Energy and Spectrum Efficient User Association in 5G Heterogeneous Networks

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Abstract—Due to the dense small cell deployment to cope with the increased data traffic of fifth generation (5G) networks, the direct backhaul (BH) connection of all small cells to the core network becomes challenging. To that end, millimeter wave (mmWave) is a promising solution for cost-efficient high capacity small cell BH links. However, due to the severe signal attenuation at high frequencies, mmWave can provide good coverage only for short distances, thus favoring a multi-hop 5G BH architecture. In this context, user association that impacts both the network and user performance calls for BH-aware strategies. Hence, in this paper, we study the user association problem aiming at the joint energy and spectrum efficiency maximization of the network, without compromising the user quality of service. The problem is formulated as a generalized assignment problem, which considers the capacity and energy consumption both in the access network and BH links. Provided that the considered problem is shown to be NP-hard, we employ optimization techniques to obtain an upper bound on system performance. We also propose a low complexity algorithm, which is shown to outperform the state-of-the-art while achieving near-optimal performance.

Index Terms—Backhaul, cell selection, context-awareness, green networks, LTE-Advanced, millimeter wave, small cells.

I. INTRODUCTION

Due to the ever-increasing data traffic, fifth generation (5G) wireless networks call for sustainability in terms of capacity growth. To that end, the dense deployment of small cells (SCs), overlaid on the existing macrocell forming a heterogeneous network (HetNet), is expected to play a key role. When a dense SC network is deployed, the SC radius is reduced, which results in i) shorter distance between user equipments (UEs) and SCs and thus higher signal-to-interference-plus-noise ratio (SINR), and ii) higher area spectral efficiency (bps/Hz/m²).

Despite the aforementioned benefits, the high number of SCs complicates their direct connection to the core network. Fiber backhaul (BH) links are prohibitive in this case due to their high deployment cost [1]. Hence, a promising solution lies in exploiting the existing connection between the eNB site and the core network (mainly fiber), and to provide core network connectivity to SCs through the eNB site [2]. Still, in order to connect the SCs to the eNB site, new cost-efficient and high capacity wireless BH solutions are required. To that end, the use of millimeter wave (mmWave) is favored, due to its high bandwidth availability, able to provide high capacity BH [1]. It has been shown, however, that mmWave can provide good coverage for distances shorter than 200 m, otherwise,

links may not be established [1], [2]. Given that the eNB radius is typically on the order of 500 m, a multi-hop architecture is needed, to allow each SC to reach the eNB site [2], [3].

In this 5G context, user association problem, which impacts both the network and user performance, becomes even more challenging, since it directly affects the traffic that passes through each BH link and thus its energy consumption. Nevertheless, traditional user association algorithms only consider the radio access network (AN), i.e., the links between UEs and their serving base stations (BSs)¹. In LTE-Advanced (LTE-A), user association is based on the reference signal received power (RSRP) and reference signal received quality (RSRQ). The first measures the average received power over the resource elements that carry cell-specific reference signals within certain bandwidth, while the latter measures the portion of pure reference signal power over the total power received by the UE. [3]. Although these metrics maximize the instantaneous SINR of UEs [4], it has been shown that they do not increase the overall throughput significantly, since few UEs are connected to SCs [5]. Hence, range expansion (RE) was motivated, where a bias is introduced in the case the signal comes from a SC, thus favoring the UE association with SCs [5]. In this case, although a UE may be associated with a BS not providing the best SINR, better load balancing is achieved between eNB and SCs. However, the network topology changes stress the need for new BH-aware strategies, which will consider both BH capacity and energy impact [6].

To that end, the authors in [7] propose a UE association algorithm, which distributes traffic among BSs according to a load balancing strategy, considering both the AN and the BH load status. Yet, it reduces the BH congestion at the expense of lower spectral efficiency, since UEs may be assigned to non-optimal BSs in terms of SINR. In [8], a joint user association and resource allocation optimization problem is proposed, which is shown to be NP-hard. Therefore, the authors develop techniques to obtain upper bounds on the system performance. In [9], the joint problem of downlink user association and wireless BH bandwidth allocation is studied in two-tier cellular HetNets. SCs are connected through wireless BH with the eNB and the problem is formulated as a sum logarithmic user rate maximization problem under wireless BH constraints. In our

¹We will use the term BS to refer to an eNodeB (eNB) and/or a SC.

former work [10], we proposed a heuristic algorithm that takes into account the number of BH link hops to achieve an energy efficient UE association. Apparently, the aforementioned approaches either ignore completely the energy consumption [7]–[9], or examine it under the assumption of homogeneous BH links [10], thus not guaranteeing their high energy efficiency in realistic scenarios, where the BH links may vary significantly in terms of distance and, consequently, energy consumption.

Hence, in this paper, we study the user association problem aiming at the joint energy and spectrum efficiency maximization of the network, without compromising the UE quality of service (QoS), while providing the following contributions:

- We formulate the user association problem as a generalized assignment problem, which considers both the AN and BH energy consumption. The considered problem is shown to be NP-hard. Thus, by employing optimization techniques, we derive the Ross and Soland upper bound [17], which can be used as a benchmark for the performance evaluation of UE association algorithms.
- We propose a heuristic association algorithm, which considers the total power consumption (AN and BH) for the traffic of a UE to be served. This association criterion considers the actual power consumption of each BH link and thus it is valid for any scenario.
- Finally, we compare the derived bound and the proposed algorithm with existing user association solutions in scenarios that employ mmWave BH links. In the provided results, the proposed algorithm is shown to achieve notable performance gains compared to its counterparts, while achieving near-optimal performance.

The rest of the paper is organized as follows: Section II presents the system model. In Section III, the problem formulation, the proposed optimal association, as well as the energy and spectrum efficient heuristic algorithm are provided. In Section IV, the performance of the existing user association algorithms together with the proposed algorithm is evaluated and compared with the optimal association derived by the upper bound. Finally, Section V concludes the paper.

II. SYSTEM MODEL

We focus our analysis on a single eNB sector² overlaid with multiple SCs. In particular, we consider a set of BSs $\mathcal{B}$, which consists of an eNB ($j=0$) and $B-1$ SCs ($j=1\dots B-1$), where $|\mathcal{B}| = B$. In accordance with 3GPP [12], SCs are divided in N_{cl} clusters ($k=1\dots N_{cl}$), as depicted in Fig. 1. We study the downlink and make the following assumptions:

- Each SC is connected to the core network through the eNB either directly or through one or more SCs [2], [3].
- The eNB is connected to the core network through fiber, while the SCs are connected with the eNB and between them through mmWave line-of-sight (LOS) wireless BH links $\mathcal{L}=\{\mathcal{L}_1, \mathcal{L}_2, \dots, \mathcal{L}_L\}$. Each BH link l is represented by a set $\mathcal{L}_l$ that includes all cells j whose traffic passes through BH link l (i.e., $\forall j \in \mathcal{L}_l$), as depicted in Fig. 1.

²We assume that inter-sector interference is mitigated through some form of fractional frequency reuse scheme or sophisticated frequency allocation [11].

Fig. 1. System model.

- There is a total number of physical resource blocks (PRBs) available to each BS j [3], denoted by c_{jtot} .
- The total transmission power of each BS, denoted by P_{jtot} , is equally distributed among its PRBs [8].
- We consider a set $\mathcal{N}$ of fixed UEs ($i=1, \dots, N$) with guaranteed bit rate (GBR) QoS demands based on their service type/application, denoted by r_i [13].
- Each UE can be associated only with one BS at a time.

In the following, we derive the main parameters used in the network energy efficiency calculation. In particular, the SINR calculation is given in Section II-A, while the AN and BH power consumption models are given in Section II-B.

A. SINR Calculation

The signal-to-noise ratio (SNR) of UE i from BS j is [14]

$$SNR_{ij(dB)} = P_{jPRB(dBm)} + G_{Txj(dBi)} + G_{Rxi(dBi)} - L_{cbj(dB)} - L_{p_{ij}(dB)} - L_{f_{ij}(dB)} - N_{th(dBm)} - NF_{UE(dB)}, \quad (1)$$

where $P_{jPRB} = 10 \log_{10}(P_{jtot}/c_{jtot})$ is the power allocated by BS j to a PRB, with P_{jtot} and c_{jtot} as already defined.

The parameters G_{Txj} and G_{Rxi} represent the antenna gains of BS j and UE i , respectively, and L_{cbj} is the cable loss between the radio frequency connector and the antenna of BS j . The path loss between UE i and BS j is denoted by $L_{p_{ij}}$, while $L_{f_{ij}}$ are the losses due to slow-fading. Finally, N_{th} stands for the thermal noise and NF_{UE} is the noise figure. As for the SINR received by UE i from BS j , it is given by

$$SINR_{ij(dB)} = SNR_{ij(dB)} - 10 \log_{10} \left(\frac{I_{ij(mW)}}{N_{total(mW)}} + 1 \right), \quad (2)$$

where I_{ij} is the total interference experienced by UE i , when associated with SC j , caused by the interfering SCs in the same sector. This value depends on the applied frequency allocation

scheme. Finally, $N_{total} = 10^{(N_{th(dBm)} + N_{FUE(dB)})/10}$ denotes the total noise power experienced by UE i .

B. Power Consumption Models

In our study, we take into account only the transmit power consumption of BSs and BH links, since the fixed power consumption part is independent of the user association decision.

1) *Access Network Link*: The power consumption of a microwave access link between BS j and UE i equals to [10]

$$P_{ANij(dB)} = P_{jPRB(dBm)} + 10\log_{10}(c_{ij}), \quad (3)$$

where c_{ij} is the number of PRBs required when UE i is associated with BS j so that its specific throughput demands r_i are satisfied and is given by

$$c_{ij} = \left\lceil \frac{r_i}{b \log_2(1 + SINR_{ij})} \right\rceil, \quad (4)$$

where $\lceil \cdot \rceil$ stands for the ceiling function operator. The denominator of the fraction represents the maximum achievable rate derived by Shannon's theorem [14] with $SINR_{ij}$ and bandwidth b equal to the bandwidth of a PRB.

2) *Backhaul Link*: Assuming that link adaptation is employed [14], the power consumed in a mmWave BH link $\mathcal{L}_l$, can be given by [15], [16]

$$P_{BH\mathcal{L}_l(dBm)} = SINR_{\mathcal{L}_l(dB)}^{trg} + L_{p_o(dB)} + L_{p_{\mathcal{L}_l}(dB)} + IL_{(dB)} + N_{th(dBm)} + N_{F_{\mathcal{L}_l}(dB)} - G_{T_{x\mathcal{L}_l}(dBi)} - G_{R_{x\mathcal{L}_l}(dBi)}, \quad (5)$$

where $SINR_{\mathcal{L}_l}^{trg}$ corresponds to the (minimum) target SINR required at the BH receiver so that the BH link traffic is successfully transmitted. Then, L_{p_o} denotes the path loss at 1 m distance and $L_{p_{\mathcal{L}_l}} = 20\log_{10}(4\pi \frac{d_{\mathcal{L}_l}}{\lambda})$ is the path loss at distance $d_{\mathcal{L}_l}$ equal to the BH link length (i.e., distance between transmitter and receiver). Moreover, λ is the operating wavelength of the signal (e.g., for 60 GHz, $\lambda = 0.005$ m) and IL stands for the implementation loss that may account for distortion, intermodulation and/or phase noise. The rest of the parameters are equivalent to the ones described in (1). According to Shannon's theorem [14], $SINR_{\mathcal{L}_l}^{trg}$ is given by

$$SINR_{\mathcal{L}_l(dB)}^{trg} = 10\log_{10}\left(2^{\sum_{i \in \mathcal{N}} \sum_{j \in \mathcal{L}_l} r_i a_{ij} / B_{\mathcal{L}_l}} - 1\right), \quad (6)$$

where $\sum_{i \in \mathcal{N}} \sum_{j \in \mathcal{L}_l} r_i a_{ij}$ is the aggregate BH link traffic, with a_{ij} denoting the association vector (equal to 1 when the UE i is associated with BS j and 0 otherwise) and $B_{\mathcal{L}_l}$ denotes the bandwidth of the BH link $\mathcal{L}_l$.

III. PROPOSED ENERGY AND SPECTRUM EFFICIENT USER ASSOCIATION

A. Problem Formulation and Optimal Solution

The solution of the problem under study aims at the joint maximization of energy and spectrum efficiency of the network, without compromising the UE QoS (i.e., the specific UE throughput demands should be satisfied). The energy efficiency (bit/Joule) can be expressed as total throughput divided by the total power consumption (i.e., both in the AN and BH), whereas the spectral efficiency (bps/Hz) as total throughput

divided by the total bandwidth. Hence, under the constraint that the UE throughput demands should be satisfied, the joint maximization of energy and spectrum efficiency is equivalent to the joint minimization of power consumption and number of required PRBs. Thus, the problem can be formulated as

$$\begin{aligned} \min_{a_{ij}} \quad & \sum_{i \in \mathcal{N}} \sum_{j \in \mathcal{B}} a_{ij} \left(\overbrace{\beta_E(P_{ANij(W)} + P_{BHij(W)}) + \beta_S c_{ij}}^{p_{ij}} \right) \\ \text{where} \quad & P_{BHij(W)} = \sum_{\mathcal{L}_l \in \mathcal{L}} s_{\mathcal{L}_l j} \left(2^{\frac{r_i}{B_{\mathcal{L}_l}}} - 1 \right) 10^{\frac{\alpha_{\mathcal{L}_l} - 30}{10}} \\ \text{s.t.} \quad & a) \ a_{ij} \in \{0, 1\}, \forall i \in \mathcal{N}, \forall j \in \mathcal{B} \\ & b) \ \sum_{j \in \mathcal{B}} a_{ij} = 1, \forall i \in \mathcal{N} \\ & c) \ \sum_{i \in \mathcal{N}} a_{ij} c_{ij} \leq c_{jtot}, \forall j \in \mathcal{B} \\ & d) \ s_{\mathcal{L}_l j} \in \{0, 1\}, \forall \mathcal{L}_l \in \mathcal{L}, \forall j \in \mathcal{B} \\ & e) \ P_{BH\mathcal{L}_l} \leq P_{BHmax}, \forall \mathcal{L}_l \in \mathcal{L}, \end{aligned} \quad (7)$$

where the objective function (denoted by p_{ij}) is expressed as the weighted sum of our objectives, i.e., the minimization of the AN and BH power consumption, as well as the minimization of the number of PRBs required so that the UE QoS demands are satisfied. Thereby, the multi-objective optimization problem can be cast as a single-objective one, with normalized weighting coefficients $\beta_E = w_E \theta_E$ for the energy efficiency and $\beta_S = w_S \theta_S$ for the spectral efficiency, where w_n and θ_n are the weights (assigned by the decision maker based on its preference on each objective n) and the normalization factors, respectively, as defined in [18].

The aforementioned problem refers to the optimal assignment of each UE (it is reminded that a_{ij} is equal to 1 when the UE i is associated with BS j and 0 otherwise (7a)) to exactly one BS (7b), so as to minimize the objective function, without reserving from any BS more spectrum resources than its capacity, c_{jtot} (7c). The parameter $s_{\mathcal{L}_l j}$ is 1 if the traffic of the BS j passes through the BH link $\mathcal{L}_l$ and 0 otherwise (7d) and $\alpha_{\mathcal{L}_l(dB)} = L_{p_o} + L_{p_{\mathcal{L}_l}} + IL + N_{th} + N_{F_{\mathcal{L}_l}} - G_{T_{x\mathcal{L}_l}} - G_{R_{x\mathcal{L}_l}}$. Finally, the transmitted power of each BH link $\mathcal{L}_l$ should not exceed a maximum value, denoted by P_{BHmax} (7e).

The considered problem is a generalized assignment problem, which is shown to be NP-hard [17]. However, by employing optimization techniques, we are able to derive the Ross and Soland upper bound [17]. To that end, we initially relax the capacity constraint (7c) to

$$a_{ij} c_{ij} \leq c_{jtot} \quad \forall i \in \mathcal{N}, \forall j \in \mathcal{B}. \quad (8)$$

Thereby, we consider as possible associations for a UE only the cells that can satisfy its QoS requirements without exceeding their capacity considering that only this UE is associated with them. Then, the optimal solution $\hat{a}$ to the resulting problem is obtained by determining for each $i \in \mathcal{N}$ the BS j , that minimizes the objective function p_{ij} , as defined in (7), while satisfying the relaxed capacity constraint, i.e.,

$$j^* = \arg \min \{ p_{ij} : j \in \mathcal{B}, c_{ij} \leq c_{jtot} \}. \quad (9)$$

With $\hat{a}_{ij^*}=1$, $\hat{a}_{ij}=0 \forall j \in \mathcal{B} \setminus \{j^*\}$, the resulting upper bound is

$$U_0 = \sum_{i \in \mathcal{N}} p_{ij^*}. \quad (10)$$

This bound is not yet feasible, since only the relaxed capacity constraints are fulfilled (not the actual ones). Therefore, we define the following parameters

$$\mathcal{N}_j = \{i \in \mathcal{N} : \hat{a}_{ij^*} = 1\}, j \in \mathcal{B}, \quad (11)$$

$$d_j = \sum_{i \in \mathcal{N}_j} c_{ij} - c_{j_{tot}}, j \in \mathcal{B}, \quad (12)$$

$$\mathcal{B}' = \{j \in \mathcal{B} : d_j > 0\}, \mathcal{N}' = \cup_{j \in \mathcal{B}'} \mathcal{N}_j, \quad (13)$$

where $\mathcal{N}_j$ is the set of UEs optimally associated with BS j , d_j is the number of extra PRBs that exceed the actual capacity of BS j (7c), $\mathcal{B}'$ is the set of those BSs whose actual capacity constraint (7c) is violated and $\mathcal{N}'$ is their set of UEs. Given a set $\mathcal{S}$ of numbers, we denote with $\min_2 \mathcal{S}$ the second minimum value in $\mathcal{S}$. Thus, the minimum penalty incurred if UE i currently assigned to a BS in $\mathcal{B}'$ is reassigned is

$$q_i = \min_2 \{p_{ij} : j \in \mathcal{B}, c_{ij} \leq c_{j_{tot}}\} - p_{ij^*}, i \in \mathcal{N}'. \quad (14)$$

Hence, for each BS j whose capacity constraint (7c) is violated, i.e., for each $j \in \mathcal{B}'$, a lower bound on the loss of profit to be paid to satisfy the constraint (7c) is given by the solution of the 0-1 single Knapsack problem defined as

$$\begin{aligned} v_j = \min \quad & \sum_{i \in \mathcal{N}_j} q_i y_{ij} \\ \text{s.t.} \quad & a) y_{ij} \in \{0, 1\}, i \in \mathcal{N}_j \\ & b) \sum_{i \in \mathcal{N}_j} y_{ij} c_{ij} \geq d_j, \end{aligned} \quad (15)$$

where $y_{ij} = 1$ if and only if UE i is removed from BS j . With (15b), the aforementioned problem ensures that the capacity constraint (7c) of the initial problem is satisfied, while minimizing the penalty to be paid in the objective function. The resulting Ross and Soland bound [17] is then equal to

$$U_1 = U_0 - \sum_{j \in \mathcal{B}'} v_j. \quad (16)$$

B. Low Complexity User Association Algorithm

The proposed energy and spectrum efficient (ESE) algorithm, summarized in Algorithm 1, takes as an input the following context-aware information, which is available to all nodes in LTE-A networks [3], [19]: the UE measurements (SINR) and requirements (r_i), the HetNet architecture knowledge ($s_{\mathcal{L},j}$) and the available PRBs of each BS ($c_{j_{tot}}$), to associate the UEs in an energy and spectrum efficient way.

As shown in Algorithm 1, ESE considers as cell candidates for the association of a UE the BSs that satisfy its requirements with the fewest PRBs needed (c_{ij}) (line 2), thus achieving maximum spectral efficiency. Please note that the consideration of only a subset of cells reduces the computational burden induced in the system. To ensure the association of all UEs, ESE sorts them according to their number of cell candidates,

Algorithm 1 Proposed ESE user association algorithm

Input: $\mathcal{N}, \mathcal{B}, \text{SINR}_{ij}, r_i, b, c_{j_{tot}}, \mathcal{L}_l, \mathcal{L}$

- 1: Calculate c_{ij} as in (4)
- 2: $\text{Candidates}_i \leftarrow j : \min(c_{ij})$
- 3: Sort all UEs i by Candidates_i size in ascending order
- 4: Calculate $P_{AN_{ij}} + P_{BH_{ij}}$ using (3), (7) $\forall j \in \text{Candidates}_i$
- 5: Sort Candidates_i by $P_{AN_{ij}} + P_{BH_{ij}}$ in ascending order
- 6: Choose the candidate with the minimum $P_{AN_{ij}} + P_{BH_{ij}}$
- 7: **if** the chosen BS has sufficient PRBs **then**
- 8: Associate the UE to it and update remaining PRBs
- 9: **else**
- 10: Move to the next candidate and repeat the process
- 11: **end if**

starting from the UEs with the fewest options (line 3). In order to maximize the energy efficiency, ESE sorts the BS candidates by the total power consumption required in each case, so that the traffic of UE i is served (line 5). Then, ESE associates the UE with the BS candidate which involves the minimum power consumption, as long as it has sufficient PRBs to serve the UE traffic (line 7). Otherwise, it moves to the next candidate (line 11). Every time a UE is associated with a BS j , the algorithm updates the remaining PRBs of BS j .

ESE presents very low complexity, i.e., $\mathcal{O}(n \log n)$ [20]. Yet, it need not be executed at every subframe, but with lower periodicity based on the UE traffic dynamics, so that the system performance is optimized. For the new UEs that appear in the meantime, ESE could still be applied given the associations of the rest, thus achieving high scalability.

IV. PERFORMANCE EVALUATION

A. Scenario

In the simulations we executed in MATLAB[®], we consider an eNB sector of radius R , as depicted in Fig. 1, that overlaps with $N_{cl} = 2$ clusters. Each cluster consists of 4 SCs [12]. LOS mmWave BH links are considered (60 GHz band) with $B_{\mathcal{L}_l}=50$ MHz channel bandwidth [16]. As for the BH architecture, in each cluster, we consider one SC being one hop away from the eNB site, two SCs at two hops away and one SC at three hops away, based on their distances (see Fig. 1). The SCs of different clusters reuse the same frequency band thus interfering among them, while orthogonal channels are assumed for the eNB and the SC tier.

In each realization, we consider N UEs with different GBR requirements, i.e., 60% of UEs demand 728 kbps, 20% 1024 kbps and 20% 2048 kbps [13]. We further assume hotspot user distribution with 2/3 of UEs uniformly distributed within the clusters (in a radius $r=70$ m from cluster center) and 1/3 of UEs uniformly distributed in the eNB sector [12].

The rest of the simulation parameters are summarized in Table I, where f_{AN} , B_{AN} denote the frequency and the allocated bandwidth of the AN and h the antenna height. The parameter h_m denotes the mobile antenna height, while C_H stands for the antenna height correction factor and d for the distance between the BS and the UE. The slow fading is modeled by a log-normal random variable with zero mean and deviation 8 dB for the eNB and 10 dB for the SC signal.

TABLE I
SIMULATION VALUES

Parameter	Value	Parameter	Value	Parameter	Value
f_{AN}	2 GHz	$L_{p_{eNB}}$	$69.55+26.16 \log f_{AN}-13.82 \log h_{eNB}-C_H+(44.9-6.55 \log h_{eNB}) \log d, d \text{ in km}$	$G_{T_{eNB}}$	17 dBi
B_{eNB}, B_{SC}	10 MHz	$L_{p_{SC}}$	$69.55+26.16 \log f_{AN}-13.82 \log h_{SC}+(44.9-6.55 \log h_{SC}) \log d, d \text{ in km}$	$G_{T_{SC}}$	5 dBi
$c_{eNB_{tot}}, c_{SC_{tot}}$	50	C_H	$0.8+(1.1 \log f_{AN}-0.7) h_m-1.56 \log f_{AN}$	$G_{R_{UE}}$	0 dBi
$P_{eNB_{tot}}$	46 dBm	h_{eNB}	25 m	$G_{T_{x_{L1}}}, G_{R_{x_{L1}}}$	23 dBi
$P_{SC_{tot}}$	30 dBm	h_{SC}	2.5 m	L_{p_o}	57.5 dB
$P_{BH_{max}}$	37 dBm	h_m	1.5 m	R	500 m
NF_{UE}	9 dB	N_{th}	-174 dBm/Hz	$d_{min_{eNB}}$	35 m
NF_{L1}	7 dB	IL	7 dB	$d_{min_{SC}}$	5 m

Fig. 2. Average network energy efficiency for different weights (w_E for energy efficiency and w_S for spectral efficiency) and N values.

TABLE II
AVERAGE NETWORK POWER CONSUMPTION (W)

$\{w_E = 0.1, w_S = 0.9\}$				$\{w_E = 0.5, w_S = 0.5\}$				$\{w_E = 0.9, w_S = 0.1\}$			
N=30		N=90		N=30		N=90		N=30		N=90	
AN	BH	AN	BH	AN	BH	AN	BH	AN	BH	AN	BH
5.3	9.7	15.3	34.4	4.7	9.8	13.8	35.0	4.3	9.9	13.2	35.7

Using as a benchmark the theoretical bound of Section III-A (denoted by Optimal), we compare the performance of the proposed ESE algorithm with the following reference schemes:

- Minimum path loss (MPL): a UE is associated with the BS from which it has the minimum path loss [8].
- Best SINR (B-SINR): association with the BS with the strongest signal [3], [4].
- Range expansion (RE): a UE connects to the BS with the strongest signal, given that a $bias=13 \text{ dB}^3$ is added to it, if the signal comes from a SC [5], [11].
- BH hop-aware: the spectrum and energy-efficient user association algorithm of [10], which considers the number of BH link hops in the UE association decision.

The range of the number of UEs, N , has been appropriately selected to avoid system overloading. Thus, all algorithms satisfy the UE QoS demands and consequently, the total energy efficiency depends only on the total power consumption.

B. Results

In Fig. 2 and 3, the average network energy and spectrum efficiency of the derived bound is depicted for different weight values, when $N=\{30, 90\}$ UEs. As it can be observed in both graphs, for high w_E values, the energy efficiency increases at the expense of lower spectral efficiency and vice versa.

³The selected value corresponds to an average value. Higher values than that achieve performance close to MPL, whereas lower values close to B-SINR.

Fig. 3. Average network spectrum efficiency for different weights (w_E for energy efficiency and w_S for spectral efficiency) and N values.

However, the increase in one objective is not proportional to the loss in the other. This stems from the fact that, when energy efficiency is preferred ($w_E=0.9$), most UEs get associated with SCs. Thereby, although the BH power consumption increases (see Table II), the AN power consumption decreases significantly (the AN power consumption per PRB is much lower for a SC than for the eNB). On the other hand, as depicted in Fig. 3, the spectral efficiency is decreased by 25-26% for both $N=\{30, 90\}$, as the UEs that are located far from the SC clusters may require a high number of PRBs to get connected to SCs. On the contrary, when spectral efficiency is preferred ($w_S=0.9$), the number of UEs associated to the eNB increases. In this case, although the total BH power consumption decreases, the total AN power consumption increases (see Table II) and thus the energy efficiency decreases (-9% for low traffic and -4% for high traffic). Notice that this decrease is lower for high traffic, as the eNB is limited by its maximum capacity and thus more UEs get connected to SCs (this also explains the slightly lower spectrum efficiency decrease for high traffic, i.e., from 26% to 25%, in Fig. 3).

In Fig. 4, the average network energy efficiency is depicted for all algorithms versus the number of UEs, N . In order to evaluate the energy efficiency performance of the reference algorithms that maximize the spectral efficiency, we include the behavior of the derived bound with $w_S=0.99$ (maximum spectrum efficiency). As shown in Fig. 4, ESE significantly outperforms its counterparts (up to 76% gains), while achieving optimal performance. As for the rest of the algorithms, for low traffic, MPL outperforms the rest, as it associates most UEs to SCs, resulting in very low AN power consumption (the power per subcarrier is much higher for the eNB than for a

Fig. 4. Average total network energy efficiency for different N values.

TABLE III
AVERAGE NETWORK SPECTRAL EFFICIENCY

User association algorithm	bps/Hz
Optimal with $w_S=0.99$, ESE, B-SINR, BH hop-aware	2.920
RE	2.919
MPL	2.739

SC). Regarding RE, it achieves lower energy efficiency than MPL, since there are fewer UEs associated with SCs, leading to higher AN power consumption. BH hop-aware achieves the worst performance for low traffic, as it gives priority to the BS candidate with the fewest BH link hops and thus most of the UEs get connected to the eNB. As a result, although the BH energy consumption is equal to zero, there is high energy consumption in the AN. For high traffic, however, the BH power consumption of MPL becomes very high and thus its energy efficiency decreases. RE and B-SINR achieve slightly higher energy efficiency than MPL due to their lower BH power consumption. BH hop-aware minimizes the BH power consumption, and thus it presents the best performance among the state-of-the-art. Yet, ESE achieves the best performance in all cases, as by minimizing the total power consumption, it presents no dependency on the employed scenario.

In Table III, the average network spectral efficiency is presented for all algorithms. As it can be noticed, the algorithms that aim at spectral efficiency maximization (i.e., ESE, BH hop-aware, B-SINR) as well as the derived bound with $w_S=0.99$ achieve the highest performance, since they favor the UE association that requires the minimum number of PRBs (to satisfy the UE QoS). On the contrary, RE achieves slightly lower spectral efficiency due to the bias imposed on the signal strength, which may result in the UE association with BSs with lower SINR (thus requiring more PRBs for their QoS to be satisfied). Finally, MPL, presents the lowest spectral efficiency, as it associates the UEs independently of their SINR.

V. CONCLUSION

We studied the user association problem in a 5G HetNet with mmWave BH links, aiming at the joint maximization of energy and spectrum efficiency of the network, without compromising the UE QoS. Considering both the AN and BH

power consumption, we derived a theoretical upper bound, which can be used as a benchmark for the performance evaluation of user association algorithms. We also proposed a low complexity algorithm, which was shown to achieve up to 76% energy efficiency gains compared to state-of-the-art approaches, while achieving near-optimal performance.

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