighted sum of completed flows and system throughput, especially compared with STDMA.

INDEX TERMS Terahertz communication, bandwidth allocation, quality of service, concurrent scheduling, the conflict graph, maximum independent set.

I. INTRODUCTION

According to Edholm's law of bandwidth [1], wireless data rates have doubled every 18 months over the last three decades and are quickly approaching the capacity of wired communication system [2]. In order to address this tremendous capacity demands, the wireless network is now marching forward to the fifth generation (5G) era. Although 5G has introduced several novel technologies, such as massive multiple-input multiple-output (MIMO), full-duplexing (FD), and millimetre wave (mmWave), there is still a lack of efficiency and flexibility in handling huge amount of data services oriented from quality of service (QoS) and experience (QoE) [3]. Since currently used frequency spectrum for 5G has limited capacity, THz communication has gradually become an attractive complementing choice for optical-fibre communication that is less flexible and more expensive, as well as for the lower data-rate system [4]. With the coming 5G era, the interweaving mobile Internet and the Internet of Things based on 5G will witness an explosive growth in terms of mobile data traffic, and the result of which is faster speed and larger capacity in wireless communication. Also in recent years, THz communication has become one of the research hot spots. The THz band generally refers to the electromagnetic wave whose frequency range is from 0.1 to 10THz, and the wavelength is between microwave and far infrared [5],

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[6]. Thanks to the available wide frequency band, THz communication system has the potential of achieving ultra-high rate communication, and can even provide transmission rate comparable to that of an optical fiber, thus offers an effective solution to meeting the demand of ultra-high rate wireless communication for 5G and beyond [7]. In addition, THz communication will also play an important role in wireless backhaul network [8].

In September 2018, Jessica Rosenworcel, a Federal Communications Commission (FCC) commissioner stated at the Mobile World Congress of the United States that sixth generation (6G) would head towards THz frequency era, and that wireless network was becoming more dense [9]. As one of the key technologies of the 6G mobile networks, THz technology has many advantages. For example, THz waves can be easily absorbed by moisture from the air, and are therefore useful for high-speed, short-range wireless communication. Also, the beamforming and large scale multiple-input multiple-output (MIMO) multiplexing gain of THz technology can not only help overcome rainfall attenuation, but also fade the propagation so as to meet urban coverage requirements [10]. Furthermore, the THz technology, due to its strong anti-interference capability, can provide a narrower beam and a better directivity for secure communication. Along with the development of the Internet of Things, the ubiquitous connections are now calling for greater ultra-dense backhaul network support. The peak data rate of 6G is at least 1 Tb/s [11], which is 100 times that of 5G. For some special scenarios, such as THz wireless backhaul [11], the peak data rate is expected to reach up to 10 Tb/s. Based on IEEE 802.15.3d [12], data rate for the wireless backhaul network is required to be further more than 100 Gbps. Although considerable prior work on millimeter wave wireless backhaul network transmission scheduling has been done [13]–[16], the millimeter wave frequency spectrum resource still fails to reach the over 100Gbps data rate required by future wireless backhaul network, satisfy the QoS of data flow, or improve system efficiency of future backhaul communication system [3]. For example, in [13], considering the characteristics of mmWave and the QoS requirements of flows, Qiao *et al.* proposed a concurrent scheduling algorithm, which was called STDMA. Its system throughput is only more than 10Gbps in mmWave network. In [16], this paper is full-duplex concurrent scheduling in mmWave wireless backhaul network, whose system throughput is only up to 60Gbps. For THz wireless network, in [17], there has been proposed a distance-aware bandwidth-adaptive resource allocation scheme for wireless systems in the THz band on each sub-window, whose data rate reaches 100Gbps. But it is not practical for wireless backhaul network because of the short transmission distance and its bandwidth allocation is about a flow occupying a frequency band, which doesn't make use of the concurrent transmission. Chen *et al.* [18] designed a dual-frequency antenna for THz wireless communication, showing that the multi-frequency antenna is able to be realized, which is great of practical significance for the concurrent scheduling of multiple frequency bands. Therefore, considering the cost of operation including deployment, maintenance, and optimization, an efficient scheduling for backhaul communication system is now really required. And it is significant to research on how to combine the spatially multiplexed concurrent transmission with the rich spectrum of THz to improve the system throughput and satisfy the QoS of as many data flows as possible. In this paper, data flow is simply ''flow'' for short.

The objective of this paper is to maximize the weighted sum of completed flows under a variety of constraints. Meanwhile, this paper also considers existing hardware system that is difficult to realize ultra-wide bandwidth wireless backhaul communication, hoping to meet the capacity of future wireless backhaul network without increasing the difficulty of future hardware implementation in bandwidth. Inspired by the [17], we explore transmission scheduling in THz wireless backhaul network through the following two methods. Firstly, instead of being utilized as a whole, the bandwidth is divided into several sub-bands at different center frequencies. Secondly, to better apply to the actual business situation, the QoS requirement and priority of flow are particularly emphasized meanwhile. Here, the QoS requirements mean the minimum throughput requirements. The research has three key points: first, how to allocate the requested flow to the corresponding frequency band; second, how to divide the bandwidth of each frequency band more reasonably; third, how to divide the time slot of each frequency band.

In an attempt to solve this problem including three points, we propose a new concurrent scheduling algorithm, which combines QoS with bandwidth allocation under half-duplex communication. The contributions of this paper are significant in the following three aspects.

- We formulate the problem of optimal scheduling in THz wireless backhaul network as a mixed integer nonlinear programming (MINLP). QoS awareness and bandwidth allocation are jointly optimized to improve both the weighted sum of completed flows and the system throughput.
- We propose a heuristic algorithm to solve the problem. In this paper, the MIS is obtained by using the conflict graph constructed by the condition of half-duplex and interference threshold. The bandwidth allocation is about a MIS with many flows occupying a frequency band, and multiple different MISs also transmit in different frequency bands at the same time. We take full advantage of concurrent transmission.
- We evaluate our algorithm for the backhaul network in the 326-374GHz bands, and the realistic antenna model is adopted in the simulation. The simulation results demonstrate the superior performance of our algorithm in terms of the weighted sum of completed flows and the system throughput compared with other algorithms.

The remainder of this paper is organized as follows. Section II describes the system model and presents the problem to be discussed. In Section III, we put forward a QoS-aware bandwidth allocation and concurrent scheduling algorithm for terahertz wireless backhaul networks. In section IV, we analyze the impact of interference threshold choice and bandwidth allocation on the performance of our algorithm. And the performance comparison between the proposed algorithm and other algorithms under different system parameters is given in Section V. Finally, Section VI concludes this paper.

II. SYSTEM MODEL AND PROBLEM FORMULATION

A. SYSTEM MODEL

We present a typical scenario of densely deployed small cells underlying the macrocell cellular network, as shown in Fig. 1. The network includes the N micro base stations (MBSs), which communicate with each other through the THz frequency band. When a MBS has a traffic demand for another MBS, it is considered to generate a flow. In this paper, the word "flow" only refers to the single-hop link. There are one or more MBSs connected to the backbone network via the macro station, which are called gateways [14]. And one of the gateways has a backhaul network controller (BNC), which is able to obtain transmission requests and location information of other MBSs [19]. Each MBS is equipped with multiple directional antennas that can be freely adjusted in half-duplex mode, which means that the MBS can only receive or send a flow in the same frequency band at the same time. While for those flows at different frequencies, the MBS can receive or send several flows at the same time. As shown in Fig. 2, flows $\{1, 2, 3\}$ or $\{2, 3, 4\}$ or $\{2, 3, 5\}$ can be transmitted simultaneously in the corresponding frequency band, while flows $\{1, 4, 5\}$ cannot be transmitted simultaneously.

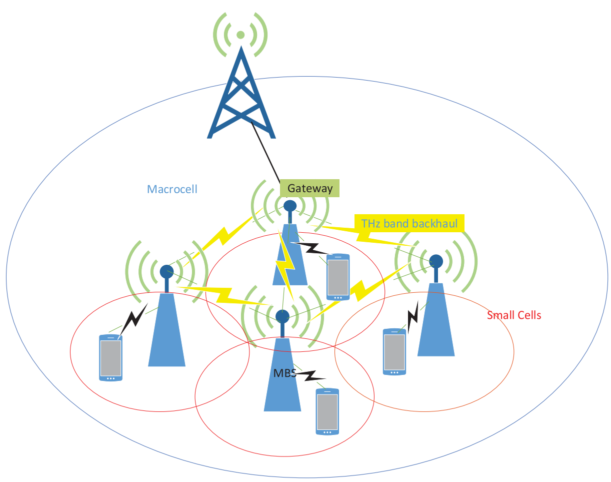

FIGURE 1. The THz backhaul network in the small cells densely deployed scenario.

In our investigated system, time is partitioned into a series of superframes. The frame structure in the MAC layer is shown in Fig. 3. Each superframe includes a scheduling phase and a transmission phase. In the scheduling phase, BNC receives the transmission requests of each flow and makes the scheduling decision. Then it broadcasts the scheduling

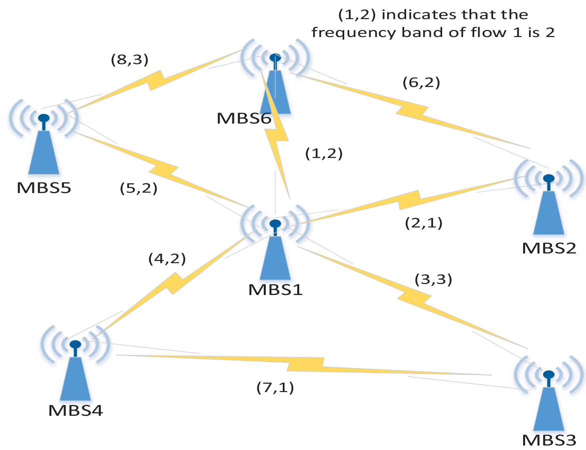

FIGURE 2. Half-duplex multi-frequency concurrent scheduling.

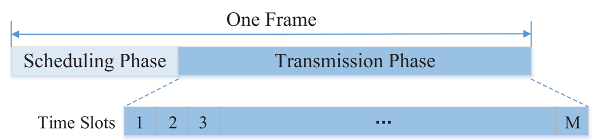

FIGURE 3. The structure of one superframe.

decision to the whole network. In the transmission phase, time is further divided into M equal time slots (TSs). In every TS, some flows can be transmitted concurrently according to the scheduling decision.

In this paper, we use the narrow beam antenna model of F. 699-7 recommended by ITU-R [20]. This antenna model is suitable for communication systems around 300 GHz. According to ITU-R F. 699-7, the gain relative to the isotropic antenna $G(\varphi)$ is given by:

$$G(\varphi) = \begin{cases} G_{max} - 2.5 \times 10^{-3\left(\frac{D}{\lambda}\varphi\right)^2}, & 0^\circ < \varphi < \varphi_m \\ G_1, & \varphi_{m\leq}\varphi < \varphi_r \\ 32 - 25\log\varphi, & \varphi_r \leq \varphi < 48^\circ \\ -13, & 48^\circ \leq \varphi < 180^\circ, \end{cases} \tag{1}$$

where, G_{max} is the maximum antenna gain (dBi), which is also the main lobe antenna gain; φ is the off-axis angle, unit: degree; D is the antenna diameter; λ is the wavelength; $G_1 = 2 + 15log\left(\frac{D}{\lambda}\right)$ is the gain of the second side lobe (dBi); $\varphi_m = \frac{20\lambda}{D}\sqrt{G_{max} - G_1}$; and $\varphi_r = 15.85\left(\frac{D}{\lambda}\right)^{-0.6}$. Cassegreen antenna is selected as the directional antenna with $G_{max} = 47$dBi and $\frac{D}{\lambda} = 152$.

Since the THz signals suffer great attenuation in non-line-of-sight transmissions, this paper considers line-of-sight (LOS) transmissions and calculates the free space path loss of THz as: $PL = 92.4 + 20\lg(f)\,(\text{GHz}) + 20\lg(d)(\text{km})$. For flow i, the received power from the transmitter t_i to its receiver r_i is expressed as:

$$P_R(t_i, r_i) = P_T + G_T(t_i, r_i) + G_R(t_i, r_i) - PL(t_i, r_i), \tag{2}$$

where P_T is the transmission power of transmitter; $G_T(t_i, r_i)$ denotes the transmitter antenna gain from t_i to r_i, and $G_R(t_i, r_i)$ represents the receiver antenna gain from t_i to r_i. In the half-duplex mode, interference between different flows in the same frequency band is regarded as same-frequency interference or multi-user interference (MUI). MUI of flow i at the receiver r_i caused by the transmitter t_l of flow l is defined as:

$$P_R(t_l, r_i) = \rho\left(P_T + G_T(t_l, r_i) + G_R(t_l, r_i) - PL(t_l, r_i)\right), \quad (3)$$

where ρ is a multi-user factor, which is related to the correlation of signals between different links. Due to the half-duplex assumption, adjacent links cannot be scheduled for concurrent transmissions. If flow l and flow i are not adjacent in the same frequency band, we denote it by $l \propto i$. In THz communications, the multipath effect is reduced by directional transmission. So the THz channel can be approximated as an additive gaussian white noise channel (AWGN) [19]. According to Shannon channel capacity, the data rate of flow i can be expressed as

$$R_i = \eta W log_2\left(1 + \frac{P_R(t_i, r_i)}{N_0 W + \sum_{l \propto i} P_R(t_l, r_i)}\right), \quad (4)$$

where η is the factor that describes the efficiency of the transceiver design, which is in the range of (0,1). W is the channel bandwidth, and N_0 is the onesided power spectral density of white Gaussian noise [13]. In this paper, interference between flows that are in different frequency bands is negligible.

B. PROBLEM FORMULATION

In this section, we formulate the optimal scheduling problem when bandwidth allocation and QoS awareness coexist into an MINLP.

The air molecular absorption in the THz frequency may easily lead to frequency and distance-related path loss, which makes certain frequency windows unsuitable for establishing communication links [21]. To tackle this problem, a section of available spectrum window is selected to avoid excessive peak path loss, and it is assumed that the selected spectrum window is f_0 to f. We divide the bandwidth $W = f - f_0$ into B sub-bandwidths, each of which is B_g = 1GHz. And the selected spectrum window is continuously partitioned into D frequency bands. The bandwidth of frequency band d is W_d $(1 \le d \le D)$ and thus the number of sub-bandwidth of the frequency band d is n_d, that is, $W_d = B_g \cdot n_d$. In order to obtain path loss more accurately, we use the central frequency of every band to calculate path loss. The central frequency of the band d is obtained as

$$f_d = f_0 + \sum_{i=0}^{d-1} W_i + \frac{W_d}{2}, \quad (5)$$

where $W_0 = 0$.

Since the total bandwidth is limited, the sum of the bandwidth of all bands should not exceed the provided total bandwidth, which can be expressed as

$$\sum_{d=1}^{D} W_d \le W. \quad (6)$$

In order to reduce the hardware system implementation difficulty, we assume the maximum bandwidth limit is the maximum bandwidth that can be supported by current or future hardware. We define the maximum bandwidth limit as α, thus the bandwidth of each frequency band is bounded by

$$W_d \le \alpha. \quad (7)$$

In the transmission phase, we divide M TSs of the frequency band d into K slot segments. Then the requested flows are assigned to different frequency bands for concurrent scheduling. The number of TSs for the kth slot segment of frequency band d is δ_d^k. The sum of TSs of the K slot segments in band d is at most M TSs, which is described as

$$\sum_{k=1}^{K} \delta_d^k \le M. \quad (8)$$

This paper ignores interference between flows scheduled in different frequency bands. The binary variable $a_{i_d}^k$ is defined to indicate whether the concurrent transmission for flow i is scheduled in the kth slot segment of frequency band d. If it is, $a_{i_d}^k$ is equal to 1; otherwise, $a_{i_d}^k$ is equal to 0. Then from (4), the achievable transmission rate for flow i in each TSs of the kth slot segment for frequency band d can be calculated as

$$R_{i_d}^k = \eta W_d \log\left(1 + \frac{P_R(t_i, r_i)}{N_0 W_d + \sum_{l \propto i, l \ne i} P_R(t_l, r_i)}\right). \quad (9)$$

Then we can obtain the throughput of flow i as:

$$C_i = \frac{\sum_{b=1}^{\delta_d^k} a_{i_d}^k \cdot R_{i_d}^k \cdot \Delta}{T_{sch} + M \cdot \Delta}, \quad (10)$$

where T_{sch} is the scheduling time duration in one frame, and Δ is the duration of one TS. We assume that the QoS requirement for each flow i is the minimum throughput requirement, and denote it by Q_i. Then we define a binary variable I_i to indicate whether the QoS requirement of flow i is satisfied in scheduling. If so, $I_i = 1$, which denotes flow i is completed; otherwise, $I_i = 0$, i.e.,

$$\begin{cases} I_i = 1, & C_i \ge Q_i \\ I_i = 0, & others \end{cases} \quad (11)$$

In order to avoid scheduling the same flow repeatedly, every flow is scheduled only once, which can be expressed as

$$\sum_{d=1}^{D} \sum_{k=1}^{K} a_{i_d}^k \le 1, \forall i \quad (12)$$

In the half-duplex mode, adjacent links cannot be scheduled for concurrent transmissions since there is at most one connection for each node in the same frequency band. We describe it as

$$a_{i_d}^k + a_{l_d}^k \leq 1, \text{ if } i \text{ and } l \text{ are adjacent in the same band.} \quad (13)$$

By contract, multiple flows at the same MBS can be received or sent in different frequency bands.

In a real network, there would be prioritization based on business importance, so this paper assigns each flow with a priority, which denotes it by λ_i. And it is stipulated that the higher the priority, the smaller the corresponding value. The flow with priority 1 has the highest priority. To reflect priority in optimization problem, we introduce the weighted value of flow i, which can be calculated as

$$w_i = \frac{1}{\lambda_i}. \quad (14)$$

Taking all these into account, our optimal scheduling problem (**P1**) can be formulated as maximizing the weighted sum of completed flows, i.e.,

$$(P1) \quad \max \sum_{i=1}^{L} w_i I_i$$
$$\text{s.t. Constraints } (6) - (14). \quad (15)$$

Problem **P1** is a mixed integer nonlinear programming problem (MINLP), where w_i is float variable, I_i is binary variable. There are complex nonlinear terms in the objective function and constraint (11). In constraint (11), C_i is related to W_d and δ_d^k. This problem is also NP-hard. It's complex and is difficult to be solved in polynomial time. Therefore, we propose a heuristic concurrent scheduling algorithm to solve it.

III. SCHEDULING ALGORITHM DESIGN

In this section, we propose the QoS-aware bandwidth allocation based concurrent scheduling algorithm (IHQB) for problem **P1**. In order to maximize the weighted sum of completed flows, the algorithm schedules the flows with high priority first and chooses the maximum independent set (MIS) as flow set of concurrent scheduling in each slot segment of each frequency band. To obtain the MIS, we introduce the conflict graph established by using the conditions of half-duplex and interference threshold. To satisfy the QoS requirements of more flows, we choose the maximum bandwidth limit as the bandwidth of every frequency band. Next we introduce the concepts of conflict graph and MIS, and describe our scheduling algorithm in detail.

A. CONFLICT GRAPH ESTABLISHMENT

We construct the conflict graph. In conflict graph, each vertex represents a flow. In this paper, $G(V, E)$ is used to denote the conflict graph, where V denotes the set of vertices and E denotes the set of edges. If two flows can't be concurrently scheduled (i.e., there is a conflict between them), an edge is inserted between the two corresponding vertices. In the half-duplex wireless backhaul network, two flows are said to be conflicting if and only if they satisfy at least one of the following conditions:

(C1) there are common nodes between the two flows. This is further divided into three situations: C1a) the same node as the transmitter of two flows at the same time; C1b) the same node as the receiver of two flows at the same time; C1c) the same node as the transmitter of one flow and the receiver of the other flow at the same time.

(C2) Relative-Interference between the two flows is greater than a given threshold. This parameter, called the interference threshold, is a key parameter that affects system performance and can be adjusted according to the actual situation. If there is a large interference between the two concurrent flows, their respective transmission rates will be reduced, which is unfavorable to satisfy the QoS requirements of the flows.

Our paper does not consider interference between different spectra, and so there is no conflict between two flows transmitted in different bands. In order to find the set of flows in each frequency band, we establish the first conflict graph $G_1(V, E)$ under the hypothesis of half-duplex, which is based on the condition (C1). A single flow does not conflict itself. In the conflict matrix, 1 at row i column j means there is conflict between flows i and j; and 0 means there is no conflict, as shown in Fig. 4.

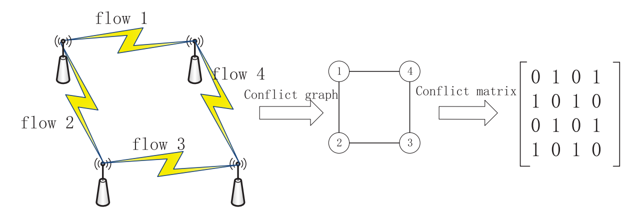

FIGURE 4. The first conflict graph is established.

For the second conflict graph $G_2(V, E)$, it is based on the conditions (C1) and (C2). In our paper, we use two conflict graphs to simulate respectively. The definition of relative interference is

$$RI_{i,j} = \frac{P_R(t_i, r_j)}{P_R(t_j, r_j)}, \quad (16)$$

where $P_R(t_j, r_j)$ and $P_R(t_i, r_j)$ are given by (2) and (3), respectively. If $\max(RI_{i,j}, RI_{j,i}) > \sigma$, an edge is inserted between flow i and flow j, where σ is the interference threshold.

B. MAXIMUM INDEPENDENT SET

The overall goal of the maximum independent set (MIS) problem is to find as many vertices that are not adjacent to each other as possible on a given graph. The MIS of conflict graph is the set of flows that have no edge between each other on the conflict graph with the maximum cardinality [14]. Because obtaining the MIS of a basic graph is NP complete, we adopt the minimum degree greedy algorithm to approximate the MIS [16]. In graph theory, the degree of a vertex of a graph is the number of edges connected to the vertex [14].

For example, in Fig. 2, $\{2, 7\}$ is a MIS, $\{5, 6\}$ is a MIS, and $\{3, 8\}$ is a MIS. Three MISs can transmit at the same time, because they belong to different frequency bands. In our paper, for flows with the same minimum degree, a flow with high priority will be selected for scheduling.

In Algorithm 1, we present the concurrent scheduling MIS (C-MIS) algorithm pseudo-code. V is the set of flows that need to be scheduled; V_1 is the set of flows that may be scheduled; $d(v)$ represents the degree of flow v; $\Re$ denotes the MIS that is selected for concurrent scheduling; $N(v)$ represents the neighbor vertex of flow v (if there is an edge between two vertices, they are called neighbor vertices); $\Re_0$ denotes the residual flows except for those in the MIS. A minimum degree greedy algorithm is used to obtain the MIS, as indicated in lines 3-6. In line 4, if there is more than one flow with the minimum degree, we give priority to scheduling the flow with high priority. The computation of Algorithm 1 is $O(V_1)$. In this paper, each MIS acquired is assigned to the corresponding slot segment of the corresponding frequency band. The number of TSs required by each flow for kth slot segment of frequency band d is calculated as

$$T_{i_d}^k = \frac{Q_i \cdot (T_{sch} + M \cdot \Delta)}{\eta W_d \log_2 \left(1 + \frac{P_R(t_i, r_i)}{N_0 W_d + \sum_{l \in \Re, l \neq i} P_R(t_l, r_i)}\right)}. \quad (17)$$

And the number of TSs allocated for the kth slot segment of frequency band d can be estimated as $\delta_d^k = \max_{i \in \Re} \left(T_{i_d}^k\right)$.

Algorithm 1 Maximum Independent Set for Concurrent Transmission (C-MIS) Algorithm

1: **Input:** conflict graph $G(V, E)$, priority of all flows λ_i, flows to be scheduled V;
2: **Initialization:** $\Re = \varnothing$, $\Re_0 = \varnothing$, $V_1 = V$;
3: **while** $|V_1| > 0$ **do**
4: Obtain $v \in V$ to make $d(v) = \min_{w \in V} d(w)$
5: $\Re = \Re \cup v$
6: $V_1 = V_1 - \{v \cup N(v)\}$
7: **end while**
8: $\Re_0 = V - \Re$
9: **Output:** $\Re$, $\Re_0$

C. QoS-AWARE BANDWIDTH ALLOCATION AND CONCURRENT SCHEDULING ALGORITHM

The following is a detailed description of the proposed algorithm. A half-duplex QoS-aware bandwidth allocation and concurrent scheduling algorithm for THz wireless backhaul network is proposed, which is called IHQB algorithm in this paper. The conflict graph of IHQB algorithm is established by half-duplex condition and interference threshold. The maximum bandwidth limit is set as the bandwidth of each frequency band. When flows of a MIS in one slot segment of one frequency band all achieve their QoS requirements, a new MIS is obtained by C-MIS to schedule in the next slot segment of this band. To know which band all flows of a MIS are completed flows, the algorithm calculates θ_d^k and gets the total number of TSs occupied by the scheduled MISs for each frequency band. Then a new MIS is added to the band with the minimum total number of TSs occupied. The above steps don't stop until all the flows are scheduled or all slots for each bandwidth are allocated. The pseudo-code of the proposed scheduling algorithm is shown in Algorithm 2.

Some initialization work is shown in line 1-5, and the main part of the algorithm is described by lines 6 - 46. First, BNC receives information from the requested flows, including location information **Loc**, their QoS requirements Q_i, and their priorities λ_i in line 1. Line 2 is the initial stipulation for the maximum bandwidth limit, the total bandwidth and the total number of TSs and obtains D which is the number of divided frequency bands. We establish the conflict graph $G_2(V, E)$ according to the half-duplex condition and interference threshold in line 3. In line 4-5, we initialize t which stores the total number of TSs occupied for each frequency band, and the scheduling status *Schedule* for each flow in M time slots. When $Schedule(t(d), i) = 1$, it indicates that flow i is scheduled in the band d at the slot $t(d)$, otherwise it is not scheduled. The storage variables of the bandwidth allocated and the central frequency of the frequency band for each flow are defined as BW and $Freq$, respectively. The variable *Slot* stores δ_d^k, and the variable c records the number of the divided slot segment for each frequency band.

We assume every band transmits at most 100 MISs in line 6. Lines 7-9 are to obtain the total number of TSs allocated according to the number of TSs allocated of each slot segment for each frequency band. We obtain the minimum total number of TSs allocated in line 10. When the minimum sum TSs is less than or equal to M, we perform subsequent operations. We find the frequency band with the minimum total number of TSs allocated and estimate how many corresponding frequency bands are. Then the MIS scheduling is carried out for the next slot segment of each frequency band obtained. In line 16-43, this algorithm carries out the bandwidth allocation and calculates the corresponding number of TSs under the condition that the obtained MIS is not empty. This algorithm records the number of slot segments of each band to adjust iteration s conveniently in line 17. In line 18, we calculate the number of TSs required by each flow for the kth slot segment of the current frequency band d, i.e., $T_{i_d}^k$. And the number of TSs allocated for the kth slot segment of frequency band d is obtained by $\delta_d^k = max_{i \in \Re}(T_{i_d}^k)$. To prevent invalid transmitting, we delete flows whose the number of slots required is greater than the remaining slots and then regain δ_d^k in line 19-26. The remaining flows unscheduled are obtain in line 27. In line 28-40, we calculate the transmission rate of each flow in real time and obtain the practical transmission slot interval of each flow accurately. To avoid the repeated transmission of a flow in the allocated slot segment, once a flow is completed flow, we label $num(i) = 1$ and delete it in $\Re$. Meantime, we adjust the number of TSs allocated for transmission slot segment if all flows in $\Re$ complete transmission in advance in allocated slot segment. We record

Algorithm 2 QoS-Aware Bandwidth Allocation and Concurrent Scheduling Algorithm for THz Wireless Backhaul Network

1: **Input:** BNC gets the location *Loc*, priority λ_i, and QoS requirements Q_i of the F flows to be scheduled
2: Set the maximum bandwidth limit α, the total bandwidth W, the total time slots number M, and get D frequency bands, $D = \lceil \frac{W}{\alpha} \rceil$
3: Establish the conflict graph $G_2(V, E)$
4: $Schedule = zeros(M, F)$; $BW = zeros(1, F)$; $num = zeros(1, F)$; $Freq = zeros(1, F)$; $Slot = zeros(D, 100)$
5: $t = zeros(D, 1)$; $c = zeros(D, 1)$
6: **for** $s = 1{:}100$ **do**
7:   **for** $d = 1{:}D$ **do**
8:     $t(d) = sum(Slot(d, :))$
9:   **end for**
10:   $minslot = min(t)$
11:   **if** $(minslot < M)$ **then**
12:     $F_{loc} = find(t == minslot)$
13:     $N = length(F_{loc})$
14:     **for** $n = 1 : N$ **do**
15:       $[\Re, \Re_0] = C - MIS(V, G_2, \lambda_i)$
16:       **if** $(\Re \neq \emptyset)$ **then**
17:         $d = F_{loc}(n)$; $c(d) = c(d) + 1$; $k = c(d)$
18:         Calculate the number of TSs $T_{i_d}^k$ to obtain $\delta_d^k = max_{i \in \Re}(T_{i_d}^k)$
19:         **if** $(t(d) + \delta_d^k > M)$ **then**
20:           $\delta_d^k = M - t(d)$
21:         **end if**
22:         **for** $i \in \Re$ **do**
23:           **if** $(T_{i_d}^k > slot)$ **then**
24:             $\Re = \Re / i$
25:           **end if**
26:         **end for**
27:         $V = V - \Re$
28:         **for** $st = 1 : \delta_d^k$ **do**
29:           **for** $i \in \Re$ **do**
30:             **if** $(C_i \geq Q_i)$ **then**
31:               $Schedule(t(d) + 1 : t(d) + st, i) = 1$
32:               $Freq(1, i) = f_d$
33:               $BW(1, i) = \alpha$
34:               $num(i) = 1$; $\Re = \Re / i$
35:             **end if**
36:             **if** $(\Re == \emptyset)$ **then**
37:               $\delta_d^k = st$
38:             **end if**
39:           **end for**
40:         **end for**
41:         $Slot(d, c(d)) = \delta_d^k$
42:       **end if**
43:     **end for**
44:   **end if**
45: **end for**
46: **Output:** $Schedule, BW, Freq, num * 1/\lambda$

the final allocated number of TSs for the kth slot segment of frequency band d in line 41. The algorithm returns the slot allocation matrix for each flow, the bandwidth allocation and the central frequency of the frequency band for each flow, as well as the value for our objective problem in line 46.

To estimate the algorithm complexity, we can observe the outer for loop has s iterations, which is determined by the number of MISs. The inner if condition and two for loop has $D * M * F$ iterations in the worst case. Due to the values of D and s are small for that of M and F, $D * s$ can be denoted by a constant coefficient z. Thus the scheduling algorithm has the complexity of $O(zMF)$, which can be implemented in practice.

IV. PERFORMANCE ANALYSIS

In this section, we analyze the impact of interference threshold choice and bandwidth allocation on the performance of IHQB. To fully reap the benefits of concurrent transmissions, the sum of transmission rates of flows scheduled for transmission in the same time slot should be maximized. This sum can also be regarded as the throughput in one time slot, and has a big impact on the system performance. We denote the set of concurrent flows scheduled in the mth slot of frequency band d as S_d^m. For one flow $i \in S_d^m$, we can obtain its transmission rate as

$$R_{i_d}^m = \eta W_d \log\left(1 + \frac{P_R(t_i, r_i)}{N_0 W_d + \sum_{l \neq i, l \in S_d^m} P_R(t_l, r_i)}\right). \quad (18)$$

The sum of transmission rates of flows scheduled in the mth slot for provided bandwidth can be obtained as

$$\sum_{d=1}^{D} \sum_{i \in S_d^m} R_d^m = \sum_{d=1}^{D} \sum_{i \in S_d^m} \eta W_d \cdot \log\left(1 + \frac{P_R(t_i, r_i)}{N_0 W_d + \sum_{l \neq i, l \in S_d^m} P_R(t_l, r_i)}\right). \quad (19)$$

As stated before, concurrent flows should have no conflict. The interference between concurrent flows is less than or equal to $\sigma P_R(t_i, r_i)$. Thus, the sum rate meets

$$\sum_{d=1}^{D} \sum_{i \in S_d^m} R_d^m \geq \sum_{d=1}^{D} \sum_{i \in S_d^m} \eta W_d \cdot \log\left(1 + \frac{P_R(t_i, r_i)}{N_0 W_d + (|S_d^m| - 1)\sigma P_R(t_i, r_i)}\right). \quad (20)$$

The right side of (20) can be regarded as a lower bound of the sum rate. Firstly, we assume the bandwidth of each frequency band is fixed. To maximize the sum rate, we can optimize the interference threshold σ to maximize the lower bound, which can be expressed as

$$\begin{aligned}\sum_{d=1}^{D}\sum_{i\in S_d^m}\eta W_d\cdot\log\left(1+\frac{P_R(t_i,r_i)}{N_0W_d+(\left|S_d^m\right|-1)\sigma P_R(t_i,r_i)}\right)\\=\sum_{d=1}^{D}\eta W_d\cdot\log\prod_{i\in S_d^m}\left(1+\frac{P_R(t_i,r_i)}{N_0W_d+(\left|S_d^m\right|-1)\sigma P_R(t_i,r_i)}\right).\end{aligned}\tag{21}$$

To maximize the lower bound, we should maximize $\prod_{i\in S_d^m}\left(1+\frac{P_R(t_i,r_i)}{N_0W_d+(\left|S_d^m\right|-1)\sigma P_R(t_i,r_i)}\right)$. The number of concurrent flows $\left|S_d^m\right|$ is determined by the threshold σ. When σ increases, more flows will have no contention between each other. Thus, $\left|S_d^m\right|$ also increases, and the number of product terms increases. However, each product term will decrease. When σ decreases, $\left|S_d^m\right|$ also decreases. The number of product terms decreases, while each product term will increase. Therefore, both too large and too small σ will decrease the sum rate. There should be an optimized value of σ that can maximize the sum rate, which is consistent with the performance evaluation results in Fig. 13 and Fig. 14.

On the other hand, since the $\log_2(x)$ function is convex, we can obtain

$$\begin{aligned}\sum_{d=1}^{D}\sum_{i\in S_d^m}\eta W_d\cdot\log\left(1+\frac{P_R(t_i,r_i)}{N_0W_d+(\left|S_d^m\right|-1)\sigma P_R(t_i,r_i)}\right)\\\leqslant\sum_{d=1}^{D}\eta W_d\left|S_d^m\right|\\\cdot\log\left(1+\sum_{i\in S_d^m}\frac{P_R(t_i,r_i)}{N_0W_d\left|S_d^m\right|+\left|S_d^m\right|(\left|S_d^m\right|-1)\sigma P_R(t_i,r_i)}\right).\end{aligned}\tag{22}$$

The equal sign is taken when $\frac{P_R(t_i,r_i)}{N_0W_d+(\left|S_d^m\right|-1)\sigma P_R(t_i,r_i)}$ is equal for each flow $i\in S_d^m$. Since σ only affects the number of flows for mth slot of a frequency band, bandwidth allocation affects the total number of flows for mth slot of all frequency bands. When σ is fixed, more $\sum_{d=1}^{D}\eta W_d\left|S_d^m\right|$ can achieve higher sum rate and thus better network performance, which is indicated in Fig. 7 and Fig. 8.

V. PERFORMANCE EVALUATION

In this section, we evaluate the performance of the proposed scheduling algorithm, and compare it with the other schemes.

A. SIMULATION SETUP

In the simulations, we evaluate the performance of the proposed algorithm in a THz wireless backhaul network where 50 MBSs are uniformly distributed in a $200m\times200m$ square area. Every MBS has the same transmission power P_t. The transmitters and receivers of flows are randomly selected, and the QoS requirements of flows are uniformly distributed between 10Gbps and 80Gbps. Other parameters are shown in Table 1 [16]. This paper considers both the QoS requirements and priorities of the flows. To evaluate our proposed algorithm, the following metrics are considered:

TABLE 1. Simulation parameters.

Parameter	Symbol	Value
Transmission Power	P_t	1000mW
Multiuser interference factor	ρ	1
Transceiver efficiency factor	η	0.9
System total bandwidth	W	48GHz
Background noise	N_0	-134dbm/MHz
Slot time	δ	$18us$
Scheduling phase time	T_{sch}	850us
Number of slots in transmission phase	M	2000

- **Weighted sum of completed flows:** the sum of the product of the flow satisfying QoS and the reciprocal of the corresponding priority.
- **System throughput:** the achieved total throughput of the backhual network. In other words, this metric is the average of sum of the throughput of all flows.

We evaluate the performance of the proposed concurrent scheduling algorithm (IHQB) and compare it with another proposed algorithm (HQB) and one existing algorithm, i.e., STDMA [13]. In simulation, for the sake of making STDMA more comparable, STDMA algorithm is also simulated in THz band.

1)HQB: the conflict graph is established by the half-duplex condition, and the MIS is selected based on the conflict graph. The rest is the same as IHQB.

2)STDMA: multiple links can be scheduled concurrently in the same time slot [13]. This algorithm allows both interference and non-interference flows to be transmitted concurrently. The differences between this algorithm and the proposed algorithm are that STDMA is under one frequency band and a new flow is added if a flow is completed.

B. SIMULATION RESULTS

In order to make the simulation data more persuasive, each simulation is executed 50 times. In this paper, the topology of the network, the location of the base station and the QoS requirements of all flows vary with each simulation.

1) UNDER DIFFERENT NUMBER OF REQUESTED FLOWS

The weighted sum of completed flows satisfying QoS requirements and the system throughput of IHQB, HQB and STDMA are shown in Fig. 5 and Fig. 6 respectively. We set the interference threshold of IHQB as 10^{-8}, and the maximum bandwidth limit as 12GHz. It can be seen from Fig. 5 and Fig. 6 that when the number of requested flows increases in the network, the weighted sum of completed flows and the system throughput increase in the IHQB, HQB and STDMA. However, due to the limited time slot, the growth rate of two metrics of the three algorithms decreases with the increase of the number of request flows, especially for STDMA, because the effect of limited time slot for transmission in one frequency band is worse than that in multiple frequency bands. Due to the influence of the priority, the proposed IHQB is

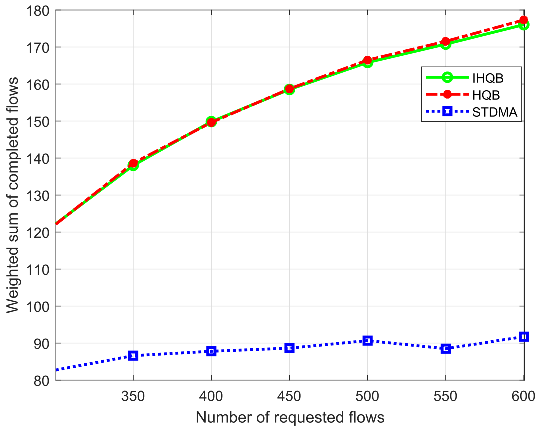

FIGURE 5. Weighted sum of completed flows under different number of requested flows.

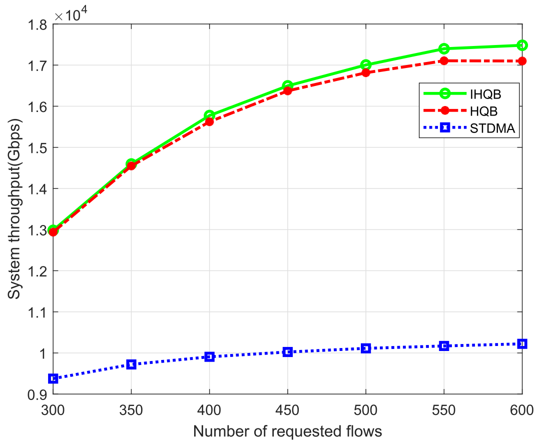

FIGURE 6. System throughput under different number of requested flows.

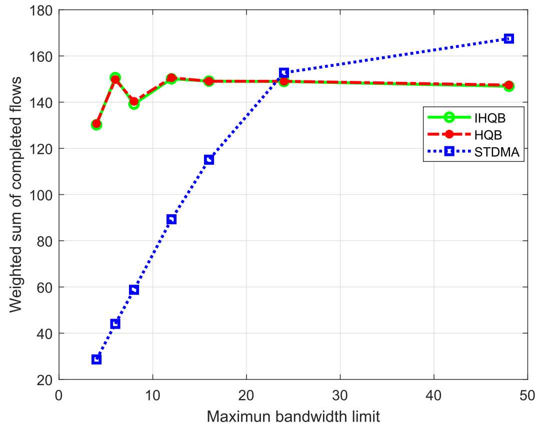

FIGURE 7. Weighted sum of completed flows under different maximum bandwidth limitation.

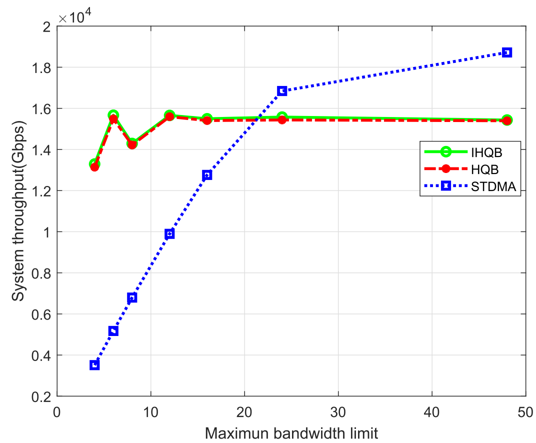

FIGURE 8. System throughput under different maximum bandwidth limitation.

basically consistent with that of HQB in terms of the weighted sum of completed flows, even if the total rate of each TS of each frequency band of IHQB is a little larger than that of HQB. From the performance comparison between IHQB and STDMA, it can be seen that while scheduling transmission, it is better to divide the total wide bandwidth into different frequency bands than only a frequency band under the maximum bandwidth limit. And the system throughput of proposed IHQB is more than 10Tbps. When the number of requested flows equals 600, compared with STDMA, the IHQB improves the weighted sum of completed flows and the system throughput by 91.9% and 71.1%, respectively.

2) UNDER DIFFERENT MAXIMUM BANDWIDTH LIMIT

The two metrics of IHQB, HQB and STDMA are shown in Fig. 7 and Fig. 8, respectively. The number of requested flows is 400 in the network. In the simulation, we choose the value of the maximum bandwidth limit which is divisible by the total system bandwidth. From Fig. 7 and Fig. 8, we can observe that when the maximum bandwidth limit is less than 24GHz, the proposed IHQB is superior to STDMA in two metrics. Because when the bandwidth is small, the main factor affecting the performance is the bandwidth. And under the requirement of the maximum bandwidth limit, IHQB takes full advantage of the total bandwidth provided, while STDMA only uses a part of the total bandwidth. But when the maximum bandwidth limit is 24GHz or greater, STDMA is better than the proposed IHQB in two metrics. Because when the bandwidth is large, the main factor affecting performance is the time slot. And STDMA makes full use of the time slot resources due to as soon as one flow is completed the new flow(s) is(are) added, while our proposed IHQB is that the flows aren't added until the flows of current MIS in one frequency all are completed, which can result in only one flow in some slots. With the increase of the maximum bandwidth limit, the two performance metrics of IHQB fluctuate. When the maximum bandwidth limit α is 6, 12, 16, that is, the bandwidth of each frequency band is 6GHz, 12GHz, 16GHz, the two performance metrics are better. Relative to the cases of $\alpha = 6$ and $\alpha = 12$, the two metrics of IHQB drop rapidly under $\alpha = 8$. Through lots of simulations and debuggings, we discover that compared with the case of $\alpha = 6$, the number of frequency band divided for IHQB is reduced by 6 under $\alpha = 8$, resulting in a significant decrease in the number of flows that can be transmitted in each time slot, and compared with the case of $\alpha = 12$, the number of frequency band divided for IHQB is only increased by 4 under $\alpha = 8$, but the bandwidth of each frequency band is reduced by 4GHz, which causes more number of TSs allocated for each slot segment of each frequency band. When the maximum bandwidth limit takes the value of 4, the weighted sum of completed flows of IHQB is about 356% higher than that of STDMA.

3) UNDER DIFFERENT NUMBER OF TIME SLOTS

In Fig. 9 and Fig. 10, we plot the weighted sum of completed flows and the system throughput under different number of time slots respectively. The number of requested flows is kept to be 400, and the maximum bandwidth limit is 12GHz. We change the number of slots in transmission phase from 500 to 3500, and evaluate the two metrics as before. From Fig. 9, we can observe the proposed IHQB can significantly increase the weighted sum of completed flows and the number of TSs is too small to satisfy the greater QoS requirements of flows, which causes the requested flows to be not transmitted well. From Fig. 10, the IHQB achieves significantly better in the system throughput than other algorithms. As we can observe, the weighted sum of completed flows and the system throughput only slightly increase as the number of time slots in transmission phase changes. With enough time slots, the system throughput of IHQB is higher than that of HQB and STDMA at about 150Gbps and 5900Gbps.

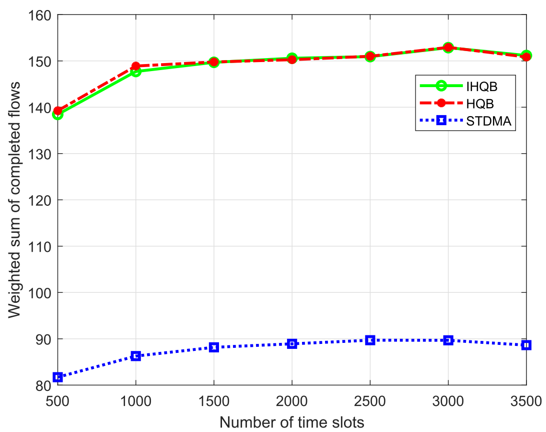

FIGURE 9. **Weighted sum of completed flows under different number of slots.**

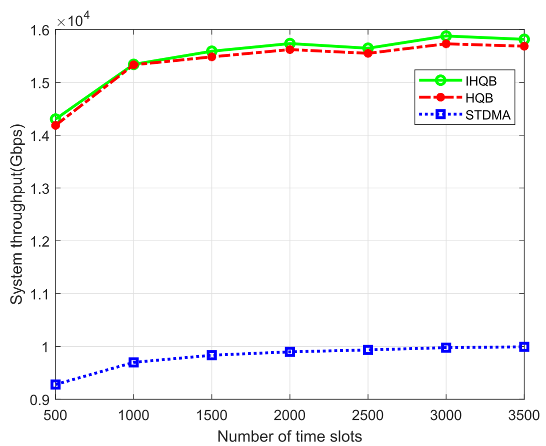

FIGURE 10. **System throughput under different number of slots.**

4) UNDER DIFFERENT PRIORITY LEVEL

To evaluate the impact of the priority level on the system performance, we plot the weighted sum of completed flows and the system throughput for the three algorithms, which are shown in Fig. 11 and Fig. 12, respectively. As we can observe from Fig. 11, the weighted sum of completed flows of the three algorithms is inversely proportional to the priority level, which can be seen from equations (14). As priority level increases, the decline of IHQB is larger than that of STDMA in the weighted sum of completed. This is because the number of completed flows of IHQB is larger than that of STDMA. It's kind of like a mathematical calculation, i.e., when two equations with the same numerator and the different denominator are subtracted from each other by fractions with the different numerator and the same denominator, the difference between the equations with the larger denominator is greater than that with the smaller denominator. In Fig. 12, when the priority level changes, there is slight fluctuation in system throughput of IHQB because priority can influence the output of the scheduled flows in a MIS. For STDMA, its system throughput is completely unaffected by priority level because priority isn't taken into account in scheduling phase.

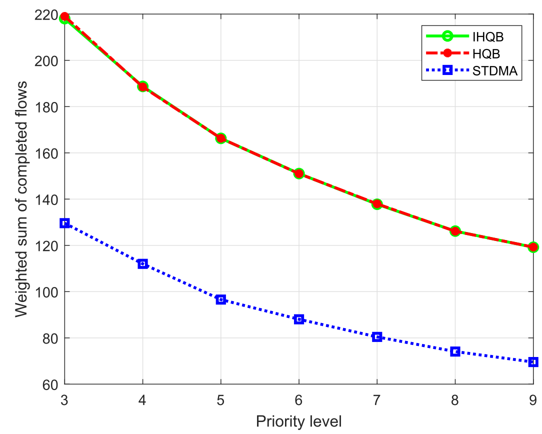

FIGURE 11. **The weighted sum of completed flows under different priority level.**

5) UNDER DIFFERENT INTERFERENCE THRESHOLD

In the figures, the abscissa is the value of the logarithm to the base of 10. For example, when the threshold is 10^{-8}, the abscissa is -8. For the sake of evaluating the impact of interference threshold on the system performance and finding the optimal threshold, the two metrics under different interference thresholds are shown in Fig. 13 and Fig. 14. From the results, we can observe the performance of the proposed IHQB changes significantly with the threshold. When the interference threshold is small, the system performance of IHQB is still better than that of STDMA, but worse than that of HQB. This is because if the threshold is too small, even if the interference between flows is small, they are considered to be in conflict and thus concurrent transmissions can't be fully utilized. At this time, the threshold is the main limiting factor for IHQB, while HQB isn't affected by it. However, when the threshold increases, the proposed IHQB could achieve better performance compared with the HQB. This is mainly because

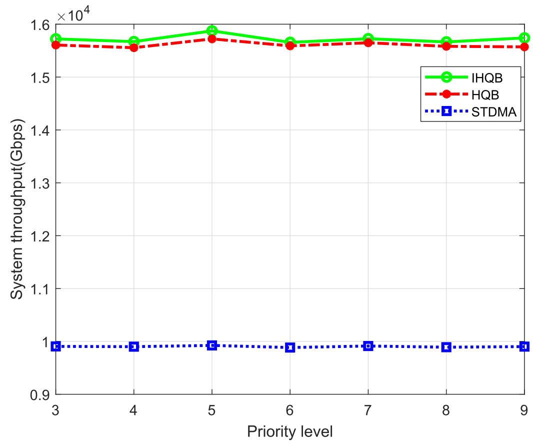

FIGURE 12. System throughput under different priority level.

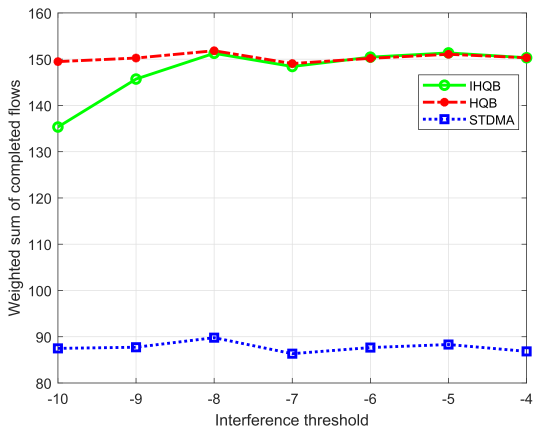

FIGURE 13. Weighted sum of completed flows under different interference threshold.

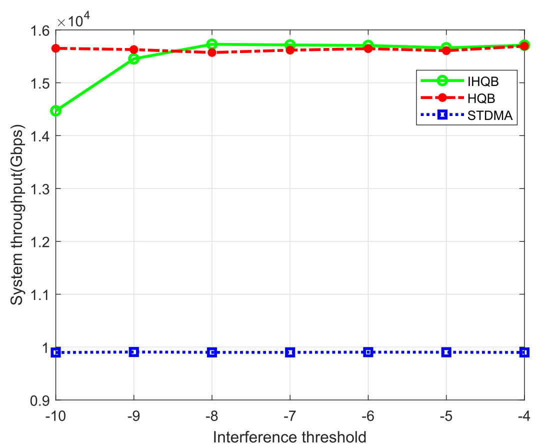

FIGURE 14. System throughput under different interference threshold.

we select flows with high link rates, which helps to satisfy the QoS requirements of more flows in the limited time; different flows select different MISs, which is beneficial to exploit concurrent transmissions to improve the performance. When the threshold is bigger than 10^{-5}, the performance of IHQB decreases. This is because if the threshold is too big, even if the interference between flows is big, they can still be scheduled simultaneously. As a result, the link rates become low, the two metrics of IHQB are almost exactly the same as HQB. When the interference threshold is 10^{-8}, the weighted sum of completed flow of IHQB is the same as that of HQB, but the system throughput of IHQB is greater than that of HQB. To sum up, choosing the appropriate interference threshold can further improve the system performance.

VI. CONCLUSIONS AND FUTURE WORK

In this paper, we propose a QoS aware bandwidth allocation and concurrent scheduling algorithm in THz wireless backhaul networks. Firstly, we consider the QoS requirements of flows and priority of flows, as well as the realizable bandwidth of the hardware in existence or in the future. Then, we formulate the problem for the situation we consider and propose a heuristic scheduling algorithm (i.e., IHQB) to solve the concurrent scheduling problem of multiple frequency bands. Extensive simulations show that the proposed IHQB algorithm was superior to the other two algorithms. Although the IHQB algorithm was basically the same as the HQB scheme in the weighted sum of completed flows, the IHQB outperforms the HQB with respect to the system throughput. Compared with the existing STDMA, when the realized bandwidth of the future hardware is less than 24GHz, the proposed algorithm IHQB can better satisfy the requirements of more than 10Tbps for system throughput in the future backhaul network.

In the future work, we will consider how to use the time slot effectively under simultaneous transmission in multiple frequency bands and also investigate the concurrent transmission scheduling in the Terahertz band on multi-hop links. Besides, we will also investigate the utilization of full duplex technology in THz band to improve network performance.

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