minFAST: Minimum Span Frequency Assignment Technique for Integrated Access and Backhaul Networks

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***Abstract*—We propose novel centralized minimum span frequency assignment (MS-FA) techniques allowing partially overlapped channels (POCs) to improve cost and spectral efficiency for integrated access and backhaul (IAB) networks. We first revisit the conventional MS-FA problem (MS-FAP) that minimizes the required bandwidth for given quality-of-service (QoS) requirements, and then design a novel integer linear programming (ILP)-based *optimal* MS-FA technique with POCs. However, the optimal technique may not be feasible for large-scale IAB networks due to its NP-hardness. Hence, we propose a novel low-complexity MS-FA algorithm that achieves a near-optimal performance while significantly reducing the computational complexity. To the best of our knowledge, no MS-FA technique exists to consider both POCs and the physical interference model in the literature. Simulation results show that the spectral efficiency becomes significantly improved by reducing the required bandwidth in practical IAB networks.**

***Index Terms*—Integrated access and backhaul, millimeter wave, minimum span frequency assignment problem, partially overlapped channel, physical interference model.**

I. Introduction

Recently, mobile data traffic and broadband use cases from various wireless terminals have drastically increased, and the spectrum scarcity problem has emerged in wireless communication systems [1], [2]. Millimeter-wave (mmWave) communication with network densification has received much attention as a promising solution to address this issue, thanks to the vast spectrum available in the mmWave band. Along with this trend, integrated access and backhaul (IAB) is anticipated to be a prominent network architecture for next-generation cellular networks with the introduction of unmanned aerial vehicle (UAV), high altitude platform station (HAPS), low earth orbit (LEO) satellite, and reconfigurable intelligent surface (RIS), etc [2], [3], [4], [5]. In general, an IAB network consists of a macro-cell base station (MBS, IAB donor) and a large number of small-cell base stations (SBSs, IAB nodes) within the macro-cell boundary. Only the MBS is connected to the core network (CN) through wired links like optical fibers, while other links such as BS-BS (backhaul link) and BS-user equipment (UE) (access link) are connected via wireless links. It has been highlighted that this network architecture has a trade-off between cost and quality-of-service (QoS) because wireless backhaul connections are more economical than wired backhaul but less reliable [5], [6], [7].

There exist several studies on the resource assignment for the IAB network in the literature [4], [8], [9], [10], [11], [12], [13], [14]. The authors of [8] proposed a Markov approximation-based frequency assignment (FA) technique to maximize the sum rate while guaranteeing the data rate requirements of backhaul links. In [9], the authors studied a joint incentive and time resource assignment to improve the user experience and network throughput in an IAB-based user-provided network (UPN), where they formulated a Nash bargaining problem considering fairness between users, user energy consumption, and network resource limitations. In [10], a joint power and frequency assignment and IAB node placement optimization were developed to maximize the downlink sum rate in a multi-hop IAB network. In [11], a model-free FA framework was proposed to maximize the downlink sum log-rate, where the authors formulated the FA problem (FAP) with mixed-integer nonlinear programming (MINLP) and solved this by exploiting double deep Q-network (DDQN) and actor-critic techniques. In [12], a joint power and frequency assignment problem was investigated with the sequential convex programming (SCP) method, where the authors considered the user rate requirements and the physical interference model to reflect the realistic scenario of the IAB network. In [13], a two-tier hierarchical auction-based resource block (RB) assignment algorithm was proposed that considers the number of required RBs for each user and the total number of available RBs in the IAB network to maximize the social welfare of the auction. More recently, the authors of [4] introduced a RIS-aided and UAV-assisted IAB network and proposed a Stackelberg game-based dynamic resource management framework for phase shifts of RIS elements, system bandwidth partitioning ratio between access and backhaul, and transmission powers to maximize energy efficiency or data rate. In [14], iterative joint frequency and power assignment schemes were proposed to maximize the sum backhaul capacity in an out-of-band IAB network. In short, the literature mainly dealt with the data rate maximization aspect.

In contrast to the aforementioned studies, we revisit the traditional minimum span FAP (MS-FAP) [15] that minimizes the total required bandwidth, closely related to the spectrum usage fee, while ensuring each link's QoS in order to facilitate the cost-effectiveness and overcome the spectral scarcity of next-generation wireless networks. Then, we propose novel MS-FA techniques for the IAB network. In particular, the *physical* interference model is applied to reflect more realistic wireless communication scenarios. It is worth noting that the conventional MS-FAPs only considered the *protocol* interference model for convenience, even though they cannot capture the more practical effects of wireless channels, such as multipath fading, path-loss, interference, etc [12], [16]. We also exploit the partially overlapped channel (POC) that allows the overlapping assignment of multiple channels under a certain level of adjacent channel interference (ACI) to further enhance our objective [17]. To the best of our knowledge, this is the first MS-FA framework for IAB networks. In particular, MS-FAP has not been well investigated since the literature [18], and no MS-FA technique exists considering both the *physical interference model* and *POC*.

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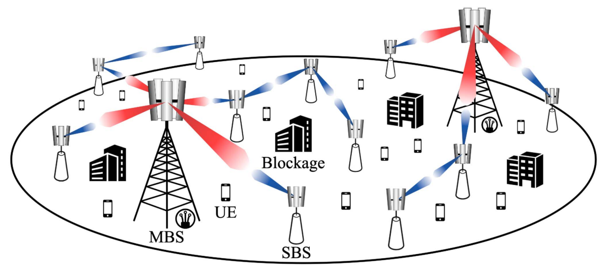

Fig. 1. An example of the mmWave IAB network focused on multi-hop backhaul links with directional beamforming.

II. System Model

We consider a mmWave IAB network consisting of multiple MBSs, SBSs, and UEs within a circular disk area. In particular, we focus on the multi-hop wireless backhaul, as illustrated in Fig. 1, which is an example of the IAB network.

A. Spatial Model

All BSs are distributed in a finite region $\mathcal{A}$, a circular disk with radius R. In particular, we used stochastic geometry modeling to configure various IAB network models as in [5], [6]. Specifically, we assume that SBSs (IAB nodes) are randomly distributed within area $\mathcal{A}$ according to a homogeneous Poisson point process (PPP) Φ_{S} with density λ_{S}, and MBSs (IAB donors) are deployed within the same area $\mathcal{A}$ according to pre-planning to increase cost-efficiency and ensure minimum received signal strength (RSS) of backhaul links considering blockages.[1] Let $\mathcal{N}\ (=\mathcal{N}_{\mathsf{MBS}} \cup \mathcal{N}_{\mathsf{SBS}})$ be the set of all BSs deployed in area $\mathcal{A}$, where $\mathcal{N}_{\mathsf{MBS}}$ and $\mathcal{N}_{\mathsf{SBS}}$ represent sets of MBSs and SBSs, respectively.

On the other hand, since mmWave signals experience severe penetration losses when passing through blockages such as buildings, the RSS will deteriorate significantly if the link between BSs is not line-of-sight (LoS) but non-LoS (NLoS). Hence, a sophisticated model for blockages is required, and we employ a stochastic model known as the *germ-grain* model as in the literature [5], [6]. Specifically, the blockages are modeled as a sequence of line segments $\Phi_{\mathsf{B}} = \{\mathbf{p}_{\mathsf{B}}, l_{\mathsf{B}}, \theta_{\mathsf{B}}\}$ where $\mathbf{p}_{\mathsf{B}}$, l_{B}, and θ_{B} denote the location of midpoint, length, and orientation of each segment, respectively. The sequence of midpoints ($\{\mathbf{p}_{\mathsf{B}}\}$) is distributed according to a PPP with density λ_{B} in area $\mathcal{A}$, and the sequence of orientations ($\{\theta_{\mathsf{B}}\}$) is assumed to follow independent and identically distributed (i.i.d.) uniform random variables in $[0, 2\pi)$.

B. Association Policy

The association policy is based on the maximum reference signal received power (RSRP) rule.[2] In other words, each SBS is associated with a single MBS or SBS that yields the strongest RSS. It is also assumed that all BSs are equipped with multiple radio transceivers that enable them to communicate with multiple BSs simultaneously over different frequencies, where each transceiver performs the beamforming toward the desired direction without considering BS sectorization.

We assume that all MBSs and SBSs use their maximum transmission power and have the same beamforming gain. Then, the backhaul link

[1]Since MBSs are connected to the CN through wired links, the more they are deployed, the higher expenditures are required [6], [7]. From this perspective, we have optimally (deterministically) deployed the MBSs exploiting [19]. On the other hand, SBSs are assumed to be randomly placed because they are connected by wireless links and can be flexibly deployed.

[2]Although we employed the maximum RSRP-based association rule, the proposed MS-FA techniques in this paper are not limited to a certain association policy because the FA is performed after associations are determined.

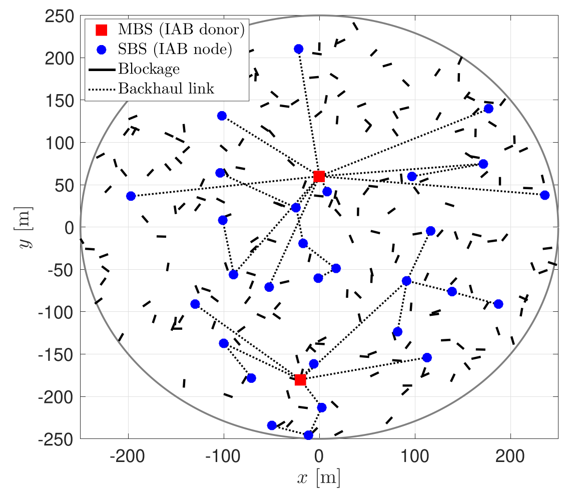

Fig. 2. A realization of the IAB system model focused on multi-hop backhaul.

association is determined from the transmit power of BSs and the path-loss between BSs as

$$c_r = \arg\max_{t \in \mathcal{N}\setminus r} P_t L_{r,t}(\|\mathbf{p}_r - \mathbf{p}_t\|),\ \forall r \in \mathcal{N}_{\mathsf{SBS}}, \tag{1}$$

where c_r represents the BS index associated with SBS r; P_t denotes the transmission power of BS t, which is defined as P_{MBS} for $t \in \mathcal{N}_{\mathsf{MBS}}$ and P_{SBS} for $t \in \mathcal{N}_{\mathsf{SBS}}$, respectively. In addition, $L_{r,t}(\|\mathbf{p}_r - \mathbf{p}_t\|)$ denotes the propagation loss, which is a function of Euclidean distance between SBS r and BS t, where $\mathbf{p}_n = [x_n, y_n]$ $(n \in \mathcal{N})$ denotes the two-dimensional (2D) Cartesian coordinates of BS n. This is defined as

$$L_{r,t}(\cdot) = \begin{cases} (\cdot)^{-\alpha_{\mathsf{L}}}, & \text{if LoS, i.e., } \#(\Phi_{\mathsf{B}} \cap \overline{\mathbf{p}_r, \mathbf{p}_t}) = 0, \\ (\cdot)^{-\alpha_{\mathsf{N}}}, & \text{if NLoS, i.e., } \#(\Phi_{\mathsf{B}} \cap \overline{\mathbf{p}_r, \mathbf{p}_t}) > 0, \end{cases} \tag{2}$$

where α_{L} and α_{N} indicate the path-loss exponents for LoS and NLoS scenarios, respectively; and the term $\#(\Phi_{\mathsf{B}} \cap \overline{\mathbf{p}_r, \mathbf{p}_t})$ denotes the number of intersections between the elements of Φ_{B} and the line segment between $\mathbf{p}_t$ and $\mathbf{p}_r$, denoted as $\overline{\mathbf{p}_r, \mathbf{p}_t}$.

Since only MBSs are connected to the CN, SBSs need to be associated with at least one MBS. However, based on (1), some SBSs may not be associated with MBS even through multiple-hop wireless connections, and only SBSs may be connected to each other. In this case, a certain SBS among them changes the association to the BS with the next strongest RSRP. This process is repeated until all SBSs are associated with MBS. In Fig. 2, we can observe that all SBSs are connected to MBSs via direct or multi-hop links (refer to the dotted lines). On the other hand, each associated link is assumed to have a frequency division duplex (FDD) link ($r \rightleftharpoons c_r, \forall r \in \mathcal{N}_{\mathsf{SBS}}$); hence two different frequencies are assigned to each link. In particular, we assume that orthogonal frequencies, which are not overlapped to each other, are assigned to each associated link to prevent self-interference in this paper [17]. We define a set $\mathcal{L}\ (= \{1, 2, \ldots, L\})$ consisting of indices for all these desired links considering FDD.

C. Propagation Model

Let $r_{j,i}$ denote the average RSS at the receiver (RX) of link $j\ (\in \mathcal{L})$ from the transmitter (TX) of link $i\ (\in \mathcal{L})$. Backhaul links are usually quasi-static, and the FAP considering instantaneous small-scale fading effects, such as Rayleigh or Rician fading, may not be feasible due to the signaling overhead for practical wireless communication systems. Hence, it is more reasonable that only the long-term RSS is used for

TABLE I
NOTATION OF SYSTEM PARAMETERS AND DESCRIPTIONS

Symbol	Description
$\mathcal{A}$, R	Circular disk area and radius of the disk
Φ_{S}, λ_{S}	PPP of SBS and its density
$\mathcal{N}$, $\mathcal{N}_{\mathsf{MBS}}$, $\mathcal{N}_{\mathsf{SBS}}$	Set of all BSs, set of MBSs, and set of SBSs
$\mathcal{L}$, $\mathcal{K}$	Set of desired links and set of channel indices
Φ_{B}, λ_{B}	Set of blockages and its density
$\mathbf{p}_{\mathsf{B}}$, l_{B}, θ_{B}	Midpoint, length, and orientation of blockages
$r_{j,i}$	RSS at the RX of link j from the TX of link i
P_i^{TX}	Transmission power of link i
$G_{j,i}^{\mathsf{TX}}$	Transmit antenna gain considering the orientation angle from the TX of link i to the RX of link j
$G_{j,i}^{\mathsf{RX}}$	Receive antenna gain considering the orientation angle from the RX of link j to the TX of link i
$\theta_{j,i}^{\Psi}$	Orientation angle between the TX of link i and the RX of link j, where $\Psi \in \{\mathsf{TX}, \mathsf{RX}\}$
θ_{HPBW}	Half-power beamwidth of antenna array
G_{main}, G_{side}	Main and side lobe gains of antenna array
$L_{(1m)}$	Reference propagation loss at 1 meter distance
$L_{j,i}(\\|\mathbf{p}_j - \mathbf{p}_i\\|)$	Propagation loss between nodes corresponding to the RX of link j and the TX of link i
$\mathbf{p}_n$	2D Cartesian coordinates of node n $(\in \mathcal{N})$
$I(\vert f_j - f_i\vert)$	Interference discount factor according to the channel index difference $\vert f_j - f_i\vert$ $(j, i \in \mathcal{L})$

FA by averaging out the small-scale fading effect. The average RSS for each link is calculated as

$$r_{j,i} = P_i^{\mathsf{TX}} G_{j,i}^{\mathsf{TX}} G_{j,i}^{\mathsf{RX}} L_{(1\,m)} L_{j,i}(\|\mathbf{p}_j - \mathbf{p}_i\|),\ \forall j, i \in \mathcal{L}, \tag{3}$$

where P_i^{TX} denotes the transmission power of link i; $G_{j,i}^{\mathsf{TX}}$ and $G_{j,i}^{\mathsf{RX}}$ denote transmit and receive antenna gains between the TX of link i and the RX of link j, respectively. For mmWave communications, large antenna arrays with directional beamforming are employed to overcome severe propagation loss. We assume these array gains with a well-known sectored-pattern array antenna model [20] as follows:

$$G_{j,i}^{\Psi} = \begin{cases} G_{\mathsf{main}}, & |\theta_{j,i}^{\Psi}| \le \frac{\theta_{\mathrm{HPBW}}}{2}, \\ G_{\mathsf{side}}, & \text{otherwise}, \end{cases}\ \Psi = \{\mathsf{TX}, \mathsf{RX}\},$$

where $\theta_{j,i}^{\Psi}$ $(\in (-\pi, \pi])$ denotes the orientation angle between the TX of link i and the RX of link j with reference to the direction of each link; θ_{HPBW} denotes the half-power beamwidth of the antenna array, which indicates that the array gains are assumed to be G_{main} for all angles within the main-lobe of beam width θ_{HPBW} and G_{side} for the rest of angles called the side-lobe. It is assumed that the beam direction between TX and RX nodes of each link, i.e., desired link, is perfectly aligned to each other $(\theta_{j,j}^{\Psi} = 0, \forall j, \Psi)$, which determines the beam orientation of the other undesired links; $L_{(1\,m)}$ $(= (\frac{c}{4\pi f_c})^2)$ represents the reference propagation loss at 1 m distance where c and f_c are the light speed (m/s) and carrier frequency (Hz), respectively; $L_{j,i}(\|\mathbf{p}_j - \mathbf{p}_i\|)$ denotes the propagation loss from the TX of link i $(\mathbf{p}_i)$ to the RX of link j $(\mathbf{p}_j)$ defined as (2).

D. Channelization

The available frequency band is divided into individual communication channels with the same bandwidth, which is called channelization. We define a set $\mathcal{K}$ $(= \{1, 2, \ldots, K\})$ consisting of center frequency indices of available channels, i.e., channel indices, where the number of elements is determined by $K \le \lfloor \frac{BW - W}{\Delta} \rfloor + 1$, where BW denotes the total available bandwidth, W denotes the bandwidth of each channel, and Δ denotes the center frequency spacing between adjacent channels with consideration of the POCs.

TABLE II
INTERFERENCE DISCOUNT FACTOR ACCORDING TO THE CHANNEL INDEX DIFFERENCE

$\vert f_j - f_i\vert$	0	1	2	3	4	$\cdots$
$I(\vert f_j - f_i\vert)$	1	0.510	0.020	0	0	0

Let $I(|f_j - f_i|)$ be the interference discount factor caused by POCs according to the channel index difference $|f_j - f_i|$, where f_j and f_i $(\in \mathcal{K})$ indicate channel indices assigned to link j and link i, respectively. Without loss of generality (w.l.o.g.), we assume that $W = 400$ MHz and $\Delta = 200$ MHz, respectively. Then, $I(\cdot)$ is set as shown in Table II based on the adjacent channel leakage ratio (ACLR) requirements for the 5G NR frequency band n257 [21]. As a special case, we can consider the system model that does not allow the POCs and only utilizes orthogonal channels by setting that $\Delta > W$ and $I(|f_j - f_i|)$ as

$$I(|f_j - f_i|) = \begin{cases} 1, & \text{when } f_j = f_i, \\ 0, & \text{otherwise.} \end{cases} \tag{4}$$

The system model parameters are summarized in Table I.

III. MINIMUM SPAN FREQUENCY ASSIGNMENT

In this section, we first formulate an integer linear programming (ILP)-based *centralized* MS-FAP considering the physical interference model and POCs. Then, we propose a low-complexity FA algorithm. The main objective is to assign frequency channels so that the span of utilized bandwidth, defined as the difference between the maximum and the minimum used frequencies, is minimized while guaranteeing the QoS for each link.

In the IAB network, the MBS can operate as a central unit to perform the centralized optimization process; hence the proposed techniques can be implemented at the CN [9], [14]. Let $\mathbf{R}$ be the RSS matrix consisting of (3) for all i and j, and it is assumed to be known at the CN.[3] Note that this matrix includes associations between the links. We define notations for optimization variables as follows:

$$z_{j,k} = \begin{cases} 1, & \text{if frequency } k \text{ is assigned to link } j, \\ 0, & \text{otherwise,} \end{cases}$$

$$z_k = \begin{cases} 1, & \text{if frequency } k \text{ is used at any link,} \\ 0, & \text{otherwise,} \end{cases}$$

where j $(\in \mathcal{L})$ and k $(\in \mathcal{K})$ represent the index of the link and frequency, respectively.

With Shannon's channel capacity theorem, the achievable data rate of link j is expressed as

$$R_j = W_j \log_2 (1 + \gamma_j), \tag{5}$$

where γ_j denotes the signal-to-interference plus noise ratio (SINR) and it is given by $\gamma_j = \frac{r_{j,j}}{\sum_{i \in \mathcal{L} \setminus j} r_{j,i} I(|f_j - f_i|) + N_0 W_j}$; N_0 and W_j represent the power spectral density of white Gaussian noise and the channel bandwidth of link j, respectively. Given rate requirement R_j, γ_j can be obtained as $\gamma_j = 2^{R_j / W_j} - 1$ by rearranging (5) in order to satisfy the QoS requirement for each link [9], [10], [12].

[3]This is a reasonable assumption as the wireless backhaul links tend to be static. It can also be implemented by employing a dual connection frequency plan that uses a higher frequency band for user data and a lower frequency band for control signals such as FA and CSI feedback [10]. Even for dynamic IAB networks, such as mobile, non-terrestrial, and RIS-aided IAB networks [2], [4], [22], it can also be realized by using predefined trajectories or RIS elements' phase shifts.

A. Problem Formulation

Including the physical interference model and POCs in addition to [18], an MS-FAP can be formulated as follows:

$$\min_{z_k} \sum_{k\in\mathcal{K}} z_k \tag{6a}$$

$$\text{s.t. } z_k \geq z_{k+1}, \quad \forall k \in \mathcal{K}\backslash K \tag{6b}$$

$$z_k \geq z_{j,k}, \quad \forall j \in \mathcal{L}, \forall k \in \mathcal{K} \tag{6c}$$

$$\sum_{k\in\mathcal{K}} z_{j,k} = 1, \quad \forall j \in \mathcal{L} \tag{6d}$$

$$\sum_{k\in\mathcal{K}} \frac{r_{j,j} z_{j,k}}{\sum\limits_{i\in\mathcal{L}\backslash j} r_{j,i} \sum\limits_{k'\in\mathcal{K}} I(|k-k'|) z_{i,k'} + N_0 W_j} \geq \underline{\gamma}_j, \forall j \in \mathcal{L}, \tag{6e}$$

where $\underline{\gamma}_j$ denotes the minimum required (threshold) SINR of link j. The objective function (6a) minimizes the number of frequency indices used in the network. Constraint (6b) indicates that a lower frequency index should be used preferentially than a higher frequency index. Constraint (6c) states that frequency k is used if it is assigned to any link j. Constraint (6d) denotes that each link is assigned a single frequency. Finally, Constraint (6e) contains the QoS requirements of each link j represented by SINR.[4]

The above formulation is an integer nonlinear programming because constraint (6e) contains optimization variables in both the numerator and denominator. By transforming (6e) into linear form, we can equivalently reformulate (6a)–(6e) to an ILP problem as follows:

$$\min_{z_k} \sum_{k\in\mathcal{K}} 2^{k-1} z_k \tag{7a}$$

$$\text{s.t. } z_k \geq \frac{1}{|\mathcal{L}|} \sum_{j\in\mathcal{L}} z_{j,k}, \quad \forall k \in \mathcal{K} \tag{7b}$$

$$\sum_{k\in\mathcal{K}} z_{j,k} = 1, \quad \forall j \in \mathcal{L} \tag{7c}$$

$$\alpha_j z_{j,k} + B(1-z_{j,k}) \geq \sum_{i\in\mathcal{L}\backslash j} r_{j,i} \sum_{k'\in\mathcal{K}} I(|k-k'|) z_{i,k'} \quad \forall j \in \mathcal{L}, \forall k \in \mathcal{K}, \tag{7d}$$

where $\alpha_j = r_{j,j}/\underline{\gamma}_j - N_0 W_j$, and B is a sufficiently large number, respectively. Here, not only constraint (6e) is transformed to linear form (7d) but also objective (6a) and constraint (6b) are combined into the objective function (7a). In addition, constraint (6c) is equivalently stated as (7b) to reduce the number of constraints and complexity. Unfortunately, we show that this formulation is an NP-hard problem in *Remark 1*. It is therefore desirable to develop heuristic algorithms with low-complexity.

Remark 1: Formulation (7a)–(7d) is an NP-hard problem.

Proof: Assuming only orthogonal frequencies are assigned, by applying (4), (7d) can be simplified as $\alpha_j z_{j,k} + B(1 - z_{j,k}) \geq \sum_{i\in\mathcal{L}\backslash j} r_{j,i} z_{i,k}$, $\forall j \in \mathcal{L}, \forall k \in \mathcal{K}$. This can be rearranged as

$$\sum_{i\in\mathcal{L}} r_{j,i} z_{i,k} \leq B, \forall j \in \mathcal{L}, \forall k \in \mathcal{K},$$

where we have redefined $r_{j,j} = B - \alpha_j$. In this case, our problem becomes a vector bin packing problem stated as follows:

- bin k = frequency k; item j = link j
- each bin k has L resources, denoted by $\beta_1, \ldots, \beta_L$
- the capacity of each resource in bin k is B
- resources consumed by item j if it is put into bin k are $\beta_1 : r_{1,j}$, $\beta_2 : r_{2,j}, \ldots, \beta_j : B - \alpha_j, \ldots, \beta_L : r_{L,j}$
- the goal is to pack all the items (or links) into the minimum number of bins (or frequencies) while the consumption of each resource β_l in each bin remains below the capacity (or SINR requirements are satisfied).

Since the vector bin packing problem is a well-known NP-hard problem [23], our problem (even beyond the case of orthogonal frequencies) is NP-hard as well. ■

[4]Specifically, the QoS requirements for each backhaul link, i.e., the achievable rate requirement considering the associated access (and backhaul) links' traffic for each SBS, can be handled by adjusting W_j and $\underline{\gamma}_j$.

Algorithm 1: Low-Complexity MS-FA (minFAST).

Input: $\mathbf{R} \in \mathbb{R}^{L\times L}$, $\mathcal{K}$.
Output: $\mathbf{f}$.
Initialization: $\mathbf{f} = \mathbf{0}^L$, $k = \lfloor K/2 \rfloor$, $\kappa = 0$.
Update $f_{j^*} = k$, where $j^* = \arg\max_{j\in\mathcal{L}} (r_{j,j})$
while $0 \in \mathbf{f}$ **do**
 ▷ ***Step I. Get Candidate Links***
 $\mathcal{L}_\mathsf{A} = \{j \,|\, f_j \neq 0, \forall j \in \mathcal{L}\}$, $\mathcal{L}_\mathsf{S} = \{j \,|\, f_j = 0, \forall j \in \mathcal{L}\}$
 $\mathcal{L}_\mathsf{C} = \{j \,\Big|\, \frac{r_{j,j}}{\sum_{i\in\mathcal{L}_\mathsf{A}} r_{j,i} I(|k-f_i|)+N_0} \geq \underline{\gamma}_j, \forall j \in \mathcal{L}_\mathsf{S}\}$
 if $\mathcal{L}_\mathsf{C} = \varnothing$ **then**
  $k \leftarrow k + (\kappa+1)(-1)^\kappa$
  $\kappa \leftarrow \kappa + 1$
  continue
 end if
 ▷ ***Step II. Frequency Assignment***
 $\mu_j = \min_{i\in\mathcal{L}_\mathsf{A}} \left(\frac{r_{i,i}}{r_{i,j} I(|f_i-k|) + \sum_{l\in\mathcal{L}_\mathsf{A}\backslash i} r_{i,l} I(|f_i-f_l|)+N_0} - \gamma_i \right)$, $\forall j \in \mathcal{L}_\mathsf{C}$
 if $\mu_j < 0, \forall j \in \mathcal{L}_\mathsf{C}$ **then**
  $k \leftarrow k + (\kappa+1)(-1)^\kappa$
  $\kappa \leftarrow \kappa + 1$
  continue
 else
  Update $f_{j^*} = k$, where $j^* = \arg\max_{j\in\mathcal{L}_\mathsf{C}} (\mu_j)$
 end if
end while

B. minFAST: Low-Complexity MS-FA Technique

We propose a novel low-complexity MS-FA technique based on the greedy algorithm for IAB networks named *minFAST*. Before elaborating on the algorithm, we define a vector $\mathbf{f}$ $(= [f_1, f_2, \ldots, f_L] \in \{\{0\} \cup \mathcal{K}\}^L)$ consisting of f_j indicating the frequency index of link j. It is initialized as a zero vector, which implies that no frequency is assigned to any link. We also define three sets: $\mathcal{L}_\mathsf{A}$ consisting of frequency-assigned (*Active*) links; $\mathcal{L}_\mathsf{S}$ consisting of frequency-unassigned (*Sleep*) links; and $\mathcal{L}_\mathsf{C}$ consisting of *Candidate* links to which frequencies can be assigned when considering the SINR margin. These sets will be iteratively updated for each loop.

Algorithm 1 represents the pseudo-code of the proposed minFAST algorithm, which consists of two steps. Since there is no frequency-assigned link at first, frequency k is assigned to link j with the highest RSS.

1) Step I. Get Candidate Links: In the while loop, two sets $\mathcal{L}_\mathsf{A}$ and $\mathcal{L}_\mathsf{S}$ are updated first and then set $\mathcal{L}_\mathsf{C}$ is updated. Note that set $\mathcal{L}_\mathsf{C}$ consists of the links to which frequency k can be assigned because the SINR is above a certain threshold even if interferences are received from the active links among the sleep links. If $\mathcal{L}_\mathsf{C}$ is an empty set, this means that frequency k cannot be assigned to any sleep link. Then, the frequency index to be assigned is shifted to reduce interference through the discount factor of POCs according to the frequency index difference. In order to increase the efficiency of frequency shift, we define the sequence of frequency indices as $[\lfloor K/2\rfloor, \lfloor K/2\rfloor+1, \lfloor K/2\rfloor-1, \lfloor K/2\rfloor+2, \lfloor K/2\rfloor-2, \ldots]$. After the frequency index to be assigned is shifted, the algorithm continues again from the first line of the while loop.

2) Step II. Frequency Assignment: If $\mathcal{L}_\mathsf{C}$ is not an empty set, this means that there are some candidate links to which frequency k can be assigned. Then, assuming that frequency k is assigned to each candidate link, the minimum SINR margins of active links, denoted by μ_j, are calculated. Here, $\mu_j < 0$ means that by assigning frequency k to the candidate link j, a link that does not satisfy the SINR constraint among existing active links occurs. If all minimum margins are less than zero, this indicates that frequency k cannot be assigned to any candidate link, so the frequency index to be assigned is shifted without assignment. Otherwise, frequency k is assigned to a candidate link that maximizes the minimum SINR margin of active links. This is because, intuitively, the larger the margin, the more the same (or adjacent) frequencies will be assigned. The algorithm terminates when all links have frequencies.

C. Computational Complexity

We theoretically analyze the computational complexity of the proposed minFAST (Algorithm 1) based on worst-case complexity. First, line 5 performs L comparison and assignment operations, so it has a computational complexity of $\mathcal{O}(L)$. Assuming orthogonal frequencies are assigned, the maximum number of iterations of the while loop is L (even assuming that POCs are assigned, it is a constant multiplication of L). Next, let us consider line 8; this requires a computational complexity of $\mathcal{O}(|\mathcal{L}_\mathsf{S}||\mathcal{L}_\mathsf{A}|)$ because $|\mathcal{L}_\mathsf{A}|$ addition and multiplication operations for interference in the denominator, one addition, division, comparison, and assignment operations are performed $|\mathcal{L}_\mathsf{S}|$ times. With the same approach, line 14, which dominantly affects the computational complexity of the minFAST, requires $\mathcal{O}(|\mathcal{L}_\mathsf{C}||\mathcal{L}_\mathsf{A}|^2)$ complexity. Since $|\mathcal{L}_\mathsf{A}|=|\mathcal{L}_\mathsf{S}|=|\mathcal{L}_\mathsf{C}|=L$ under the worst-case complexity analysis framework, the overall computational complexity, including the while loop, is given as $\mathcal{O}(L^4)$. This implies that the proposed minFAST requires polynomial computational complexity and it can be feasible even for large-scale IAB networks, while the optimal MS-FA technique may not be feasible due to its NP-hardness (Remark 1).

IV. Simulation Results

We validate the proposed MS-FA techniques through extensive computer simulations. The simulation parameters are summarized in Table III [5], [6], [12]. W.l.o.g., the same channel bandwidth and SINR threshold are assumed for all links. Furthermore, we set $\Delta = 500$ MHz and $K = L$ for cases without POCs (w/o POC) to completely suppress adjacent channel leakage, while we set $\Delta = 200$ MHz and $K = \lceil LW/\Delta\rceil = 2\,L$ for cases with POCs, respectively. The value of K corresponds to the worst case where all links are assigned orthogonal frequencies to each other. To gradually increase the complexity of the MS-FAP, we performed simulations according to the SBS density λ_S. We used the CPLEX optimization tool for solving ILP problems. As benchmark schemes, a state-of-the-art (SotA) FA with a different optimization objective of maximizing throughput, called centralized subchannel allocation (CSA) [14], and the conventional optimal MS-FA technique [18] are considered even though they do not exploit POCs.

TABLE III
SIMULATION PARAMETERS AND VALUES

Parameter	Notation	Value
Radius of the area	R	250 m
SBS density	λ_S	$20 \sim 100/\text{km}^2$
Blockage parameters	λ_B, l_B	$1000/\text{km}^2$, 10 m
Carrier frequency	f_c	28 GHz
Channel bandwidth	W	400 MHz
Path-loss exponent for LoS or NLoS	α_L, α_N	2.0, 3.0
Transmit powers of MBS and SBS	P_MBS, P_SBS	40 dBm (10 W), 30 dBm (1 W)
Main lobe gain of antenna	G_main	18 dBi
Side lobe gain of antenna	G_side	−2 dBi
Half-power beamwidth	θ_HPBW	10 °
Noise power	N_0W	-174 dBm/Hz$+10\log_{10}W$ $+10$ dB (noise-figure)
SINR threshold	$\underline{\gamma}$	20 dB

TABLE IV
RATIO OF USED BANDWIDTH TO TOTAL BANDWIDTH OF SOTA FA, CONV. MS-FA, PROPOSED OPTIMAL MS-FA, AND MINFAST ([%])

λ_S [No. of SBSs/km^2]	20	40	60	80	100
Total bandwidth [GHz]	3.91	7.45	11.21	15.86	19.76
SotA FA [14]	100	100	100	100	100
Conv. MS-FA [18]	86.16	63.07	51.65	46.62	41.98
Opt. MS-FA w/o POC	86.16	63.07	51.65	46.62	41.98
minFAST w/o POC	86.26	63.07	51.65	46.62	41.98
Opt. MS-FA with POC	62.32	44.13	35.52	Not solved	
minFAST with POC	71.49	49.21	39.94	**33.59**	**29.74**

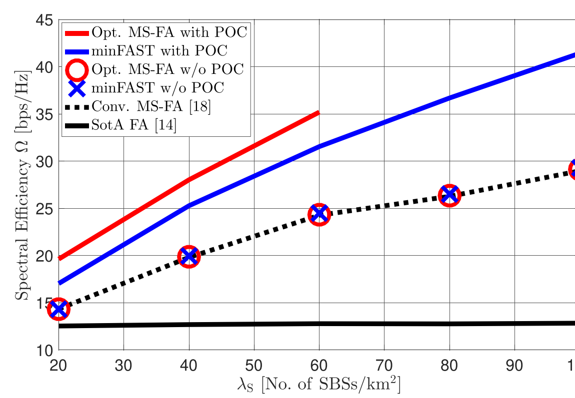

Fig. 3. Spectral efficiency comparison among SotA FA, Conv. MS-FA, proposed optimal MS-FA, and minFAST.

Table IV and Fig. 3 compare the average used (required) bandwidth ratio and the spectral efficiency of the conventional (Conv.) MS-FA, SotA FA, our optimal MS-FA ((7a)–(7d)) technique, and minFAST (Algorithm 1). In Table IV, the total bandwidth is calculated as $L \cdot 500 - 100$ MHz from the number of links L and the aforementioned worst case. Obviously, the total required bandwidth becomes larger as the SBS density increases for the same QoS. The spectral efficiency of the network Ω bps/Hz is defined as the ratio of the total throughput for all links to the total bandwidth used in the network, which can be written as $\Omega = \frac{\text{Total throughput}}{\text{Total used bandwidth}} = \frac{\sum_{j\in\mathcal{L}} R_j}{(\max(\mathbf{f})-1)\Delta+W}$.

In the case without POCs, it can be observed that the conventional MS-FA and our optimal MS-FA techniques achieve almost the same spectral efficiency while requiring exactly the same bandwidth. In particular, the spectral efficiency of both techniques is slightly different because the total throughput is not optimized. Meanwhile, the SotA FA technique improves spectral efficiency by maximizing throughput, which assigns orthogonal frequencies to each other for all links in our setup. Hence, this technique utilizes total bandwidth and results in poor cost and spectral efficiency regardless of the SBS density. Recall that used bandwidth is closely related to the actual spectrum usage fee. Most existing resource assignment techniques for IAB networks have the same results because they consider the same objective of maximizing the sum rate. It is worth noting that the proposed minFAST achieves almost the same performance as the optimal MS-FA schemes in terms of required bandwidth and spectral efficiency.

By allowing POCs, we can significantly improve spectral efficiency with reduced bandwidth, but the computational complexity of the MS-FAP becomes increased. As expected, the optimal solution cannot be obtained when the network density increases. For example, the optimal MS-FA technique is not feasible when the SBS density is larger than $60/\mathrm{km}^2$, as shown in Table IV and Fig. 3. This is because there are many links and frequency indices, which increase the size of the optimization problem. This confirms the effectiveness of the proposed minFAST algorithm. The proposed minFAST efficiently works even when the network size becomes increased. It is worth noting that the minFAST with POCs also significantly reduces the used bandwidth and improves the spectral efficiency while having feasible computational complexity. In particular, this achieves QoS constraints while saving up to about 70% of bandwidth.

V. Conclusion

We proposed novel MS-FA techniques to ameliorate the cost and spectral efficiency of mmWave IAB networks. To be specific, the objective is to minimize the required bandwidth while guaranteeing QoS of each backhaul link. In particular, we allowed partially overlapped channels (POCs) to further improve our objective, and considered the physical interference model to reflect more realistic wireless communication scenarios. Simulation results show that the proposed low-complexity MS-FA technique (minFAST) achieves excellent performance in terms of the required bandwidth and spectral efficiency with feasible computational complexity. It is worth noting that the POC has remarkable potential especially for MS-FAP. We expect that the minFAST can be effectively extended to various dynamic network scenarios including mobile, non-terrestrial, and RIS-aided IAB networks. As further work, we will jointly optimize the transmission power and frequency assignment based on a decentralized approach to improve the operation of dynamic IAB networks.

References

[1] H. Tataria, M. Shafi, A. F. Molisch, M. Dohler, H. Sjöland, and F. Tufvesson, "6G wireless systems: Vision, requirements, challenges, insights, and opportunities," *Proc. IEEE*, vol. 109, no. 7, pp. 1166–1199, Jul. 2021.

[2] B. Tezergil and E. Onur, "Wireless backhaul in 5G and beyond: Issues, challenges and opportunities," *IEEE Commun. Surveys Tuts.*, vol. 24, no. 4, pp. 2579–2632, Oct.–Dec. 2022.

[3] Y. Zhang, M. A. Kishk, and M.-S. Alouini, "A survey on integrated access and backhaul networks," *Front. Commun. Netw.*, vol. 2, Jun. 2021, Art. no. 647284.

[4] M. Diamanti, P. Charatsaris, E. E. Tsiropoulou, and S. Papavassiliou, "The prospect of reconfigurable intelligent surfaces in integrated access and backhaul networks," *IEEE Trans. Green Commun. Netw.*, vol. 6, no. 2, pp. 859–872, Jun. 2022.

[5] C. Madapatha et al., "On integrated access and backhaul networks: Current status and potentials," *IEEE Open J. Commun. Soc.*, vol. 1, pp. 1374–1389, Sep. 2020.

[6] C. Saha and H. S. Dhillon, "Millimeter wave integrated access and backhaul in 5G: Performance analysis and design insights," *IEEE J. Sel. Areas Commun.*, vol. 37, no. 12, pp. 2669–2684, Dec. 2019.

[7] M. Polese et al., "Integrated access and backhaul in 5G mmWave networks: Potential and challenges," *IEEE Commun. Mag.*, vol. 58, no. 3, pp. 62–68, Mar. 2020.

[8] W. Pu, X. Li, J. Yuan, and X. Yang, "Resource allocation for millimeter wave self-backhaul network using Markov approximation," *IEEE Access*, vol. 7, pp. 61283–61295, 2019.

[9] Y. Liu, A. Tang, and X. Wang, "Joint incentive and resource allocation design for user provided network under 5G integrated access and backhaul networks," *IEEE Trans. Netw. Sci. Eng.*, vol. 7, no. 2, pp. 673–685, Apr./Jun. 2020.

[10] J. Y. Lai, W. -H. Wu, and Y. T. Su, "Resource allocation and node placement in multi-hop heterogeneous integrated-access-and-backhaul networks," *IEEE Access*, vol. 8, pp. 122937–122958, 2020.

[11] W. Lei, Y. Ye, and M. Xiao, "Deep reinforcement learning-based spectrum allocation in integrated access and backhaul networks," *IEEE Trans. Cogn. Commun. Netw.*, vol. 6, no. 3, pp. 970–979, Sep. 2020.

[12] S. Zhang et al., "Joint spectrum and power allocation in 5G integrated access and backhaul networks at mmWave band," in *Proc. IEEE 31st Annu. Int. Symp. Pers., Indoor, Mobile Radio Commun.*, London, U.K., 2020, pp. 1–7.

[13] I. Yadav, P. Chaporkar, P. Jha, and A. Karandikar, "Spectrum allocation in IAB networks: A hierarchical auction-based approach," in *Proc. IEEE 94th Veh. Technol. Conf.-Fall*, Norman, OK, USA, 2021, pp. 1–5.

[14] J.-H. Kwon, B. Lim, and Y.-C. Ko, "Resource allocation and system design of out-band based integrated access and backhaul network at mmWave band," *IEEE Trans. Veh. Technol.*, vol. 71, no. 6, pp. 6503–6517, Jun. 2022.

[15] K. I. Aardal, S. P. M. van Hoesel, A. M. C. A. Koster, C. Mannino, and A. Sassano, "Models and solution techniques for frequency assignment problems," *Ann. Oper. Res.*, vol. 153, no. 1, pp. 79–129, Sep. 2007.

[16] J. Wildman and S. Weber, "On protocol and physical interference models in poisson wireless networks," *IEEE Trans. Wireless Commun.*, vol. 17, no. 2, pp. 808–821, Feb. 2018.

[17] F. Tang, Z. M. Fadlullah, N. Kato, F. Ono, and R. Miura, "AC-POCA: Anticoordination game based partially overlapping channels assignment in combined UAV and D2D-based networks," *IEEE Trans. Veh. Technol.*, vol. 67, no. 2, pp. 1672–1683, Feb. 2018.

[18] Z. A. Mann, *Linear Programming: New Frontiers in Theory and Applications*. Hauppauge, NY, USA: Nova Science Pub., 2012.

[19] N. Palizban, S. Szyszkowicz, and H. Yanikomeroglu, "Automation of millimeter wave network planning for outdoor coverage in dense urban areas using wall-mounted base stations," *IEEE Commun. Lett.*, vol. 6, no. 2, pp. 206–209, Apr. 2017.

[20] S. M. Azimi-Abarghouyi, B. Makki, M. Nasiri-Kenari, and T. Svensson, "Stochastic geometry modeling and analysis of finite millimeter wave wireless networks," *IEEE Trans. Veh. Technol.*, vol. 68, no. 2, pp. 1378–1393, Feb. 2019.

[21] S. Ahmadi, *5G NR: Architecture, Technology, Implementation, and Operation of 3GPP New Radio Standards*. New York, NY, USA: Academic Press, 2019.

[22] Qualcomm, New WID on mobile IAB, 3GPP TSG RAN meeting #94e Document, Tech. Rep. RP-213601, Dec. 2021. [Online]. Available: https://www.3gpp.org/ftp/TSG_RAN/TSG_RAN/TSGR_94e/Docs/RP-213601.zip

[23] R. Panigrahy, K. Talwar, L. Uyeda, and U. Wieder, "Heuristics for vector bin packing," Microsoft Research, Tech. Rep., Jan. 2011. [Online]. Available: https://www.microsoft.com/en-us/research/publication/heuristics-for-vector-bin-packing/