Green Small Cell Planning in Smart Cities under Dynamic Traffic Demand

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***Abstract*—In smart cities, cellular network plays a crucial role to support connectivity anywhere and anytime. However, the communication demand brought by applications and services is hard to predict. Traffic in cellular networks might fluctuate heavily over time to time, which causes burden and waste under different traffic states. Recently, small cell was proposed to enhance spectrum efficiency and energy efficiency in cellular networks. However, how green the small cell network can be is still a question because of the accompanying interference. To meet this challenge, new green technologies should be developed. In this paper, we propose a green small cell planning scheme considering dynamic traffic states. First, we predefine a set of candidate locations for base stations (BSs) in a geographical area and generate a connection graph which contains all possible connections between BSs and user equipments (UEs). Then we adopt a heuristic to switch off small cell BSs (s-BSs) and update BS-UE connections iteratively. Finally we obtain a cell planning solution with energy efficiency without reducing spectrum efficiency and quality-of-service (QoS) requirements. The simulation results show that our dynamic small cell planning scheme has low computational complexity and achieves a significant improvement in energy efficiency comparing with the static cell planning scheme.**

I. INTRODUCTION

Smart cities are designed to meet citizens' ever-increasing requirements efficiently and environmentally. With the extensively use of smart devices, such as smartphones, wearable devices, IP cameras and terminals on vehicles, the future wireless network is considered as internet of things (IoT) [1]. Up to now, cellular network is still considered as the key infrastructure to provide wireless access with the popularization of 4G cellular networks. However, the current cellular networks are still incapable of supplying satisfactory and economical services considering spectrum efficiency and energy efficiency [2].

According to standards of LTE and expectations of 5G, future cellular networks are expected to be heterogenous or small cell networks [3]. Heterogenous network (HetNet) is defined as a mixture of macrocells and small cells, e.g., picocells, femtocells and relays. Small cells can potentially enhance spectrum reuse and coverage while providing high data rate services and seamless connectivity [4]. Meanwhile, small cell is also foreseen as a solution to achieve ecological sustainability. However, when small cells become dense in a limited area, severe interference would happen due to spectrum reuse. Furthermore, if we consider all user equipments (UEs) in a given urban area, the distribution of UEs might fluctuate during one day, resulting in various traffic states. In this case, some base stations (BSs) might be overloaded while some might be idle. Traditional cellular networks are designed based on the estimated highest traffic demand, which results in severe energy waste and causes huge cost for operators [5]. Consequently, new technologies on energy efficiency should be implemented in small cell networks, in order to support abundant applications and services for citizens with better quality and lower cost. Tremendous existing works on energy efficiency focus on optimizing radio resources and transmit power [6], [7], [8]. The problem is, the performance gains they achieved are still not significant enough without considering dynamic cell planning. An appropriate density of small cells, neither too dense or too sparse, is very important for the overall performance of the network. The question of how green the small cell network can be still needs to be further studied. To solve these emerging challenges, new energy efficient cell planning schemes should be developed for the future cellular networks [9].

It has been stated that BSs consume most energy in a cellular network [10]. The energy consumption of a BS can be divided into two parts, which are the transmit power of radio frequency (RF) signals and circuit power consumption respectively [11]. The transmit power of RF signals is only a small part of the power amplifier (PA) considering its transformation efficiency. The circuit power consumption includes baseband processing, cooling, battery backup, etc. When a BS is switched off into sleep mode, it only consumes limited power to maintain basic operation in order to be waked up again timely. As a result, switching the idle BSs off can reduce large amount of power consumption.

Green small cell planning under dynamic traffic demand has drawn much attention recently considering the significant gain it can achieve compared with static cell planning. Some existing schemes are based on stochastic model. In [12] an automated small cell deployment method is proposed to determine the locations of small cell BSs (s-BSs) based on stochastic geometry and Monte Carlo simulations. [13] studies the combined problem of BS location and optimal power allocation. In this work the authors assume a TDMA protocol so that there is no interference among the UEs. [14] has proved that the total energy consumption can be reduced by introducing the sleep mode while the UE performance remains superior. In [15], a BS operation and UE association mechanism is presented to obtain a flexible tradeoff between flow-level performance and energy consumption.

In this paper, an energy efficient small cell planning scheme is proposed in small cell networks considering dynamic traffic states. We deal with BS deployment, BS switching on/off

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strategy and UE association jointly in our scheme in order to enhance energy efficiency of the whole system while ensuring quality-of-service (QoS) requirements. First, we give a set of candidate locations for s-BSs in a geographical area and generate all possible connections between BSs and UEs. The predefined s-BSs can be dense enough in order to acquire more exact locations for s-BSs in the end. Then we adopt a heuristic to switch off s-BSs and update BS-UE connections iteratively. At last we obtain a solution using the least number of s-BSs without reducing spectrum efficiency and connectivity quality.

The remainder of the paper is structured as follows. Section II gives the overview of the network model and formulates our defined problem. Section III proposes our green cell planning scheme. In order to show the efficacy and effectiveness of our proposed scheme, we provide simulation results and discussions in Section IV. Finally, Section V concludes the paper.

II. SYSTEM MODEL AND PROBLEM FORMULATION

We consider deploying a small cell network in an urban area as depicted in Fig. 1. There is a macro cell base station (m-BS) locating at the center of this area. The local operator has selected a number of candidate locations to deploy s-BSs around it. It is assumed that the m-BS and all candidate s-BSs are connected to a local gateway which works as a centralized controller and manages the scheduling task in the network [16]. The physical channels between the BSs and the UEs are modeled by frequency selective Rayleigh fading which is mainly determined by distance attenuation. We assume that all UEs can receive signal from both m-BS and s-BSs. The m-BS and s-BS are working on different spectrum bands so that a UE served by m-BS will not receive any interference from s-BS, vice verse. We assume that all s-BSs share the same frequency band. As a result, a UE served by a s-BS receives interference from other s-BSs.

We assume that there are T traffic states in total for the given area in one day and π_t is defined as the occurrence probability of traffic state t. The sum of all π_t is equal to 1. Given a certain traffic state, we need to determine the corresponding BS states and UE associations, which are represented by matrix $\boldsymbol{a}$ and $\boldsymbol{b}$ respectively. Based on the definition of $\boldsymbol{b}$, the degrees of BS i and UE k under any traffic state t can be calculated by $\sum_{k=1}^{M} b_{i,k,t}$ and $\sum_{i=1}^{N} b_{i,k,t}$ separately. Furthermore, we can obtain the deployment of s-BSs $\boldsymbol{c}$ by Equation (3). It shows that a BS is deployed at a certain candidate location if there is at least one active state under all traffic states. When the traffic state changes, the s-BSs can be manipulated to switch on/off in order to guarantee energy efficiency while holding QoS requirements.

$$a_{i,t} = \begin{cases} 1, & \text{if BS } i \text{ is active in state } t, \\ 0, & \text{otherwise,} \end{cases} \tag{1}$$

$$b_{i,k,t} = \begin{cases} 1, & \text{if UE } k \text{ is associated with BS } i \text{ in state } t, \\ 0, & \text{otherwise,} \end{cases} \tag{2}$$

$$c_i = \begin{cases} 1, & \text{if } \sum_{t=1}^{T} a_{i,t} > 0, \\ 0, & \text{otherwise.} \end{cases} \tag{3}$$

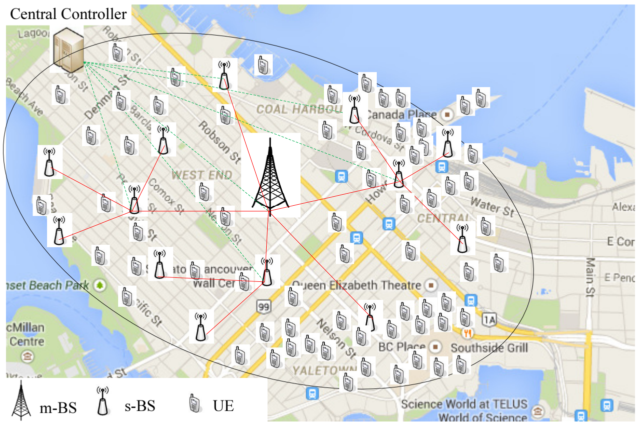


Fig. 1: Small cell network in an urban area.

We assume that UE k can be served by BS i when its received signal to interference and noise ratio (SINR) exceeds a minimum threshold Λ_{th}. The received SINR of UE k from BS i is expressed as

$$\gamma_{i,k} = \frac{p_{i,k} g_{i,k}}{\sum_{j=1, j \neq i}^{N} a_j p_{j,k} g_{j,k} + \delta^2} \geq \Lambda_{th}, \tag{4}$$

where $p_{i,k}$ is the assigned transmit power to UE k by BS i, $g_{i,k}$ is the channel gain between BS i and UE k. δ^2 is the power of terminal noise.

Consequently, the Shannon capacity obtained by UE k is represented by

$$R_{i,k} = \log_2(1 + \Gamma \cdot \gamma_{i,k}), \tag{5}$$

where Γ indicates the SINR gap under a given bit error rate (BER), which is defined as $\Gamma = -1.5/\ln(BER)$ [17].

The total capacity of the network can be written as

$$R_{sum}(\boldsymbol{a}, \boldsymbol{b}) = \sum_{i=1}^{N} a_{i,t} \sum_{k=1}^{M} b_{i,k,t} R_{i,k}, \tag{6}$$

The total power consumption of the system is

$$P_{sum}(\boldsymbol{a}, \boldsymbol{b}) = \sum_{i=1}^{N} [a_{i,t}(\gamma_i P_{i,t}^{T} + P_i^{A}) + (1 - a_{i,t}) P_i^{I}], \tag{7}$$

where γ_i is defined as the PA inefficiency factor of BS i and P_i^T is the total transmit power [11]. For instance, if $\gamma_i = 5$, it means that the power consumption of the PA is 5 times of the total power transmitted from BS i. P_i^A is the circuit power consumption of BS i when it is active, while P_i^I is the circuit power consumption when BS i is idle. We assume that equal power allocation is implemented in the system. Therefore, the transmit power for each UE served by BS i is P_i^{max}/M_i^S and the total transmit power can be calculated as

$$P_{i,t}^{T} = P_i^{max} \frac{\sum_{k=1}^{M} b_{i,k,t}}{M_i^S}, \tag{8}$$

where M_i^S is the maximum number of UEs that can be served by BS i.

Based on the above definitions, the small cell planning problem can be formulated as follows.

$$
\begin{aligned}
\max \quad & \eta_{EE} = \sum_{t=1}^{T} \pi_t \frac{R_{sum}(\boldsymbol{a},\boldsymbol{b})}{P_{sum}(\boldsymbol{a},\boldsymbol{b})}. \\
\text{s.t.} \quad & \mathrm{C1}: a_{i,t}, b_{i,k,t} \in \{0,1\}, \forall i,k,t, \\
& \mathrm{C2}: \sum_{i=1}^{N} b_{i,k,t} \le 1, \forall k,t, \\
& \mathrm{C3}: \sum_{k=1}^{M} b_{i,k,t} \le M_i^S, \forall i,t, \\
& \mathrm{C4}: b_{i,k,t} \le a_{i,t}, \forall i,k,t, \\
& \mathrm{C5}: a_i p_{i,k} g_{i,k} \ge b_{i,k,t} \Lambda_{th} \Big(\sum_{j=1, j\ne i}^{N} a_{j,t} p_{j,k} g_{j,k} + \delta^2 \Big), \\
& \qquad \qquad \forall i,k,t, \\
& \mathrm{C6}: \sum_{i=1}^{N} \sum_{k=1}^{M} b_{i,k} \ge (1-\tau) M,
\end{aligned}
\tag{9}
$$

where the objective represents the expectation of energy efficiency in one day [10]. C1 is the boolean constraint for cell planning. C2 constrains that the degree of any UE k under any traffic state t should be less than 1, which means a UE can be served by only one BS at most. C3 represents that the degree of BS i under any traffic state t should be less than M_i^S, which is the limitation of the number of connections on BS side. C4 indicates that any UE k can be served by any BS i under any traffic state t only when the BS is active. C5 is a transformation of Equation (4) to ensure QoS requirements for any UE k served by any BS i under any traffic state t. Finally, C6 sets the outage constraint which means that the percentage of UEs in outage should be lower than τ.

Different traffic states can be taken as independent events and the cell planning result in one traffic state would not affect the cell planning result in another. Consequently, the problem (9) can be decomposed into T subproblems corresponding to T traffic states. Besides, the power consumption of active state is much larger than the power consumption of sleep state for a s-BS. Therefore, if the network capacity can be maintained in a certain interval, the objectives of maximizing energy efficiency and minimizing the number of active s-BSs would have very high probability to be correlated, which means that we can achieve very close results using either objective.

III. PROPOSED GREEN SMALL CELL PLANNING SCHEME

We introduce our heuristic in this section. First we introduce an identical scenario that we consider in this paper as shown in Fig. 2, which provides all candidate locations of s-BSs in the given area. The size of the area is $1600m \times 1600m$. We consider all traffic states are combinations of some basic elements, which are listed in Fig. 3, e.g., the traffic state in Fig. 2 is the combination of Element 9 and 11. We denote it by "$9+11$" in the title of the figures.

For a given traffic state, the proposed green small cell planning algorithm is shown in Algorithm 1. In this algorithm, $\boldsymbol{a}'$ is defined as the last BS state. $\boldsymbol{\zeta}$ and $\boldsymbol{\xi}$ are denoted to record the degrees of each BS and UE respectively. $\boldsymbol{\phi}$ is the set of the candidate UEs which are connected to the selected BS and $\boldsymbol{\psi}$ is the set of degrees of the candidate UEs. The elements of $\boldsymbol{a}$, $\boldsymbol{\zeta}$ and $\boldsymbol{\xi}$ are set to 0 initially, while the initial elements of $\boldsymbol{a}'$ are set to 1. $\mathbf{N}_r$ is the set of active BSs that have not been checked in Step 3.

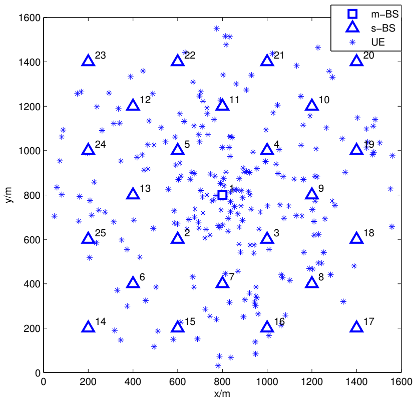
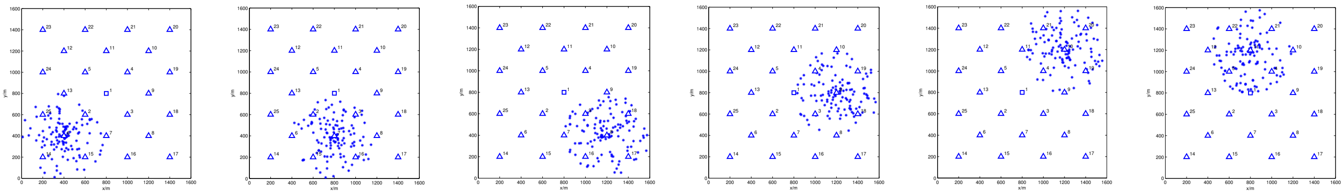
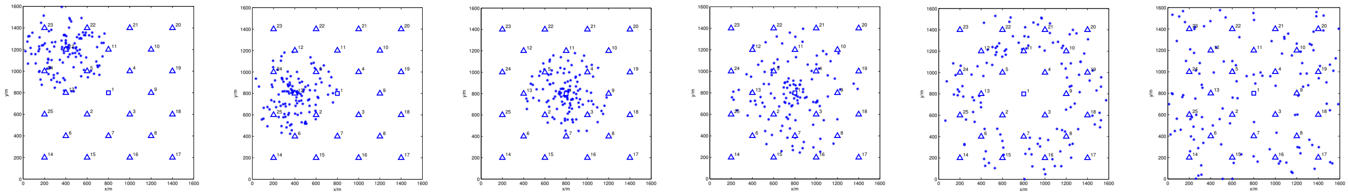


Fig. 2: Initialization of BS deployment, traffic state: $9+11$.

In each iteration, we conduct three steps to update the cell planning process. In Step 1, we mainly focus on building the connection graph. First we calculate the SINR $\gamma_{i,k}$ between each BS and UE and compare it with the threshold Λ_{th}. In this way we obtain all possible connections between BSs and UEs and save them in matrix $\boldsymbol{b}$. At the same time, we can get the degrees of all BSs and UEs, which are held in $\boldsymbol{\zeta}$ and $\boldsymbol{\xi}$ respectively. In Step 2, we aim to delete the redundant connections. If the maximum value in $\boldsymbol{\xi}$ is larger than 1, there must exist at least one UE in $\boldsymbol{\xi}$ whose degree is larger than 1, which means that we have redundant connections. To begin with, we find the index of the BS which has the maximum degree, say j. We set it to the state of active preferentially. If its degree is larger than the maximum number of UEs it can serve, we will delete its connection to the UE which has the largest degree iteratively until the degree of BS j meets the constraint C3. The reason is, the UEs which have larger degrees have more choices to connect to other BSs. Even if we delete its connection to BS j, it still has enough candidate BSs. Then we update $\boldsymbol{b}$, $\boldsymbol{\zeta}$ and $\boldsymbol{\xi}$ and repeat until we jump out of the loop. After the loop we save the previous BS state $\boldsymbol{a}$ to $\boldsymbol{a}'$ and calculate $\boldsymbol{a}$ and $\boldsymbol{c}$ based on the current $\boldsymbol{b}$. In Step 3, we check whether one more active s-BS can be switched off. If no s-BS has been switch off after Step 2 in this iteration, or $\boldsymbol{a} = \boldsymbol{a}'$, we would try to switch each active s-BS off to see whether the outage constraint C6 holds. If no more s-BSs can be switched off, the whole algorithm would end here. Otherwise, we would repeat Step 1 and Step 2 until no more s-BSs can be switched off. The end condition of the algorithm is $\boldsymbol{a} = \boldsymbol{a}'$ and C6 does not hold, which means that further switching off any s-BS would cause outage. With these two conditions we can find that the maximum iteration number is $2(N-1)$, which means the algorithm would converge within $2(N-1)$ iterations under all tested traffic states. In each iteration of Algorithm 1, the complexity of the three steps are $O(MN)$, $O(MN+2M^2)$ and $O(MN^2+M^2N)$ respectively. Consequently, the computational complexity of Algorithm 1 is $O(MN^3+M^2N^2)$.



(a) Element 1. (b) Element 2. (c) Element 3. (d) Element 4. (e) Element 5. (f) Element 6.



(g) Element 7. (h) Element 8. (i) Element 9. (j) Element 10. (k) Element 11. (l) Element 12.

Fig. 3: 12 basic traffic elements.

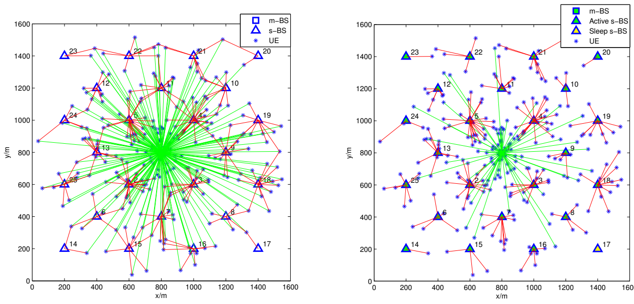
After we have all the BS states under each traffic state in the given area, the final deployment of s-BSs can be determined by the union set of all active sets in each traffic state. It can also be obtained by Equation (3). When traffic state changes, we can determine to switch on/off the s-BSs according to the results of Algorithm 1.

IV. SIMULATION RESULTS AND DISCUSSIONS

In order to validate the performance of the proposed scheme, we present numerical and simulation results in this section. Simulation setup mainly follows the guidelines of 3GPP technical reports [18]. We adopt the power consumption model from [11] and set the value of circuit power consumption for m-BS and s-BS accordingly. The primary system parameters are summarized in Table I.

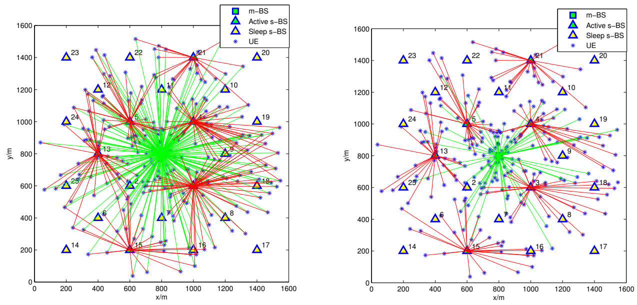
A. Performance Under a Typical Traffic State

In this subsection we study the performance under a certain typical traffic state. We select the above traffic state combined by Element 9 and 11. There are totally 250 UEs in this scenario. Fig. 4 shows the connection graph and UE association in the first iteration. Fig. 4(b) depicts the cell planning result after Step 2. We can observe that BS 17 is idle with no UE association, so it would be switched off in this iteration. Fig. 5 illustrates the connection graph and UE association in the last iteration. From Fig. 4(a) and Fig. 5(a) it can be seen that the m-BS can reach any UE in this area because of no interference from the s-BSs, while the s-BSs can only get to very limited space due to the interference from other s-BSs. We achieve the final result as shown in Fig. 5(b) after 35 iterations. As can be seen from the figure, only 6 of total 24 s-BSs remain active after our proposed scheme. Meanwhile, we observe that the s-BSs can reach farther UEs due to the decrease of interference. Fig. 6 shows the variation of the total number of served UEs in each iteration. We can observe that in the first 33 iterations, all UEs are served without any outage. In the 34th iteration, outage happens and C6 does not hold. However, the other condition $\boldsymbol{a} \neq \boldsymbol{a}'$ still holds, so it is not the end. The end condition happens after the 35th iteration and the cell planning result in the 35th iteration is the final result. Fig. 7 illustrates the number of UEs for each BS in the first iteration and the last iteration. We can see the m-BS is fully utilized since the first iteration and UEs converge to a few s-BSs at last. The results depict that computational complexity is quite low and the QoS requirements for UEs can be well guaranteed.



(a) Connection graph. (b) UE association.

Fig. 4: Cell planning in the first iteration, traffic state: 9+11, $M = 250$.



(a) Connection graph. (b) UE association.

Fig. 5: Cell planning in the last iteration, traffic state: 9+11, $M = 250$.

Fig. 8 presents the performance of the system in terms of number of active s-BSs, total power consumption, total

Algorithm 1: Green Small Cell Planning

```
Input: Traffic state $t$.
Output: $\boldsymbol{a}, \boldsymbol{b}, \boldsymbol{c}$.
Initialization: $\zeta_i := 0, a_i := 0, a'_i := 1, \forall i \in \boldsymbol{N}$; $\xi_k := 0, \forall k \in \boldsymbol{M}$.
while $\boldsymbol{a} \neq \boldsymbol{a}'$ or C6 holds do
    Step 1: Build connection graph.
    for $\forall i \in \mathbf{N}$ and $\forall k \in \mathbf{M}$ do
        Calculate the SINR $\gamma_{i,k}$ between each BS and UE.
        if $\gamma_{i,k}$ is larger than $\Lambda_{th}$ then
            $b_{i,k,t} := 1$, $\zeta_i := \zeta_i + 1$, $\xi_k := \xi_k + 1$.
        else
            $b_{i,k,t} := 0$.
    Step 2: Delete redundant connections.
    while The maximum value in $\boldsymbol{\xi}$ is larger than 1 do
        Find the index of the BS which has the maximum degree , say $j$.
        Find the set of candidate UEs which are connected to this BS, say $\boldsymbol{\phi}$.
        Save the degrees of candidate UEs to set $\boldsymbol{\psi}$.
        while The length of $\boldsymbol{\psi}$ is larger than $M_j^S$ do
            Delete the connection to the UE which has the largest degree.
        Delete the connections of the remained UEs to other BSs.
        Update $\boldsymbol{b}$, $\boldsymbol{\zeta}$ and $\boldsymbol{\xi}$.
    $\boldsymbol{a}' := \boldsymbol{a}$.
    Calculate $\boldsymbol{a}$ and $\boldsymbol{c}$ based on $\boldsymbol{b}$.
    Set the transmit power of the inactive BSs to 0.
    Step 3: Check if one more active BS can be switched off.
    if $\boldsymbol{a} = \boldsymbol{a}'$ then
        for $\forall j' \in \mathbf{N}_r$ do
            Set the transmit power of BS $j'$ to 0 and repeat Step 1 and Step 2.
            if C6 holds then
                break
            else
                Recover the transmit power of BS $j'$.
        if C6 does not hold for $\forall j' \in \mathbf{N}_r$ then
            break
```

spectrum efficiency and total energy efficiency. We can take the results of the first iteration as the results of static cell planning because all s-BSs are active even some of them are idle. In Fig. 8(a), we observe that the number of active s-BSs decreases from 24 to 6. At the same time the total power consumption drops from 1420W to 970W as shown in Fig. 8(b). We find that the total spectrum efficiency keeps stable between 37 b/s/Hz to 42 b/s/Hz as illustrated in Fig. 8(c). In Fig. 8(d), it is shown that the total energy efficiency increases gradually with the decreasing number the active s-BSs. The results validate that the problems of maximizing total energy efficiency and minimizing active s-BSs have strong correlation.

TABLE I: SIMULATION PARAMETERS

Parameter	Value
Area size	$1600m \times 1600m$
Number of m-BSs/s-BSs	1 / 20
Carrier frequency	2 GHz
Bandwidth for m-BS/s-BS	8 MHz / 3 MHz
Maximum Tx power of m-BS/s-BS	46 dBm / 40 dBm
PA inefficiency factor of m-BS/s-BS	5 / 5
Circuit power consumption of m-BS/s-BS (active)	52 dBm / 46 dBm
Circuit power consumption of m-BS/s-BS (sleep)	48 dBm / 42 dBm
Maximum number of UEs served by a m-BS/s-BS	80 / 30
Path loss model for m-BS	$128.1 + 37.6\log_{10}(d)$ dB
Path loss model for s-BS	$140.7 + 37.6\log_{10}(d)$ dB
Bit error rate(BER)	10^{-3}
Thermal noise	-174 dBm/Hz
SINR threshold	-5dB
Outage probability	0.02

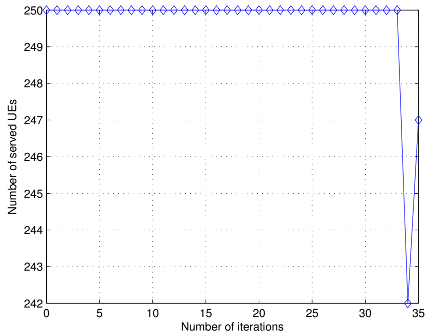


Fig. 6: Number of served UEs versus number of iterations, traffic state: 9+11, $M = 250$.

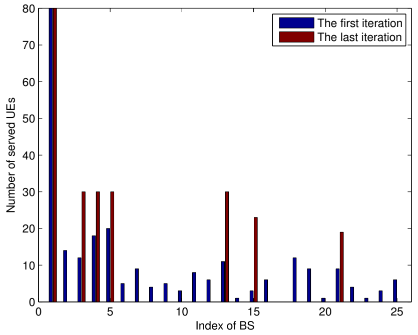
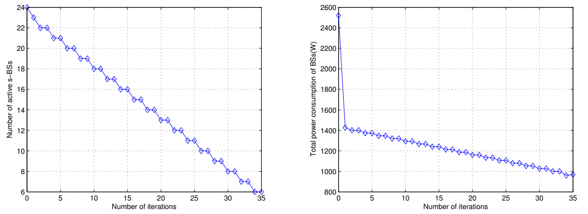


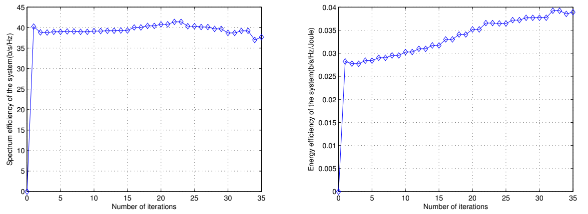
Fig. 7: Number of served UEs for each BS, traffic state: 9+11, $M = 250$.

B. Performance Under Other Traffic States

We have done numerous simulations under other traffic states and 4 of them are picked to present in this subsection. The results of BS state and UE association are presented in Fig 9. For other criterions such as spectrum efficiency and energy efficiency, we can achieve results similar to Fig. 8, which proves the efficacy and effectiveness of our scheme.

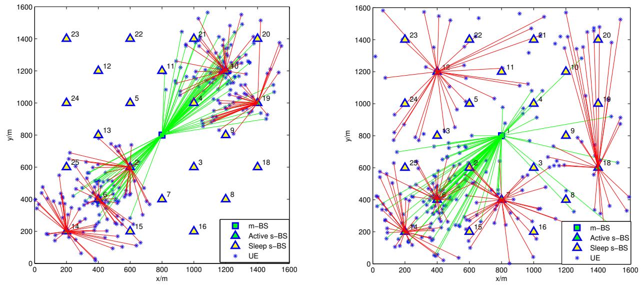


(a) Number of the active s-BSs versus number of iterations. (b) Total power consumption versus number of iterations.

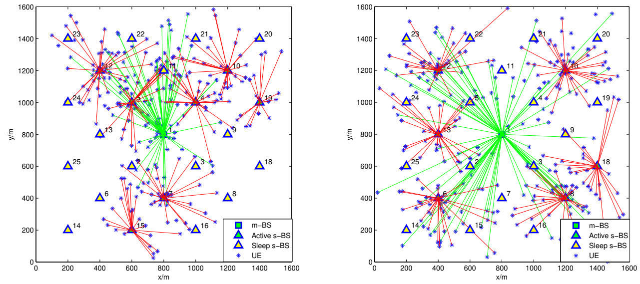


(c) Total spectrum efficiency versus number of iterations. (d) Total energy efficiency versus number of iterations.

Fig. 8: Simulation results of system performance, traffic state: 9+11, $M = 250$.



(a) 1+5. (b) 1+12.



(c) 2+5+6+7+9. (d) 1+3+5+7+9.

Fig. 9: Simulation result under different traffic states, $M = 250$.

V. CONCLUSION

In this paper, we propose an energy efficient small cell planning scheme under dynamic traffic states in small cell networks. In this scheme we adopt a heuristic to switch off s-BSs and update BS-UE connections iteratively. Finally we obtain a solution using the least number of s-BSs without reducing spectrum efficiency and connectivity quality. The simulation results show that our dynamic cell planning scheme can achieve a significant improvement in energy efficiency while maintaining QoS requirements.

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