Low-Complexity Energy Efficient Base Station Cooperation Mechanism in LTE Networks

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Abstract

Currently Energy-Saving (ES) methods in cellular networks could be improved, as compensation method for irregular Base Station (BS) deployment is not effective, most regional ES algorithm is complex, and performance decline caused by ES action is not evaluated well. To resolve above issues, a low-complexity energy efficient BS cooperation mechanism for Long Time Evolution (LTE) networks is proposed. The mechanism firstly models the ES optimization problem with coverage, resource, power and Quality of Service (QoS) constraints. To resolve the problem with low complexity, it is decomposed into two sub-problems: BS Mode Determination (BMD) problem and User Association Optimization (UAO) problem. To resolve BMD, regional dynamic multi-stage algorithms with BS cooperation pair taking account of load and geographic topology is analyzed. And then a distributed heuristic algorithm guaranteeing user QoS is adopted to resolve UAO. The mechanism is simulated under four LTE scenarios. Comparing to other algorithms, results show that the mechanism can obtain better energy efficiency with acceptable coverage, throughput, and QoS performance.

Keywords: Low-complexity, energy efficient, BS cooperation, LTE networks

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1. Introduction

Along with the development of cellular networks, varieties of services can be supplied, and sustained growth of BSs (such as BTS, NodeB, eNodeB, Femto-cell) occupy about 50%~60% of network energy consumption [1]. In the planning stage, cellular networks are usually dimensioned according to predictive peak traffic. However, during night time regional traffic is far from peak hour and much energy is wasted [2].

Frequent adjustments of wireless parameters are required to implement ES compensation in cellular networks, such as transmit power, antenna tilt, and so on [3]. Though traditional manual management is not suitable, self-management can perfectly resolve this problem. Concept of ES Management (ESM) defined by 3GPP in Self-Organized Network (SON) use case is followed: when network traffic is low, several BSs can be slept through signaling, and remain active BSs are cooperated to compensate regional coverage and capacity [4]. Currently BS cooperation is an effective method used to enhance energy efficiency in cellular networks with BS sleep mechanism [3] or non-BS sleep mechanism [5]. As BS sleep mechanism can obtain more energy-saving gain, this paper mainly concentrates on this one.

However, sleeping several BS will change regional coverage topology and no doubt introduce service quality degradation, so saving energy is a tradeoff between energy efficiency and performance. Currently ES problems have been studied from many perspectives. For specific implementation, ESM solutions mainly adopted BS cooperation to compensate coverage and capacity for switched-off BSs [6-7]. For coverage compensation of sleep BS, several methods are just suitable for regular BS deployment as in [8-9]. On account of traffic load and neighbor relationship, an ES method through cell extension was given in [10]. But only number of switched-off BS is used to denote ES gain.

Still, several above methods only consider the power saving at one time point [6-7, 10-11], ES efficiency and traffic fluctuations over the time period are ignored. For other regional ES methods considering traffic variations, traffic variation was profiling as a sinusoidal-function in [12], and ES gain with acceptable service blocking probability was analyzed then. But ES trigger and recovery conditions were neglected. Opposite pair and trigonal pair compensation solution for a single BS was analyzed in [9], but traffic distribution and compensation method are ideal. Further modified ES method based on trigonal pair compensation was proposed in [13]. It divided ES procedure into two stages, but complexity of mathematical model is high and energy efficient can be improved. A multi-stage ES method was given in [14]. It involved a traffic predication method, and takes ES actions in each divided coverage grid. But intra-grid interference and inter-grid overlap is ignored. An energy-efficient cell breathing and offloading mechanism in both macro cellular and heterogeneous net-works was studied in [15], but coverage and interference from user perspectives are not considered. Traffic-Aware relay sleep control analytical model using stochastic geometry theory was analyzed in [16], which is hard to be implemented in practical networks.

In order to provide regional and hotspot coverage in LTE networks, coverage enhancement technologies, for instance, micro-BS/cell, femto-BS/cell, BBU+RRU and relay, were adopted. Generally, macro-cell/BS is responsible for regional coverage. Other lower power nodes are mainly deployed for hotspot [17]. Coverage of micro-BS/cell is always overlapped by macro-BS/cell. Moreover, power consumption of macro-BS/cell is fairly higher than smaller one [18]. Thus research on ESM for macro-BS takes on more significance.

Based on above analysis, an energy efficient BS cooperation mechanism with low complexity is proposed for LTE networks. Its contributions are shown followed: 1) an integrated ES optimization model considering temporal-spatial affection, coverage, interference, and QoS constraint is constructed; 2) to resolve the ES optimization problem with low complexity, traffic-aware time domain division method is proposed; 3) to resolve BMD sub-problem, effective BS pair cooperation method under practical BS topology is analyzed; 4) to resolve UAO sub-problem, a distributed heuristic algorithm under QoS constraints is established. The effectiveness of our mechanism is simulated and evaluated under LTE networks at last.

The paper is organized as followed. In Section 2, the ES optimization model is constructed. We still give the description for the BMD sub-problem and UAO sub-problem. In Section 3, low-complexity solution methods for ES optimization model is analyzed, which includes time domain division method, local BS pair cooperation method, dynamic trigger and recovery algorithms for BMD sub-problem, and distributed heuristic algorithm for UAO sub-problem. In Section 4, the mechanism is simulated under four LTE scenarios for practical arrival rates for one week. Conclusions and future work are given in Section 5.

2. ES Optimization Model

To constrcut ES optimization model in LTE networks, we discuss the system model firstly, which includes resource allocation scheme and power model of BS. Then mathematical formulation for ES optimization and corresponding BMD and UAO sub-problems are introduced.

2.1 System Model for LTE

A. Resource Allocation Scheme

In LTE networks with K kinds of service, let $\mathrm{I} = \{1, 2, \ldots, I\}$ and $\mathrm{J} = \{1, 2, \ldots, J\}$ denote the set of Users and BSs. For BS j. At time t for user i and BS j, binary variable $x_{ij}(t) = 1$ if user i is serving by BS j, otherwise $x_{ij}(t) = 0$. Still, $p_{ij}(t)$ denote the transmit power of which BS j communication to user i, and $g_{ij}(t)$ denote the channel gain between BS j and user i. Then, we define $\boldsymbol{X}(t) = [x_{ij}(t)]$, $\boldsymbol{P}(t) = [p_{ij}(t)]$, and $\boldsymbol{G}(t) = [g_{ij}(t)]$ as the BS association matrix, the transmission power matrix and channel gain matrix respectively. The Signal to Interference plus Noise Ratio (SINR) experienced by user i from BS j is given by

$$\gamma_{ij}(t) = \frac{p_{ij}(t)\cdot g_{ij}(t)\cdot x_{ij}(t)}{\mathrm{N}_0 + \sum_{k=1,k\neq j}^{\mathrm{J}} p_{ik}(t)\cdot g_{ik}(t)\cdot x_{ij}(t)} \tag{1}$$

Where N_0 is the thermal noise. Assuming AMC (Adaptive Modulation and Coding) is used, and then SINR can be mapped to the spectral efficiency as

$$\varphi_{ij}(t) = \begin{cases} 0 & , \gamma_{ij}(t) < \gamma_{\min} \\ \xi \log_2(1+\gamma_{ij}(t)), & \gamma_{\min} \le \gamma_{ij}(t) < \gamma_{\max} \\ \varphi_{\max} & , \gamma_{ij}(t) \ge \gamma_{\max} \end{cases} \tag{2}$$

Here, $0 \le \xi \le 1$ is the attenuation factor, γ_{min} and γ_{max} are the minimum SINR and maximum SINR, and ψ_{max} is the maximum spectral efficiency [19]. Further, require Resource Block (RB) of user i from BS j is given by

$$\beta_{ij}(t) = \left\lceil \frac{u_{ij}(t)}{W_{\mathrm{RB}}\varphi_{ij}(t)} \right\rceil \tag{3}$$

Where $u_{ij}(t)$ is the required data rate and W_{RB} is bandwidth of each RB. Function $\lceil y \rceil$ denotes the nearest integer which is not smaller then y. Further, load factor of BS j is given by

$$L_j(t) = \frac{1}{\beta_{\mathrm{M}}} \sum_{i=1}^{\mathrm{I}} \beta_{ij}(t) \tag{4}$$

Where β_{M} is the maximum RB number for each BS. And load factor is considered as an important effect factor for dynamic part of BS power.

B. Power Model of BS

For BS j, assuming its maximum operating power when fully utilized is P_j^{M}. Moreover, portion of its fixed power to P_j^{M} is denoted as δ_j. At time t, with ES method, power of BS j is given by

$$P_j(t) = P_j^{\mathrm{M}} \left[(1-\delta_j) L_j(t) + \phi_j(t)\delta_j \right] \tag{5}$$

Where $\phi_j(t)$ denotes required power portion of fixed power to keep BS controllable when it goes to sleep mode. δ_j can be used to denote non-energy-proportional BS such as $0 < \delta_j < 1$ for macro-BS, energy-proportional BS such as $\delta_j = 0$ for micro-BS and femto-BS, and other fixed power nodes when $\delta_j = 1$[11]. Furthermore, we give definition of $\phi_j(t)$ as

$$\phi_j(t) = \begin{cases} 1, L_j(t) > 0 \\ \varepsilon, L_j(t) = 0 \end{cases} \tag{6}$$

Where ε is a small value denoting power ratio for maintaining basic management function. When $L_j(t) > 0$, BS j is active with full power operation. When $L_j(t) = 0$, which means none user is served by BS j, it can be set into sleep mode with minimum operation power. So with (5)~(6) we can evaluate BS in different mode. Then for the LTE networks, energy required for BSs on time period $[0, T]$ is given by

$$E_T = \int_0^T \sum_{j=1}^{\mathrm{J}} P_j(t)dt \tag{7}$$

2.2 Mathematical Formulation for ES Optimization

For LTE networks, the target of ES optimization problem is minimum energy consumption on the time period with acceptable performance. Taking BS association matrix and transmission power matrix as variables, the optimization problem is decribed as

$$\mathrm{P}: \min_{\boldsymbol{X}(t), \boldsymbol{P}(t)} E_T = \int_0^T \sum_{j=1}^{\mathrm{J}} P_j(t)dt \tag{8}$$

$s.t.,$

$$\forall i, j, t \quad \sum_{j=1}^{\mathrm{J}} x_{ij}(t) \le 1 \tag{9}$$

$$\forall j, k, t \quad P_{jk}^{\mathrm{B}}(t) \le P_{\mathrm{M}}^{\mathrm{B}} \tag{10}$$

$$\forall i, j, t \quad \sum_{i=1}^{\mathrm{I}} \beta_{ij}(t) \le C_j(t) < \beta_{\mathrm{M}} \tag{11}$$

$$\forall i, j, t \quad \sum_{i=1}^{I} \beta_{ij}(t) p_{ij}(t) \le \alpha P_j^{\mathrm{T}} \tag{12}$$

$$\forall i, j, t \quad \text{if } x_{ij}(t) = 1, \gamma_{ij}(t) \ge \gamma_{\min} \tag{13}$$

$$\forall i, j, t \quad \text{if } x_{ij}(t) = 1, \sigma_{ij}(t) = p_{ij}(t) g_{ij}(t) \ge \chi \tag{14}$$

Where constraint (9) makes sure that one user can only be served by no more than one BS simultaneously. Constraint (10) is adopted to keep blocking probability for service *k* at BS *j* (denoted as $P_{jk}^{\mathrm{B}}(t)$) below threshold $P_{\mathrm{M}}^{\mathrm{B}}$ [8]. Constraint (11) is used to guarantee that none BS is overload, and $C_j(t)$ is the available RB number for BS *j* at time *t*. Constraint (12) is restriction for transmit power P_j^{T} of BS *j* with control factor *α*. Constraint (13) and (14) make sure interference and signal strength for serving user *i* are all keep above target value, where χ is the lower threshold for signal strength. Constraint (10) and (13) can be considered as important QoS parameters.

As motivation for saving energy in LTE networks is the traffic variations, so we must find correlation between sleep BS number and traffic profile. However, practical traffic always fluctuates with times, so ES mechanism should avoid frequent BS on-off actions on the time period. To resolve this problem, we propose a traffic-aware time domain division method firstly, and we can obtain at least two monotone time intervals. Only during monotone interval we should resolve problem P.

Referring to mathematical analysis in [19], we can find that P is a non-convex combinational problem with non-linear constraint. Classical mathematical solutions may not be effective. As ES mechanism should consider the BS sleep strategy and QoS maintenance scheme, so we can consider P from BS perspective and user perspective separately. To reduce the computation complexity of the problem, we then decompose the problem into temporal BMD sub-problem and spatial UAO sub-problem.

From BS perspective, we should find a strategy to maximum sleep BS number and meanwhile maintaining regional coverage and capacity constraints, that is what BMD problems aims to resolve. Once BS mode is determined, from user perspective, we should then find proper BS-user connections and corresponding parameter adjustments to minimize regional power above acceptable QoS constraints, that is what UAO problem aims to resolve.

A. Temporal BMD Problem

As fixed part of BS power occupies most energy consumption, so the target of BMD problem is maximizing the number of sleep BS on the time period. However, in order to keep coverage constraint and resource constraint and minimize the negative affect, number of sleep times for each BS should be control. Thus BMD problem is given as

$$\mathsf{P1}: \min_{\boldsymbol{L}(t)} \int_0^T \sum_{j=1}^{J} s_j(t) dt \tag{15}$$

$$s.t.,$$

$$\forall j, t, \; L_j(t) < 1 \tag{16}$$

$$\forall j, \quad \int_0^T |1 - s_j(t)| dt \le w \tag{17}$$

$$\forall j, t \; \text{ if } s_j(t) = 0, \sum_{m \in \boldsymbol{U}_j(t)} |s_m(t)| \ge \iota \tag{18}$$

Where $\boldsymbol{L}(t)$ is the load factor vector for each $L_j(t)$. $s_j(t)$ is a binary variable denoting the mode of BS *j* at time *t* , which is can be set as 0 and 1 meaning sleep mode and active mode. That is, if $L_j(t) > 0$, $s_j(t) = 1$, otherwise, $s_j(t) = 0$. On the time period, the more BSs turning to sleep mode, the smaller P1 becoming, which equals to maximize the number of sleep BSs.For sleep BS, its load is allocated to active neighbouring BSs. Constraint (16) makes sure none BS is overload. As described in [14], on one period the sleep times for each BS should be controlled to reduce negative effect to the network topology. Constraint (17) guarantees the sleep times lower than target value w. In constraint (18), $\boldsymbol{U}_j(t)$ is the neighbor BS set of BS j. So for BS under sleep mode, at least ι active BSs exist in its neighbor list to guarantee coverage.

BMD problem determines BS mode and load re-allocation method for each BS at arbitrary time t. However, connections among users and BSs with spatial considerations should be resolved through UAO problems.

B. Spatial UAO Problem

For UAO problem, its target is to minimum regional BS power with performance constraints at time t. So spatial BS association matrix and transmission power matrix are taken as variables without time considerations. Then UAO problem is given by

$$\mathrm{P2}: \min_{\boldsymbol{X},\boldsymbol{P}} \sum_{j=1}^{J} P_j, s.t. \ (9) \sim (14) \qquad (19)$$

We can find that P1and P2 are still mix-integer non-convex problems. As P1and P2 should be resolved for arbitrary time t, each BS j and each user i, they may cost much time and computation resource for Operation Administration and Maintenance (OAM) system. For practical implementation, the expense is not economic. To resolve them, we explore the solutions with low complexity. Firstly, we can assume that traffic for each BS and the network is almost constant in each hour, so P1and P2 can be just resolved at the beginning of each hour. The solutions for the two sub-problems will be analyzed in detail later.

C. Resolving methods and algorithms for ES optimization problem

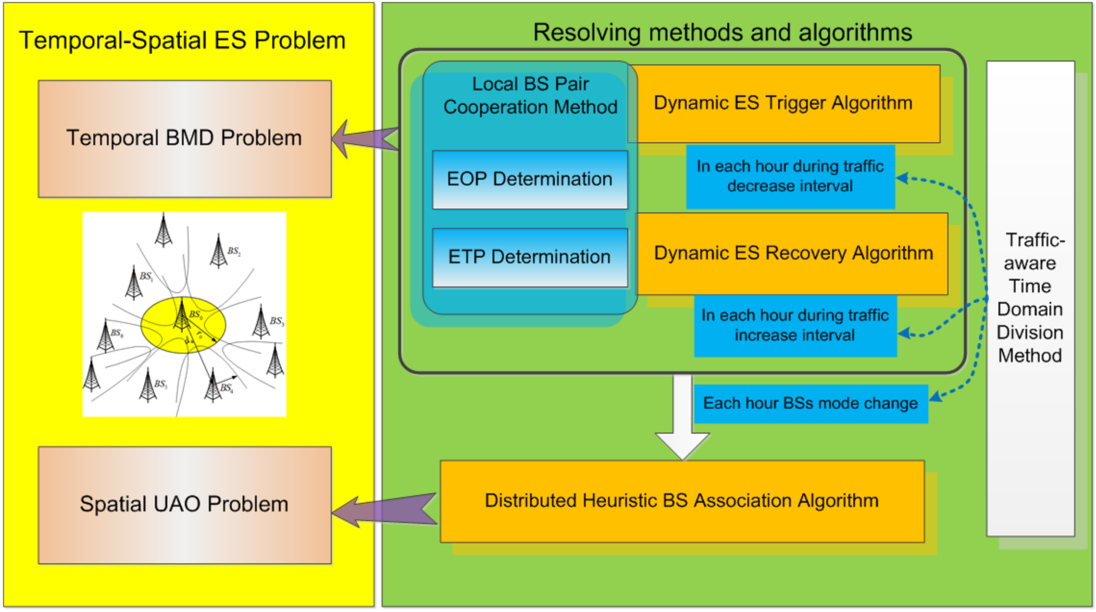

Fig. 1. Resolutions for ES optimization problem

Resolutions for above sub-problems are show in **Fig. 1**. As described in **Fig. 1**, low-complexity resolving algorithms and methods for the optimization problem mainly contain traffic-aware time domain division method, local BS pair cooperation method, dynamic ES trigger algorithm, dynamic ES recovery trigger algorithm and distributed heuristic BS association algorithm. Relations among these methods and algorithms will be described below:

1) Traffic-aware time domain division method firstly divides each day into four intervals to avoid frequent BS sleeping, which are traffic decreasing interval, low-traffic interval, traffic increasing interval and high-traffic interval. During low-traffic interval and high-traffic interval regional traffic is fluctuant and none algorithm will be executed.

2) To resolve temporal BMD problem, dynamic ES trigger algorithm will be executed for each hour during traffic decreasing interval, which makes sure number of sleep BS increasing along with time. Still, dynamic ES recovery algorithm will be executed for each hour during traffic increasing interval, which makes sure number of active BS increasing along with time. And these two algorithms will guarantee that each BS will be slept at most once.

3) Dynamic ES trigger algorithm and dynamic ES recovery algorithm will give the modes of each BS according to regional traffic and regional BS topology. Local BS pair cooperation method gives detailed analysis for EOP and ETP determination, which shows how to compensate a single BS with neighbor BSs topology. EOP and ETP are basis of above two BS mode determination algorithms.

4) In each hour, once dynamic ES trigger algorithm or dynamic ES recovery algorithm is executed, regional BS mode will change and user may handover to proper BS to guarantee QoS. As UAO problem should consider many factors from user perspective, much overhead is required if concentrated control is used. Thus, distributed heuristic BS association algorithm will be executed to resolve UAO problem.

Next, these methods and algorithms will be introduced in detail.

3. Low-complexity Solution Methods and Algorithms for ES Optimization Model

3.1 Traffic-aware Time Domain Division Method

To understanding traffic variations in LTE networks, normalized traffic variations for one week from a district in Beijing are shown in **Fig. 2**. The traffic profile denotes that: 1) Traffic variations during weekdays and weekends are different, and load during weekends is always lower than weekdays. Moreover, basic varying cycle is 24 hours. 2) During midnight, such as from 1:00 to 5:00, traffic is lower than 10% of peak value. 3) Traffic variation in each day always consists of more than two monotone intervals. Thus we should consider divide each day into different time domains.

As regional traffic load at time t is $\mathrm{T}(t)$. Based on above features, we divide each day into four time domains. We firstly determine busy traffic threshold Th_{max} and slight traffic threshold Th_{min} according to empirical value, and then we will divide each day into four time domains as below.

Step 1: Train out integer time points t_a and t_b as shown in **Fig. 2**, which satisfy that $t_a < t_b$ in each day, and for arbitrary $t \in [t_a, t_b]$, $\mathrm{T}(t) \geq Th_{min}$ is constantly tenable;

Step 2: Train out integer time points t_c and t_d as shown in **Fig. 2** with followed conditions: a). $t_b \leq t_c$ and $t_c \leq t_d$; b). $\mathrm{T}(t_c) \leq Th_{max}$ and $\mathrm{T}(t_d) \leq Th_{max}$; c). $\mathrm{T}(t)$ is monotone decreasing in $[t_d, t_a + 24]$ and monotone increasing in (t_b, t_c).

From above steps we can then divide each day into four time domains, which are $T_1 = [t_d, t_a + 24)$, $T_2 = [t_a, t_b]$, $T_3 = (t_b, t_c)$, $T_4 = [t_c, t_d)$, respectively. Furthermore, we denote that different ES actions should be executed for each time domain as:

1) During T_1, traffic load gradually decreases, so dynamic multi-stage ES trigger algorithm will be executed at the beginning of each hour;

2) During T_2, regional traffic is fairly low and may be fluctuant, so modes of each BS will keep on the status at time point t_a;

3) During T_3, traffic load gradually increases, so dynamic multi-stage ES recovery algorithm will be executed at the beginning of each hour;

4) At time point t_c, all the BS will be recovered to active mode, and keep on active during T_4.

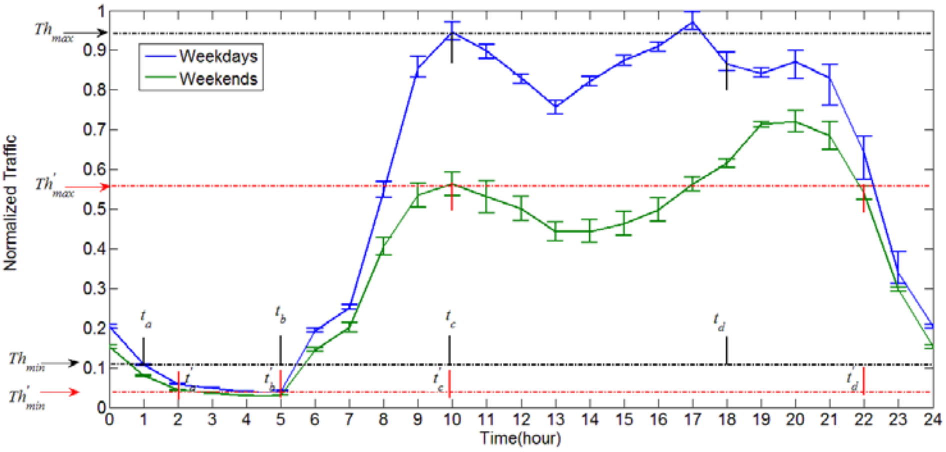

Fig. 2. Normalized traffic variations in one week

From **Fig. 2** we can still find that $[t_d, t_a + 24]$ may stretch across two days. Above analysis implies that ES trigger algorithm and ES recovery algorithm are two key issues. However, these two algorithms mainly aim at resolving BMD problems. And each hour, distributed heuristic BS association algorithm for UAO should be executed as well, so as to keep regional coverage, capacity and interference above acceptable level.

Before we introduce the dynamic multi-stage algorithms, we will analyze local BS pair cooperation method will be analyzed firstly.

3.2 Local BS Pair Cooperation Method

When traffic of BS is low, two or three neighbor BSs were cooperated to compensation its coverage [9]. This method is not suitable for irregular BS deployments. According to our previous work on Opposite Pair (OP)[20] and Trigonal Pair (TP)[13] compensation, we define more practical cooperation method with virtual compensation radius. Our method consists of two stages: 1) determination of OP/TP set; 2) selection of an effective OP/TP. Notice that this method just aims at macro-BS.

A. Determination of OP/TP set

Assuming radius of BS i is r_i, inter-BS distance of BS i and BS j is d_{ij}. For BS i requiring compensation, assume its neighbor BS set is $\boldsymbol{S}_{\mathrm{N}}^{i}$. And $\boldsymbol{S}_{\mathrm{D}}^{i} = \{j \mid r_i + r_j < d_{ij}\}$ represents BS set whose coverage overlaps with BS i. Then candidate compensation BS set of BS i is $\boldsymbol{S}_{\mathrm{C}}^{i} = \boldsymbol{S}_{\mathrm{N}}^{i} \cap \boldsymbol{S}_{\mathrm{D}}^{i}$. We will discuss determination for OP and TP set respectively.

- Candidate OP Set

Now we consider how BS i can be compensated by opposite BS j and k. As shown in **Fig. 3**, when coverage radiuses of BS j and k increase and intersect at point A which is just on the coverage edge of BS *i*, coverage of BS *i* can be totally compensated.

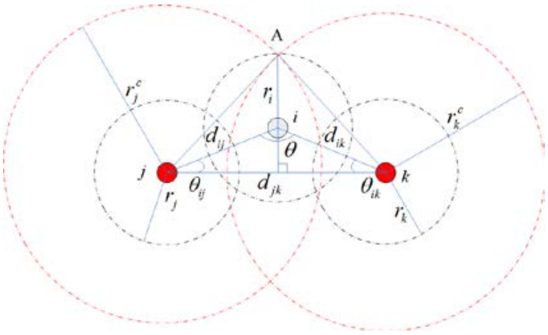

Fig. 3. A opposite pair compensation case for BS *i*

For BS *i*, to decrease interference caused by coverage adjustments, for BS *j* and *k*, their compensation radiuses r_j^{c} and r_k^{c} must be minimal. Through geometrical analysis we can find that when $\theta = \angle jik = \pi$, r_j^{c} and r_k^{c} can target minimum value with d_{ij} and d_{ik} separately. When θ decrease, r_j^{c} and r_k^{c} will increase. So constraint for θ is required. Based on analysis in [17], we define the value space of θ as $(5\pi/6, \pi]$. And for irregular BS deployments, we firstly give the definition of OP as followed.

Definition 1: For BS *i*, if BS pair $\{j, k\}$ satisfied that $j, k \in \boldsymbol{S}_{\mathrm{C}}^{i}$, and $5\pi/6 < \theta \leqslant \pi$, then we call pair $\{j, k\}$ as a OP of BS *i*.

For BS *i*, denoting its OP set as $\boldsymbol{S}_{\mathrm{op}}^{i}$, then $\boldsymbol{S}_{\mathrm{op}}^{i}$ is determined through the followed steps:

Step 1: $\boldsymbol{S}_{\mathrm{op}}^{i} \Leftarrow \varnothing, \boldsymbol{S}_{\mathrm{cop}}^{i} \Leftarrow \{\{j,k\} \mid j \in \boldsymbol{S}_{\mathrm{C}}^{i} \text{ and } k \in \boldsymbol{S}_{\mathrm{C}}^{i}, j \neq k\}$;

Step 2: if $\boldsymbol{S}_{\mathrm{cop}}^{i} = \varnothing$, terminate the algorithm and output $\boldsymbol{S}_{\mathrm{op}}^{i}$; otherwise choose $\{j, k\}$ from $\boldsymbol{S}_{\mathrm{cop}}^{i}$, $\boldsymbol{S}_{\mathrm{cop}}^{i} \Leftarrow \boldsymbol{S}_{\mathrm{cop}}^{i} \setminus \{\{j,k\},\{k,j\}\}$, go to **Step** 3;

Step 3: if $\{j, k\}$ is a OP of BS *i*, $\boldsymbol{S}_{\mathrm{op}}^{i} \Leftarrow \boldsymbol{S}_{\mathrm{op}}^{i} \cup \{j,k\}$, go back to **Step** 2; otherwise go back to **Step** 2 directly.

Generally at most six neighbor BSs exist around one BSs, so $|\boldsymbol{S}_{\mathrm{cop}}^{i}| \leq 30$. Then we get time complexity of above algorithm is just O(J). J is the regional BS number. As determination of $\boldsymbol{S}_{\mathrm{op}}^{i}$ is only related with static BS topology information. So it can be obtained advanced and stored. After obtaining $\boldsymbol{S}_{\mathrm{op}}^{i}$, we should select a proper OP for BS *i* and analyze the best compensation radius.

- Candidate TP Set

Then we consider when BS *i* can be compensated by trigonal BS *j*, *k* and *l*. As shown in **Fig.4**, when coverage radiuses of BS *j*, *k* and *l* increase and intersect at site location of BS *i*, coverage of BS *i* can be totally compensated. As analyzed in [13], constraints for angles θ_1, θ_2 and θ_3 are: $\theta_1 + \theta_2 + \theta_3 = 2\pi$, and value space of each angle is $[2\pi/3, 5\pi/6]$. For irregular BS deployments, we give the definition of TP below.

Definition 2: For BS *i*, if BS pair $\{j, k, l\}$ satisfied that $j, k, l \in \boldsymbol{S}_{\mathrm{C}}^{i}$, and $2\pi/3 < \theta_1, \theta_2, \theta_3 \leqslant 5\pi/6$, then we call pair $\{j, k, l\}$ as a TP of BS *i*.

For BS *i*, assuming its TP set is $\boldsymbol{S}_{\mathrm{tp}}^{i}$, then $\boldsymbol{S}_{\mathrm{tp}}^{i}$ can be obtained as the same steps of $\boldsymbol{S}_{\mathrm{op}}^{i}$ with complexity of O(J). Moreover, proper TP for BS *i* with best compensation radius will be analyzed then.

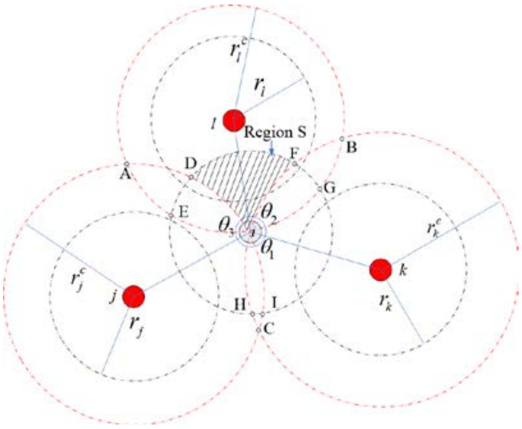

Fig. 4. A trigonal pair compensation case for BS *i*

B. Effective OP/TP selection

In order to guarantee effective coverage for BS *i*, for each OP/TP, we will figure out proper compensation radius for each BS in these pairs to get effective OP/TP.

- Effective OP Determination

In order to guarantee effective coverage for BS *i*, we give the following definitions firstly.

Definition 3: For OP pair {*j*, *k*} of BS *i*, if BS *j* and BS *k* intersects at two points, then we call the point near BS *i* as a CRP (Coverage Reference Point) for this OP, as point A in **Fig. 3**. If distances from the two points to BS *i* are equal, anyone can be set as the CRP.

Definition 4: For BS *i*, if OP = {*j*, *k*} can totally compensate its coverage, but $r_j^c < d_{ij} + r_i$ and $r_k^c < d_{ik} + r_i$, which means only BS *j* or BS *k* could not cover BS *i* entirely, then we call this OP as an EOP (Effective OP).

Based on above definitions, we can get **Theorem** 1.

Theorem 1: For OP = {*j*, *k*} of BS *i*, assuming extension line of segment *ji* intersect coverage edge of BS *i* at point C, and extension line of segment *ki* intersect with coverage edge of BS *i* at point D. As shown in **Fig. 5**, when CRP A slide on the minor arc (or semi-circle) CD (not including point C and D), then {*j*, *k*} is an EOP for BS *i*.

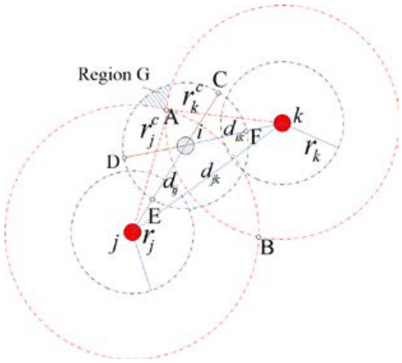

Fig. 5. Proof description for theorem 1

Proof: Assume segment *ij* intersects with coverage edge of BS *i* at point E, and segment *ik* intersects with coverage edge of BS *i* at point F, as shown in **Fig. 5**. If CRP A exists and slide on coverage edge of BS *i*, geometrical feature implies that A could not be on the minor arc (or semi-circle, including point E and F) EF. Still, length of segment $d_{Cj} = d_{ij} + r_i$ is the largest distance from BS *j* to coverage edge of BS *i*, and length of segment $d_{Dk} = d_{ik} + r_i$ is the largest distance from BS *k* to coverage edge of BS *i*.

When CRP A locates at inner coverage of BS *i*, then shadow region G could not be covered. So {*j*, *k*} is not effective. If CRP A locates at point C or D, then from **Definition** 4 we can conclude that {*j*, *k*} is not an EOP as well. When CRP A locates on arc DE, point D could not be covered. Similarly, when CRP A locates on arc CF, point E could not be covered as well. So {*j*, *k*} may not be effective.

When CRP A slides on minor arc CD, we have $r_j^c < d_{ij} + r_i$ and $r_k^c < d_{ik} + r_i$. Assume another intersection point for coverage edge of BS *j* and BS *k* is B, and then B is outside coverage of BS *i*. It's easy to find that remain part of coverage of BS *i* outside BS *j* can be wholly absorbed by BS *k*. So {*j*, *k*} is an EOP. Proof is completed.

Theorem 1 proves that for any OP={*j*, *k*} of BS *i* with coverage extension, we can find corresponding EOP with CRP locating on coverage edge of BS *i*. For each EOP, we should compute out compensation radiuses for each compensation BS next. We construct the following two-dimension axis for BS *i* in **Fig. 6**. Initially, d_{ij}, d_{ik}, d_{jk} and r_i is known. With d_{ij}, d_{ik} and d_{jk}, we can obtain the angle θ, θ_1 and θ_2 by cosine theorem.

We set coordinate of CRP A as ($r_i \cdot \cos\omega$, $r_i \cdot \sin\omega$), then we can express compensation radiuses r_j^c and r_k^c below:

$$r_j^c = \sqrt{(r_i \cdot \cos\omega + d_{ij} \cdot \cos\theta_1)^2 + (r_i \cdot \sin\omega + d_{ij} \cdot \sin\theta_1)^2} \tag{20}$$

$$r_k^c = \sqrt{(r_i \cdot \cos\omega - d_{ik} \cdot \cos\theta_2)^2 + (r_i \cdot \sin\omega + d_{ik} \cdot \sin\theta_2)^2} \tag{21}$$

In fact many EOPs may originate from one OP. To computation simply, we can consider d_{ij} and d_{ik} for compensation coverage of BS *i*. In order to make compensation effect uniformly, we set proportion of r_j^c and r_k^c as followed:

$$r_j^c / r_k^c = d_{ij} / d_{ik} \tag{22}$$

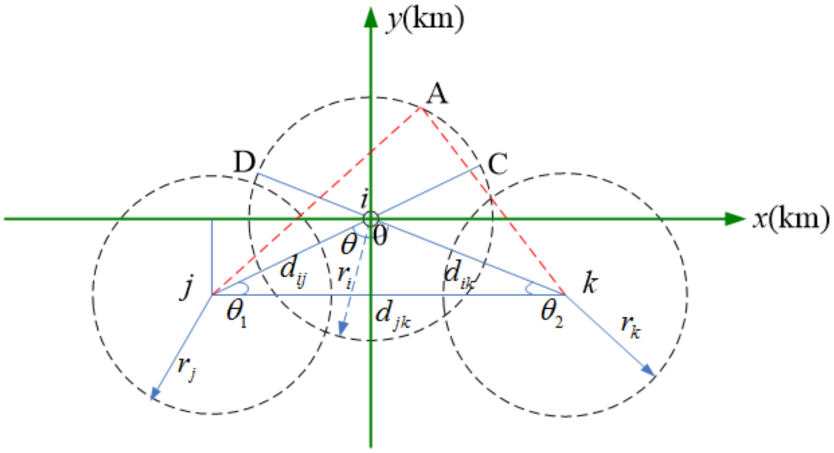

Fig. 6. Analysis of compensation radius for EOP

Theoretically, we can figure out r_j^c and r_k^c from (20) to (22). Then we prove the existence for the compensation radiuses as Theorem 2.

Theorem 2: For EOP={*j*, *k*} of BS *i*, when CRP slides on coverage edge of BS *i*, only one solution exists with $r_j^c / r_k^c = d_{ij} / d_{ik}$.

Proof: as shown in **Fig. 6**, for EOP of BS *i*, $\omega \in (\theta_1, \pi\text{-}\theta_2)$. Assume $f(\omega)$ = $f(\omega) = r_j^c(\omega) / r_k^c(\omega)$. As α increase, $r_j^c(\alpha)$ decreases but $r_k^c(\alpha)$ increase, so $f(\omega)$ is monotone decreasing in this domain. And maximal value of $f(\omega)$ is obtained when $\omega = \theta_1$ as followed:

$$f(\theta_1) = (d_{ij} + r_i) / \sqrt{d_{ik}^2 + r_i^2 - 2d_{ik} \cdot r_i \cdot \cos(\theta_1 + \theta_2)} \tag{23}$$

Similarly, minimal value of $f(\omega)$ is obtained when $\omega = \pi - \theta_2$ as followed:

$$f(\pi - \theta_2) = \sqrt{d_{ij}^2 + r_i^2 - 2d_{ij} \cdot r_i \cdot \cos(\theta_1 + \theta_2)} / (d_{ik} + r_i) \tag{24}$$

Under practical networks, $d_{ij} > r_i$ and $d_{ik} > r_k$. With **Definition** 1 we have $0 \leq \theta_1 + \theta_2 = \pi - \theta < 5\pi/6$. Through deviation we can get that $f(\pi - \theta_2) < d_{ij} / d_{ik} < f(\theta_1)$. As $f(\omega)$ is monotone, so only one value $\omega^* \in (\theta_1, \pi\text{-}\theta_2)$ satisfied that $f(\omega^*) = d_{ij} / d_{ik}$. Proof is completed.

Definition 5: For an EOP={*j*, *k*} of BS *i*, when its CRP locates on coverage edge of BS *i*, and $r_j^c / r_k^c = d_{ij} / d_{ik}$, we call this unique EOP as BOP (Balanced OP) of BS *i*. r_j^c and r_k^c are corresponding BRs (Balanced Radiuses) respectively.

- Effective TP Determination

Similarly, for TP compensation, we can give definition of effective TP below:

Definition 6: For BS *i*, if TP={*j*, *k*, *l*} satisfies the following conditions: 1) this TP can totally compensate BS *i* coverage; 2) $r_j^c < d_{ij} + r_i$, $r_k^c < d_{ik} + r_i$ and $r_l^c < d_{il} + r_i$, which means only BS *j*, *k* or *l* could not cover BS *i* entirely; and 3) none OP exists in this TP; then we call this TP as an ETP (Effective TP).

Moreover, based on **Definition** 6, we can obtain the followed theorem.

Theorem 3: For TP = {*j*, *k*, *l*} of BS *i*, if $r_j^c = d_{ij}$, $r_k^c = d_{ik}$ and $r_l^c = d_{il}$, and for each two BSs in TP, a crossover point of their coverage (the other one is site location of BS *i*) is outsides of coverage of BS *i*, then {*j*, *k*, *l*} is an ETP for BS *i*.

Proof: as shown in **Fig. 4**, if only BS *j* and BS *k* provide coverage for BS *i*, point C is one of the crossover points of their coverage which is outside coverage of BS *i*. We can find that shadow region S could not be covered. However, as BS *l* intersects with BS *j* and BS *k* at crossover points A and B, we can find that region S is just under coverage of BS *l*. So BS *i* can be entirely covered. Moreover, angle constraints make none OP exists in this TP. So TP={ *j*, *k*, *l*} is an ETP for BS *i*. Proof is completed. Still, r_j^c, r_k^c and r_l^c are called as BRs (Balanced Radiuses) respectively.

Above analysis proves compensation feasibility for a single BS by BS cooperation from static geographic topology perspective. However, practical wireless networks are dynamic with traffic fluctuations. Next we should determine the ES trigger and recovery algorithms based on traffic load. But EOP and ETP just consider coverage from BS perspective, to guarantee user QoS, distributed heuristic BS association algorithm should be executed at last.

3.3 Dynamic ES Trigger Algorithm

ES trigger algorithm is executed in each hour of time domain $[t_d, t_a + 24]$, and make sure each BS is slept at most once. Assume set of BS is J, distance matrix is $\boldsymbol{D}=[d_{ij}]$ and regional traffic vector at *t* time is $\mathsf{T}(t)=\{\mathsf{T}_1(t),\ldots,\mathsf{T}_J(t)\}$. For BS *j*, $\mathsf{T}_j(t)$ can be considered as $L_j(t)$. Regional OP vector, TP vector, BS mode vector and BS radius vector are $\boldsymbol{S}_{\text{op}} = \{\boldsymbol{S}_{\text{op}}^1,\ldots,\boldsymbol{S}_{\text{op}}^J\}$, $\boldsymbol{S}_{\text{tp}}$ =

{ $\boldsymbol{S}_{\mathrm{tp}}^{1}$,…, $\boldsymbol{S}_{\mathrm{tp}}^{J}$ }, $\mathcal{S}(t) = \{s_1(t),.., s_J(t)\}$ and $\boldsymbol{R}(t) = \{r_1(t),…, r_J(t)\}$ separately. Taking OP and TP compensation into consideration, regional ES trigger algorithm is shown in **Table 1**.

In order to determine mode of each BS, when one BS is under active mode, we will confirm the possibility to sleep it. Only OP = {k, l} satisfies the following conditions can be put into candidate set $\boldsymbol{OPB}_i$:

1) None of BS k and l is under sleep mode;

and 2) traffic of BS i can be accommodated, so $\Delta\mathcal{T}_{ik}(t) > 0$ and $\Delta\mathcal{T}_{il}(t) > 0$.

Then we can still obtain candidate set for TP as $\boldsymbol{TPB}_i$ with a similar way. ϕ_a is the traffic load distribution ratio, defined as below:

$$\phi_a = d_{ia}^2 / \sum_a d_{ia}^2, a \in \mathcal{C}_{ij} \tag{25}$$

To maximize compensation efficiency, candidate CP(Compensation Pair) in $\boldsymbol{OPB}_i \cup \boldsymbol{TPB}_i$ with maximal c_{ij} should be considered. Here o_{ij} and c_{ij} are number of sleep BS and compensating BS is each pair. These CPs are put into $\boldsymbol{S}_{\mathrm{m}}^{i}$. $\mathcal{T}_{\mathrm{M}}$ is the capacity for each BS. Moreover, we should prevent the traffic of compensation BS from overload, so $\mathcal{C}_{ij^*}$ in $\boldsymbol{S}_{\mathrm{m}}^{i}$ with maximal $\Delta\mathcal{T}_i(t) > 0$ will be selected. For $\mathcal{C}_{ij^*}$, we then find it EOP/BRs or ETP/BRs through **Definition 5** or **Definition 6**. Traffic load and radius for BS in $\mathcal{C}_{ij^*}$ will be updated next to achieve compensation.

Table 1. Dynamic ES Trigger Algorithm

```
Input: $\mathcal{J}$, $\boldsymbol{D}$, $\mathcal{T}(t)$, $\mathcal{S}(t)$, $\boldsymbol{S}_{\mathrm{op}}$, $\boldsymbol{S}_{\mathrm{tp}}$, $\boldsymbol{R}(t)$
Output: $\mathcal{T}(t)$, $\mathcal{S}(t)$, $\boldsymbol{R}(t)$

for $\forall j \in \mathcal{J}$, $\mathcal{T}_j'(t) = \mathcal{T}_j(t), r_j'(t) = r_j(t)$, $\boldsymbol{TPB}_j = \boldsymbol{OPB}_j = \varnothing$
while $\mathcal{J} \neq \varnothing$, for $i = \arg\min_j\{\mathcal{T}_j'(t) \mid j \in \mathcal{J}\}$ with $s_i(t) = 0$, do
  while $\boldsymbol{S}_{\mathrm{op}}^{i} \neq \varnothing \,\|\, \boldsymbol{S}_{\mathrm{tp}}^{i} \neq \varnothing$, do //obtain effective OP/TP set
    for $\forall \mathcal{C}_{ij} = \{k, l\} \in \boldsymbol{S}_{\mathrm{op}}^{i}$ or $\forall \mathcal{C}_{ij} = \{k, l, m\} \in \boldsymbol{S}_{\mathrm{tp}}^{i}$, get $o_{ij}$, $c_{ij}$
    $\Delta\mathcal{T}_i(t) \Leftarrow \sum_a [\Delta\mathcal{T}_{ia}(t)]^2, \Delta\mathcal{T}_{ia}(t) = \mathcal{T}_{\mathrm{M}} - \phi_a \mathcal{T}_i'(t) - \mathcal{T}_a'(t), a \in \mathcal{C}_{ij}$
    if $\mathcal{C}_{ij} = \{k, l\}$, then //OP set determination
      if $o_{ij} = 0$, $\Delta\mathcal{T}_{ik}(t) > 0$ and $\Delta\mathcal{T}_{il}(t) > 0$, then
        $\boldsymbol{OPB}_i \Leftarrow \boldsymbol{OPB}_i \cup \mathcal{C}_{ij}$
      end if
      $\boldsymbol{S}_{\mathrm{op}}^{i} \Leftarrow \boldsymbol{S}_{\mathrm{op}}^{i} - \mathcal{C}_{ij}$
    end if
    if $\mathcal{C}_{ij} = \{k, l, m\}$, then //TP set determination
      if $o_{ij} = 0$, $\Delta\mathcal{T}_{ik}(t) > 0$, $\Delta\mathcal{T}_{il}(t) > 0$ and $\Delta\mathcal{T}_{im}(t) > 0$, then
        $\boldsymbol{TPB}_i \Leftarrow \boldsymbol{TPB}_i \cup \mathcal{C}_{ij}$
      end if
      $\boldsymbol{S}_{\mathrm{tp}}^{i} \Leftarrow \boldsymbol{S}_{\mathrm{tp}}^{i} - \mathcal{C}_{ij}$
    end if
  end while
  if $\boldsymbol{OPB}_i \neq \varnothing \,\|\, \boldsymbol{TPB}_i \neq \varnothing$, then
    $\boldsymbol{S}_{\mathrm{m}}^{i} = \varnothing$, $\boldsymbol{S}_{\mathrm{m}}^{i} \Leftarrow \boldsymbol{S}_{\mathrm{m}}^{i} \cup \{\arg\max_{\mathcal{C}_{ij} \in \boldsymbol{OPB}_i \cup \boldsymbol{TPB}_i}\{c_{ij}\}\}$
    $\mathcal{C}_{ij^*} \Leftarrow \arg\max_{\mathcal{C}_{ij} \in \boldsymbol{S}_{\mathrm{m}}^{i}}\{\Delta\mathcal{T}_i(t)\}$
    get EOP/BRs, or ETP/BRs for $\mathcal{C}_{ij^*}$
    $\mathcal{T}_a'(t) \Leftarrow \mathcal{T}_a'(t) + \phi_a \mathcal{T}_i'(t), r_a'(t) \Leftarrow \max\{r_a'(t), r_a^c(t)\}, a \in \mathcal{C}_{ij^*}$
    set $s_i(t)=1$, $s_a(t) = 1$, $a \in \mathcal{C}_{ij^*}$
  end if
  $\mathcal{J} \Leftarrow \mathcal{J} - \{i\}$
end while
for each BS $i$, $r_i(t) = r_i'(t), \mathcal{T}_i(t) = \mathcal{T}_i'(t)$
//One BS can be totally covered by another one
if exist BS $i, j \in \mathcal{J}$, $s_i(t) \neq 0$, $s_j(t) \neq 0$, $r_i + d_{ij} \leq r_j$ and $\mathcal{T}_i(t) + \mathcal{T}_j(t) \leq \mathcal{T}_{\mathrm{M}}$ then
  set $\mathcal{T}_j(t) \Leftarrow \mathcal{T}_j(t) + \mathcal{T}_i(t), s_i(t) = 0$
end if
```

After execute effective compensation for BS under active mode, we should consider the probability that one micro BS which can be absorbed by a macro BS. As shown in the end of Algorithm 1, when traffic accommodation requirement is satisfied, micro BS i can be slept as well. So this algorithm is suitable for heterogeneous network scenarios.

We can easy find that complexity of above algorithm is $O(\mathcal{J} \cdot \max\{|\boldsymbol{S}_{\mathrm{op}}^{i}|, |\boldsymbol{S}_{\mathrm{tp}}^{i}|\})$. Based on analysis in section 3.2, we know that $\max\{|\boldsymbol{S}_{\mathrm{op}}^{i}|,|\boldsymbol{S}_{\mathrm{tp}}^{i}|\} \lesssim 20$. So $O(J \cdot \max\{|\boldsymbol{S}_{\mathrm{op}}^{i}|,|\boldsymbol{S}_{\mathrm{tp}}^{i}|\}) \approx O(J)$, which means complexity is only determined by regional BS number.

3.4 Dynamic ES Recovery Algorithm

ES recovery algorithm is the inverse process of ES trigger algorithm. This algorithm is executed in each hour of time domain (t_b, t_c).

For each BS under sleep mode, once it's recovered, its mode will not change. Assuming $\mathbf{T}^0(t)$ and $\boldsymbol{R}^0(t)$ represent the traffic vector and radius vector when network is under active mode. $\mathbf{AS}_i$ is compensation BS set for sleep mode BS i, and $\mathbf{CS}_i$ is compensated BS set of compensation BS i. And then ES recovery algorithm is shown in **Table 2**.

Through recovering several BS to active mode, this algorithm can guarantee that users can still be accommodated when regional traffic arises. In order to maximize coverage effect for compensation BS, the micro BS under its coverage will be considered firstly. Here τ is a small buffering value.

In this algorithm, we firstly find the BS i with heaviest traffic. And slept micro BS under BS i is considered then. For macro BS, we get the minimal BS set $\mathbf{PS}_i$ which can decrease the load of BS i under T_{M}. Then we update traffic of compensation BSs and recover BS $a \in \mathbf{PS}_i$ to active mode. Compensation radiuses will still be guaranteed by remaining active BSs in $\mathbf{CS}_i$.

For ES recovery algorithm, similarly, we can get that its complexity is $O(J \cdot \max\{|\boldsymbol{CS}_i|\})$, as maximal value of $\boldsymbol{CS}_i$ is 6, so complexity of algorithm is just $O(J)$ as well.

Table 2. Dynamic ES Recovery Algorithm

```
Input: $J$, $\boldsymbol{D}$, $\mathbf{T}(t)$, $\mathbf{T}^0(t)$, $\mathrm{S}(t)$, $\boldsymbol{R}^0(t)$, $\boldsymbol{R}(t)$, $\{\boldsymbol{AS}_i\}$, $\{\boldsymbol{CS}_i\}$
Output: $\mathbf{T}(t)$, $\mathrm{S}(t)$, $\boldsymbol{R}(t)$
for $\forall j \in J$, $\mathrm{T}_j'(t) = \mathrm{T}_j(t), r_j'(t) = r_j(t)$, sort $\mathbf{CS}_i$ with decreasing traffic order
while $J \neq \varnothing$, for $i = \arg\max_j\{\mathrm{T}_j'(t) \mid j \in J\}$ with $s_i(t) = 1$, do
 if $\mathrm{T}_i'(t) + \tau \geq \mathrm{T}_{\mathrm{M}}$  //Recover high load BS
  if exist BS $j$, $s_j(t) = 0$, $r_j^0(t) + d_{ij} \leq r_i'(t), \mathrm{T}_i'(t) - \mathrm{T}_j^0(t) < \mathrm{T}_{\mathrm{M}}$, then
    set $\mathrm{T}_i'(t) \Leftarrow \mathrm{T}_i'(t) - \mathrm{T}_j^0(t), \mathbf{CS}_i = \mathbf{CS}_i - \{j\}, s_j(t) = 1, r_j'(t) = r_j^0(t)$
  else get minimal $\mathbf{PS}_i \subseteq \mathbf{CS}_i, \mathrm{T}_i'(t) - \sum_a \phi_a \mathrm{T}_a^0(t) < \mathrm{T}_{\mathrm{M}}, a \in \mathbf{PS}_i$
    while $\mathbf{PS}_i \neq \varnothing$, for each $a \in \mathbf{PS}_i$, do
     for $\forall b \in \mathbf{AS}_a, \mathrm{T}_b'(t) \Leftarrow \mathrm{T}_b'(t) - \phi_b \mathrm{T}_a'(t)$
     $r_b'(t) = \max\{\mathrm{BR}_c, c \in \mathbf{CS}_b\}$, $\mathbf{CS}_b \Leftarrow \mathbf{CS}_b - \{a\}$
     $r_a'(t) = r_a^0(t), \mathbf{PS}_i = \mathbf{PS}_i - \{a\}$, $s_a(t) = 1$, $\mathbf{AS}_a = \varnothing$
    end while
    $\mathbf{CS}_i \Leftarrow \mathbf{CS}_i - \mathbf{PS}_i$, $r_i'(t) = \max\{\mathrm{BR}_a, a \in \mathbf{CS}_i\}$
    $\mathrm{T}_i'(t) \Leftarrow \mathrm{T}_i'(t) - \sum_a \phi_a \mathrm{T}_a^0(t)$
  end if
 end if
 $J \Leftarrow J - \{i\}$
end while
for each BS $i$, $r_i(t) = r_i'(t), \mathrm{T}_i(t) = \mathrm{T}_i'(t)$, if $s_a(t) = 1$ and $\boldsymbol{CS}_i = \varnothing$, then
 $r_i(t) = r_i^0(t)$
end if
```

Definite wireless parameters can determine the radius of one BS. So with above two algorithms we can obtain wireless parameter adjustments with low complexity, rather than complex mathematical problem which need intelligent algorithm to resolve as in [13]. So our algorithms are of high efficiency.

However, as our algorithms are executed each hour, and radiuses of BSs may change each hour as well, which means wireless parameters should be adjustment frequently. This is the tradeoff for high efficiency. As adjustments for transmit power may introduce extra interference to the network, so electrical tilt adjustment is a proper method here [21]. Moreover, in emerging technologies, many new features such as BS CoMP [7] and user cooperation [22] could be adopted to compensation coverage and capacity for sleep BS without wireless parameters adjustments. And our algorithms are still suitable for these scenarios.

3.5 Distributed Heuristic BS Association Algorithm

Dynamic ES trigger and recovery algorithms determine BS modes and radiuses without considering user QoS.UAO problem still require effective solutions to keep QoS above acceptable level. Here we propose a distributed heuristic BS association algorithm to resolve it, as show in **Table 3**.

Table 3. Distributed Heuristic BS Association Algorithm

```
Input: $\mathrm{I}$, $\mathrm{J}$, $\boldsymbol{D}$, $\boldsymbol{R}(t)$, $\boldsymbol{L}(t)$, $\mathrm{S}(t)$, $\boldsymbol{X}(t)$, $\boldsymbol{P}(t)$, $\boldsymbol{G}(t)$
Output: $\boldsymbol{X}(t)$, $\boldsymbol{P}(t)$

While $\mathrm{I} \neq \varnothing$, do
  for $\forall i \in \mathrm{I}$, find BS set $\boldsymbol{B}_j$ with $d_{ij} \le r_{ij}$ and $s_j(t) = 1$
  $j^* \Leftarrow \arg\max_{j \in \boldsymbol{B}_j} \{\sigma_{ij}\}$, set $x_{ij^*} = 1$
  while $\sigma_{ij^*} = p_{ij^*} g_{ij^*} < \chi$ or $\gamma_{ij^*} < \gamma_{\min}$ do
      $p_{ij^*} \Leftarrow p_{ij^*} + \Delta p$ or $g_{ij^*} \Leftarrow g_{ij^*} + \Delta g$
      if $\sum_{i=1}^{\mathrm{I}} \beta_{ij^*} p_{ij^*} > \alpha P_{j^*}^{\mathrm{T}}$, then break; end if
      if $L_{j^*}(t) \ge 1$ or $\exists k, P_{j^*k}^{\mathrm{B}} > P_{\mathrm{M}}^{\mathrm{B}}$, then break; end if
      if $p_{ij^*} \ge \chi$ and $\sigma_{ij^*} \ge \gamma_{\min}(\mathrm{N}_0 + p_{ij^\#} \sum_{k=1,k\neq j}^{\mathrm{J}} g_{ik})$, then
          break;
      end if
  end while
  $\mathrm{I} = \mathrm{I} - \{i\}$
end while
```

Distributed algorithm considers γ_{ij} and σ_{ij} from user perspective. Firstly, BS j^* with strongest signal strength will be set as serving BS for user *i*. When γ_{ij^*} or σ_{ij^*} is below the target value, p_{ij^*} or g_{ij^*} will be adjusted with step Δp or Δg. Still, constraints for power, load and service quality shoud be satisfied as well. To make the algorithm distributedly, only p_{ij^*} is the effective factor. As $\sum_{k=1,k\neq j}^{\mathrm{J}} p_{ik} \cdot g_{ik} \le p_{ij^\#} \sum_{k=1,k\neq j}^{\mathrm{J}} g_{ik}$, where $p_{ij^\#}$ is the maximal p_{ij} in the network, we have $\sigma_{ij^*} \ge \gamma_{\min}(\mathrm{N}_0 + p_{ij^\#} \sum_{k=1,k\neq j}^{\mathrm{J}} g_{ik})$ means γ_{ij^*} is above $\gamma_{\min}$ as well.

Assuming adjusting number for each power or channel gain is Λ_i, and the computational complexity for blocking probability is Φ, then we have the total complexity for this algorithm is $\mathrm{O}(\mathrm{I}^2 \mathrm{J}^2 K \max\{\Lambda_i\} \Phi)$, which is still acceptable.

3.6 Complexity analysis for our mechanism

In this part, the solution methods and algorithms for ES optimization model is low-complexity with detailed analysis below:

1) To avoid computing at each time point, traffic-aware time domain division method is effective. It divides each period (often 24 hours) into different time intervals, and only during monotone intervals ES actions will be executed at the beginning of each hour. So running times of our mechanism is fairly low and no more than 24 times each day. Still, if threshold Th_{max} and Th_{min} is determined advanced, computation complexity of this method is just O(1).

2) Local BS pair cooperation method determines OP pairs and TP pairs to compensate coverage of a single BS. In fact, the information we requiring is only BS location and its radius. Such information is always stored in the OAM system. With this method, we can get BOP and BTP for each BS and their corresponding BRs. So we can store these useful data in the OAM

advanced as well, which can be considered as static information in the networks without additional complexity. Still, computation complexity for BOP or EOP is O(1) as well, because the neighbor BS of each BS is no more than 6.

3) For dynamic ES trigger/recovery algorithm, they take both local BS pair cooperation and traffic distribution into consideration. As described above,their computation complexities are just $O(J)$, that is, determined by the BS number, which is fairly low.

4) For distributed heuristic BS association algorithm, it only requires local BS and user information, and interactions between BSs and OAM systems are not necessary. So control information is fairly little. Moreover, computation complexity of this algorithm is just $O(I^2J^2K\max\{\Lambda_i\}\Phi)$.As K is always a constant, and Λ_i is definite when range and step of p_{ij} or g_{ij} is known, so computation complexity is just $O(I^2J^2\Phi)$.

From above analysis, we can find the complexity of our mechanism is $O(I^2J^2\Phi+J+J)$ $= O(I^2J^2\Phi)$. And if blocking probability is ignored, its computation complexity will be just $O(I^2J^2\Phi)$, which is fairly low. That is why we call our mechanism is low-complexity.

4. Simulation and Analysis

4.1 Simulation Scenario

Irregular BS topology for LTE network is adopted in the simulation. As shown in **Fig. 7**, four different regions are considered. These regions mainly consist of macro BSs and micro BSs. BS means eNodeB here. Detail descriptions for these scenarios are shown in **Table 4**.

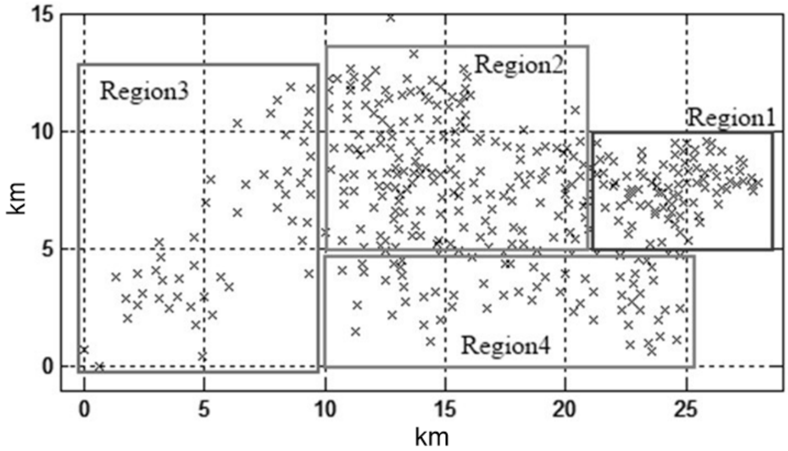

Fig. 7. LTE deployments in our simulation

In our simulation, height of BS is between 10m~30m, and antenna tilt is between 11.4 and 14.8 degree. Maximal transmit power, antenna gain, PDCCH power and allowed uplink power is 46 dBm, 15 dBi, 29 dBm and -101.5dBm. RB of each BS is 100. Each macro BS contains three sectors. For UE, average antenna height, maximal transmit power, antenna gain and allowed downlink power are 1.5m, 23dBm, 1dBi and -120dBm. Propagation model for uplink and downlink budget is same in [19]. We consider only 512 kbps CBR services of in the network. Moreover, assuming settings for each BS is same, and other important parameter settings is show in **Table 5**. Here $\lambda_{max}(t)$ is the maximal arrive rate and $\mu(t)$ is the service rate. The arrivial variations of CBR service is consistent with practical data of one week from a

Chinese telecom operator.

Table 4. Scenarios descriptions

Region	BS number	BS density	Type
Region 1	82	2.05/km^2	urban
Region 2	181	1.94/km^2	urban
Region 3	51	0.41/km^2	suburban
Region 4	69	0.92/km^2	suburban

Moreover, to evaluate the efficiency of our mechanism, we will compare it with OP compensation and TP compensation. Moreover, we call the method in [14] as GreenBSN and compare it to our mechanism as well, though it's not suitable for heterogeneous LTE networks, we still set it as a baseline. Multiple parameter adjustment method in [13] is adopted.

Table 5. Important parameters settings

Parameter	Value	Parameter	Value
N_0	-174dBm/Hz	α	0.9
γ_{min}	-10dB	χ	-120dBm
γ_{max}	25dB	w	1
φ_{max}	4.8bps/Hz	ι	1
ξ	0.95	T_M	1
W_{RB}	3MHz	Δp	0.1 dBm
β_{M}	90	Δg	0.1 dB
P^{M}	1500W	τ	0.01
δ_j	0.6	Th_{min}	0.1
ε	1/6	Th_{max}	0.9
$P_{\mathrm{M}}^{\mathrm{B}}$	0.01	$\lambda_{max}(t)$	0.3/s
P^{T}	20W	$\mu(t)$	3 minute

4.2 Result analysis

For the result, we firstly give the traffic variations in our simulation. Then we will evaluate energy efficiency and performance for our mechanism and comparing them with other ES methods.

As shown in **Fig. 8**, regional traffic variations of practical model show its regularity. Still, variations during weekdays and weekends are different, and weekday's traffic is higher. In each day, regional traffic is fluctuant as well. According to Th_{max} and Th_{min}, for each day , T_1= [22:00, 1:00), T_2=[1:00, 6:00], T_3= (6:00, 10:00), T_4=[10:00, 22:00).

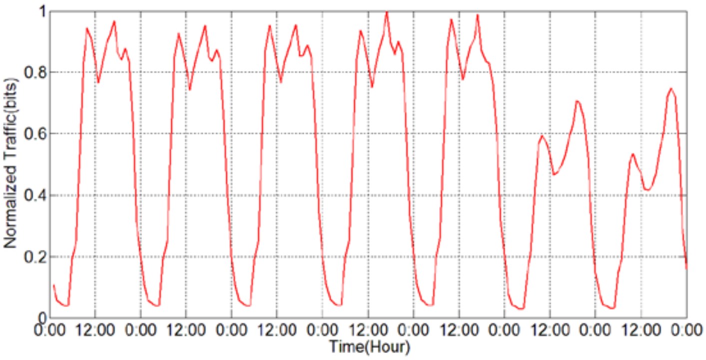

Fig. 8. Regional traffic variations during one week

Based on above traffic variations, we will analyze energy efficiency and performance respectively. With above analysis, we can find that our mechanism is an integrated mechanism for saving energy of LTE networks. It's hard to compare our mechanism in each dimension to any method in the references. So for BS sleep numbers and ES gains, we compare our mechanism with our previous work in [20] (named as OPM) and [13] (named as TPM) , and another three classical ES methods, which are self-organizing cooperative method in [9] (named as SOC), the best dynamic base station switching-on/off strategy in [12] (named as $SWES_{(1,1)}$), and the near-optimization method in [14] (named as GreenBSN). We will put above analysis in simulation part as well.

- **Energy Efficiency Evaluation**

Firstly, regional energy efficiency for different ES methods and different regions will be discussed.We can find maximum sleep BS ratios of each hour in **Fig. 9**. Maximal ratio is obtained by $SWES_{(1,1)}$ with 54% in region 1. And our mechanism can obtain maximal ratio with 39.3% in region 2. Still, our mechanism can sleep more BSs than other methods for region 3 and region 4.

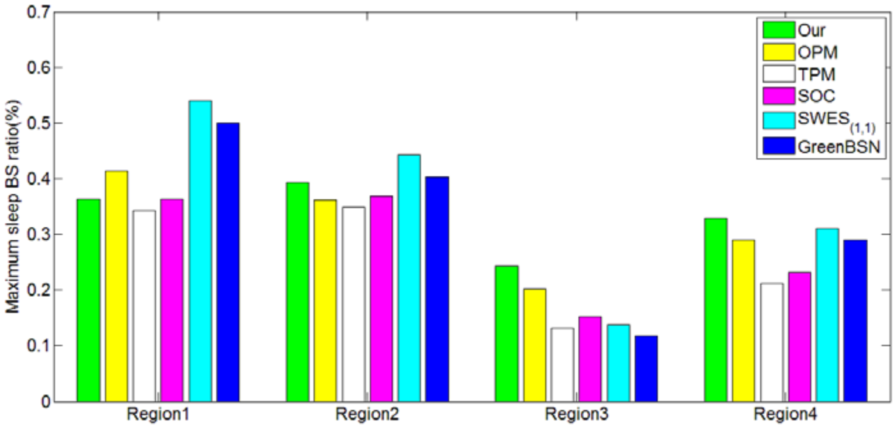

Fig. 9. Maximum sleep BS ratios of four regions

Next we will analyze energy-saving ratios for these methods as shown in **Fig. 10**. Still, ES gains are not consistent with BS sleep ratios due to different methods have different energy saving intervals. It shows that our mechanism takes on better performance is sparse region 3 and region 4. As $SWES_{(1,1)}$ and GreenBSN are two near-optimal solutions for dense BS deployment, they can save more energy in region 1 and region 2. Urban regions include more BSs, so they can sleep more BSs with higher saving energy as well. For urban region 1, the highest energy saving ratio can be obtained by $SWES_{(1,1)}$ with 17.62%, and the best one of our mechanism is for region 2 with 13.92%. So our method is more suitable for sparse BS deployments scenarios.

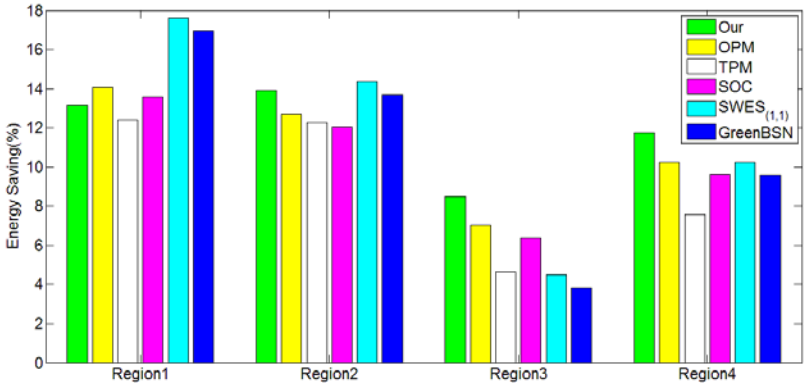

Fig. 10. Energy-saving ratios of four regions

- Performance Evaluation

As GreenBSN did not consider coverage and service from user perspective, so it hard to evaluate RSRP, SINR and other performance indicators. However, our method can resolve this problem with distributed heuristic BS association algorithm in **Table 3**. To evaluate efficiency of our method, we will analysis the distribution feature from coverage, and service quality perspectives. To make the evaluation more creditable, maximal BS sleep number interval at 24:00 of Sunday will be considered.

➢ Coverage Performance

For LTE, RSRP is a important indicator to evaluate coverage. Though constraint for RSRP of users is not lower than -120 dBm, the heuristic BS association algorithm may not guarantee it. For 24:00 of Sunday, we will compare the probability of RSRP not lower than -120dBm with ES method and without ES methods. For GreenBSN, we just assume that power adjustment is consistent with BS radius. As show in **Fig. 11**, we can find that ES method will decrease regional RSRP strength as several BSs are slept. Still, dense BS deployment scenarios will obtain better RSRP distributions. As $SWES_{(1,1)}$ did not consider power adjustment, so its RSRP distribution is worst. Due to proper control, our mechanism can obtain the second best coverage quality for each region, which is just lower than TPM. Still, the minimal probability for RSRP (≥ -120 dBm) of our mechanism is 95.9% which is still above acceptable level.

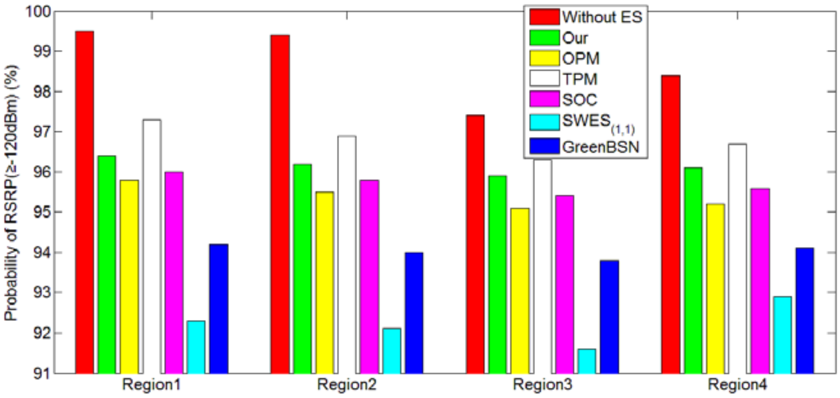

Fig. 11. Probability of RSRP of four regions

- **Quality of Service Performance**

To evalute service quality, SINR, users' throughput and blocking probability will be considered as QoS indicators for LTE networks.

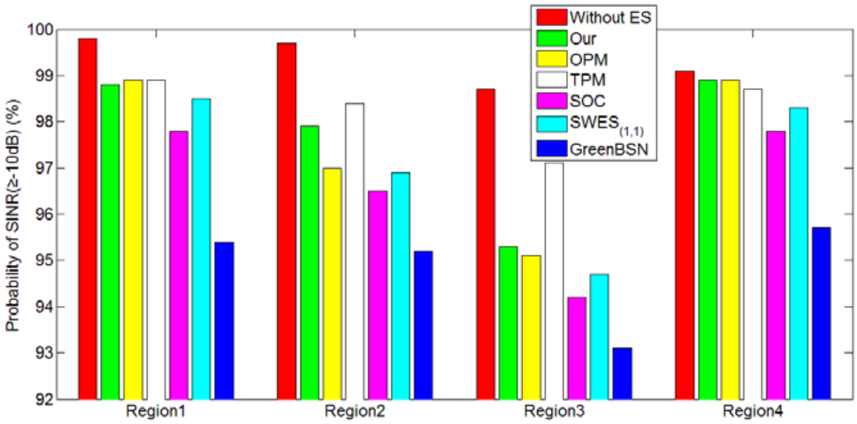

Fig. 12. Probability of SINR of four regions

For 24:00 of Sunday, we will compare the probability of SINR not lower than -10dB with different ES methods and without ES methods. As show in **Fig. 12**, we can find that ES method will increase regional interference as regional power distributions are changed. Still, dense BS deployment scenarios will cause better SINR distributions as well. GreenBSN take on worse performance as well. Our mechanism can obtain best SINR performance than SOC, $SWES_{(1,1)}$, and GreenBSN for each region. The minimal probability for SINR ($\geq$-10 dB) in the four regions for our mechanism is 95.3% in region 3, which is still above acceptable level.

Furthermore, as shown in **Fig. 13**, %5 edge user throughput for 24:00 of Sunday in different regions are decreased due to SINR distribution decrease. For non-ES scenarios, the maximal and minimal probability for %5 edge user throughput is 1.50 Mbps and 1.36 Mbps respectively. For different ES methods, none is best for each region on throughput. Moreover, the lowest %5 edge user throughput will be obtianed by our method in region 3 by GreenBSN. Due to throughputs of other methods are always above 1 Mbps, so these ES method can still make throughput above acceptable level. And the minimum throughput of our mechanism can be obtained in region 3 with 1.09 Mbps.

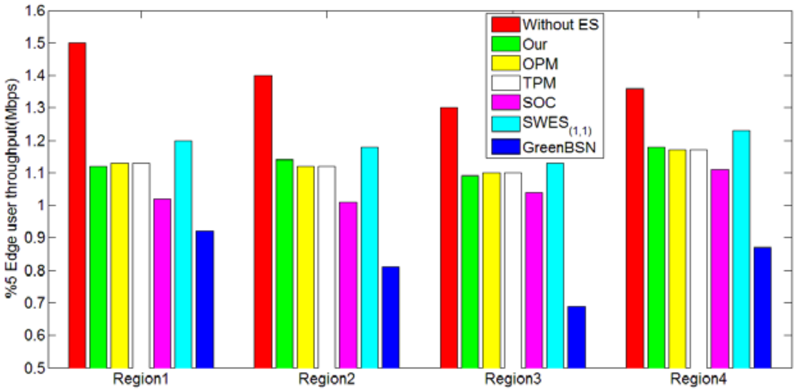

Fig. 13. Probability of %5 edge throughput of four regions

For different regions, traffic variations will increase blocking probability. For different ES methods, none is best for each region on blocking probability as well. However, we find that for each region and each method, maximal block probability is 0.0098, which is lower than target value 0.01, thus each ES method can satisfy service quality constraint.

- **Complexity comparison**

Still, we compare computation complexities of different ES methods without blocking probability, as shown in **Table 6**. Here we will give the complexity analysis for BS mode determination and user association respectively. We can find that our mechanism takes on lowest computation complexity for BS mode determination, which is the same as OPM and TPM method. However, due to user assocation in OPM and TPM are resolved with simulated annealing algorithm, their computation complexities is hard to compute accurately, but no doubt they are high than $O(I^2J^2)$.

For other ES methods, computation complexity of user assocation for SOC and $SWES_{(1,1)}$ are $O(I^2J^2)$ and O(1), respectively. So their entire computation complexities are the same with our mechanism. As our mechanism take more factors, such as coverage, interference into consideration, so we can obtain better network performance than SOC and $SWES_{(1,1)}$.

As GreenBSN did not give user association method, so we cloud not know the use association strategy. But for BS mode determination, our mechanism takes on better performance.

So we can conclude that our mechanism is low-complexity, and can resolve ES problem under acceptable network performance.

Table 6. Computation Complexity among different ES methods

Methods	Computation Complexity	
	BS mode determination	**User association**
Our	$O(J)$	$O(I^2J^2)$
OPM	$O(J)$	$> O(I^2J^2)$Not determined
TPM	$O(J)$	$> O(I^2J^2)$Not determined
SOC	$O(J^2)$	$O(I^2J^2)$
$SWES_{(1,1)}$	$O(I^2J^2)$	O(1)
GreenBSN	$O(J^2)$	None

Above analysis show that different ES methods take on different ES gains and performance, that is, saving energy is a tradeoff between energy efficiency and performance. Our mechanism with low complexity take on much better energy efficiency for sparse BS deployment scenarios with fluctuant traffic under acceptable performance. And our mechanism is the most balanced one as well.

5. Conclusions and Future Work

A low-complexity energy-efficient BS cooperation mechanism for LTE networks is proposed in this paper. It gives an complex ES optimization model considering temporal-spatial affection and decomposes it into two sub-problems. To resolve the two problems, we give two practical methods and algorithms with low complexity. With simulation under four LTE network scenarios, we can find that our method takes on better energy efficiency with acceptable coverage, inteference and QoS levels for sparse BS deployment scenarios. So it's a effective, practical ES solution. Next new technologies such as CoMP, ICIC will be considered in our mechanism. Moreover, other efficient evaluation metrics for ESM mechanism such as ECG, and energy consumed per bit and per km will be assessed as well.

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