Optimal User Association, Backhaul Routing and Switching off in 5G Heterogeneous Networks with Mesh Millimeter Wave Backhaul Links

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Abstract

Next generation, i.e., fifth generation (5G), cellular networks will provide a significant higher capacity per area to support the ever-increasing traffic demands. In order to achieve that, many small cells need to be deployed that are connected using a combination of optical fiber links and millimeter-wave (mmWave) backhaul architecture to forward heterogeneous traffic over mesh topologies. In this paper, we present a general optimization framework for the design of policies that optimally solve the problem of where to associate a user, over which links to route its traffic towards which mesh gateway, and which base stations and backhaul links to switch off in order to minimize the energy cost for the network operator and still satisfy the user demands. We develop an optimal policy based on mixed integer linear programming (MILP) which considers different user distribution and traffic demands over multiple time periods. We develop also a fast iterative two-phase solution heuristic, which associates users and calculates backhaul routes to maximize energy savings. Our strategies optimize the backhaul network configuration at each timeslot based on the current demands and user locations. We discuss the application of our policies to backhaul management of mmWave cellular networks in light of current

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trend of network softwarization (Software-Defined Networking, SDN). Finally, we present extensive numerical simulations of our proposed policies, which show how the algorithms can efficiently trade-off energy consumption with required capacity, while satisfying flow demand requirements.
Keywords: 5G, energy efficiency, green networks, mesh backhaul, millimeter wave, optimization, routing, software defined networking (SDN), switching off, user association

1. Introduction

In this section, we will first describe the motivation behind this work. Subsequently, we will highlight our main contributions and finally we will present the organization of the paper.

1.1. Motivation

Future wireless systems need to support the ever-increasing data rate demands imposed by the growing number of user equipment (UE) devices, and data-intense applications. This requires a significant increase in capacity per region, especially in dense urban or suburban areas. Despite enhancing spectral efficiency and data rate, the current trend is to increase the density of base station (BS) deployment, reduce the cell size and deploy a massive amount of small cells (SCs) [1]. However, a denser BS deployment and usage of more transmit antennas will lead to a decrease of the energy efficiency and result in a significant increase in operational and energy costs for the network operator due to the dynamic user distribution and traffic variation [2]. This is due to the fact that the user distribution and traffic demand varies for a given location over time of the day and over day of the week. Consequently, deploying SCs for the highest traffic scenario may result in a highly underutilized network infrastructure and in high energy consumption for the operator, while deploying a less dense network may lead to congestion and low user satisfaction during peak hour demands.

Since UE demand fluctuates over time for each location, dimensioning a mobile network based on peak demand becomes more and more challenging. Using a massive amount of SCs is energy-efficient only if the demand is high and evenly distributed, but significantly lower if the demand is low or fluctuates due to fixed power consumption and static resource provisioning [3]. In order to provide ubiquitous coverage, SCs have to be integrated with the macro network to form heterogeneous networks (HetNets). This enables the adaptive power on/off operation for BSs in order to provide the additional capacity whenever and wherever needed.

Another challenge to solve is the capital expenditure for such dense SC networks, as it is very costly to deploy optical fiber to each SC. Current investigation for fifth generation (5G) technology points towards the importance of directional millimeter wave (mmWave) networks for both access network (AN) and backhaul (BH) by virtue of the massive amount of spectrum available in the 28 GHz or 60/70 GHz frequency bands and the low cost of mmWave backhauling. Due to the short range of mmWave links (up to 200 meters in dense urban environments), a multi-hop mesh topology is expected for the BH: it is thus important to manage such mesh network to provide the required capacity, while minimizing the total required energy consumption of the network infrastructure. In this context, it becomes important to develop green network management and operation policies that allow to efficiently use all the available network resources for the energy-efficient operation of the whole network, comprising both the AN links as well as the BH network required to transport the user data from the operator core network to the access interface.

1.2. Contributions

In this paper, we develop green optimization policies that guide how to manage and operate a 5G network of mmWave mesh BH links for minimal energy consumption. We consider a mixed integer linear programming (MILP) based formulation and the goal of the policy is to decide i) where each UE should be associated, ii) over which BH path to route its traffic, iii) which BH links should be activated or switched off, and consequently iv) which the mesh BH configuration should be, and finally v) which BSs to power on/off. We consider energy models for BS and BH transceivers operating in the mmWave band, mmWave propagation models and assume knowledge about user demand profiles. Our optimization model calculates the most energy optimal configuration of both mesh BH and AN for a given time snapshot, subject to capacity, power and quality of service (QoS) constraints.

We also propose a fast online solution policy based on a two phase greedy iterative algorithm. In the first phase, our algorithm calculates the most energy-efficient UE association and BH routing strategy, while still giving enough freedom to power down some BSs. In the second phase, we order the BSs and BH links according to the idle power, i.e., the power they consume at zero load. Thereafter, we start with the BS that, when powered down, achieves the highest energy saving and we determine, if we can re-associate all the associated UEs to another BS. In this case and as long as this action leads to positive energy saving gain, we power down this BS and continue until all active BSs are processed. Furthermore, we discuss how our optimization policies can be implemented in the context of future software defined networking (SDN) architecture for cellular networks, where an SDN controller is in charge of running our policies and triggering the reconfiguration of the BH network to implement our optimization policies.

Finally, we perform several representative numerical simulations focusing on a hotspot scenario, to evaluate the potential energy saving of our optimization policies. We use multiple snapshots over time and quantify the achievable energy efficiency gain over a whole day. We compare both optimal and heuristic solutions against state-of-the-art. Our evaluation shows that we can achieve up to 49 times more energy efficiency gain compared to existing approaches, showing the effectiveness of our approach.

1.3. Paper Organization

The rest of this paper is organized as follows. In Section 2, we present the related work. In Section 3, we develop our optimal joint user association, BH routing and BS and BH link switch off policy for 5G networks with mmWave mesh BH. We also develop a fast online heuristic and discuss implementation aspects for SDN-based mesh BH (re)-configuration using our algorithms. In Section 4, we provide representative numerical simulation results that illustrate the benefits of our optimization algorithms. Finally, Section 5 concludes the paper.

2. Related Work

One of the objectives set by the European Commission for 2020 is reducing the total energy consumption by 20%; the target was recently updated to 30% for 2030 [4]. According to the authors in [5], the wireless access networks are large power consumers, e.g., the power consumption per year recorded a 10% increase in the five-year period from 2007 till 2012. This amount is expected to increase when considering that the number of mobile subscriptions is growing at almost 6% year-on-year, expecting to reach 1 billion by the end of 2023 [6]; also, the total mobile data traffic is expected to rise at a compound annual growth rate of 42%, with the monthly global mobile data traffic surpassing 100 ExaBytes (EB) in 2023. However, traditionally networks such as LTE have been optimized for capacity [7], and only recently, energy-efficient system design approaches are becoming more and more important. In particular, as the radio access nodes are responsible for more than the 80% of the total energy consumption in the entire access network [8], the research community has focused its interests in developing techniques that are able to significantly reduce the energy consumed at the radio access [9].

The majority of the works in this direction focus on sleep strategies which are shown to achieve notable performance gains [10, 11, 12]. In particular, in [10], the authors present a long duration global optimization approach on user association and BS switching on/off to maximize the total system rate over the total network energy consumption. A switching off strategy is proposed in [11], which gives priority to the switching off of the eNodeB (eNB) and then to the lowest loaded SCs. For each BS, the algorithm checks whether its UEs can be re-associated to the BS from which they receive the second highest signal. If this is possible, it switches off the BS as long as this move involves energy efficiency gain. Otherwise, it continues with the next BS to be evaluated. Furthermore, in [12], two different approaches are proposed. In the first, a fixed percentage of the initial set of BSs are randomly selected to be switched off, as long as there are other active BSs to guarantee the QoS of the re-associated users [12]. On the other hand, the second approach selects to switch off a fixed percentage of the initial set of BSs but starting from those with the lowest number of UEs instead of randomly. Nevertheless, all the aforementioned approaches do not take into account the BH conditions. Still, the envision of an ultra-dense SC deployment in 5G cellular networks, where mmWave links are established among SCs and form the wireless BH, brings a considerable increase in the network power consumption, thus pushing the research community to develop new green strategies that also involve the power consumed in the BH nodes.

To the best of the authors' knowledge, only few works have considered the BH conditions in the user association decision so far. An analytical framework for the user association is proposed in [13], where several parameters from both the AN and BH network are taken into account (e.g., spectrum efficiency, BS load, BH link capacity and topology, different types of traffic, etc.). The joint problem of user association and resource allocation has been recently studied in [14], where the maximum BH capacity, the resource consumption and the energy budget of BSs are taken into account. In [15], the power allocation and bandwidth allocation problem is studied in a heterogeneous small cell network where the SCs use wireless backhauling to maximize the downlink energy efficiency of power allocation and unified bandwidth allocation under power constraints and data rate requirements. However, the wireless BH is defined as the connection between macro BS and SCs, thus neglecting the added problem of how to efficiently route the traffic in the meshed BH. In [16], an energy-efficient algorithm was proposed, which considers both the AN and BH. In particular, the proposed algorithm favors the association that involves the minimum variable power consumption, while guaranteeing the UE QoS. In the case of alternative BH routes, the traffic of the already associated UEs was taken into account so that load balancing is achieved. Still, all the aforementioned approaches do not consider the switching off possibility. As a result, in the case where energy saving modes are enabled, the high energy efficiency of these approaches cannot be guaranteed.

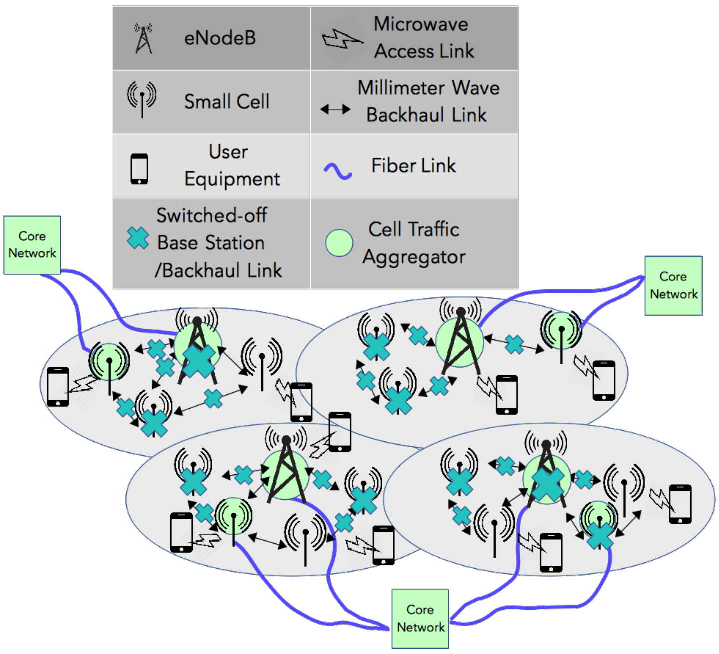
Being the closest to our work, in [17], the joint problem of user association, traffic routing in the multi-hop BH and switching off of the unused SCs and BH links has been studied. An optimization model was developed with the objective of minimizing the total power consumed by the BH and access nodes in the network for given user capacity demands. The proposed model, however, was limited by the following assumptions: a) the eNB switching off option was not enabled, b) the switching off of a subset of BH links of a node was not enabled, i.e., all the BH links of a node were active as long as there was traffic passing through at least one of its BH links, c) a single aggregator point for the BH traffic was considered, located at the eNB site, and d) the model was not validated through simulations by comparing it to state-of-the-art approaches. In this work, we overcome the aforementioned limitations by developing a general model which provides the optimal solution to the joint problem of user association, BH traffic routing and BS/BH link switching off. We also propose a fast online heuristic, which achieves performance close to optimal in much less time. In addition, we validate the high performance of our proposals by comparing it to other state-of-the-art algorithms. Finally, we give insights on the implementation of our proposed solutions through SDN.

3. Joint User Association, Backhaul Routing and Switching off for Green 5G Networks with mmWave Mesh Backhaul

In this section, we will first describe the employed system model. We then provide the formulation of the joint problem of switching off, user association and BH traffic routing in 5G networks. Finally, due to the increased complexity of the derived optimal solution, we also propose a fast online algorithm. The proposed heuristic aims at providing energy-efficient solutions to the problem, close to the optimal, with reduced complexity.

3.1. System Model

Figure 1: System Model.



We focus on a 5G network, consisting of a set of BSs, i.e., eNBs and SCs, denoted by $\mathcal{B}$. Each eNB area is overlaid with SCs, as depicted in Fig. 1. A set of line-of-sight (LOS) mmWave BH links, denoted as $\mathcal{L}_{BH}$, is also considered for the interconnection of SCs, as well as for their connection with the eNBs. Thereby, a mesh BH network of mmWave links is formed. Moreover, each eNB as well as a given number of SCs per eNB area have a direct fiber connection to the core network, thus playing the role of the aggregators for the eNB area traffic (see Fig. 1). The set of aggregators is denoted by $\mathcal{A}$ with $\mathcal{A} \subseteq \mathcal{B}$. We also consider a set of UEs, denoted by $\mathcal{U}$. We assume a strict guaranteed bit rate (GBR) demand for each UE, represented by D_u, based on its service [18].

In the AN, i.e., for the links between the UEs and their serving BSs, we assume a set of microwave links, denoted by $\mathcal{L}_{AN}$. We also consider flat slow fading channels. Therefore, we employ constant power allocation, i.e., the maximum transmitted power of each BS is divided equally in its physical resource blocks (PRBs). In addition, each UE can be associated only with one BS at a time. We study the downlink case, where the source node is the core network and the sinks are the UEs. As a result, each flow of traffic is routed from the core through the aggregators over some mesh BH links to reach the UE.

3.2. Proposed Analytical Model

The aim of the model is to provide 1) the set of UE associations (i.e., which access link out of the set $\mathcal{L}_{AN}$ each UE will utilize in order to download the data through an aggregator); 2) the routing path that is followed in the BH mesh (i.e., which BH links out of the set $\mathcal{L}_{BH}$ will be used to route each user's traffic and consequently which BH links may be switched off as they do not carry any traffic); and 3) the set of BSs $\mathcal{B}$ (eNBs and/or SCs) that may be switched off.

Without loss of generality, and for the sake of simplicity, from now on, we exclude from our study the fiber links. In other words, we assume that the fiber links, i.e., the links from the core network to the aggregators, are characterized by very high capacity links (e.g. 10, 40 or 100 Gbps) and have negligible power consumption.

The problem is formulated as a MILP, whose objective function is to minimize the total power consumed by the BSs in the network, considering the access and the BH links, which is given by

$$
\begin{aligned}
&\underset{x^u_{(i,u)}, x^u_{(i,j)}, s^{\text{AN}}_i, s^{\text{BH}}_{(i,j)}}{argmin} \quad \sum_{i \in \mathcal{B}} p_i, \\
&\text{s.t.} \qquad a)\ x^u_{(i,u)}, x^u_{(i,j)} \in \{0,1\},\ \forall (i,u) \in \mathcal{L}_{AN},\ \forall (i,j) \in \mathcal{L}_{\text{BH}}, \forall u \in \mathcal{U}, \\
&\qquad\quad b)\ s^{\text{AN}}_i, s^{\text{BH}}_{(i,j)} \in \{0,1\},\ \forall i \in \mathcal{B},\ \forall (i,j) \in \mathcal{L}_{\text{BH}}, \\
&\qquad\quad c)\ \text{Capacity constraint} \\
&\qquad\quad d)\ \text{Power constraints} \\
&\qquad\quad e)\ \text{Switch ON/OFF constraints} \\
&\qquad\quad f)\ \text{Path conservation constraints}
\end{aligned} \tag{1}
$$

where p_i is the total power consumed at BS i considering both the AN and BH links.

3.2.1. Binary Constraints (1a), (1b)

The parameters $x^u_{(i,u)}$ and $x^u_{(i,j)}$ are binary variables that are 1 when the traffic of UE u is routed through the AN link (i,u) or the BH link (i,j), respectively, and 0 otherwise (constraint (1a)). Equivalently, s^{AN}_i, $s^{\text{BH}}_{(i,j)}$ are binary variables that are 1 when the BS i or BH link (i,j), respectively, are active and 0 otherwise (constraint (1b)).

3.2.2. Capacity Constraint (1c)

The total power should be minimized while guaranteeing the traffic demand D_u of each UE. Each UE will thus need a given number of PRBs, denoted by $c_{(i,u)}$, when associated with BS i in order to satisfy this traffic demand D_u, which is given by

$$c_{(i,u)} = \left\lceil \frac{D_u}{BW_{PRB}\ log_2(1 + SINR_{(i,u)})} \right\rceil, \tag{2}$$

where BW_{PRB} is the bandwidth (BW) of a PRB and $SINR_{(i,u)}$ is the effective SINR of the AN link (i,u).

To that end, the total number of used PRBs at each BS cannot exceed its maximum capacity, i.e.,

$$\sum_{u\in\mathcal{U}} \sum_{(i,u)\in\mathcal{L}_{AN}} x^u_{(i,u)} c_{(i,u)} \leq c_{i_{\max}}, \qquad \forall\, i \in \mathcal{B}, \tag{3}$$

where $c_{i_{\max}}$ is the maximum number of PRBs available at BS i.

3.2.3. Power Constraints (1d)

According to our scenario, the total power consumed at each BS i is composed of the power consumed in the microwave links that serve each associated UE (p_i^{AN}), plus the power consumed in the BH links that connect the BS to the rest of the mesh network (p_i^{BH}), i.e.,

$$p_i = p_i^{\mathrm{AN}} + p_i^{\mathrm{BH}} \qquad \forall i \in \mathcal{B}. \tag{4}$$

Each power component, p_i^{AN} and p_i^{BH}, actually consists of two parts: a static one for each active BS or BH link, respectively, and a dynamic one that depends on the traffic volume served on each BS or BH link, respectively.

Thus, in the **AN component**, following the linear approximation suggested in the EARTH project [19], the relationship between the relative RF output power p_{out} and the power consumption at BS i are nearly linear, i.e.,

$$p_i^{\mathrm{AN}} = NTX_i^{\mathrm{AN}}(\, s_i^{\mathrm{AN}} p_{0_i}^{\mathrm{AN}} + \, \Delta_{p_i}\, p_{out_i}^{\mathrm{AN}}), \qquad \forall i \in \mathcal{B}, \tag{5}$$

where NTX_i^{AN} is the number of transceiver chains of BS i (e.g., 8 for 8X8 MIMO), s_i^{AN} is a binary variable that is 1 if BS i is active and 0 otherwise (see (1b)); $p_{0_i}^{\mathrm{AN}}$ is the minimum non-zero output power of the AN transceiver at BS i; $\Delta_{p_i}^{\mathrm{AN}}$ is the slope of the load-dependent power consumption, which can take different values based on the type of antenna used [19]. The parameter $p_{out_i}^{\mathrm{AN}}$ stands for the total transmission power consumed by BS i, which is calculated by

$$p_{out_i}^{\mathrm{AN}} = \frac{p_{\max_i}^{\mathrm{AN}}}{c_{i_{\max}}} \sum_{u\in\mathcal{U}} (x^u_{(i,u)}\; c_{(i,u)}), \qquad \forall i \in \mathcal{B}, \tag{6}$$

where $p_{max_i}^{\mathrm{AN}}$ is the maximum transmission power of BS i. Please note that, due to constant power allocation, the power per PRB is calculated by dividing the maximum transmission power of BS i ($p^{\text{AN}}_{\max_i}$) by the total number of PRBs available to it ($c_{i_{\max}}$).

Similarly, the **BH power component** can be written as

$$p_i^{\text{BH}} = \sum_{(i,j)\in\mathcal{L}_{\text{BH}}} NTX^{\text{BH}}_{(i,j)} \left(s^{\text{BH}}_{(i,j)} p^{BH}_{0_{(i,j)}} + \Delta^{\text{BH}}_{p_{(i,j)}} p^{BH}_{out_{(i,j)}} \right), \qquad \forall i \in \mathcal{B}, \tag{7}$$

where $NTX^{\text{BH}}_{(i,j)}$ is the number of transceiver chains in the BH link (i,j); $p^{\text{BH}}_{0_{(i,j)}}$ is the minimum non-zero output power of the BH transceiver of link (i,j); $s^{\text{BH}}_{(i,j)}$ is a binary variable that is 1 when the BH link (i,j) is active and 0 otherwise, as already mentioned in (1b); and $\Delta^{\text{BH}}_{p_{(i,j)}}$ is the slope of the load-dependent power consumption on the BH link (i,j). The parameter $p^{BH}_{out_{(i,j)}}$ stands for the power consumed by the BH transceiver of link (i,j), and is equal to

$$p^{BH}_{out_{(i,j)}} = \left(2^{\frac{\sum_{u\in\mathcal{U}} x^u_{(i,j)} D_u}{BW_{(i,j)}}} - 1 \right) \alpha_{(i,j)}, \qquad \forall (i,j) \in \mathcal{L}_{\text{BH}}, \tag{8}$$

where $BW_{(i,j)}$ is the BW allocated to the BH link (i,j) and $\sum_{u\in\mathcal{U}} x^u_{(i,j)} D_u$ is the aggregated traffic that passes through it. Moreover, parameter $\alpha_{(i,j)}$ represents the total losses minus the gains of the transmitter and the receiver of the BH link (i,j) and is measured in Watt.

In order to keep the model linear, a linear interpolation function has been used [20]. The linearized version of (8) is thus represented by

$$p^{BH}_{out_{(i,j)}} = \begin{cases} slope_1\ \alpha_{(i,j)}, & \text{if } load^{\text{BH}}_{(i,j)} \leq bkp_1 \\ slope_2\ \alpha_{(i,j)}, & \text{if } bkp_1 \leq load^{\text{BH}}_{(i,j)} \leq bkp_2 \\ \vdots & \\ slope_k\ \alpha_{(i,j)}, & \text{if } load^{\text{BH}}_{(i,j)} \geq bkp_{(k-1)} \end{cases}, \qquad \forall (i,j) \in \mathcal{L}_{\text{BH}}, \tag{9}$$

where $slope_{1\ldots k}$ are the slopes of the piecewise function; $bkp_{1\ldots(k-1)}$ are the breakpoints at which the slope of the piecewise changes [20]; and the parameter $load^{\text{BH}}_{(i,j)}$ can be computed as

$$load^{\text{BH}}_{(i,j)} = \frac{\sum_{u\in\mathcal{U}} x^u_{(i,j)} D_u}{BW_{(i,j)}}. \tag{10}$$

The output transmitted power of the BH link (i,j) is bounded by the maximum transmission power permitted on a BH link ($p^{\mathrm{BH}}_{max_{(i,j)}}$), i.e,

$$0 \leq p^{\mathrm{BH}}_{out_{(i,j)}} \leq p^{\mathrm{BH}}_{max_{(i,j)}}. \tag{11}$$

3.2.4. Switch ON/OFF Constraints (1e)

As already explained, two binary variables have been used for modeling the activity at each BS: one for the AN of each BS (s^{AN}_i) and another one for each BH link ($s^{\mathrm{BH}}_{(i,j)}$). The parameter s^{AN}_i is 1 when at least one UE is associated to BS i (we remind that $x^u_{(i,u)} = 1$ when UE u is associated to BS i, and 0 otherwise). Therefore, we have

$$\begin{cases} \sum_{u\in\mathcal{U}} \sum_{(i,u)\in\mathcal{L}_{\mathrm{AN}}} x^u_{(i,u)} > 0 \implies s^{\mathrm{AN}}_i = 1 \\ \sum_{u\in\mathcal{U}} \sum_{(i,u)\in\mathcal{L}_{\mathrm{AN}}} x^u_{(i,u)} = 0 \implies s^{\mathrm{AN}}_i = 0 \end{cases} \quad \forall\, i \in \mathcal{B}. \tag{12}$$

Employing linear problem transformation techniques, (12) can be written as

$$\left(1 \leq \sum_{u\in\mathcal{U}} \sum_{(i,u)\in\mathcal{L}_{\mathrm{AN}}} x^u_{(i,u)} \quad \text{and} \quad 1 \leq s^{\mathrm{AN}}_i\right) \quad \text{or} \quad \left(\sum_{u\in\mathcal{U}} \sum_{(i,u)\in\mathcal{L}_{\mathrm{AN}}} x^u_{(i,u)} \leq 0\right), \tag{13}$$

$\forall i \in \mathcal{B}$. By defining a new binary variable y^{AN}_i, we can thus rewrite (13) through the following three linear constraints

$$\begin{cases} \sum_{u\in\mathcal{U}} \sum_{(i,u)\in\mathcal{L}_{\mathrm{AN}}} x^u_{(i,u)} + M1\, y^{\mathrm{AN}}_i \geq 1 \\ s^{\mathrm{AN}}_i + M1\, y^{\mathrm{AN}}_i \geq 1 \\ \sum_{u\in\mathcal{U}} \sum_{(i,u)\in\mathcal{L}_{\mathrm{AN}}} x^u_{(i,u)} \leq M2\,(1 - y^{\mathrm{AN}}_i) \end{cases} \quad \forall\, i \in \mathcal{B}, \tag{14}$$

where M1 and M2 are big positive numbers.

Similarly, $s^{\mathrm{BH}}_{(i,j)}$ represents the activity in the BH link (i,j), and it is 0 when no traffic is routed on link (i,j), as already mentioned. Thus,

$$\begin{cases} \sum_{u\in\mathcal{U}} x^u_{(i,j)} > 0 \implies s^{\mathrm{BH}}_{(i,j)} = 1 \\ \sum_{u\in\mathcal{U}} x^u_{(i,j)} = 0 \implies s^{\mathrm{BH}}_{(i,j)} = 0 \end{cases} \quad \forall\, (i,j) \in \mathcal{L}_{\mathrm{BH}}. \tag{15}$$

Eq. 15 can be rewritten through the three following linear constraints

$$\begin{cases} \sum_{u\in\mathcal{U}} x^u_{(i,j)} + M3\, y^{\mathrm{BH}}_{(i,j)} \geq 1 \\ s^{\mathrm{BH}}_{(i,j)} + M3\, y^{\mathrm{BH}}_{(i,j)} \geq 1 \\ \sum_{u\in\mathcal{U}} x^u_{(i,j)} \leq M4\,(1 - y^{\mathrm{BH}}_{(i,j)}) \end{cases} \qquad \forall\,(i,j) \in \mathcal{L}_{\mathrm{BH}}, \tag{16}$$

where M3 and M4 are big positive numbers.

3.2.5. Path Conservation Constraints (1f)

The traffic for each UE u is generated at the source node (i.e., the core network in this work), flows on a given route in the mesh BH network and is delivered at the sink (i.e., one UE in this work). Thus, the path conservation constraints enforce that the traffic entering a given BS must exit it, unless the BS is the source or the sink of the traffic. Thus,

$$\sum_{(i,j)\in\mathcal{L}_{\mathrm{BH}}\cup\mathcal{L}_{\mathrm{AN}}} x^u_{(i,j)} - \sum_{(j,i)\in\mathcal{L}_{\mathrm{BH}}\cup\mathcal{L}_{\mathrm{AN}}} x^u_{(j,i)} = \begin{cases} 1, & \text{if } i = \text{ source}, \\ -1, & \text{if } i = u \text{ (sink)}, \\ 0, & \text{otherwise}, \end{cases} \tag{17}$$

$\forall u \in \mathcal{U},\ \ \forall i$ and $j \in \mathcal{B} \cup \mathcal{U}$.

Also, we must ensure that the traffic of each UE follows a single route (i.e., flows are not allowed to be split over multiple paths). Hence, for every user $u \in \mathcal{U}$ whose traffic passes through BS i, among all the links exiting i only one can carry the traffic of UE u (i.e., $x^u_{(i,j)}$ can be 1 for only one of all possible links (i,j) exiting BS i). Therefore,

$$\sum_{(i,j)\in\mathcal{L}_{\mathrm{BH}}\cup\mathcal{L}_{\mathrm{AN}}} x^u_{(i,j)} \leq 1, \qquad \forall u \in \mathcal{U},\ \forall i \in \mathcal{B}. \tag{18}$$

Finally, each UE u can connect to a single BS at a time. Hence,

$$\sum_{(i,u)\in\mathcal{L}_{\mathrm{AN}}} x^u_{(i,u)} = 1, \qquad \forall u \in \mathcal{U}. \tag{19}$$

3.3. Proposed Heuristic Algorithm (PHEUR)

The complexity of the optimal solution derived by Section 3.2 increases significantly for a higher number of BSs and UEs. In particular, a brute-force search

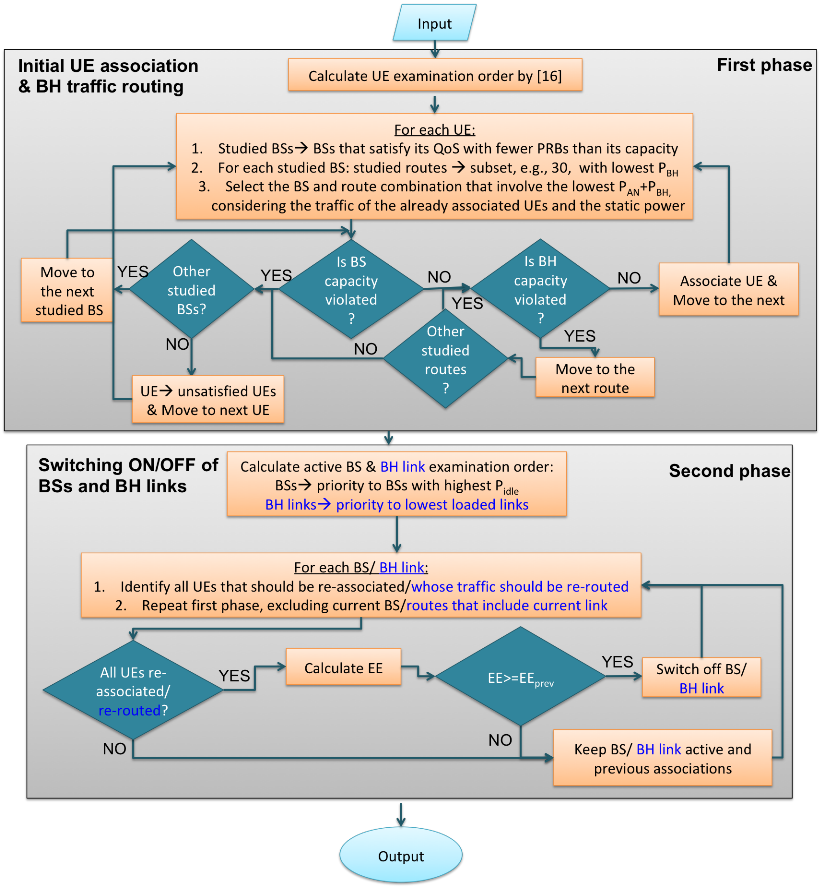


Figure 2: Proposed heuristic algorithm (PHEUR) flowchart.

method would involve examining $(\sum_{i=1}^{\mathcal{B}} \mathcal{L}_{routes_i})^{\mathcal{U}}$ different combinations, with $\mathcal{L}_{routes_i}$ standing for the set of alternative routes when connected to BS i. As a result, it presents $\mathcal{O}(n^n)$ complexity, which is prohibitive for large systems. To that end, we propose a heuristic algorithm, named as PHEUR, which decides the user association, the BH traffic routing and consequently the switching off of BS and BH links, so that high network energy efficiency is achieved.

PHEUR consists of two phases, as depicted in the algorithm flowchart in Fig. 2. The first phase refers to the initial association and BH routing decision and the second to the switching off of BSs and BH links and the recalculation of association and BH routing. In the first phase, the order in which the UEs will be examined is first decided according to [16], targeting at high energy efficiency. To that end, priority is given to the UEs for whom another association and routing than the "considered as best" will provoke a higher loss in energy efficiency, as explained in [16]. Once the UE examination order is decided, for each UE a subset of BSs is selected and for each one of them a subset of alternative routes in order to decrease the algorithm complexity. In particular, given that each UE demands a specific number of PRBs (different for each BS, since a different signal-to-interefence-plus-noise ratio (SINR) is received by each one of them) to meet its QoS, only the BSs that can satisfy the UE QoS without violating their capacity are considered. In parallel, for each of these BSs, only a subset of routes, e.g., 30, that involve the lowest power consumption, are considered. Among the different combinations of BSs and BH routes, the one that involves the lowest power consumption is selected, once both the traffic of the already associated UEs, as well as the static power consumption are taken into account. The rationale behind that is to minimize the BH power consumption not only by selecting the less energy consuming route but also by distributing the traffic in the BH links so that fewer bottlenecks are created.

In the second phase, we first categorize the active BSs (that have non-zero load) according to their idle power (the power consumed under zero load) as well the idle power of the BH links of their less energy consuming route in descending order (starting with the BS with the highest power value). This stems from the fact that the energy efficiency gain when switching off the BS with the highest P_{idle} will be higher. In parallel, even for BSs with the same P_{idle}, switching off the BS whose traffic is routed through more BH hops, thus involving higher P_{idle} in the BH, would result in further energy efficiency gain. Once the examination order of the active BSs is defined, PHEUR starts with the first BS and examines if all its associated UEs can be re-associated to other BSs, applying the criteria already described. In case all the UEs of the BS can be re-associated, PHEUR compares the energy efficiency of the system before and after the deactivation of the BS. Only in case of energy efficiency gain, PHEUR switches off the BS and re-associates its UEs, as decided. This procedure is repeated until all active BSs have been processed. Finally, a similar procedure takes place for the BH links. In particular, only a subset of links is considered to reduce the algorithm run-time, e.g., the BH links with utilization lower than 40%. For these links, we check if their traffic can be routed through other routes applying the criteria already described. If all the traffic of the link can be re-routed, the link is deactivated if this action involves positive energy efficiency gain. Then, the next links are processed until the process is terminated.

3.4. Energy-aware SDN-based mmWave Mesh Backhaul Management

In this section, we discuss how our model can be implemented in a real mesh-based BH network. By adopting an SDN-based architecture, the control plane is decoupled from the data plane, and a centralized entity (SDN controller) can be responsible for the management of the BH network. More concretely, the SDN controller can manage a wireless mesh BH control plane, by installing forwarding rules in the mesh nodes, but also by configuring the used links and network devices (e.g., power management or wireless link configuration) [21]. Forwarding rules are mostly managed through the OpenFlow (OF) protocol, while the remaining configurations can be performed by the Simple Network Management Protocol (SNMP), or by using OF itself with additional extensions that introduce new configuration primitives to its Southbound APIs, or through custom-made communication protocols. On top of it, network applications can communicate with the controller and enforce network policies through its Northbound API (typically through RESTful services).

To enable the configuration of a mesh BH with the aid of the proposed algorithms, additional system design decisions need to be considered. The topology data that is needed as input to our model needs to be extracted by the SDN controller (which can include the existing links, nodes, traffic demands and mesh nodes/UE positioning), and parsed into a commonly used data format, e.g., JSON, that can be sent to a REST server, which translates it into an input that can be read by the network optimizer, which runs the optimization model using e.g., the optimal solution derived by the model or the heuristic. The inverse steps are required for the computed solutions, as they need to be transformed from a model output (or from the heuristic) to a data format that the SDN controller will receive in one of its Northbound APIs. Then, internally, the SDN controller must orchestrate the received solution into the respective (re-)configuration steps that are necessary to (re-)configure the BH, according to the optimizer output.

Additionally, while the proposed algorithm can provide the SDN controller with a new configuration snapshot of the managed network, the process of how to enforce the new configuration requires special attention, as this process should be as seamless as possible, to minimize the disruption of the existing network traffic [22]. In order to go from a previous network state to a new configuration, changes may be necessary that require e.g., powering on/off mesh nodes, configuring mmWave interfaces (through hardware and software) and updating the respective OF rules. This may require to consider additional configuration times, which require additional constraints to be imposed. For example, a mesh node can take several seconds to boot from an off or idle state, having its network interfaces' configuration only possible to be triggered after the node is on. Simultaneously, the mmWave interface in the other end of the link might be in use before the new configuration is enforced and any major changes to its setup can affect the ongoing UE or BH traffic. Therefore, the orchestration of the new network state needs to have additional logic that defines when the power, link and forwarding rules arrangement should happen, which is outside the scope of this paper.

This process can turn out to be significantly complex, if we consider that there are service availability constraints in our network, and that backup paths (not necessarily having only nodes from the model's output solution) need to be established, as intermediate steps of the network reconfiguration. Due to the complexity of this new problem, it is also possible that the SDN controller outsources the reconfiguration procedure order into a different computational entity that can return a set of timed instructions related to the network configuration (e.g., at t=1, power on node A, at t=4 establish link between interface 1 of node A and interface 2 of node B).

Figure 3 depicts an example of an SDN architecture that uses the proposed algorithm for obtaining a new network configuration. Its output is then parsed by the SDN controller, which has internal components that translate the received power, link and rule configuration instructions into OF messages that are sent to the mesh nodes, through the existing control channel.

Finally, what triggers a mesh network reconfiguration request from the SDN controller needs to be specified, as multiple factors can influence this decision. A very basic one can be a periodic reconfiguration request (every hour, for example), while more aggressive reactive triggers can induce the need for a new setup, such as the increase of UEs/traffic in parts of the mesh network, connectivity problems with the mmWave links (e.g., a long-lasting transition from LOS to non line-of-sight (NLOS)), or more complex approaches based on periodic power/traffic/energy efficiency measurements that can detect the need of a new network configuration.

4. Evaluation

In this section, we evaluate the performance of the proposed solutions under 3GPP scenarios of varying traffic conditions. In particular, the proposed heuristic algorithm (PHEUR) is compared both with the optimal solution, derived by the analytical model proposed in Section 3.2, as well as with state-of-the-art algorithms of the field.

4.1. Simulation Scenario

4.1.1. Topology

In our simulations, without loss of generality and in accordance with the scenario specifications proposed by 3GPP [23], we focus on a single eNB sector of a radius of 500 m, overlapped with two clusters of SCs, as depicted in Fig. 4.

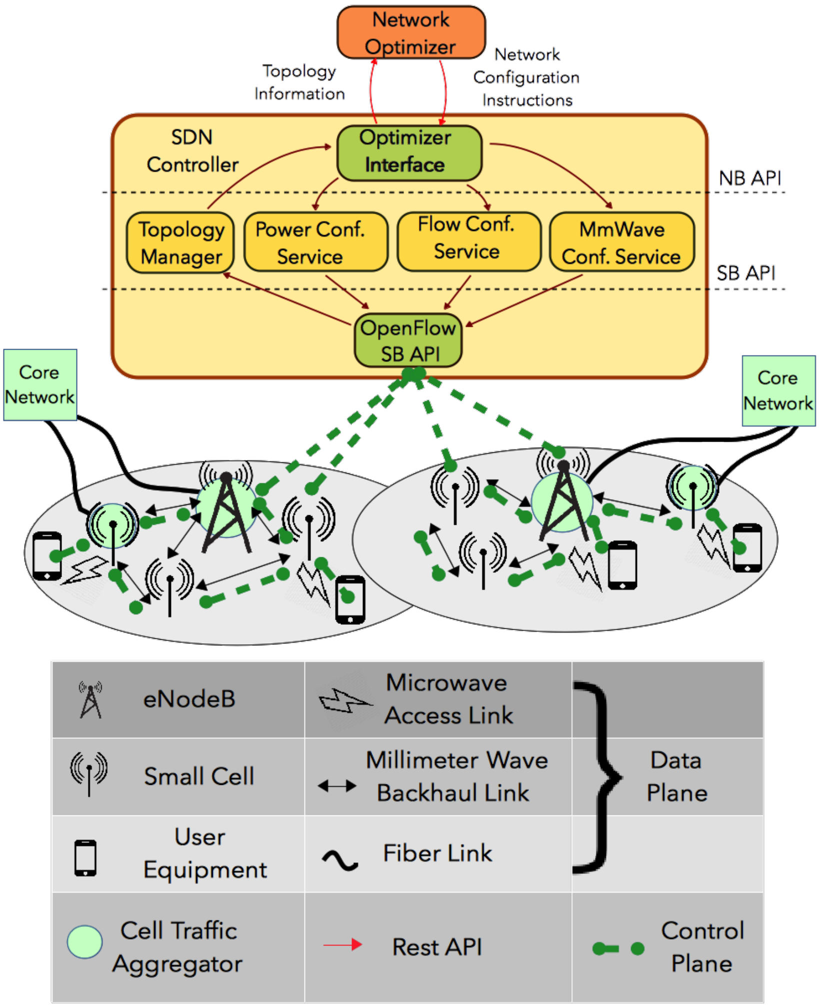


Figure 3: MmWave mesh backhaul network optimization using a Software Defined Networking (SDN) based architecture.

Figure 4: Simulation scenario example.

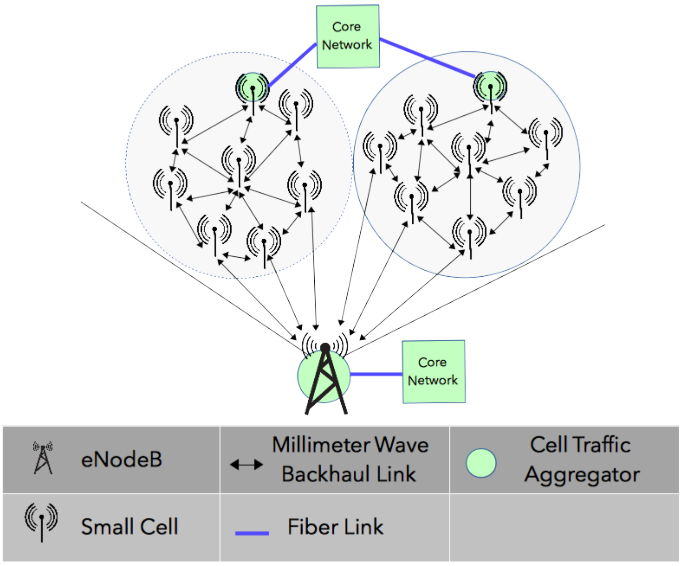


Table 1: Minimum allowable distances [23].

	Min. distance (m)
SC-SC	20
SC-UE	5
eNB-cluster center	105
eNB-UE	35
cluster center-cluster center	2*Radius for small cell dropping in a cluster= 200

Each cluster center is uniformly dropped in the eNB sector area. Each cluster consists of eight SCs, which are uniformly dropped in an 100-m-radius from the cluster centers. The minimum allowable distances are summarized in Table 1 according to [23]. The eNB is assumed to have a direct connection through fiber to the core network. Moreover, we randomly select one SC per cluster to be also fiber-connected directly to the core (see Fig. 4). These three nodes act as traffic aggregators which distribute the traffic through the BH to the UEs.

4.1.2. Backhaul Network

The mesh BH network consists of LOS mmWave links operating at 60 GHz with 200 MHz channel bandwidth and $G^{BH}_{T_X,(i,j)}$=$G^{BH}_{R_X,(i,j)}$=30 dBi transceiver antenna gain for each BH link (i,j). The transmitter and receiver losses are equal to $T_{X_{loss},(i,j)}$=$R_{X_{loss},(i,j)}$=5 dB, while the receiver noise figure is $NF^{BH}_{(i,j)}$=30 dB for each link (i,j). To make the mesh BH setup more realistic, we take into account all the possible BH links as long as they are shorter than 150 m. The rationale behind that is to consider multi-hop routes of short LOS mmWave BH links of good coverage [24].

For 60 GHz, the maximum transmitted power is calculated as [25]

$$p^{\mathrm{BH}}_{max_{(i,j)}(dBm)} = EIRP_{max(dBm)} + T_{X_{loss},(i,j)(dB)} - G^{BH}_{T_X,(i,j)(dBi)}, \tag{20}$$

where $EIRP_{max}$ is the maximum equivalent isotropically radiated power, equal to

$$EIRP_{max(dBm)} = 85_{(dBm)} - 2 \cdot x_{(dB)}, \tag{21}$$

where x represents the number of dB that the antenna gain of the transmitter ($G^{BH}_{T_X,(i,j)}$) is lower than 51 dBi, i.e., x=21, and consequently $p^{\mathrm{BH}}_{max_{(i,j)}}$=18 dBm=0.0631 W. For the total path loss at 60 GHz, i.e., the sum of the free space path loss [26] and the signal attenuation due to oxygen, vapour [27] and rain [28], we use the model described in [25]. We assume rain rate equal to 50 mm/h, path elevation angle 0° and polarization tilt angle relative to horizontal 0°. The total air pressure is assumed to be equal to 1013.25 hPa, the temperature to 25 °C and the water vapour concentration to 7.5 g/m^3. The link margin is assumed to be 15 dB and the thermal noise density is -174 dBm/Hz. In addition, we consider the interference among adjacent BH links negligible, due to the high signal attenuation at these high frequencies. This is a viable assumption, as the interference can be also mitigated by low-complexity frequency allocation techniques that can be performed at an initial stage due to the static nature of the BH network.

4.1.3. Access Network

For the AN links, we assume that they operate at 2 GHz with a 20 MHz channel (100 PRBs) allocated to each BS. The maximum transmitted power of the eNB is 46 dBm=39.8107 W and of each SC is 30 dBm=1 W [23]. We exploit 8x8 MIMO for both the eNB and the SCs. The path loss model of [24] is employed, where

$$L_p = 69.55 + 26.16 log f_{AN(MHz)} - 13.82 log h_{(m)} - CH + \\ + \left(44.9 - 6.55 log h_{(m)}\right) log d_{(km)}, \tag{22}$$

with f_{AN} the operating frequency in MHz (f_{AN}=2000), h is the antenna height (h_{eNB}=25m, h_{SC}=2.5m and h_{UE}=1.5). The noise figure for the UE is 9 dB and the antenna gains are $G_{T_x eNB}$=17dB and $G_{T_x SC}$=5dB. The antenna correction factor for the SC is equal to 0, whereas for the eNB is calculated as [24]

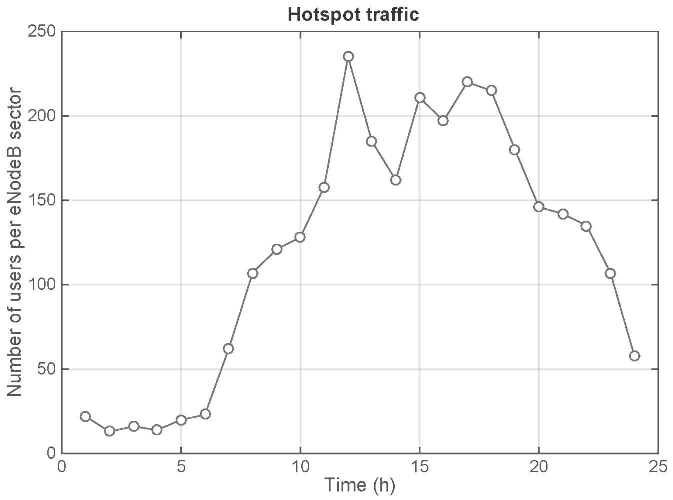
$$C_H = 0.8 + (1.1 log f_{(MHz)} - 0.7) h_{UE(m)} - 1.56 log f_{(MHz)}. \tag{23}$$

The eNB uses orthogonal channels compared to the SCs so as not to interfere with them. However, the SC frequencies are reused per cluster and thus a SC belonging to a cluster interferes to one SC of the other cluster. To mitigate this generated interference, we allocate the same frequencies to SCs based on their distances, so as to ensure the highest distance possible among SCs that use the same spectrum resources. The shadowing is modeled through a log-normal random variable with 0 dB mean and variance 8 dB for the eNB and 10 dB for the SCs [23].

4.1.4. User Traffic Profile

We assume hotspot UE traffic distribution, with 2/3 of UEs randomly located in a 100-m-radius from the cluster centers and 1/3 uniformly distributed in the eNB sector area [23]. We also consider the traffic pattern of [10], which refers to the fluctuations in terms of number of UEs (per eNB sector) throughout a day. In addition, we assume the following statistics for the GBR demands of the UEs: 70% of UEs require 100 Mbps, 20% 200 Mbps and 10% 300 Mbps [18].

Figure 5: Traffic pattern throughout a day in terms of number of users per eNodeB (eNB) sector area [10].



4.1.5. Energy-related Parameters

The number of transceiver chains is assumed to be 8 for both the eNB, the SCs and each BH link and the traffic-dependent energy coefficient is Δ_{eNB}=4.7 for the eNB, Δ_{SC}=4 for the SCs and Δ_{BH}=10^5 for each BH link [19]. The power consumed at zero load is assumed equal to 130 W for the eNB, 6.8 W for the SC and 3.9 for each BH link transceiver [29].

4.1.6. Studied Algorithms

Proposed Algorithms.

- **Optimal**: The optimal solution of the analytical framework proposed in Section 3.2. It is implemented in CPLEX, through an exhaustive branch-and-cut search algorithm. Thereby, it finds the optimal combinations for user association, BH traffic routing and BS/BH link switching off so as to maximize the network energy efficiency at the expense of potentially higher computational time.

- **PHEUR**: The proposed heuristic algorithm, which was elaborated in Section 3.3. *PHEUR*, aims at providing low complexity energy-efficient solutions to the aforementioned problem, while considering both the AN and BH links.

State-of-the-art Algorithms.

- **Joint-no switch off**: The energy-efficient algorithm that was proposed in [16], which considers both the AN and BH, but no switch off option. In particular, *Joint-no switch off* favors the association that involves the minimum variable power consumption (the static part was not taken into account), while guaranteeing the UE QoS. In the case of alternative BH routes, the traffic of the already associated UEs is taken into account so that load balancing is achieved.

- **TVT**: The switching off algorithm, proposed in [11]. Initially, the UEs get associated to the BSs based on their SINR. For the switching off process, the algorithm examines first the eNB and then the SCs starting with the lowest loaded ones. For each BS, it checks whether its UEs can be re-associated to the BS from which they receive the second highest signal. If this is possible, it switches off the BS as long as this move involves energy efficiency gain. Otherwise, it continues with next BS to be studied. As this algorithm does not take into account the BH, for a fair comparison, we extended it by selecting the route that involves the lowest power consumption, considering both the static and the variable power consumption part (assuming the same load for all routes to compare them under the same basis). Thereby, e.g., if we assume the same antenna gain and bandwidth available per link, priority is given to the routes with fewer BH hops and shorter links.

- **50%-random**: Half of the initial set of BSs are randomly selected to switch off, as long as there are other active BSs to guarantee the QoS of the re-associated users [12]. In terms of BH traffic routing, for a fair comparison, we extended this approach with the BH routing strategy described in TVT.

- **50%-lowest load**: Similar to 50%-random, however, half of the initial set of BSs with the lowest number of UEs are selected to be switched off, as long as there are other active BSs to guarantee the QoS of the re-associated users [12]. As for the BH routing, we extended also this approach with the BH routing strategy described in TVT.

- **SINR**: No switch off, where the UEs connect to the cells with the highest received signal power [7]. As this algorithm only considers the AN, for a fair comparison, we combine it with the following BH traffic routing algorithms.

  – **random**: Among alternative BH routes, a random choice takes place.

  – **min power**: The BH route that involves the lowest power consumption is selected, considering both the static and the variable power consumption part, as explained in TVT.

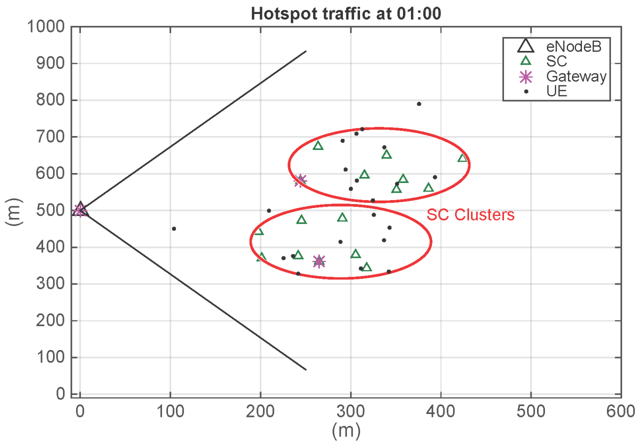
Please note that for a fair comparison, in all cases if a BS or a BH has zero load, it is switched off. Furthermore, for all the switching off algorithms that do not propose an initial user association (50%-random, 50%-lowest load) we assume that the UEs are initially associated based on the SINR-min power and then the switching off algorithms are applied.

4.1.7. Simulation Environment

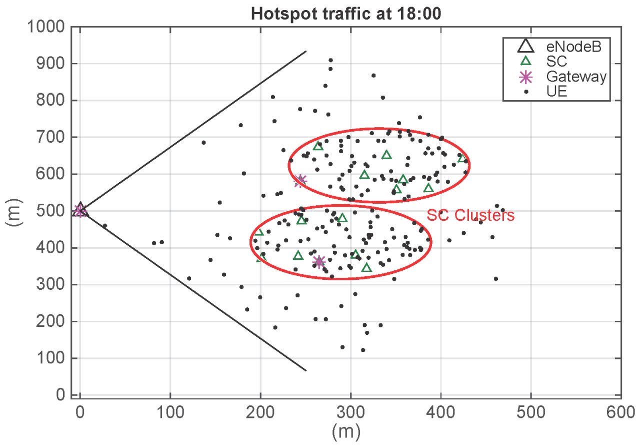
Extensive simulations were executed in MATLAB© 2014b. We studied 5 different deployment scenarios and we examined the average performance of the studied metrics per hour. An example of a deployment scenario for two different time instants, for low and high traffic, respectively, is depicted in Fig. 6.

4.2. Simulation Results

In Fig. 7, we depict the normalized average energy efficiency of the network compared to *Optimal* for all algorithms throughout the day. As the traffic in-



(a)



(b)

Figure 6: Simulation scenario example for low and high traffic, i.e., at hours 1:00 and 18.00, respectively.

creases, the performance of all algorithms deteriorates, since there are higher capacity demands and thus fewer switching off opportunities. The *Optimal* achieves the best performance, as expected, which, however, comes at the expense of increased complexity, as shown in Fig. 8. Note, for example, that at

Figure 7: Normalized network energy efficiency throughout a day compared to Optimal for all algorithms.

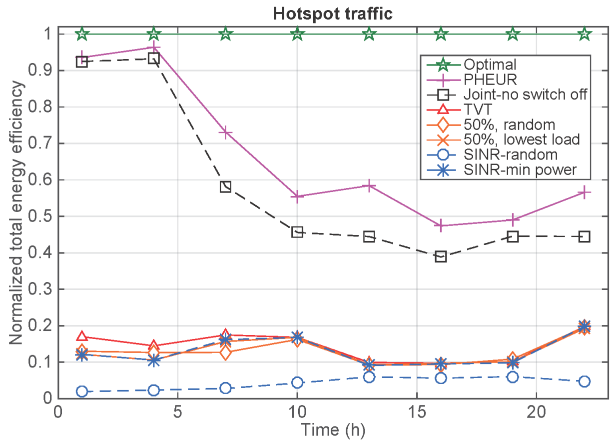
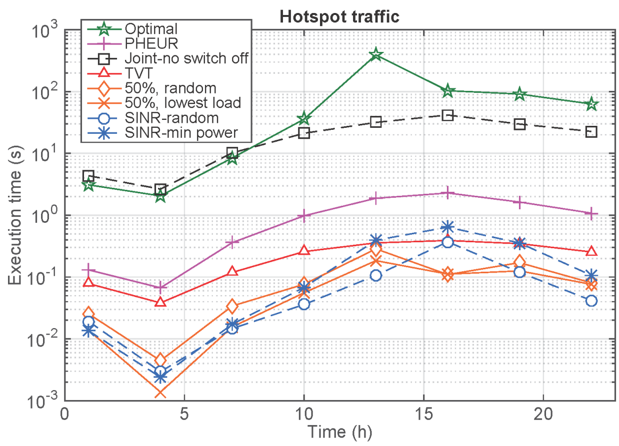


Figure 8: Average execution time in seconds in logarithmic scale for all algorithms.



13:00 the *Optimal* requires up to 10 times higher execution time than the state-of-the-art. Still, it provides much more energy-efficient solutions compared to the other algorithms. Another important parameter is that the *Optimal*, unlike the state-of-the-art, achieves zero blocking probability, i.e., it satisfies the

Figure 9: Average blocking probability in % throughout a day for all algorithms.

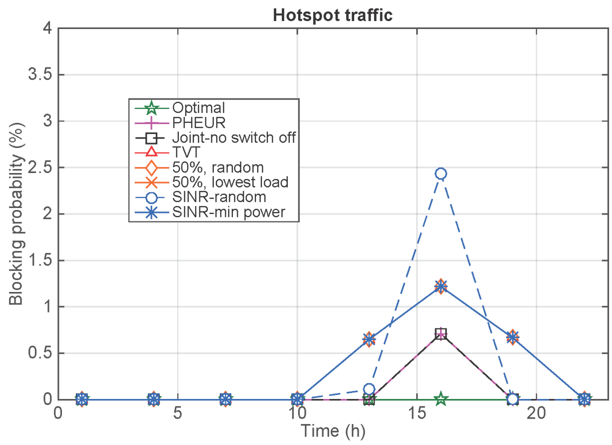
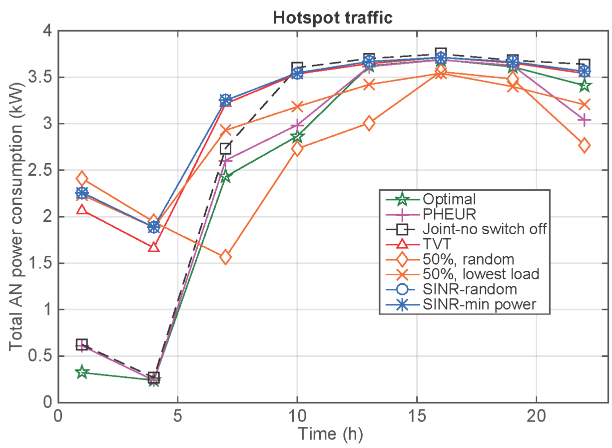


Figure 10: Average total power consumed in the access network throughout a day for all algorithms.



demands of all UEs throughout a day, as depicted in Fig. 9. This is due to the fact that, for high traffic, there is a very small number of feasible solutions, which *Optimal* is able to find after long execution time periods.

As for the rest of the algorithms, *PHEUR* and *Joint-no switch off* achieve

Figure 11: Average total power consumed in the backhaul network throughout a day for all algorithms.

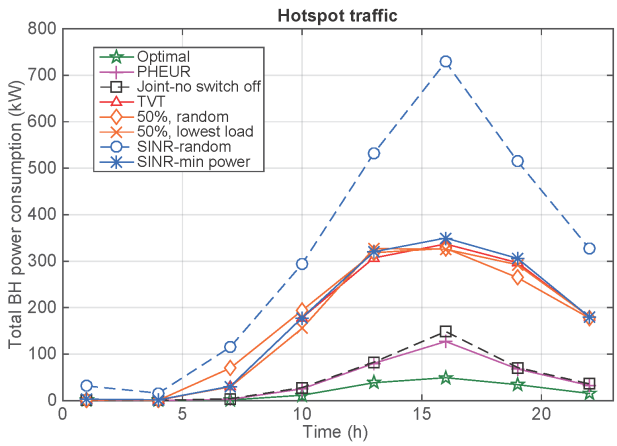
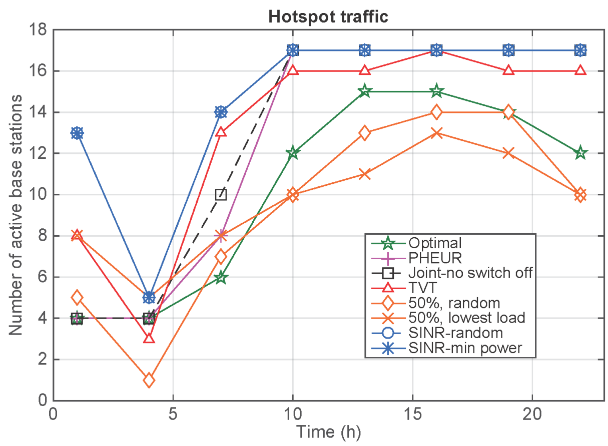
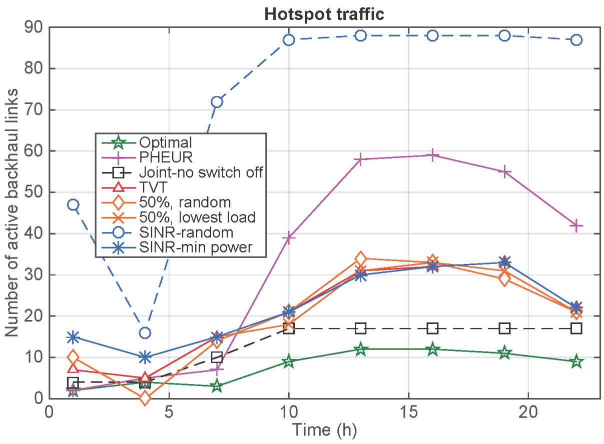


Figure 12: Average number of active base stations throughout a day for all algorithms.



performance close to optimal with decreased complexity. Still, *PHEUR* outperforms *Joint-no switch off* both in terms of energy efficiency and execution time. This stems from the fact that *Joint-no switch off*, unlike *PHEUR*, examines all possible BH link paths, which results in much higher overhead in such

Figure 13: Average number of active backhaul links throughout a day for all algorithms.



mesh topologies where a very high number of alternative paths is available. Moreover, the static part of the BSs and BH links is not taken into account, unlike *PHEUR*, which favors the switching off of BSs with high static power consumption, e.g., the eNB, by avoiding associating the UEs to them, as long as this is possible. Thereby, *PHEUR* achieves higher energy saving gains up to 49 times higher than the state-of-the-art solutions. In terms of blocking probability, *PHEUR* and *Joint-no switch off* achieve the same performance as the BH traffic is distributed more evenly and thus BH bottlenecks are avoided. In order to gain further insights, we depict in Fig. 10 and 11, the AN and BH power consumption, respectively, in kW for all algorithms throughout a day. In addition, the average number of active BSs and BH links is depicted in Fig. 12 and 13, respectively. It is worth pointing out that the BH power consumption of *PHEUR* is lower, although it involves a higher number of active *BH* links than most algorithms. This shows the ability of the algorithm to adapt to the system parameters. In this case, for instance due to the high traffic-dependent energy coefficient value ($\Delta^{BH}_{p_{(i,j)}}$), it is more preferable to distribute evenly the traffic in the links and thus to create more links of lower traffic.

The rest of the state-of-the-art achieves similar performance in terms of energy efficiency except for *SINR-random*, which selects the BH routes randomly. Hence, it results in much higher BH power consumption (up to 86 times higher), as shown in Fig. 11. Due to the randomness in the BH traffic routing of *SINR-random*, this algorithm presents higher blocking probability for high traffic (see Fig. 9), as most BH links reach their capacity limit. Then, TVT achieves better performance than the state-of-the-art but only for low traffic, as it gives the ability to re-associate the UEs only to the BS from which they receive the second highest SINR. As a result, for high traffic the switching off possibilities become very low. Finally, *50%-random* achieves initially better performance than *50%-lowest load*, as in some cases the eNB is selected randomly to switch off, thus leading to high energy saving. On the other hand, as the traffic increases *50%-lowest load* achieves better performance, since the probability of switching off a low loaded BS is higher. Therefore, *50%-lowest load* is able to switch off more BSs (see Fig. 12).

5. Conclusion

In this paper, we have developed an energy optimal policy for joint user association, backhaul traffic routing and base station and backhaul link switching off for green 5G networks with mmWave mesh backhaul links that satisfies user demands in terms of rate. As the policy is based on a mixed integer optimization model, it is complex to solve but allows to calculate a theoretical optimal energy-efficient configuration of such networks. For online optimization, we developed a fast iterative solution heuristic, which solves in the first phase the energy-efficient user association and backhaul routing problem while calculating alternative options for association and backhaul routing that are both energy-efficient and satisfy the user demands. In the second phase, we sort the active base stations and backhaul links by their static power consumption in descending order. Iteratively, the heuristic tries to re-associate users and reroute the flows until all users of a base station can be served by other cells and if so it powers down the given cell/backhaul link if this leads to a more energy-efficient configuration of the network.

An extensive numerical evaluation demonstrates the benefit of our optimization policies in terms of energy efficiency while guaranteeing the users traffic demands. We have also discussed the feasibility of implementing our optimization policies into the framework of SDN-based mesh backhaul configuration, where an SDN controller is in charge to run the model or the heuristic and enforce the resulting backhaul reconfigurations. We believe the optimization policies provide an important basis for the design of real protocols for mmWave-based mesh backhaul networks and our SDN-based reconfiguration provides an important input into the architecture discussion for next generation (5G) cellular network design.

Acknowledgements

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