optimization 은 좋. RRH는 없냐

Towards Energy Efficiency in Ultra Dense Networks

Wei Yu*, Hansong Xu*, Amirshahram Hematian*, David Griffith†, and Nada Golmie†
*Towson University, Emails: wyu@towson.edu, {hxu2,ahemat1}@students.towson.edu
†National Institute of Standards and Technology, Emails:{david.griffith,nada.golmie}@nist.gov

optimization 문제라고 어떻게 formulate 되는지 같은 방법도 설명해주면 좋을.

***Abstract*—The Ultra Dense Network (UDN), as a key enabler for future wireless networks (such as 5G), is comprised of a massive number of small cells in the network. Nonetheless, energy consumption will be non-negligible when a large number of small-cell Base Stations (BSs) are densely deployed. One practical and effective approach to reduce the energy consumption of the UDN is through dynamically controlling the power saving mode of BSs, while the challenge is to maintain network coverage and satisfy the performance requirements of User Equipment (UEs). In this paper, we formalize the problem of minimizing the energy consumption of BSs by optimally controlling the BS's power saving mode (switching between awake mode and sleep mode). We focus on optimal BS selection with the objective of energy efficiency, while the considering the constraints of the coverage of UEs, the capacity of BSs, and the data rate UEs. To validate the effectiveness of our proposed scheme, we have conducted performance evaluations with a comprehensive scenario design, consisting of UE density, distribution, and mobility, as well as BS deployment. The evaluation results demonstrate favorable energy efficiency improvement at averages of 38.82 % and 48.05 % in scenarios where UEs are uniformly distributed and non-uniformly distributed in the network. Meanwhile, network coverage and UE's Quality of Service (QoS) requirements are provided.**

***Keywords*—5G Ultra Dense Networks, Energy Efficiency, Performance Modeling and Evaluation**

I. Introduction

The globally overwhelming growth of the density, intensity, and diversity of communication devices raises significant challenges and requirements on the capacity of future communication networks. In the foreseeable future, the manifold applications and services, which enrich the quality of life, pose high demands on the performance of communication networks. As stated in [1], [2], future communication networks are facing multiple performance requirements, including thousand-fold traffic volume, multi-gigabit per second data rates, and communication devices on the order of hundreds of millions. To this end, 5G relevant technologies (Ultra Dense Network (UDN), Millimeter wave (MMwave), Massive Multi Input and Multi Output (Massive MIMO), etc.) have been actively studied for improving network performance.

Generally speaking, the UDN is an extension of the Heterogeneous Network (HetNet), where a large number of small cells are deployed to offload network traffic from over-crowded macro cells, such that the overall network capacity can be improved [3]. In other words, in a UDN, the small cells (i.e., femtocells, picocells) will be densely deployed by network operators and/or users, in comparison with the existing non-dense deployment in HetNet, based on Long-Term Evolution (LTE) standard. The network capacity in UDN can be significantly improved according to the intense spatial reuse, which is led by largely reduced communication distance between the UE and BS, and the increased frequency reuse.

Therefore, the UDN becomes one of the key technologies to boost network performance (capacity, data rate, latency, etc.). One key feature of the UDN is the densely deployed small cells (i.e., femtocells, picocells). In an ideal case, the optimal deployment density ratio will be one BS per UE, based on the study in [4]. The high density of small cells raises the issue of resource management with respect to spectrum resource efficiency, energy efficiency, control overhead, and others. For example, considering the energy consumption, a small-cell BS utilizes less energy on operation and communication in comparison with a macro cell BS. Nonetheless, the sum of the energy consumption on BSs in all small cells is still non-negligible, especially when densely deployed. Also, BSs consume more than 80 % of the total energy cost in a cellular network [5], [6]. Thus, how to efficiently manage the energy consumption in UDN is a critical issue.

Due to the random activity of UEs, partial small-cell BSs can be put into sleep or idle mode when there are no UEs connected. Nonetheless, how to determine the optimal set of BSs to be turned to sleep mode is a complicated problem, because both energy efficiency and network performance need to be considered. Particularly, the network capacity that will be boosted by the dense deployment of small cells (e.g., closer communication distance) is a tradeoff with energy efficiency, illustrated as follows: (i) To reduce energy consumption by turning a large number of BSs to the sleep mode, the network performance (latency, capacity, etc.) could be degraded due to less available BSs. (ii) To satisfy the network performance requirements for each UE, the number of UEs that can connect to one BS should be limited. Otherwise, the energy efficiency may be improved by connecting more UE to one BS, which reduces the bandwidth obtained by each UE. (iii) If more BSs are turned to sleep, the density of the BSs is reduced. Then, the average communication distance increases, which further reduces the network capacity. Thus, finding an optimal solution to obtain both energy efficiency and network performance remains vital and challenging.

Aware of the complicated tradeoff between energy efficiency and network performance, in this paper we seek to address this critical issue and optimize BS awake/sleep scheduling. Notice that among the large number of users in the network, not all users are simultaneously transmitting data. In most cases, users transmit data for a period of time and then become idle until next data transmission. Also, in UDN, the number

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of BSs increases to equivalent or greater than the number of UEs in order to boost the network capacity and deal with the growing number of users. It is highly possible that there are a number of small-cell BSs that are not frequently utilized. Thus, the selection of a proper set of BSs in the sleep mode can significantly improve the energy efficiency.

In this paper, we first present several constraints on network performance based on the Quality of Service (QoS) requirements of users and the capacity of the network, including UE coverage, average data rate, and the capacity of BS. Then, we formalize the problem as an optimization problem, requiring the selection of an optimal set of BSs for BS awake/sleep scheduling. Further, we propose the algorithm to solve the optimization problem, where the complexity and feasibility are considered and evaluated. Our designed algorithm computes the overall optimal set of BSs based on the satisfaction of constraints and maximization of energy efficiency simultaneously.

To validate the effectiveness of our proposed scheme, we design experimental scenarios consisting of UE behavior and BS deployment, including the distribution, density, and mobility with respect to UE, and the density and distribution in BS. Additionally, we conduct the performance evaluation of the comprehensive scenarios to demonstrate the effectiveness of our scheme in the Vienna LTE toolbox in Matlab[1] [7]. Our simulation results show that, by using our approach, an average 38.82 % energy efficiency is improved in one scenario, where UEs are uniformly distributed, and an average 48.05 % energy efficiency is improved in the scenario, where UEs are non-uniformly distributed, while network coverage and UE's QoS requirements are provided simultaneously. We also investigate the relationship between the network performance versus the density ratio (BS and UE).

The remainder of the paper is organized as follows: In Section II, we review the related works on energy efficiency in wireless networks from both BS and UE aspects. In Section III, we present our approach, including the system model, problem formalization, proposed algorithm, and discussion. In Section IV, we evaluate the comprehensive experiments that are conducted. We conclude the paper in Section V.

II. Related Work

The UDN consists of various network components, including macro-cell BSs, small-cell BSs (e.g., femtocell BS, picocell BS), relays, moving nodes, etc. Especially, the small-cell BSs are densely deployed under the coverage of the macro-cell BS to provide the coverage and connectivity to the overwhelming UEs. Due to the massive data traffic volume and a large number of UEs, UEs and BSs are the most power consuming components in the network. From the aspect of network operation, a large number of small cells could lead to not only additional deployment cost, but also additional energy consumption. To improve the energy efficiency, a number of energy saving schemes have been investigated and can be applied to both BSs and UEs.

On one hand, the energy efficiency scheme on the BS can be categorized as the BS energy consumption minimization, BS power management, system tradeoff optimization, and alternative energy according to the study of Hasan *et al.* in [8]. Related to power management, one representative technique is to leverage the concept of "sleep mode", which is the power-saving mode in the BS. The BS can be selectively switched to the power-saving mode when the traffic load is light. There have been a number of research efforts in this direction. For example, Koudouridis *et al.* in [9], [10] investigated the BS ON/OFF (awake/sleep) control schemes to reduce the energy consumption on HetNet. To reduce the energy consumption through BS power management, Saker *et al.* in [11] proposed a centralized awake/sleep scheme to wake up sleep femtocells for off-loading the increased data traffic. The wake-up command was sent from the network (i.e., macro cell BS) to femtocells according to the location information and traffic loads of UEs.

Likewise, Zhou *et al.* in [12] formalized an optimization problem, which considers not only the energy efficiency and network throughput, but also the frequent handovers among available BSs. Based on the game-theoretical formalization, the sweet point on balancing the network throughput and energy consumption was identified. To further To improve the energy efficiency, Emmanuel *et al.* in [13], [14] proposed schemes to maintain a database to support cluster-based small-cell deployment in both indoor and outdoor environment.

The energy efficiency on the UE is also critical, due to the battery capacity limit from the small size of the device, large data volume transmission, applications that consume high energy, etc. The existing approaches to reduce energy consumption on UEs are led by the design of advanced transceivers, signal processing and channel coding schemes, multi-antenna techniques, and the sleep mode on UEs, among others [15]–[18]. For example, Tommaso *et al.* in [19] investigated the wake-up radio on UEs with respect to energy efficiency, where the energy efficiency improvement is based on the wake up on-demand mechanism. Furthermore, energy efficiency can be improved through multi-antenna, together with the adaptive modulation, such as the diversity gain and multiplexing gain in the spatial domain [20], [21].

III. Our Approach

In this section, we first give an overview of our approach. We then present the network model and problem formalization. Finally, we propose and discuss our algorithm to resolve the problem.

A. Overview

Recall that the UDN consists of a massive number of BSs, and that the BSs consume more than 80 % of energy in a

[1]Certain commercial equipment, instruments, or materials are identified in this chapter in order to specify the experimental procedure adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the materials or equipment identified are necessarily the best available for the purpose.

TABLE I: Notations

Symbols	Descriptions
BS	Small cell BS
UE	User Equipment
S_B	Status information for all BS
s_i	BS i status (awake/sleep)
E	Energy consumption function of small-cell BS
(X_{B_i}, Y_{B_i})	Location information of BS i
(X_{U_j}, Y_{U_j})	Location information of UE j
D	Communication distance of small-cell BS
C	Capacity limitation for small-cell BS
R	Demand data rate for UE
B	UE's bandwidth
W	Connection information of UE and BS
$w_{i,j}$	Connection information of UE j with BS i

network [22], [23]. Thus, the energy consumption of UDN is a critical issue. To address this issue, some BSs can go into sleep mode when no active UEs are connected. By doing so, the energy consumption can be reduced. The sleep mode concept has been used to induce low-power operation of hardware, and partial hardware components can be switched to sleep mode [24]. In the UDN, how to determine which BSs go into the sleep mode is critical, as it can affect the coverage and connectivity of UEs, and consequently jeopardize the performance of the network.

The optimal selection of BSs to enter sleep mode must consider a number of constraints: (i) *Constraint 1. The coverage of UEs.* To maintain the coverage of UEs, for a given UE, at least one small-cell BS needs to be located within its communication range. (ii) *Constraint 2. The capacity of small-cell BSs.* Because the UE is randomly located in the UDN, it is possible that there is no UE in the coverage area of a small-cell BS, or that there exists one or more UEs in the coverage area of a small-cell BS. In the second case, UEs that are connected to the BS should not exceed the capacity of the BS. Thus, from the capacity of the BS, we need to make sure that the sum of demanded bandwidths from all UEs that connect to a small-cell BS should not exceed its capacity. (iii) *Constraint 3. Data rate of UEs.* To meet the quality of service requirement, each UE requests a data rate, which should be satisfied.

B. Network Model and Problem Formalization

We now describe the network model and present the problem formalization. All notations used in the paper can be found in Table I.

1) Network Model: The UDN consists of macro cells, small cells, and UEs. The macro cells are hexagonally deployed as the traditional cellular network, and provide the umbrella coverage. Meanwhile, the small cells, denoted by the set of BS, are irregularly deployed within the macro-cell covered area and provide traffic offloading capabilities when macro-cell BSs cannot cope with the large volume of data traffic. In this paper, the small-cell BSs are deployed in outdoor open space (e.g., 1 km^2). It is worth noting that, for the sake of simplicity, the small cells have uniform configurations, including uniform communication distance, transmission power, connection capacity, etc. Also, our problem formalization and proposed algorithm can be easily extended to the case where communication distance and capacity of BSs and the communication distance and demand date rate of UEs are different. Also, the UEs, denoted as the set of UE, are randomly distributed in the network.

2) Problem Formalization: Assume that there are m small cells and n UEs, and the location information is available through macro-cell BSs. For m small-cell BSs, the status information of awake/sleep mode can be collected in S_B, shown as Equation (1).

$$S_B = \begin{bmatrix} s_1 & ... & s_i & ... & s_m, \end{bmatrix}, i \in [1, m], \tag{1}$$

where the s_i represents the status of awake or sleep mode for BS i.

Particularly, the awake/sleep status of a small-cell BS can be represented by

$$s_i = \begin{cases} 1 & \text{awake} \\ 0 & \text{sleep} \end{cases}, i \in [1, m]. \tag{2}$$

Here, when $s_i = 1$, the BS i is in awake mode, and when $s_i = 0$, the BS i is in sleep mode.

To describe the connectivity information of UEs and BSs (a number of UEs connect to one BS and one UE only connects to one BS), we have

$$W = \begin{bmatrix} w_{1,1} & ... & w_{1,j} & ... & w_{1,n} \\ . & ... & . & ... & . \\ w_{i,1} & ... & w_{i,j} & ... & w_{i,n} \\ . & ... & . & ... & . \\ w_{m,1} & ... & w_{m,j} & ... & w_{m,n} \end{bmatrix}, \tag{3}$$

where, each row in matrix W means the number of BSs from 1 to m. Each column represents the number of UEs from 1 to n, and $w_{i,j}$ is the connection information between BS i and UE j.

In addition, the connectivity information is shown as:

$$w_{i,j} = \begin{cases} 0 & F_i \text{ not connect to } U_j, \\ 1 & F_i \text{ connect to } U_j. \end{cases} \tag{4}$$

When $w_{i,j} = 1$, the UE j is connected to BS i, while when $w_{i,j} = 0$, the UE j is not connected to BS i.

In Equation (3), j column shows the connectivity information for UE j (i.e., UE j connects to which BS). Notice that as we do not consider dual connectivity in this paper and all the UEs need to be connected, one UE can only select and connect to one BS. Then, the sum of each column is equal to 1, shown as:

$$\sum_{i=1}^{m} w_{i,j} = 1. \tag{5}$$

Besides, in Equation (3), i row represents the connectivity of BS i (i.e., all the UEs are connected to the corresponding BS). Here, multiple UEs can connect to BS i, and the sum of bandwidth of the UEs that connected to one BS should not exceed its capacity.

The objective of our approach is to find the minimum number of small cells that are in awake mode, and at the same time, the constraints described in Section III-A should be satisfied. As shown in Equation (6), the objective function can be represented by $\min \sum_{i=1}^{m} E \cdot s_i$, where E is the energy consumption function of a small-cell BS. Recall that s_i represents the awake status of BSs, shown as Equation (2). The energy consumption can be expressed as $E = 1/\eta E_t + E_r + E_0$, where E_t represents the transmission power, η represents the amplifier efficiency, E_r represents the RF component energy consumption, and E_0 represents non-transmission power [25]. Compared to the awake mode, the sleep mode energy consumption reduction is obtained from the shutdown of the functions of transmission, RF component, etc.

The optimization problem is described as:

$$\text{Objective: } \min \sum_{i=1}^{m} E \cdot s_i, \tag{6}$$

$s.t.$

$$\forall j \in (1, n), \sum_{i=1}^{m} w_{i,j} = 1, \tag{7}$$

$$\forall j \in (1, n), \\ \sum_{i=1}^{m} w_{i,j} \sqrt{(X_{B_i} - X_{U_j})^2 + (Y_{B_i} - Y_{U_j})^2} < D, \tag{8}$$

$$\forall i \in (1, m), \sum_{j=1}^{n} B \cdot w_{i,j} < C, \tag{9}$$

$$B \geqslant R \tag{10}$$

Here, in addition to the notation defined above, C represents the capacity of BS, B is the UE bandwidth, and R is the UE demand data rate.

In the aforementioned optimization problem, the overall objective is to minimize the energy consumption, which can be achieved by keeping only the minimum number of small-cell BSs in the awake status, as shown in Equation (6). At the same time, several constraints should be satisfied, which are listed as Equations (7) to (10).

To satisfy *Constraint 1, the coverage of UEs*, we need to make sure that there is at least one BS that can be connected to by every UE. Notice that the one UE can only connect to one BS. As shown in Equation (7), for all UEs, only one BS can be selected among m BSs and connected to by one UE. Moreover, to satisfy the coverage of all UEs, in Equation (8), the BSs can be connected by UEs in their coverage area. The location of a BS i can be expressed as (X_{B_i}, Y_{B_i}), and the location of a UE j can be expressed as (X_{U_j}, Y_{U_j}).

Constraint 2, the capacity of small-cell BSs, which is focused on the satisfaction on the BS capacity, can be achieved by Equation (9). Notice that the UEs, which are connected to one BS, share the capacity provided by the BS. Thus, the sum of shared bandwidth of all UEs should not exceed the BS capacity. Here, for instance, the BSs have uniform configuration (i.e., uniform BS capacity). Our problem formalization and the proposed algorithm can be easily adapted to handle the case, where BSs and UEs have different configurations. As shown in Equation (9), the bandwidth B for all UEs that are connected to the BS are summed, shown as $\sum_{j=1}^{n} B \cdot w_{i,j}$, where the sum should be smaller than the capacity C.

Constraint 3, data rate of UE, must satisfy the minimum data rate requirement of a UE for the sake of the UE's QoS. Here, we set the minimum data rate for UE is R. As shown in Equation (10), the bandwidth B of UE should be larger that the demand data rate R, in order to guarantee the UE's QoS. Particularly, when the number of UEs that share the bandwidth from one BS is limited, the data rate of the UE can be ensured.

Recall from Equation (2), s_i shows the status of the BS (i.e., awake/sleep). To determine the status of all BSs, the number of UEs that connect to one BS is the main parameter. Specifically, when the sum of the connection of all UEs for one BS is equal to 0, the BS's status is sleep, and when the sum is not equal to 0, the BS's status is awake, as shown in Equation (11).

$$s_i = \begin{cases} 1 & \sum_{j=1}^{n} w_{i,j} \neq 0, \\ 0 & \sum_{j=1}^{n} w_{i,j} = 0. \end{cases} \tag{11}$$

넣어가도 되는데 기울어서 넣어주세요

Algorithm 1: BS awake/sleep control algorithm

Input: $w = zeros(N)$, $W = zeros(N)$, W stores the connectivity information, N demonstrates the equal number of BS and UE, A stores the distances of BS to each UE, R_{UE} is the communication range of UE, C_{BS} is the BS capacity, $MinR$ constraints the number of UE connected to BS

Output: $Result$

```
1  CR = size(W)
2  if CR(2) ≠ 1 then
3      for i = 1 : CR(1) do
4          if (A(i, N+1-CR(2))) ≤ R_UE(i) then
5              W(i, N+1-CR(2)) = 1
6              w = zeros(CR(1), CR(2)-1)
7              Algorithm 1(w, W, A, R_UE, C_BS)
8              w(i, 1) = 0
9              W(i, N+1-CR(2)) = 0
10 else
11     for j = 1 : CR(1) do
12         if (A(j, N+1-CR(2)) ≤ R_UE(j)) then
13             W(j, N+1-CR(1)) = 1
14             if (∑(W, 1)) ≤ C_BS then
15                 if (length(find(∑(W, 1))) < MinR) then
16                     Result=W
17                     MinR = length(find(∑(W, 1)))
18             W(j, N+1-CR(1)) = 0
19 return Result
```

C. Algorithm

Based on the above mathematical illustration, we now show the algorithm to solve the optimization problem of BS awake/sleep. The detailed procedures are based on recursive and are shown in Algorithm 1, which can be executed as three steps, described as follows:

Step 1: To satisfy *Constraint 1, the coverage of UEs*, we allocate and sort the BSs that can be connected by each UE based on its geo-location information, shown as line 3 in Algorithm 1. The potential selectable BSs are found and ready for further selection. Then, the algorithm performs the iteration operation for further selection on the connectivity information of the potential BSs.

Step 2: Here, we further reduce the number of BSs that need to be in the awake status according to *Constraint 2, the capacity of small-cell BSs*. Line 13 in Algorithm 1 indicates the physical limitation of the BS capacity. Considering the BS supports multiple UEs simultaneously, all UEs that are connected to one BS share the bandwidth resource from the BS. In this case, by using the selection process in line 13, the BS only connects to a limited number of UEs, until the BS's capacity is reached.

Step 3: Considering *Constraint 3, data rate of UE*, we set R, which indicates the required UE's data rate for user's QoS satisfaction. In order to satisfy the data rate per UE, the sum of the bandwidth per UE that connects to one BS should not exceed the BSs capacity. In other words, the number of UEs that connect to one BS should be limited. As shown in line 14, the number of UEs on each BS should smaller than the limit, i.e., C/R.

Generally speaking, the complexity of the proposed algorithm is $O((N_c)^{N_U} + N_B \cdot N_U)$, where N_c is the maximum number of BSs that a UE is in communication range with. To be specific, the iteration for each UE is based on the maximum number of BSs, which a UE can be connected to. Thus, the complexity is exponentially related to the number of UEs and maximum connectable BSs. In addition, the complexity of evaluating the connectivity between UE and BS is a multiplication relation, shown as $N_B \cdot N_U$. In other words, the computing complexity depends on parameters, including the number of BSs, the number of UEs, and the maximum connectable BSs.

To further reduce the computing complexity, we can divide the network into a number of small regions where the BS control is performed in each individual region. In this way, separated control between individual regions provides advantages, including: (i) fitting the UE distribution to the real-world scenarios (i.e., regions such as communities, enterprises, etc.), (ii) reducing the computing complexity and overhead by reducing the number of BSs and UEs in the controlled region, and (iii) obtaining robustness and flexibility on the BS awake/sleep control, with minor tradeoffs from the system coordination.

D. Discussion

Towards the energy efficiency of the large-scale deployment of small-cells, implementing the sleep mode (i.e., idle mode) of small-cell BSs has proved to be effective and vital [24], [26], [27]. When the BS goes into sleep mode, the energy consumption can be significantly reduced. To achieve energy efficiency and low latency of UE activation in sleep mode, existing standardization efforts have been working toward the WUR (Wake Up Receiver), where a wake-up packet can be used for UE activation [28]. Notice that while the concept of the WUR is currently focused on the UE side, it can be extended to the small-cell BS.

In addition, considering the mobility of the UE, various mobility models can be used to describe the mobility pattern of a user in different scenarios. Thus, the time interval for executing the control scheme should be considered based on the scenarios. As an example, when the UE is moving at high speed, the channel quality will change significantly. If the executing time interval is small, the overall network capacity may be reduced. On the contrary, if the time interval is set to high, it may lead to frequent handovers, which further degrades the UE's performance. Notice that the time interval should be selected based on the UE's mobility models in specific scenarios.

As the cornerstone, the macro-cell BS receives the Information Elements (IE) from each UE, where the specific information (the UE identification, geo-location, channel quality information, and others) can be derived based on the measurement report from UEs. In UMTS and LTE, a UE measures and reports the IE periodically, or it is driven by events [29]. In this case, all the information about a UE and small-cell can be collected and evaluated. By doing this, our proposed algorithm can be effective in finding the optimal BS awake/sleep scheduling. In addition, the sleep mode of BSs can have some positive effects (interference reduction [4]). This is because turning RF components to sleep mode can prevent the interference with other nearby RF components in BSs and UEs.

IV. Performance Evaluation

To evaluate the feasibility and effectiveness of our approach that enables the BS awake/sleep scheduling, we have conducted an extensive performance evaluation. In the following, we first show the evaluation methodology, and then present the evaluation results.

A. Evaluation Methodology

In a UDN, UE density, BS density, UE distribution, and UE mobility pattern are the key features that describe its characteristics. The UE density is one of the key features in the UDN. For example, in a 1 km^2 open space, where the UEs are uniformly distributed, the density of the awake UEs varies among 100, 300, or 600 per km^2, which can be viewed as the user density in a rural area, city area, and dense area (e.g., Manhattan), respectively. Then, the small-cell BS density can be measured by various Inter Site Distance (ISD). For example, when ISD is 10 m, 50 m, 100 m, and 200 m, correspondingly, the BS density is 11548, 462, 116, and 29 per km^2. Smaller BS ISD leads to larger BS density. To cope with the UE density, the deployment of BS density should equal the UE density in order to achieve a deployment ratio of 1 (BS per UE). Also, various UE mobility models can be used according to the patterns of user mobility (the classic random walk model, spatial dependence velocity, etc.).

The key features for designing evaluation scenarios are summarized as follows: (i) *Uniform and non-uniform distribution.* "Uniform distribution" means that the UEs are uniformly disbursed in the target area as shown in Figure 1, while

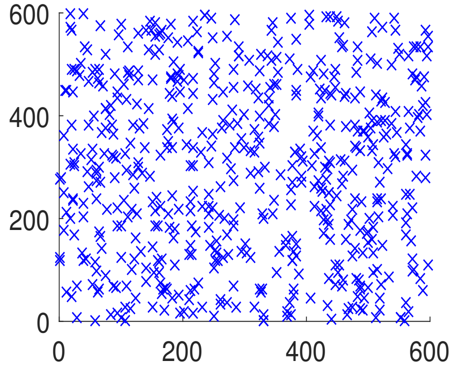

Fig. 1: UE with uniform distribution

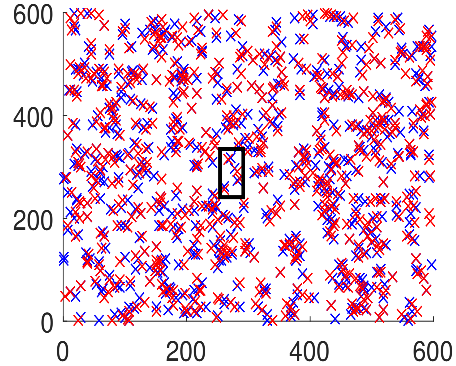

Fig. 2: UE movement with random walk

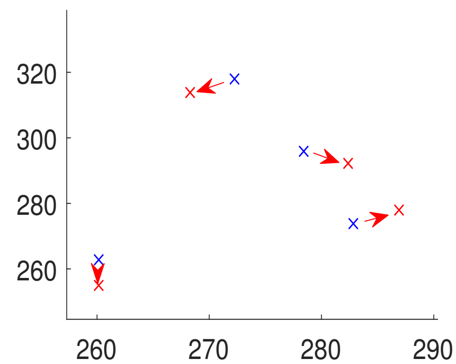

Fig. 3: An example of the UE movement

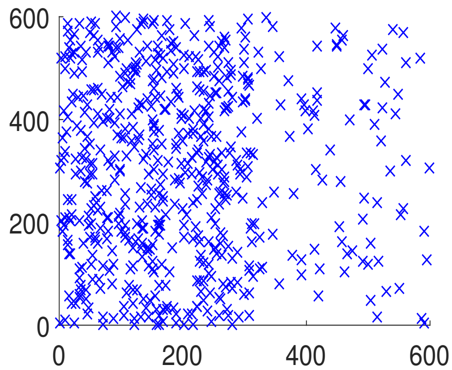

Fig. 4: UE with non-uniform distribution

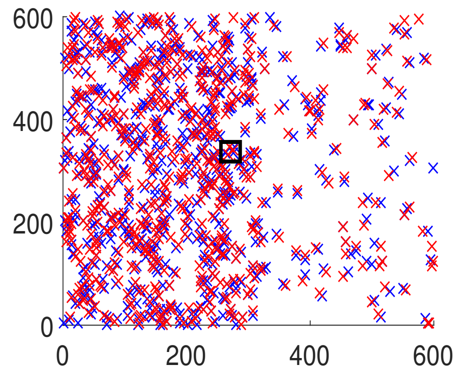

Fig. 5: UE movement with random walk

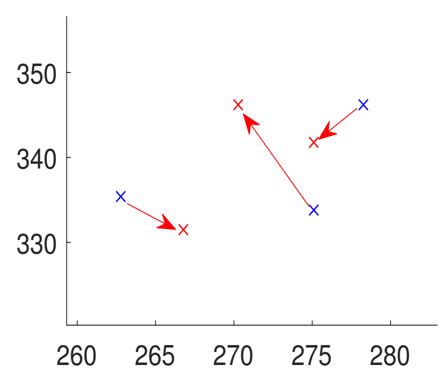

Fig. 6: An example of the UE movement

"non-uniform distribution" means that UEs are partitioned into two groups and each group is uniformly distributed in a separate region as shown in Figure 4. (ii) *UE mobility model.* We consider the random walk model as one classic UE mobility model, where the UE is moving with random direction and random speed. (iii) *Network performance versus BS-UE density ratio.* In a UDN, the sweet point of BS deployment density will be 1 BS per UE [4]. We evaluate the network throughput versus the BS-UE density ratio, which is defined as the ratio of the number of BS to the number of UE. Particularly, we first implement 600 per km^2 UEs with uniform distribution in the network. Then, we increase the number of BSs based on the ratio from 0.1 to 2, compared to the number of UEs. Based on the results, we can show the relationship between the network performance and the BS-UE density ratio.

Based on the features described, we have the following evaluation scenarios: (i) *Scenario 1.* It represents the scenario where the UE is uniformly distributed in the network and the UE's mobility model is a random walk. (ii) *Scenario 2.* It represents the scenarios where the UE is non-uniformly distributed in the network and the UE's mobility model is random walk. (iii) *Scenario 3.* It represents the scenario where the network consists of different BS-UE density ratios where the UE is uniformly distributed in the network, and the UE's mobility pattern is random walk.

For the small-cell BS, we consider the density and topology features of the BS. Particularly, we deploy small-cell BSs with the hexagonal grid topology as an example. The ISD is set at 25 m to cope with the UE density to a ratio of near 1 BS per UE in a 625×625 m^2 open area. In scenario 1, the network consists of BSs deployed in square grids, non-uniformly distributed UEs, and a mobility model based on the random walk. Similarly, in scenario 2, the network consists of BSs deployed in square grids, UEs uniformly distributed, and the random walk mobility model. Notice other distributions of UE and mobility models can be further designed and implemented. The scenario 3 is to evaluate the performance of the network with respect and different BS-UE density ratios.

We implement scenarios 1, 2, and 3 to validate the feasibility and effectiveness of the proposed scheme. We first use the Matlab to compute the theoretical results for resolving the optimization problem described in Section III. Then, using the theoretical results as input, we utilize the Vienna LTE toolbox [7] to conduct the simulation study. Notice that Vienna LTE toolbox allows the implementation of the self-defined network topology, deployment, and algorithms, and provides the measurement of network performance (average throughput, average spectrum efficiency, etc.).

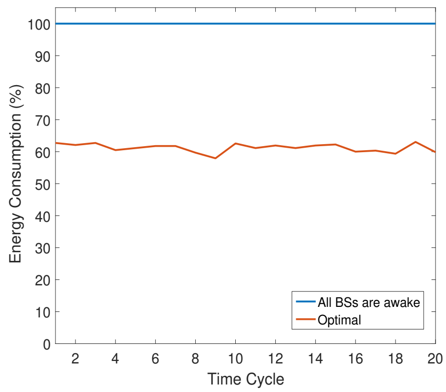

Fig. 7: Energy efficiency (uniform distribution)

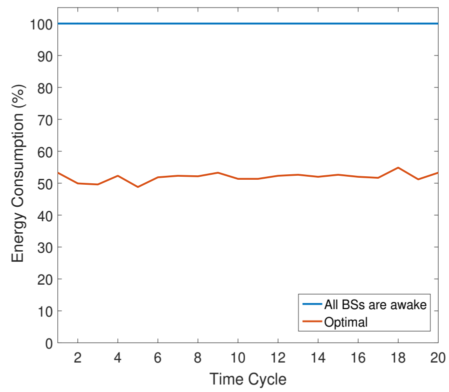

Fig. 8: Energy efficiency (non-uniform distribution)

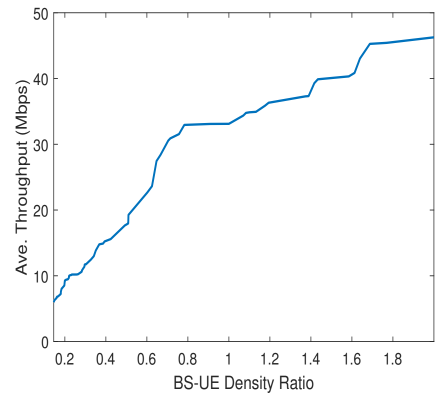

Fig. 9: Network throughput versus BS-UE density ratio

B. Evaluation Results

We now present the evaluation results of the three scenarios described.

1) Scenario 1: Recall that in scenario 1, the network consists of a number of UEs, which are non-uniformly distributed, and their mobility pattern follows the random walk mobility model. BSs are deployed in a hexagonal grid topology. In scenario 1, the UE distribution is implemented at 625 UE per 625×625 m^2, which also reflects the high density of UEs, i.e., 600 per km^2 [4]. UEs are randomly deployed in the area, as shown in Figure 1. In real-world practice, the UE could move with random direction and random speed in an open space. Figures 2 and 3 show the UE movement with the random walk mobility model. Particularly, Figure 2 shows the UE at the original locations, in blue, and after one time step the UEs have moved to another location, appearing in red. The enlarged figure, Figure 3, shows the detail of the UE movement with the uniform UE distribution. As shown in Figure 3, the trace of the UE follows the randomness and haphazardness of human movement. In our evaluation, we use the random walk mobility model, which is a representative one, where each UE randomly selects the moving direction and moving speed. The moving speed is set to 1 m/s, which approximates the typical walking speed of a person.

We execute our algorithm over time, and capture the optimal selection results. Figure 7 shows the effectiveness on energy consumption reduction when our proposed approach is in place. As we can see from Figure 7, nearly 38.82 % of energy reduction can be achieved by scheduling BSs to sleep mode, in comparison with all BSs remain awake. To give a numerical detail of the energy efficiency improvement in watts, we can compute that the average energy consumption is 19.12 W when our proposed scheme is in place, while the energy consumption is 31.25 W when all BSs (625 BS per km^2) remain awake. Notice that we assume that the average power consumption of a small-cell BS is $P_{max} = 0.05$ W [30].

2) Scenario 2: We consider both the high density and low density UE distributions. From Figure 4, we split the 625 m×652 m into two regions, in which the high density UE distribution is used in the left side region, while the low density UE distribution is used in the right side region. The blue symbol shows the original UE distribution, and the red symbol shows the UE location after movement, respectively in Figure 5. Figure 6 shows an example of the UE mobility with random direction and speed.

As shown in Figure 8, nearly average 48.05 % of energy reduction can be achieved, compared to the case where all BSs are awake. Also, the energy consumption is 16.23 W when our proposed optimal BS awake/sleep scheduling is used, while the energy consumption is 31.25 W when all BSs remain awake. From the figure, the energy efficiency results in the case of the non-uniform UE distribution performs better than the case of the uniform UE distribution. The reason is that in the region where less UEs are deployed, more BSs can go into the sleep mode, which leads to more energy saved.

3) Scenario 3: We have also conducted the performance evaluation to identify the relationship between the network performance and BS-UE density ratio in the UDN (i.e., the optimal BS-UE density ratio). Particularly, we have implemented the network with varying UE densities, including 100, 300, and 600 UEs per km^2. Based on different BS-UE density ratio, we measure the performance of the network (network throughput, data rate, spectrum efficiency, etc.).

Figure 9 shows the network performance (e.g., average throughput) versus the BS-UE density ratio. From the figure, we can see that with the increase of the density ratio, the network throughput improves significantly, especially when the density ratio is less than unity. This is because the more BSs used, the high the performance the UEs can achieve. Also, the densely deployed small cells improve the frequency reuse. We can observe that the peak increasing slope appears at the density ratio prior to one BS per UE point. We can also observe that the network throughput increases at a lower rate above the 1 BS per UE. This is because the over-dense BS deployment can reduce the network performance due to extra handovers, inter-tier interference, etc. When the BS-UE density ratio is larger than 1, each UE can have multiple BSs available so that UEs can have a better chance to select a better BS that is closer to UE.

V. Final Remark

In this paper, we addressed the energy efficiency issue in UDN by designing an approach to optimally enable the small-cell BS awake/sleep mode scheduling. To provide an optimal solution for the BS awake/sleep mode scheduling, we formalized the problem of achieving the tradeoff between energy efficiency and network performance as an optimization problem. We proposed the algorithm to solve the optimization problem, which considered the BS coverage, capacity per BS, and UE data rate as constraints. As the results of the algorithm, an optimal set of BSs are selected to enter sleep mode so that the energy consumption can be reduced. To evaluate the effectiveness and feasibility of our algorithm, we conducted the performance evaluation in comprehensive scenarios that involve the uniform and non-uniform UE distribution, random-walk mobility model, BS square grid topology, and others. Our experimental data shows that, with our proposed approach, the energy efficiency of the UDN is improved significantly in various UE distribution and UE mobility scenarios, while at the same time, the network performance is guaranteed.

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