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Hierarchical Channel Assignment for Multihop IAB Networks with Multi-Connectivity

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***Abstract*—This work examines the downlink channel assignment for integrated access and backhaul (IAB) networks employing multihop and multi-connectivity operations. Multi-connectivity allows user equipments (UEs) and base stations (BSs) to receive information from multiple upstream BSs and, thus, increases the flexibility of spectrum utilization. We formulate the channel assignment problem as a hierarchical multiple knapsack with discrete fractional assignments problem that aims to maximize the total accommodated data-rate demands of the UEs. We propose a multi-connectivity-aware hierarchical resource allocation (MuCH-RA) algorithm that consists of two stages: a sequential multiple knapsack assignment (SMKA) stage and a UE deselection (UED) stage. The SMKA stage assigns channels to UEs and BSs by solving a sequence of single knapsack problems at the BSs in a bottom-up tier-by-tier fashion, followed by the efficient removal of redundant assignments. The UED stage removes the UEs that could not be fully served and releases their channels for possible reassignment in the next iteration. The proposed MuCH-RA algorithm jointly considers the load and the channel quality of BSs and UEs and, thus, is able to serve larger overall data-rate demands than pure load-based and channel-based greedy algorithms. Numerical simulations are provided to demonstrate the effectiveness of the proposed algorithm.**

I. Introduction

With the exponential growth in data traffic, next-generation mobile networks are expected to achieve a significant increase in network capacity that broadband transmissions at higher frequencies must support. In fact, with limited availability in the sub-6GHz spectrum, the 3rd Generation Partnership Project (3GPP) has promoted the use of the mmWave spectrum from 30 GHz to 100 GHz [1] to support these demands in the 5th generation (5G) network. While large contiguous bandwidth is available at the mmWave frequency, the high propagation loss and susceptibility to blockage require a dense deployment of base stations (BSs) to reduce the distance between BSs and user equipments (UEs) [2]. However, providing fiber backhaul to all BSs is impractical and, thus, cost-effective solutions must be developed to support the deployment flexibility of BSs.

Integrated Access and Backhaul (IAB) [3], adopted recently by 3GPP, refers to a wireless backhaul architecture that utilizes the same infrastructure and bandwidth resources of the access network to support the backhaul transmissions of densely deployed BSs. In this case, data can be delivered from fiber-connected BSs (i.e., the IAB donors) to wireless-connected BSs (i.e., the IAB nodes) or UEs. Recent proposals have also adopted multihop and multi-connectivity operations to further enhance deployment flexibility [4], [5]. However, while wireless backhaul solutions enable low-cost deployment of BSs, the backhaul capacity and reliability are limited by the wireless connection. Therefore, the efficient allocation of resources among backhaul and access links is essential to support the high data-rate demands of 5G networks.

Several recent studies, e.g., [6]–[10], have examined the resource allocation problem in IAB networks. Specifically, [6] analyzed the effectiveness of two bandwidth partitioning strategies, namely, equal partition and load-based partition, from a stochastic geometry perspective. [7] determined the spectrum allocation among IAB nodes by maximizing the sum log-rate of all UE groups. A solution was proposed using the actor-critic deep reinforcement learning approach. [8] proposed an auction-based dynamic spectrum allocation algorithm that takes into account both spatial and temporal variations of the network traffic. However, the above works consider only a single-hop IAB network, where all IAB nodes are connected directly to the IAB donor. For multihop IAB networks, [9] examined the optimal path selection and rate allocation problem subject to latency constraints, and solved the joint optimization by reinforcement learning and successive convex approximation. [10] formulated the resource allocation problem in IAB networks as a maximum weighted matching problem and proposed a semi-centralized solution that can be applied to spanning tree architectures. Different from the above works, we further exploit the advantage of multi-connectivity to enhance the flexibility of spectrum utilization and the robustness to link blockage. With multi-connectivity, the resource allocation at a BS or UE may impact the resource allocation of upstream BSs on different paths. This results in a resource allocation problem on directed acyclic graphs, which is considerably more difficult to solve than cases without multi-connectivity and that yield spanning tree architectures.

The main objective of this work is to propose an efficient channel assignment algorithm that maximizes the downlink data-rate demands of UEs that can be accommodated in a multihop IAB network with multi-connectivity. Different from

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most existing works, we assume that each BS and UE may be served by more than one upstream BS, enabling more flexibility in the channel assignment to account for the diverse load and channel quality of BSs and UEs. We propose a multi-connectivity-aware hierarchical resource allocation (MuCH-RA) algorithm that consists of two stages: a sequential multiple knapsack assignment (SMKA) stage and a UE deselection (UED) stage. The SMKA stage first assigns channels to UEs and BSs by solving a sequence of single knapsack problems at the BSs in a bottom-up tier-by-tier fashion and then removes the channels that are redundantly assigned by less efficient BSs. The UED stage then removes the UEs that cannot be fully served and releases their channels for possible reassignment in the next iteration. MuCH-RA jointly considers the load and channel quality of BSs and UEs and thus is able to achieve a better overall throughput than pure load-based and channel-based greedy algorithms. Numerical simulations are provided to demonstrate the effectiveness of the proposed algorithm.

II. System Model and Problem Formulation

We consider a downlink multihop IAB network that consists of a macro base-station (MBS), denoted by BS 0, and B small-cell BSs (SBSs), denoted by BSs $1, 2, \ldots, B$. The MBS is the only fiber-connected node and, thus, the SBSs are connected to the MBS or other SBSs through wireless backhaul links. We partition the BSs into multiple tiers. The MBS forms the initial tier $\mathcal{B}_0 = \{0\}$ whereas the SBSs are split into K tiers $\mathcal{B}_1$, …, $\mathcal{B}_K$. We refer to the MBS as the IAB donor and the SBSs as the IAB nodes [8]. For convenience, we shall also treat the UEs as the last tier of the network, i.e., tier $K+1$, and denote the set of UEs as $\mathcal{B}_{K+1} = \{B+1, \ldots, B+U\}$. The tiers are defined such that a BS can only transmit to other BSs or UEs in lower tiers. An example is provided in Fig. 1 for the case with $B = 3$ SBSs, $K = 2$ tiers, and $U = 5$ UEs. In this case, the IAB network forms a directed acyclic graph with the MBS as the root node. A node in the directed acyclic graph may correspond to either a BS or a UE, and an edge from node v to node v' can exist only if $v \in \mathcal{B}_k$ and $v' \in \mathcal{B}_{k'}$ with $k < k'$ are within the transmission range of each other. The sets of outgoing and incoming neighbors of node v are denoted by $\mathcal{N}_v^{\text{out}}$ and $\mathcal{N}_v^{\text{in}}$, respectively. Notice that, due to multi-connectivity, each UE or BS can be served by more than one of its upstream neighbors.

Suppose that the total available spectrum with bandwidth W is divided into M frequency channels each with bandwidth $\Delta w = W/M$. For example, in 5G NR [1], the spectrum allocated to a physical resource block (PRB) under numerology μ occupies bandwidth $\Delta w = 12 \times 15 \times 2^\mu$ kHz, where the number of subcarriers is 12 and the subcarrier spacing is 15 kHz. Each BS, say BS b, is allocated a subset of M_b spectrum channels that is disjoint from other BSs within its interference range. Therefore, no interference exists among the transmissions by neighboring BSs. By adopting frequency reuse, the total number of available channels at the BSs, i.e., $\sum_{b\in\mathcal{B}} M_b$, may in general be larger than M. The channels are assigned to the backhaul and access links at the beginning of each transmission time interval (TTI) to maximize the total accommodated data-rate demands of the UEs.

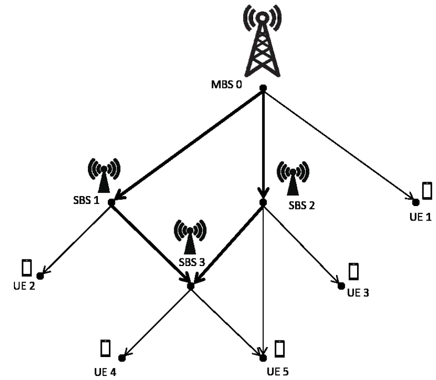

Fig. 1. An example of a multihop IAB network with multi-connectivity for the case with $B = 3$ SBSs, $K = 2$ tiers, and $U = 5$ UEs.

Let R_u be the downlink data-rate demand of UE $u \in \mathcal{B}_{K+1}$, e.g., for video streaming services. Due to multi-connectivity, each UE may receive service either directly from the MBS or through relaying by SBSs. Therefore, the channels must be properly assigned along the paths from the MBS to UE u to ensure that the sum of the achievable rates of all paths arriving at UE u is at least R_u. However, due to limited spectrum resources, only a subset of UEs can be served by the IAB network. Therefore, the choice of UEs to serve and the channel assignments at the BSs should be jointly determined to maximize the total data-rate demands that can be served.

Channel Model. Here, we consider mmWave transmissions on all IAB links. To incorporate the impact of blockage, we adopt the link state model proposed in [11], where link (v, v'), i.e., the link from node v to node v', can be line-of-sight (LoS) and non-LoS (NLoS) with probabilities $p_{v,v'}^{\text{LoS}} = e^{-\delta_{v'} d_{v,v'}}$ and $p_{v,v'}^{\text{NLoS}} = 1 - p_{v,v'}^{\text{LoS}}$, respectively, where $d_{v,v'}$ is the distance between nodes v and v', and $\delta_{v'}$ is a scaling parameter that reflects the blockage density of the area. Following [12], the channel gain under LoS can be written in dB as

$$g_{v,v'(\text{dB})}^{\text{LoS}} = G_{v(\text{dBi})} - \text{PL}_{v,v'(\text{dB})}^{\text{LoS}}, \tag{1}$$

where G_v is the antenna gain at node v and $\text{PL}_{v,v'}^{\text{LoS}}$ is the path loss under LoS on link (v, v'). The path loss in dB can be computed as $\text{PL}_{v,v'(\text{dB})}^{\text{LoS}} = 10\alpha^{\text{LoS}} \log_{10} d_{v,v'} + \beta^{\text{LoS}} + 10\gamma^{\text{LoS}} \log_{10} f_c$ [13], where f_c is the carrier frequency in GHz. Moreover, α^{LoS}, β^{LoS}, and γ^{LoS} are constant parameters that depend on the environment. Typical values of these parameters can be found in [13]. The channel gain $g_{b,v}^{\text{NLoS}}$ under NLoS is given similarly. Since the presence or absence of blockage is unknown before transmission, we perform channel assignment based on the average achievable rate of link (v, v') given by

$$C_{v,v'} = \sum_{s\in\{\text{LoS},\text{NLoS}\}} p_{v,v'}^{s} \Delta w \log_2\left(1 + \frac{P_b g_{v,v'}^{s}}{\sigma^2}\right), \tag{2}$$

where P_b denotes the transmission power of BS b and σ^2 is the additive white Gaussian noise (AWGN) variance.

Problem Formulation. The main objective of this work is to maximize the total downlink data-rate demands that can be served through the channel assignment at the BSs. In this case, we must determine which UE to serve, how to split the traffic among BSs in the presence of multi-connectivity, and how to allocate channel resources to accommodate the traffic.

Specifically, let r_v be an auxiliary rate allocation variable that specifies the data-rate demand of node v, which can be any intermediate BS or UE. Here, r_v can be viewed as the total data rate that node v must receive from its upstream BSs to serve itself or its downstream neighbors. If node v is a UE that the system chooses to serve, then the allocated data rate r_v should be equal to the UE's demand R_v. If node v is a BS, then the allocated data rate r_v must be sufficient to serve its downstream neighbors. Due to multi-connectivity, the demand r_v can be fulfilled by multiple upstream BSs of node v.

Suppose that $x_{b,v} \in [0,1]$ is the fraction of r_v that node v receives from its upstream BS $b \in \mathcal{N}_v^{\text{in}}$. In this case, the allocated data rate r_v is feasible only if $\sum_{b\in\mathcal{N}_v^{\text{in}}} x_{b,v} \geq 1$. Similarly, the fractions of data rates that node v can provide to its downstream nodes in $\mathcal{N}_v^{\text{out}}$ must satisfy $\sum_{v'\in\mathcal{N}_v^{\text{out}}} x_{v,v'} r_{v'} \leq r_v$ due to the flow conservation principle. The fractions of data rates allocated to downstream nodes are achieved through the channel assignment at the BSs. In particular, given the rate allocation $r_{v'}$ and the average achievable rate $C_{v,v'}$ of link (v,v'), the number of channels that node v needs to fully serve the allocated data rate at node v' is $W_{v,v'} = \lceil \frac{r_{v'}}{C_{v,v'}} \rceil$. However, due to multi-connectivity, it is possible for node v to supply only a fraction of these channels and leave the remaining for other nodes in $\mathcal{N}_{v'}^{\text{in}}$ to provide. Since only integer numbers of channels can be provided by node v, the fraction $x_{v,v'}$ can only take on finite fractional values in the set $\{0, \frac{1}{W_{v,v'}}, \frac{2}{W_{v,v'}}, \ldots, \frac{W_{v,v'}}{W_{v,v'}}\}$. The total number of channels that node v provides to its downstream neighbors must not exceed M_v, i.e., $\sum_{v'\in\mathcal{N}_v^{\text{out}}} x_{v,v'} W_{v,v'} \leq M_v$.

Let $\phi_u \in \{0,1\}$, $\forall u \in \mathcal{B}_{K+1}$, be the binary UE selection variable defined such that $\phi_u = 1$ if UE u is selected and 0, otherwise. In this case, the problem can be formulated as

$$\max_{\substack{\phi_u, \forall u\in\mathcal{B}_{K+1}, r_v, x_{v,v'},\\ \forall v'\in\mathcal{N}_v^{\text{out}}, \forall v\in\cup_{k=0}^K \mathcal{B}_k}} \quad \sum_{u=1}^{U} \phi_u R_u \tag{3a}$$

$$\text{subject to} \quad \phi_u \in \{0,1\}, \forall u \in \mathcal{B}_{K+1} \tag{3b}$$

$$x_{v,v'} \in \Big\{0, \frac{1}{W_{v,v'}}, \frac{2}{W_{v,v'}}, \ldots, \frac{W_{v,v'}}{W_{v,v'}}\Big\}, \quad \forall v' \in \mathcal{N}_v^{\text{out}}, \forall v \in \cup_{k=0}^K \mathcal{B}_k, \tag{3c}$$

$$\sum_{v'\in\mathcal{N}_v^{\text{out}}} x_{v,v'} W_{v,v'} \leq M_v, \ \forall v \in \cup_{k=0}^K \mathcal{B}_k \tag{3d}$$

$$\sum_{b\in\mathcal{N}_v^{\text{in}}} x_{b,v} \geq 1, \ \forall v \in \cup_{k=1}^K \mathcal{B}_k, \tag{3e}$$

$$\sum_{b\in\mathcal{N}_v^{\text{in}}} x_{b,v} \geq \phi_v, \ \forall v \in \mathcal{B}_{K+1}, \tag{3f}$$

$$\sum_{v'\in\mathcal{N}_v^{\text{out}}} x_{v,v'} r_{v'} \leq r_v, \ \forall v \in \cup_{k=0}^K \mathcal{B}_k, \tag{3g}$$

where (3d) ensures that the number of channels assigned by node v does not exceed M_v, (3e) and (3f) ensure that the data-rate demands of SBSs and UEs are satisfied, and (3g) follows from the flow conservation principle. We assume that the backhaul capacity of the fiber-connected MBS is unbounded (i.e., $r_0 = \infty$) and set $r_u = R_u$, for all $u \in \mathcal{B}_{K+1}$. When $r_{v'} = 0$ (and, thus, $W_{v,v'} = 0$), we set $\frac{W_{v,v'}}{W_{v,v'}} = 1$.

It is worthwhile to remark that the above problem can be viewed as a generalization of different knapsack problems. In fact, when $K = 1$, $\mathcal{N}_0^{\text{out}} = \mathcal{B}_1$, $C_{0,b} = \infty$, and $C_{b,u} = \bar{C}_u$, for all $b \in \mathcal{B}_1$ and $u \in \mathcal{B}_2$, and no multi-connectivity (i.e., $x_{b,u} \in \{0,1\}$), the problem reduces to a multiple knapsack with assignment restrictions (MKAR) problem [14]. Moreover, by further relaxing the integer constraint such that $x_{b,u} \in [0,1]$, the problem becomes a fractional knapsack (FK) problem that can be solved in polynomial time by a simple greedy algorithm [15] (when $B = 1$). However, compared to MKAR (which is already NP-hard [14]), our problem is considerably more difficult to solve due to its hierarchical structure, meaning that the assignment in lower tiers of the network will impact the allocated data rates of nodes in upper tiers. Moreover, compared to FK, our assignment $x_{v,v'}$ can only take on discrete fractional values. and thus is no longer solvable in polynomial time as in the original FK problem.

III. Multi-Connectivity-Aware Hierarchical Resource Allocation (MuCH-RA) Algorithm

In this section, we propose an efficient approach for solving the channel assignment problem in multi-tier IAB networks. The proposed multi-connectivity-aware hierarchical resource allocation (MuCH-RA) algorithm consists of two stages: a sequential multiple knapsack assignment (SMKA) stage and a UE deselection (UED) stage. In the SMKA stage, local channel assignments are first determined by solving separate single-knapsack problems at the BSs. This is done in a sequential tier-by-tier manner from bottom to top. Then, redundancy removal is performed to release the channels that were redundantly assigned as a result of the separate local assignments. In the UED stage, we identify UEs that have not yet been fully served at the end of the SMKA stage and release their channels for reassignment in the next iteration. The two stages are repeated until no other UEs can be selected and served.

Stage 1: Sequential multiple knapsack Assignment (SMKA)

In the SMKA stage, we perform an inner iteration between a sequential single knapsack assignment (SSKA) step in Stage 1(a) and a redundancy removal (RR) step in Stage 1(b). Specifically, let $\mathcal{B}_{K+1}^{(t)}$ be the set of UEs whose data rate demands have not yet been fully satisfied at the beginning of inner iteration t, let $R_u^{(t)}$ be the remaining data-rate demand of UE $u \in \mathcal{B}_{K+1}^{(t)}$, and let $M_b^{(t)}$ be the remaining number of available channels at BS b. Then, the two steps of Stage 1 in iteration t can be described as follows.

(a) Sequential Single Knapsack Assignment (SSKA): In Stage 1(a), we first solve separate single knapsack problems at the BSs in a sequential tier-by-tier manner, starting from

BSs in the lowest tier (i.e., BSs in $\mathcal{B}_K$) to those in the highest tier (i.e., the MBS in $\mathcal{B}_0$). In particular, we first set the allocated data rate of UE $u \in \mathcal{B}_{K+1}$ as $r_u^{(t)} = R_u^{(t)}$. Then, starting from tier K, each BS in $\mathcal{B}_K$, say node $b \in \mathcal{B}_K$, first computes the number of channels required to fully serve each downstream neighbor, i.e., $W_{b,v}^{(t)} = \left\lceil \frac{r_v^{(t)}}{C_{b,v}} \right\rceil$, for all $v \in \mathcal{N}_b^{\text{out}}$, and then determines the values of the assignment variables $x_{b,v}^{(t)} \in \left\{0, \frac{1}{W_{b,v}^{(t)}}, \ldots, \frac{W_{b,v}^{(t)}}{W_{b,v}^{(t)}}\right\}$, $\forall v \in \mathcal{N}_b^{\text{out}}$, by maximizing the local downlink data rate, i.e.,

$$\max_{x_{b,v}, \forall v \in \mathcal{N}_b^{\text{out}}} \sum_{v \in \mathcal{N}_b^{\text{out}}} x_{b,v} r_v^{(t)} \tag{4a}$$

$$\text{subject to } x_{b,v} \in \left\{0, \frac{1}{W_{b,v}^{(t)}}, \ldots, \frac{W_{b,v}^{(t)}}{W_{b,v}^{(t)}}\right\}, \ \forall v \in \mathcal{N}_b^{\text{out}} \tag{4b}$$

$$\sum_{v \in \mathcal{N}_b^{\text{out}}} x_{b,v} W_{b,v}^{(t)} \leq M_b^{(t)}. \tag{4c}$$

Notice that the above is a single knapsack problem with $M_b^{(t)}$ being the size of the knapsack at BS b, and $r_v^{(t)}$ and $W_{b,v}^{(t)}$ being the value and weight of node v.

To solve the single knapsack problem at BS b, we consider a greedy procedure where the channels are assigned to nodes in $\mathcal{N}_b^{\text{out}}$ in decreasing order of their *value-to-weight ratios* (i.e., $\text{VWR}_{b,v}^{(t)} = \frac{r_v^{(t)}}{W_{b,v}^{(t)}}$, for node v). The channels are assigned to fulfill as much as possible the allocated data rates of the nodes in $\mathcal{N}_b^{\text{out}}$ until there is no remaining channel to assign. More specifically, let $\pi_b : \{1, \ldots, |\mathcal{N}_b^{\text{out}}|\} \rightarrow \mathcal{N}_b^{\text{out}}$ be an ordering of nodes in $\mathcal{N}_b^{\text{out}}$ defined such that $\text{VWR}_{b,\pi_b(1)}^{(t)} \geq \text{VWR}_{b,\pi_b(2)}^{(t)} \geq \cdots \geq \text{VWR}_{b,\pi_b(|\mathcal{N}_b^{\text{out}}|)}^{(t)}$. In this case, the solution obtained by node b is $x_{b,\pi_b(i)} = \max\left\{ \min\left\{ \frac{M_b^{(t)} - \sum_{i'=1}^{i-1} W_{b,\pi_b(i')}^{(t)}}{W_{b,\pi_b(i)}^{(t)}}, 1 \right\}, 0 \right\}$.

After the channel assignment of BSs in $\mathcal{B}_K$ have been completed, we update their auxiliary data-rate demands as

$$r_b^{(t)} = \sum_{v \in \mathcal{N}_b^{\text{out}}} x_{b,v} r_v^{(t)}, \ \forall b \in \mathcal{B}_K. \tag{5}$$

Given $r_b^{(t)}$, for all $b \in \mathcal{B}_K \cup \mathcal{B}_{K+1}$, we can proceed to find the channel assignment of BSs in $\mathcal{B}_{K-1}$ and their auxiliary data-rate demands following the same procedure mentioned above. The process is repeated in a sequential tier-by-tier manner until the local assignments of all BSs have been completed.

Notice that, since knapsack problems are solved independently at the BSs, there is no guarantee that the constraint in (3e) can be satisfied for all v. That is, node v may only be able to receive a fraction of the allocated data rate $r_v^{(t)}$ from its upstream neighbors in $\mathcal{N}_v^{\text{in}}$ (i.e., $\sum_{b \in \mathcal{N}_v^{\text{in}}} x_{b,v} < 1$). In this case, node v must reduce the rate allocated to its downstream neighbors by removing certain assigned channels. We propose to do this in a greedy fashion by removing the assigned channels one by one in increasing order of their associated value-to-weight ratios. The auxiliary data-rate demand of node v, i.e., $r_v^{(t)}$, is then updated accordingly. The above feasibility check is performed from top to bottom, starting from BSs in $\mathcal{B}_1$ to those in $\mathcal{B}_K$.

(b) Redundancy Removal (RR): Note that, due to the independent assignment of channels at different BSs in Stage 1(a), it is possible that a node may be allocated more channels than necessary by its upstream BSs. This results in inefficient use of the spectrum resources. Hence, in Stage 1(b), we seek to remove the redundantly assigned channels so that they may be reassigned in the next iteration. This is also done in a sequential tier-by-tier manner, from $\mathcal{B}_{K+1}$ to $\mathcal{B}_1$.

Suppose that RR has been performed up to tier $k+1$ (i.e., the channels redundantly assigned to nodes in tier $k+1$ have been removed) and the rates allocated by the BSs to its downstream nodes have been updated accordingly and are denoted by $\tilde{r}_v^{(t)}$, $\forall v$. Then, to proceed to tier k, we first compute the excess data rate that is allocated to node v, $\forall v \in \mathcal{B}_k$, as

$$E_v^{(t)} = \sum_{b \in \mathcal{N}_v^{\text{in}}} x_{b,v}^{(t)} r_v^{(t)} - \tilde{r}_v^{(t)}. \tag{6}$$

Here, E_v represents the difference between the rate allocated to node v by its upstream neighbors and its updated data-rate demand $\tilde{r}_v^{(t)}$. When $E_v^{(t)} > 0$, it may be desirable to release certain channels assigned to node v so that they may be reassigned to other nodes in the next iteration. Here, we propose to balance the redundancy removal among all BSs that are serving node v. That is, the rate that BS $b \in \mathcal{N}_v^{\text{in}}$ allocates to node v is reduced to $\frac{x_{b,v}^{(t)}}{\sum_{b \in \mathcal{N}_v^{\text{in}}} x_{b,v}^{(t)}} \tilde{r}_v^{(t)}$, and, thus, the total data-rate allocated to its downstream nodes can be updated as

$$\tilde{r}_b^{(t)} = \sum_{v \in \mathcal{N}_b^{\text{out}}} \frac{x_{b,v}^{(t)}}{\sum_{b \in \mathcal{N}_v^{\text{in}}} x_{b,v}^{(t)}} \tilde{r}_v^{(t)}. \tag{7}$$

The redundancy removal in tier k reduces the auxiliary data-rate demand of BSs in tier $k-1$. The process is performed from tier $\mathcal{B}_K$ up to tier $\mathcal{B}_0$ (i.e., the MBS).

Note that the removal of the excess data rate allocated by BS b to a downstream node v may not be sufficient to enable the release of a channel even if the capacity of the channel (e.g., $C_{b,v}$) is not fully utilized. Hence, to improve the efficiency of each channel usage and, thus, reduce the total number of channels required to serve each downstream node, we pack the rates allocated to each downstream node into the smallest number of channels possible. In this case, the number of channels that BS b actually allocates to node $v \in \mathcal{N}_b^{\text{out}}$ in iteration t is $\left\lceil \frac{\tilde{r}_{b,v}^{(t)}}{C_{b,v}} \right\rceil$ and, thus, the remaining channels available for future assignment is

$$M_b^{(t+1)} = M_b^{(t)} - \sum_{v \in \mathcal{N}_b^{\text{out}}} \left\lceil \frac{\tilde{r}_{b,v}^{(t)}}{C_{b,v}} \right\rceil. \tag{8}$$

After the SSKA and RR steps in iteration t, we can update the set of UEs that have not yet been fully served as

$$\mathcal{B}_{K+1}^{(t+1)} = \left\{ u \in \mathcal{B}_{K+1}^{(t)} : \sum_{b \in \mathcal{N}_u^{\text{in}}} x_{b,u}^{(t)} < 1 \right\} \tag{9}$$

and also update the remaining data-rate demands of UEs in $\mathcal{B}_{K+1}^{(t+1)}$ as

$$R_u^{(t+1)} = R_u^{(t)} \left(1 - \sum_{b \in \mathcal{N}_u^{\text{in}}} x_{b,u}^{(t)}\right). \tag{10}$$

Given the above updates, we repeat the SMKA and RR steps (i.e., Stages 1(a) and 1(b)) again to assign the remaining channels. Stage 1 is repeated iteratively until no additional channels can be assigned or until all UEs are fully served.

Stage 2: UE Deselection

After completing the iterative assignment in Stages 1 and 2, there may be UEs that still have not been fully served. The channels assigned to these partially served UEs do not contribute to the objective of our problem and, thus, should be reassigned. Hence, we propose a final UE deselection procedure that releases the channels of less efficiently served UEs so that they may be reassigned to other UEs that have not yet been fully served. To do so, we compute the potential value of each partially served UE, say UE $v \in \mathcal{S}^c$ as $\text{PV}_v = \max_b \frac{R_v}{W_{b,v}}$, where $W_{b,v}$ is the remaining number of channels needed for BS b to fully serve node v. Notice that a UE with fewer remaining channels needed will have a higher potential value and, thus, be served with a higher priority. We eliminate the UE with the smallest potential value and release its previously assigned channels to the pool. The channels are again removed in a tier-by-tier fashion, starting from the lowest tier. That is, suppose that node v is the UE to be deselected and that $x_{b,v}R_v^{(t)}$ is the rate that BS b originally allocated to node v. Then, the rate of BS b is updated as $r_b^{(t)} - x_{b,v}R_v^{(t)}$ and the rates are removed proportionally from the upstream nodes accordingly, similar to that in RR. The channels are then reassigned to other UEs by performing the SMKA and RR procedures in Stage 1 again. Stages 1 and 2 are repeated until no remaining UEs can be fully served.

IV. SIMULATION RESULTS

In this section, we provide numerical simulations to demonstrate the effectiveness of our proposed MuCH-RA algorithm. In these experiments, we consider a multihop IAB network with B SBSs split into $K = 2$ tiers. The BSs and UEs are randomly deployed according to a uniform distribution in a 4×4 km^2 area with the MBS at the center. The SBSs within 1.5 km of the MBS are in tier 1, and the remaining SBSs are in tier 2. The height of the MBS, the SBSs, and the UEs are set as 25, 3, and 1.5 meters, respectively. The UEs' data rate demands are uniformly distributed from 15 to 45 Mbps. Moreover, we consider mmWave transmission at 28 GHz. The total bandwidth available at the MBS is 100 MHz and that at each SBS is 20 MHz. Following the 5G NR specification [1], a PRB consisting of 12 subcarriers with subcarrier spacing 15 kHz and bandwidth $\Delta w = 12 \times 15 \times 2^{\mu} = 720$ kHz under numerology $\mu = 2$. Hence, the number of channels available at the MBS and at each SBS are 125 and 25, respectively. The transmit powers of the MBS and the SBS are 40 dBm and 33 dBm [12], respectively,

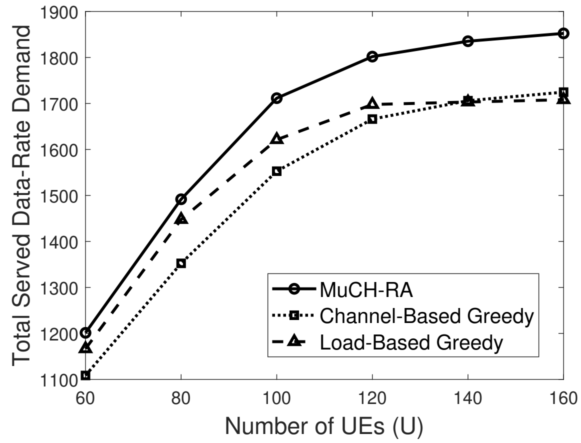

Fig. 2. Average throughput versus the number of UEs.

and the total noise power spectral density is -174 dBm/Hz. The path loss coefficients are set as $(\alpha^{\text{LoS}}, \beta^{\text{LoS}}, \gamma^{\text{LoS}}) = (2.8, 11.4, 2.3)$ and $(\alpha^{\text{NLoS}}, \beta^{\text{NLoS}}, \gamma^{\text{NLoS}}) = (3.3, 17.6, 2.0)$ for the MBS, and $(\alpha^{\text{LoS}}, \beta^{\text{LoS}}, \gamma^{\text{LoS}}) = (2.6, 24.4, 1.6)$ and $(\alpha^{\text{NLoS}}, \beta^{\text{NLoS}}, \gamma^{\text{NLoS}}) = (4.4, 2.4, 1.9)$ for the SBS.

We compare the proposed MuCH-RA algorithm with two baseline approaches, i.e., load-based and channel-based greedy algorithms. In the baseline approaches, the channel assignments are performed bottom-up from the SBSs in tier K up to the MBS in tier 0. In the load-based greedy algorithm, the downstream neighbors of the SBSs are served one by one in the order of their remaining auxiliary rate demands. That is, we start from the downstream neighbor with the largest remaining rate demand and allocate to it the best available channels until its remaining demand is fulfilled. The channel assignment of SBSs in tier k is completed when all available channels have been assigned or when the auxiliary data rate demands of all downstream neighbors have been fulfilled. After completing the channel assignment in all tiers, the allocated channels that the backhaul capacity of each SBS cannot support will be removed following the procedure at the end of Stage 1(a). Similarly, in the channel-based greedy algorithm, the channels of the SBSs in tier k are assigned one by one in the order of their quality to downstream neighbors that have not yet been fully served. The results are averaged over 1000 random deployments of the BSs and UEs.

In Fig. 2, we show the total served data-rate demand with respect to the number of UEs for the case with $B = 8$ SBSs. We can see that the total served data-rate demand increases with the number of UEs in all cases due to multiuser diversity but gradually saturates as the system capacity is exceeded. The proposed MuCH-RA algorithm outperforms both load-based and channel-based greedy algorithms since it is able to balance both metrics through the consideration of the value-to-weight ratio and can best utilize the redundant resources through several rounds of reassignment. The load-based greedy approach serves the node with the largest remaining rate demand and, thus, does not fully utilize the channels with better channel quality, and vice versa for the channel-based greedy approach.

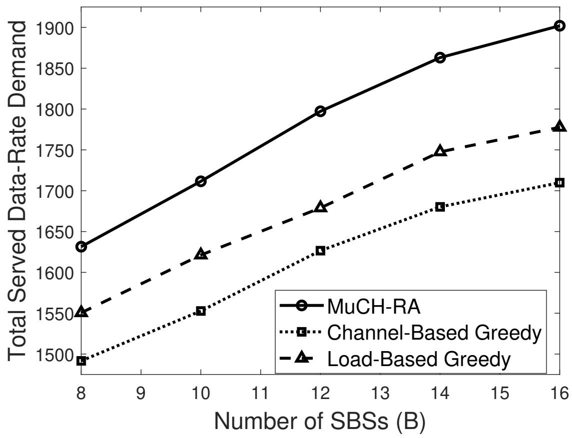

Fig. 3. Average throughput versus the number of SBSs.

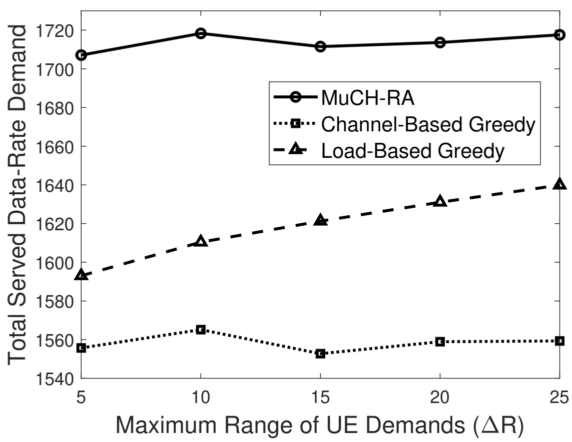

Fig. 4. Average throughput versus the maximum range of UE demands.

In Fig. 3, we show the total served data-rate demand with respect to the number of SBSs for the case with $U = 100$ UEs. We can see that the total served data-rate increases as the number of SBSs increases since the distances between SBSs and their associated UEs are reduced. As expected, the proposed MuCH-RA algorithm outperforms the two baseline greedy algorithms in all cases. The advantage slightly increases as the number of SBSs increases since, in this case, UEs will have more opportunity to exploit multi-connectivity through our proposed algorithm. Similar to Fig. 2, the two baseline greedy algorithms do not perform as well due to their unbalanced treatment of the load and channel quality.

In Fig. 4, we show the total served data-rate demand with respect to the maximum range of UE demands. In particular, the UE demands are chosen randomly from the interval $[30 - \Delta R/2, 30 + \Delta R/2]$, where ΔR is the maximum range of UE demands. We can see again that our proposed scheme outperforms both baseline algorithms. However, the difference with the load-based greedy approach gradually decreases as the UE demands become more diverse since, with ΔR large, the performance will be dominated by the heavy loaded UEs and, thus, allocating resources to these UEs is favorable. The performance of the channel-based approach remains roughly unchanged since it does not take into account the UE load.

V. Conclusion

In this work, we proposed a channel assignment algorithm for multihop IAB networks with multi-connectivity. We formulated the problem as a hierarchical multiple knapsack problem with finite fractional values. The proposed MuCH-RA algorithm consists of two stages, namely, a sequential multiple knapsack assignment (SMKA) stage and a UE deselection (UED) stage. The SMKA stage assigns the channels at the BSs by performing a sequence of single knapsack problems in a bottom-up layer-by-layer fashion. The UED stage removes UEs that have not yet been fully served and releases their assigned channels for possible reassignment to other UEs. The proposed scheme jointly considers both the load and channel quality of UEs and BSs in the assignment. Numerical simulations demonstrated the effectiveness of the proposed scheme over other greedy baseline policies.

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