Energy-efficient Context-aware User Association for Outdoor Small Cell Heterogeneous Networks

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Abstract—To meet the ever-increasing traffic demands, future cellular networks are about to include a plethora of small cells (SCs), with user equipments (UEs) being able of communicating via multiple bands. Given that SCs are expected to be eventually as close as 50 m apart, some of them will not have a direct connection to the core network, and thus will forward their traffic to the neighboring SCs until they reach it. In such architectures, the user association problem becomes challenging with backhaul (BH) energy consumption playing a key role. Thus, in this paper, we study the user association problem aiming at maximizing the network energy efficiency. The problem is formulated as an optimization problem, which is NP-hard. Therefore, we propose a cognitive heuristic algorithm that exploits context-aware information (i.e., UE measurements and requirements, the HetNet architecture knowledge and the available spectrum resources of each base station (BS)) to associate the UEs in an energy-efficient way, while considering both the access and the BH energy consumption. We evaluate the performance of the proposed algorithm under two study-case scenarios and we prove that it achieves significantly higher energy efficiency than the reference algorithms, while maintaining high spectral efficiency.

Index Terms—User association, context-awareness, LTE-Advanced, backhaul, small cells, green communications.

I. INTRODUCTION

During the last years, the mobile data traffic is growing exponentially, resulting in increased energy consumption. Hence, it becomes urgent for mobile operators to maintain sustainable capacity growth to meet these new demands and at the same time, to limit their electric bill. Consequently, the maximization of the network energy efficiency will be of high importance when dealing with next generation networks [1].

A way of achieving capacity enhancement is to add more macrocell base stations (BSs) (i.e., eNodeBs (eNBs) in the long term evolution (LTE) terminology) to the network. When eNBs are added: i) the distance between user equipments (UEs) and eNBs is reduced and thus the signal to interference plus noise ratio (SINR) increases and ii) each UE competes with a smaller number of UEs for an eNB's bandwidth and backhaul (BH) connection. However, in many important markets, adding further eNBs is not viable due to cost and the lack of available sites and proper connections among them. Consequently, future cellular networks will be organic deployments of BSs of widely varying transmit powers and coverage areas (i.e., eNBs and/or small cells (SCs)), carrier frequencies, BH connection types, and communication protocols. In such

heterogeneous networks (HetNets), UEs will be capable of communicating via multiple bands over various protocols, thus making the user association a challenging problem.

At the same time, as SCs are expected to be eventually as close as 50 m apart [2], not all of them will have a direct connection to the core network. To that end, LTE-Advanced (LTE-A) [3] considers that a SC may be connected to the core network through a gateway, known as Home eNB gateway. NGMN Alliance [4] and Tellabs [5] also consider an optional aggregation gateway to be introduced for better scalability (e.g., reducing the logical S1 interfaces to be supported by the core network). Moreover, assuming that the operator already has a radio network in place, a straightforward option is to connect the SC directly to the eNB site, especially in cases where there is fiber access available [4], [5]. From a topology perspective, this would look like a traditional hub-and-spoke, with SCs as spokes and the eNB as hub, while chain, tree or mesh [6] topologies can provide further connectivity between SCs [5]. In such topologies, where one SC backhauls its traffic to the neighbor SC, the user association becomes even more challenging. Thus, although most user association approaches so far take into account only the access network, future architectures call for backhaul-aware strategies.

In parallel, backhauling imposes new challenges. Due to the large number of BH links, the BH network dimensioning becomes more complicated, the capital expenditure (CAPEX) increases and so does the network energy consumption (i.e., operational expenditure, (OPEX)). Thus, maximizing the total energy efficiency becomes of high importance.

To that end, in this paper, we study the user association problem aiming at maximizing the network energy efficiency in scenarios where several SCs backhaul their traffic to the neighboring SCs until they reach the core network. We formulate the problem as an optimization problem, which is shown to be NP-hard. Therefore, we propose a cognitive heuristic algorithm that exploits the available context-aware information (i.e., UE measurements and requirements, the HetNet architecture knowledge and the available spectrum resources of each BS) to associate the UEs in an energy-efficient way. Specifically: i) it maximizes the spectral efficiency by selecting as candidates for a UE only the cells that demand the minimum resources to satisfy its requirements and ii) it maximizes the network energy efficiency exploiting

its HetNet architecture cognition, by favoring the candidate with the fewer hops to reach the core network, or in case there are more, the one with the less loaded BH route in order to achieve load balancing. Note that this context-aware information can be readily available to all nodes in a LTE-A network, while introducing low overhead (e.g., by transmitting it during the almost blank subframes (ABS) or through the X2 interface between BSs (eNBs and/or SCs) [3]). Finally, we evaluate the performance of the proposed algorithm under two traffic distribution scenarios and we show that it significantly outperforms the other state-of-the-art (SoA) algorithms, while maintaining high spectral efficiency.

The rest of the paper is organized as follows: In Sections II and III, the related work and the system model are respectively presented. In Section IV, the network energy efficiency optimization problem is formulated and in Section V, a heuristic algorithm is proposed that achieves high network energy efficiency. In Section VI, the performance of the proposed algorithm in comparison to other SoA algorithms is evaluated. Finally, Section VII concludes the paper.

II. RELATED WORK

In the literature, the user association problem has received a lot of attention. Specifically in LTE-A, the user association is based on the reference signal received power (RSRP) and/or reference signal received quality (RSRQ). The first measures the average received power over the resource elements that carry cell-specific reference signals (RSs) within certain frequency bandwidth, while the latter measures the portion of pure RS power over the total power received by the UE. Although these criteria maximize the SINR of UEs [7], simulations and field trials have shown that they do not increase the overall throughput as much as hoped, because many of the SCs will typically have few active users. Thus, biasing is motivated, whereby users are actively pushed onto SCs [8]–[16]. Despite a potentially significant SINR hit for that UE, this has the potential for a win-win situation, because the UE gains access to a much larger portion of resources, while the eNB reclaims the ones that would have been allocated to it.

Nevertheless, all the aforementioned approaches consider only the access network, thus totally overlooking any BH issues. Still, the BH is forecast to become the most challenging part for future SCs, especially when considering scenarios as the ones previously described with wireless BH links. In such cases, considering only the best-received signal strength or/and the load of each cell when examining the user association problem is not sufficient. To that end, in [17], the authors model a backhaul-aware BS assignment problem as an optimization problem using a utility-based framework, imposing constraints on both radio and BH resources, and mapped into a multiple-choice multidimensional Knapsack problem (MMKP). The main idea behind their algorithm is to distribute traffic among BSs according to a load balancing strategy, considering both radio and BH load status. However, their algorithm, unlike our work, reduces the BH congestion at the expense of lower spectral efficiency, since some UEs may be

Fig. 1. System model.

assigned to BSs not being their “best” radio choice. Moreover, it considers a simple system model consisting only of eNBs, whereas future cellular networks are about to be dense HetNet deployments of more sophisticated architecture, as previously described, thus posing new challenges in the user association problem. Finally, although the network energy efficiency is expected to play a key role, as already analyzed, the algorithm totally ignores the energy consumption impact.

III. SYSTEM MODEL

We consider an LTE-A network composed of a set of BSs $\mathcal{C} = \{0, 1, \dots, j, \dots, C-1\}$: one eNB ($j = 0$) overlaid with $C-1$ SCs ($j = 1, \dots, C-1$), as depicted in Fig. III, where C is the cardinality of the set $\mathcal{C}$. We study the downlink and make the following assumptions:

- Each UE is associated only with one BS at a time.
- Each SC is connected to the core network through the eNB aggregation gateway either directly or through one or more SC aggregation gateways.
- We consider a set $\mathcal{L} = \{\mathcal{L}_1, \mathcal{L}_2, \dots, \mathcal{L}_k, \dots, \mathcal{L}_K\}$ of out-of-band BH links and a fiber link from the eNB site to the core network, as depicted in Fig. 1. Each BH link $\mathcal{L}_k$ includes all cells j that backhaul their traffic through it.
- The channels allocated to the eNB and to the SCs are assumed to be orthogonal, while the SCs that are sufficiently far from each other in order not to interfere may reuse the same frequency bands. Thus, from now we will use the terms SINR and signal to noise ratio (SNR) interchangeably.
- We assume that the total transmit power of each BS is equally distributed among its subcarriers.
- There is a set of $\mathcal{N} = \{1, \dots, i, \dots, N\}$ fixed UEs with specific service-dependent throughput demands.

A. SNR calculation

The SNR received by UE i from BS j is given by [18]

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

where $P_{jsub} = 10 \log_{10}(P_{jmax}/(12N_jN_{RBP_{jmax}}))$ is the power allocated by BS j to each subcarrier, with P_{jmax} denoting its maximum transmission power in mW, N_j the number of antennas of BS j and $N_{RBP_{jmax}}$ the maximum

number of RBs allocated to it (please note that 1 RB is equal to 12 subcarriers in the frequency domain and 0.5 ms in the time domain). The parameter $G_{T_{xj}}$ represents the antenna gain and L_{cbj} the cable loss between the radio RF connector and the antenna, while $L_{p_{ij}}$ the pathloss between UE i and BS j and $L_{f_{ij}}$ the losses due to slow-fading. Then, N_{th} refers to the thermal noise and NF to the noise figure.

B. Power consumption models

1) *Access link*: The power consumed in the access link between a BS j and a UE i can be calculated as

$$P_{AN_{ij}} = P_{RBP_j} N_{RBP_{ij}} \quad (2)$$

where P_{RBP_j} denotes the power allocated to a RB pair (RBP) by BS j (equal to one subframe time (1ms) in the time domain) and $N_{RBP_{ij}}$ the number of RBPs needed for the association of UE i with the BS j , which equals to

$$N_{RBP_{ij}} = \lceil \frac{r_i}{f(SNR_{ij})} \rceil \quad (3)$$

with r_i denoting the throughput demand of UE i , $f(SNR_{ij})$ its spectral efficiency and $\lceil \cdot \rceil$ the ceiling function operator. The spectral efficiency of a UE is a function $f(\cdot)$ of its SNR_{ij} , which maps the SNR received by user i from BS j to a corresponding rate in bits/s. In LTE, $f(\cdot)$ is a scalar function with each step corresponding to a specific modulation and coding scheme (MCS) [19]. Finally, P_{RBP_j} is given by

$$P_{RBP_j} = \frac{P_{jmax}}{N_j N_{RBP_{jmax}}} \quad (4)$$

2) *Backhaul link*: The power consumed in a BH link $\mathcal{L}_k$ can be given by

$$P_{\mathcal{L}_k} = g(\sum_{i \in \mathcal{N}} r_i a_{ij}), \quad \forall j \in \mathcal{L}_k \quad (5)$$

where $g(\cdot)$ is a scalar function that maps the aggregated throughput that passes through the link (i.e., the sum of the total throughput of all the SCs that backhaul their traffic through the link $\mathcal{L}_k$, namely $\forall j \in \mathcal{L}_k$) to a specific power consumption. Specifically, given that adaptive modulation and coding is used, the aggregated throughput that passes through the link is mapped to a target SNR (inverse mapping compared to $f(\cdot)$) and then the power consumption of the link is calculated from the link budget equation similarly to (1) depending on the technology used for the BH.

IV. PROBLEM FORMULATION

As previously mentioned, we select as our global objective the maximization of the network energy efficiency. This can be expressed as the total number of successfully transmitted bits by all the UEs divided by the total energy consumption (i.e., the sum of the energy consumed in the access network

Algorithm 1 User association algorithm

Input: $\mathcal{N}, \mathcal{C}, SNR_{ij}, r_i, N_{RBP_{jmax}}, \mathcal{L}_k, \mathcal{L}$

- 1: Calculate $N_{RBP_{ij}}$ from (3)
- 2: $Candidates_i \leftarrow j : \min(N_{RBP_{ij}})$
- 3: Sort all UEs i by $Candidates_i$ size in ascending order
- 4: Calculate $N_{hops} \forall j \in Candidates_i$
- 5: Sort $Candidates_i$ by N_{hops} in ascending order
- 6: **if** $\exists$ only one candidate having the least N_{hops} **then**
- 7: Choose this one
- 8: **else**
- 9: Choose the one with the less loaded BH route
- 10: **end if**
- 11: **if** the chosen BS has sufficient RBPs **then**
- 12: Associate the UE to it
- 13: Update remaining RBPs, cell throughput and the throughput that passes through the link $\mathcal{L}_k \ni j$
- 14: **else**
- 15: Move to the next candidate and repeat the process
- 16: **end if**

and in the BH links) that can be formulated as

$$\begin{aligned} \max_{a_{ij}} \quad & \frac{\sum_{i \in \mathcal{N}} \sum_{j \in \mathcal{C}} r_i a_{ij} t_{TTI}}{(\sum_{i \in \mathcal{N}} \sum_{j \in \mathcal{C}} P_{AN_{ij}} a_{ij} + \sum_{\mathcal{L}_k \in \mathcal{L}} P_{\mathcal{L}_k}) t_{TTI}} \\ \text{s.t.} \quad & a) \ a_{ij} \in \{0, 1\}, \forall i \in \mathcal{N}, \forall j \in \mathcal{C} \\ & b) \ \sum_{j \in \mathcal{C}} a_{ij} = 1, \forall i \in \mathcal{N} \\ & c) \ \sum_{i \in \mathcal{N}} a_{ij} N_{RBP_{ij}} \leq N_{RBP_{jmax}}, \forall j \in \mathcal{C} \end{aligned} \quad (6)$$

where t_{TTI} is the system observation time (i.e., one subframe time). Notice that the energy efficiency is independent of the observation time for steady state behavior. Then, the parameter a_{ij} is the association vector that equals to 1 when user i is associated with BS j and 0 otherwise (6a). Each UE can be associated only with one BS at a time (6b). Furthermore, the total number of RBPs used by BS j cannot exceed the maximum number of the RBPs allocated to it (6c).

As it can be easily understood, the aforementioned problem is a non-convex problem that cannot be solved in polynomial time (i.e., it is NP-hard). Therefore, in the next section we propose and analyze a novel context-aware heuristic algorithm that associates the UEs aiming at maximizing the network energy efficiency, while having low computational complexity.

V. HEURISTIC ALGORITHM

The proposed algorithm (PA), summarized in Algorithm 1, takes as input the available context-aware information: the UEs' measurements and requirements, the HetNet architecture knowledge and the available spectrum resources of each BS, to associate the UEs aiming at maximizing the network energy efficiency. At the same time, it achieves high spectral efficiency by considering as candidate cells for a UE the cells that satisfy its requirements with the minimum number of

TABLE I
SIMULATION VALUES

Parameter	Value	Parameter	Value
f_{AN}	2.0 GHz	B_{eNB}, B_{SC}	10 MHz
f_{BH}	60 GHz	B_{BH}	50 MHz
$N_{RBP_{eNB_{max}}}, N_{RBP_{SC_{max}}}$	50	NF	6 dB
$P_{eNB_{max}}$	46 dBm	h_{SC}	2.5 m
$P_{SC_{max}}$	30 dBm	h_m	1.7 m
$L_{p_{eNB}}$	$69.55+26.16 \log f_{AN}-13.82 \log h_{eNB}-C_H+(44.9-6.55 \log h_{eNB}) \log d, d \text{ in km}$	$G_{T_{eNB}}$	14 dBi
$L_{p_{SC}}$	$69.55+26.16 \log f_{AN}-13.82 \log h_{SC}+(44.9-6.55 \log h_{SC}) \log d, d \text{ in km}$	$G_{T_{SC}}$	5 dBi
C_H	$0.8+(1.1 \log f_{AN}-0.7) h_m-1.56 \log f_{AN}$	R	450 m
h_{eNB}	30 m	r	60 m
$L_{cb_{eNB}}$	2 dB	N_{eNB}, N_{SC}	2
N_{th}	-174 dBm/Hz		

finite RBPs needed (line 2). To ensure that all the UEs will be associated, PA sorts the UEs by their number of candidates and starts with the UEs with the fewer candidates (line 3). Note that a cell cannot be considered as candidate if the received SNR by the UE is so low that the spectral efficiency equals to zero and thus infinite RBPs are needed to meet the UE requirements. Then, to maximize the network energy efficiency, PA sorts the candidate cells by the number of hops until their traffic reaches the core network denoted by N_{hops} (line 5) and it associates the UE to the candidate with the least hops, as long as it has sufficient RBPs to serve it (lines 7, 11). Otherwise, it moves to the next candidate (line 15). Every time a UE is associated with a BS j , the algorithm updates the remaining RBPs of j , its cell throughput and the throughput that passes through the link $\mathcal{L}_k \ni j$. In the case there are more candidates with the same number of hops, PA associates the UE to the one with the less loaded BH route, as long as it has sufficient RBPs, to achieve BH load balancing (lines 9, 11). Load balancing achieves further energy efficiency improvement, as the energy consumption of a BH link does not increase linearly to its traffic load, as previously explained.

In terms of scalability, PA may be executed in each eNB sector at a specific time interval based on the dynamics of the UE traffic distribution, so that the system performance is optimized. For the new UEs that appear in the meantime, PA is executed as before given the associations of the rest. However, in that case, the context-aware information includes the remaining RBPs and the throughput of each BS/cell, and the throughput that passes through each BH link, given the traffic of the already associated UEs.

VI. PERFORMANCE EVALUATION

A. Scenarios

In the extensive simulations we executed in MATLAB, we consider a sector area of an eNB, which overlaps with 5 SCs, as depicted in Fig. 2. The BH network consists of millimetre wave (mmW) links (60 GHz band) with 50 MHz channel bandwidth [20]. In each realization we consider N fixed UEs of different throughput requirements. Specifically, 80% of UEs demand 500 kbps, 10% 700 kbps and 10% 1 Mbps. We further consider two scenarios. In the first one (scenario 1), the UEs are uniformly distributed in the sector area of radius R , while in the second (scenario 2) they form hotspots. In particular,

Fig. 2. Simulation scenario topology.

in scenario 2, we consider that 40% of the UEs are uniformly distributed in a radius r from the SC 3, other 40% in a radius r from the SC 4 and the rest uniformly distributed in the whole sector area. Scenario 2 constitutes a more realistic scenario, as in future HetNets the UEs are expected to be very close to SCs and to generate hotspot traffic of highly bursty nature [2].

All the simulation parameters are summarized in Table I, where f_{AN} , f_{BH} denote the frequencies used in the access and the BH network, respectively. Moreover, h_{eNB} and h_{SC} denote the BS antenna height of the eNB ($j = 0$) and the SCs ($j \neq 0$), respectively. Generally, the subscript eNB is used when a parameter refers to the eNB, while the SC , when it refers to a SC. Furthermore, 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. Furthermore, the association of the received SNR to the achievable spectral efficiency in bps/Hz (i.e., $f(\cdot)$ function) is given by [18, Table A.2], while the mmW link budget equation is equal to [19, eq. 1.4].

As reference algorithms we consider the following ones:

- RSRP, where a UE connects to the BS from which it receives the strongest RS [3], [7]

$$j^* = \operatorname{argmax}_{j \in \mathcal{C}} (RSRP_{ij}) \quad (7)$$

- Range expansion (RE), where a $bias = 6$ dB is added to

Fig. 3. Average network energy efficiency for different number of users (N), when the UEs are uniformly distributed in the sector area (scenario 1).

Fig. 4. Average traffic of each backhaul link for scenario 1 for $N=100$ UEs.

the RSRP if the signal comes from a SC [8]–[15]

$$j^* = \underset{j \in \mathcal{C}}{\operatorname{argmax}} (RSRP_{ij} + \text{bias}_j) \quad (8)$$

- Minimum pathloss (MPL), where a UE connects to the BS from which it has the minimum pathloss ($L_{ij} = L_{p_{ij}} + L_{f_{ij}}$) [16], independently of its received power

$$j^* = \underset{j \in \mathcal{C}}{\operatorname{argmin}} (L_{ij}) \quad (9)$$

B. Results

In terms of throughput, all algorithms achieve the same performance (e.g., for $N=100$ UEs the total network throughput is 57 Mbps), as the UEs have specific throughput requirements and all algorithms ensure that their demands are satisfied.

Regarding the network energy efficiency for scenario 1, PA achieves slightly better performance than RSRP for values higher than $N=70$ UEs, as depicted in Fig. 3. This is due to the fact that PA gives priority to the candidate cell with the fewer hops and thus most of the UEs get connected to the eNB. As a result, for low values of N there is higher energy consumption in the access network compared to RSRP (the power per subcarrier is much higher for the eNB than for a SC), while the BH energy consumption is almost the same for both algorithms and equal to the minimum. However, for higher values, there are no available RBPs in the eNB at some point and thus the UEs are associated with the candidate SC with the fewest hops, which results in lower BH energy consumption compared to

Fig. 5. Average network energy efficiency for different number of users (N), for hotspot traffic (scenario 2).

Fig. 6. Average traffic of each backhaul link for scenario 2 when $N=100$.

RSRP. This can be also noticed in Fig. 4, where the average traffic of each BH link of the simulation scenario (Fig. 2) is depicted for $N=100$ UEs. According to it, PA achieves better load balancing among the BH links that are the same number of hops away from the core network than the other algorithms. Then, regarding RE, it achieves lower energy efficiency, as there are more UEs associated with SCs, resulting in higher BH energy consumption. Finally, MPL can be considered as an aggressive RE algorithm, where it is likely for the UEs to be closer to a SC and thus to be associated to it. Although MPL achieves the maximum offloading to SCs, it has very poor energy efficiency performance, as the BH traffic is much higher than the other approaches (see Fig. 4) and thus the BH energy consumption is much higher as well.

Accordingly, in Fig. 5 the average network energy efficiency is depicted for scenario 2, which constitutes a more realistic scenario as previously explained. In this case, PA achieves gains up to 102%, as the BH energy consumption is being optimized. Specifically, in comparison to RSRP, PA achieves up to 42% energy efficiency gain. This stems from the fact that the UEs located around the SC 3 or 4, that have as candidate cells the SCs 1 or 2, will be associated with SC 3 or 4 when RSRP is applied, given that they receive higher SNR, whereas to SC 1 or 2 with PA, given that less hops are required to reach the core network. As a result, PA generates globally less traffic for the BH links and thus the BH energy consumption

Fig. 7. Average network spectral efficiency for both UE traffic scenarios.

becomes much lower. This is better explained in Fig. 6, where the average traffic per BH link is depicted for scenario 2 when $N=100$ UEs. As it is shown, PA achieves again much better BH load balancing, as e.g., the UEs around SC 4 that have as a candidate cell the SC 5, will be connected to the SC that has the less loaded BH route. Then, regarding RE, it has poor energy efficiency performance, as there are more UEs associated to the SCs than in RSRP and thus it presents higher BH energy consumption. Finally, MPL presents the lowest energy efficiency, as most UEs are associated with the closest SCs, resulting in the most highly loaded BH links (see Fig. 6) and thus in the highest BH energy consumption.

In Fig. 7, the average network spectral efficiency is depicted for all algorithms. As it is shown, PA achieves equally high spectral efficiency to RSRP and RE for both scenarios, as it achieves the same throughput with the same amount of total RBPs used. The key point of the high spectral efficiency of PA is that it considers as candidate cells for a UE only the cells that demand the minimum amount of RBPs to serve its traffic. MPL, unlike the rest algorithms, presents much lower spectral efficiency as it associates the UEs independently of their SNR. Thus, it is very likely that a UE is associated to a SC from which it has the minimum path loss, although its SNR is low and therefore more RBPs will be needed to achieve the same throughput. Moreover, for scenario 2, MPL achieves higher spectral efficiency than in scenario 1. This is due to the fact that the UEs that form a hotspot around a SC, will have both low path loss and a high SNR received from it and thus will need a lower number of RBPs to satisfy their requirements.

VII. CONCLUSION

In this paper, we studied the user association problem in a HetNet, where several SCs forward their traffic through the BH to the neighboring ones until it reaches the core network. We aimed at maximizing the network energy efficiency while maintaining high spectral efficiency. The problem has been formulated as an optimization problem, which was shown to be NP-hard. Therefore, we proposed a cognitive heuristic algorithm that exploits the available context-aware information (i.e., UE measurements and requirements, the HetNet architecture knowledge and the available spectrum resources of

each BS) to assign the UEs to the candidate cell with the least number of hops in order to minimize the BH energy consumption or in case there are more candidate cells with the same number of hops, to the candidate with the less loaded BH route to achieve load balancing. We evaluated the performance of the proposed algorithm under two simulation scenarios and we showed that it can achieve up to two times more network energy efficiency than the reference algorithms.

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