Cell Zooming for Cost-Efficient Green Cellular Networks

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ABSTRACT

Cell size in cellular networks is in general fixed based on the estimated traffic load. However, the traffic load can have significant spatial and temporal fluctuations, which bring both challenges and opportunities to the planning and operating of cellular networks. This article introduces a concept of cell zooming, which adaptively adjusts the cell size according to traffic load, user requirements and channel conditions. The implementation issues of cell zooming are then presented. Finally a usage case of cell zooming for energy saving is investigated. Centralized and distributed cell zooming algorithms are developed, and simulation results show that the proposed algorithms can greatly reduce the energy consumption, which leads to green cellular networks.

INTRODUCTION

Wireless cellular networks have been growing rapidly in the last few decades. The subscriber number and traffic volume in cellular networks have explosively increased. Network operators are always trying their best to satisfy user requirements cost-efficiently. In each cell, the base station (BS) transmits common control signals and data signals to mobile users (MUs), and the cell size is defined as the area in which MUs can receive control signals from the BS. At the stage of network planning, cell size and capacity are usually fixed based on the estimation of peak traffic load.

However, traffic load in cellular networks can have significant spatial and temporal fluctuations due to user mobility and bursty nature of many data applications [1]. For example, for a cellular network in a city, the traffic load in the daytime is relatively heavy in office areas and light in residential areas, while the opposite things happen in the evening. If the capacity is planned based on the peak traffic load for each cell, there are always some cells under light load, while others are under heavy load. In this case, any static cell deployment will not be optimal as traffic load fluctuates. Traffic load fluctuations can be even more serious as the next generation cellular networks move towards smaller cells such as micro-cells, pico-cells, and femto-cells, which make the cell deployment even harder.

On the other hand, traffic load fluctuations can also contribute to cellular networks if we know the discipline of the variation. For example, in some parts of a cellular network, traffic load increases to be higher than the planned capacity, then some MUs will be unable to get services. In the meantime, traffic load in the neighboring cells is light. Load balancing schemes can be used to satisfy user requirements as far as possible [2, references therein].

Energy consumption has become one of the most important issues in the world, as the carbon emissions of energy sources have great negative impact on the environment, and the price of energy is also increasing. Network operators are considering how to reduce the energy consumption and design *green* cellular networks. The large number of BSs contribute a major portion of the energy consumption of cellular networks. When a BS is in its working mode, the energy consumption of processing circuits and air conditioner takes up about 60 percent of the total consumption [3]. Therefore, by merely controlling the transmit power of radio equipments, the effect of energy saving is marginal. However, most of the efforts for energy saving in cellular networks still focus on reducing the transmit power of BSs and MUs. To save the energy of the whole network, the phenomenon of traffic load fluctuation implies that some BSs can be switched off when the traffic load is light. There have been many switching on/off schemes proposed in both academia and industry [4–7].

In this article, we propose a new concept of *cell zooming*, which adaptively adjusts the cell size according to traffic conditions. Cell zooming has the potential to balance the traffic load and reduce the energy consumption. An example of cell zooming is illustrated in Fig. 1. It is a cellular network with five cells. One central cell is surrounded by four neighboring cells. BSs are located at the respective center of the cells, denoted by hollow squares; MUs are randomly distributed in the cells, denoted by solid dots. When some MUs move into the central cell and make it congested, the central cell can zoom in to reduce the cell size and therefore release from the congestion (Fig. 1b). On the contrary, if some MUs move out of the central cell and cause the neighboring cells congested, the neighboring cells can zoom in and the central cell zooms out to avoid any possible coverage hole. If the neighboring cells are designed to have high capacity, and therefore not necessarily zoom in, the central cell can also choose to sleep to reduce the energy consumption. In this case, the neighboring cells can either zoom out to take care of the coverage as in Fig. 1d, or serve the left MUs by transmitting cooperatively as in Fig. 1e. This example shows that cell zooming has the potential to achieve green cellular networks.

In the following sections of this article, the implementation issues of cell zooming are first presented, including techniques, benefits, and challenges to implement cell zooming. Then a usage case of cell zooming for energy saving in cellular networks is investigated, and cell zooming algorithms are proposed and evaluated through simulation. Finally, conclusion is given in the end.

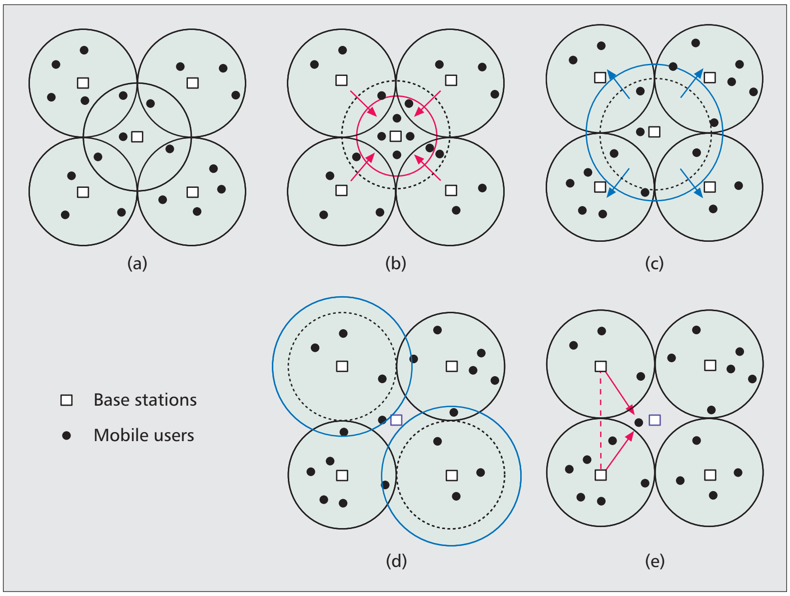

Figure 1. *Cell zooming operations in cellular networks: a) Cells with original size; b) Central cell zooms in when load increases; c) Central cell zooms out when load decreases; d) Central cell sleeps and neighboring cells zoom out; e) Central cell sleeps and neighboring cells transmit cooperatively.*

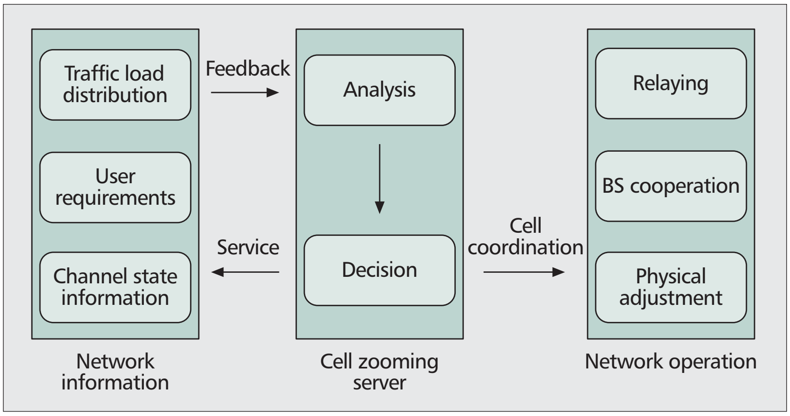

Figure 2. *Framework of cell zooming.*

Implementation of Cell Zooming

Implementing cell zooming in cellular networks needs to introduce some new components and corresponding functionalities to current network architecture. The framework of cell zooming is illustrated in Fig. 2. There is a cell zooming server (CS), which controls the procedure of cell zooming. The CS is a virtual entity in the network, which can be either implemented in the gateway or distributed in the BSs. The CS will first sense the network state information for cell zooming, such as traffic load, channel conditions, user requirements, and so on. The sensing process can be realized by specific control messages. After collecting the information, the CS will analyze whether there are opportunities for cell zooming and make decisions. If a cell needs to zoom in or zoom out, it will coordinate with its neighbor cells with the help of CS. Then these cells will either zoom in or zoom out by network operations such as physical adjustment, BS cooperation and relaying.

Techniques

Many techniques can be used to implement cell zooming. A simple and straightforward way is to adjust the physical parameters such as the transmit power of BSs. Besides physical adjustment, other techniques can also be used for cell zooming, as illustrated in Fig. 3. A detailed discussion of the techniques used for cell zooming is given as follows.

Physical Adjustment: Adjusting physical parameters of network deployment can help to implement cell zooming. Cells can zoom out by increasing the transmit power of BS, and vice versa. Furthermore, antenna height and antenna tilt of BSs can also be adjusted for cells to zoom in or zoom out (Fig. 3a). Such adjustments need the help of additional mechanical instruments.

BS Cooperation: BS cooperation means multiple BSs form a cluster, and cooperatively transmit to or receive from MUs, which is also named as Coordinated Multi-Point (CoMP) transmit/receive in 3GPP Long Term Evolution Advanced (LTE-A) [8]. The new formed cluster is a new cell from MUs' perspective, whose cell size is the sum of the original size of the BSs in cooperation. The size can be even larger, as BS cooperation can reduce inter-cell interference. In this case, cells zoom out to improve the coverage (Fig. 3b).

Relaying: Relay stations (RSs) are deployed in cellular networks to improve the performance of cell-edge MUs, which is also an important technique in 3GPP LTE-A. The cell with RSs zooms out as shown in Fig. 3b. RSs can also be deployed near the boundary of two neighboring cells. In this case, RSs can relay the traffic from the cell under heavy load to the cell under light load. The former cell zooms in, and the latter cell zooms out.

BS Sleeping: When a BS is working in sleep mode, the air-conditioner and other energy consuming equipments can be switched off. BS sleeping can largely reduce the energy consumption of cellular network. In this case, the cell with BS working in sleep mode zooms in to 0, and its neighbor cells will zoom out to guarantee the coverage.

Benefits

Cell zooming can provide various benefits in cellular networks. Firstly, cell zooming can be used for load balancing by transferring traffic from cells under heavy load to cells under light load. Secondly, cell zooming can be used for energy

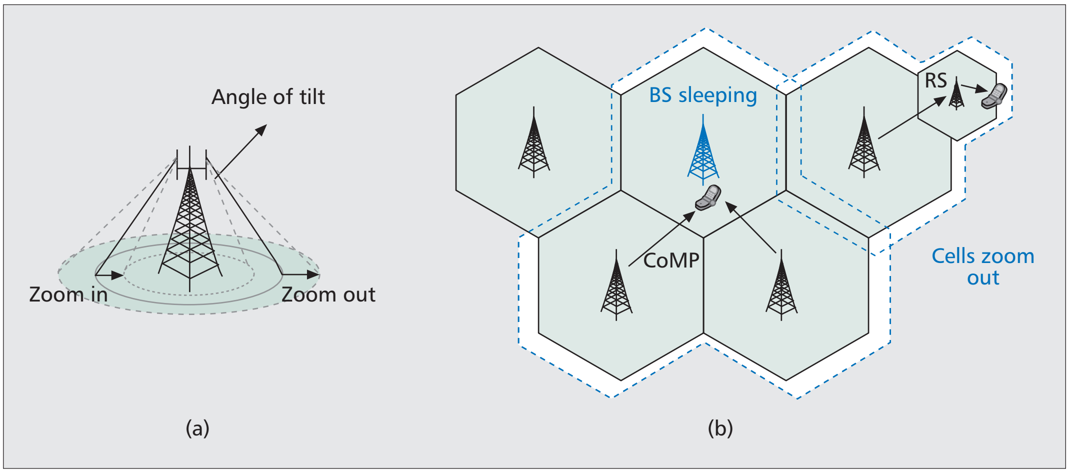

Figure 3. *Techniques to implement cell zooming: a) Cell zooms in or zooms out with physical adjustments; b) cells zoom out through BS cooperation and relaying.*

There exist many challenges to implement cell zooming. To make cell zooming efficient and flexible, traffic load fluctuations should be exactly traced and fed back to the CS. However, significant spatial and temporal fluctuations make it a challenging problem.

saving. Contrary to the usage for load balancing, here cells zoom in to zero when the traffic load is light enough. Some BSs work in sleep mode, and the neighbor cells zoom out accordingly to guarantee the coverage. Therefore, cell zooming can both disperse load for load balancing and concentrate load for energy saving. In both cases, the resources are allocated to match the traffic distribution, however, the load transfer direction is opposite. It is a challenging problem to decide when to disperse load for load balancing and when to concentrate load for energy saving.

User experience can be improved by cell zooming, such as throughput, battery life, and so on. Techniques like BS cooperation and relaying can reduce the inter-cell interference, mitigate impact of shadowing and multipath fading, and reduce handover frequency. The techniques can also be jointly used. For example, in the scenario of isolated cell coverage, when cells zoom out by adjusting physical parameters such as antenna tilt, there will be more overlap among the cells. This provides opportunities for BS cooperation so that more MUs can achieve higher diversity gain, and coverage is also improved. As user requirements are better satisfied, there is no need for upgrading the network frequently, and this will reduce the operational cost of network operators.

Power control in cellular networks has been studied extensively in the literature [9, references therein]. Power control can help to ensure efficient spatial reuse and minimize energy consumption. These functionalities is quite similar to that of cell zooming. However, cell zooming is different from power control in many ways. Power control focuses on the link-level performance and transmit power consumption, while cell zooming techniques focus on the network-level performance and energy consumption of the whole network. Power control does not actively change the cell size, while cell zooming actively changes the cell size by adjusting the transmit power of control signals.

Challenges

There exist many challenges to implement cell zooming. To make cell zooming efficient and flexible, traffic load fluctuations should be exactly traced and fed back to the CS. However, significant spatial and temporal fluctuations make it a challenging problem. One possible way to model the fluctuations is to divide it into long-term scale fluctuations and short-term scale fluctuations. The long-term scale fluctuations reflect the variation of traffic arrival rate, whose time scale is hours or days. The short-term scale fluctuation reflects the random arrival of users, whose time scale is seconds or minutes. It would be an interesting topic to find other models for the spatial and temporal traffic load fluctuations.

Compatibility is another challenging issue. Some of the techniques of cell zooming are not supported by current cellular networks, such as the additional mechanical equipments to adjust the antenna height and tilt, BS cooperation and relaying techniques. Implementing cell zooming also needs to change current structure of network management. For example, feeding back the network information for cell zooming requires special control channels.

Cell zooming may cause other problems, such as inter-cell interference and coverage holes. When some neighboring cells zooms out together, there will be more inter-cell interference among them. If BS cooperation is infeasible, additional interference management schemes are needed to reduce the interference. Cell zooming may also produce coverage holes. When cells zoom in or zoom out, some areas in the network are possible have no coverage. In order to provide service to newly arrival MUs, the neighboring cells need to zoom in so as to cover these areas.

A Usage Case of Cell Zooming for Energy Saving

In this section, a usage case of cell zooming for energy saving in cellular network is investigated. When traffic load is light, some cells can work in sleep mode to save energy, and other cells take care of the coverage. There have been many related studies about BS sleeping in cellular networks. In [4], a predefined BS sleeping scheme is presented according to a deterministic traffic

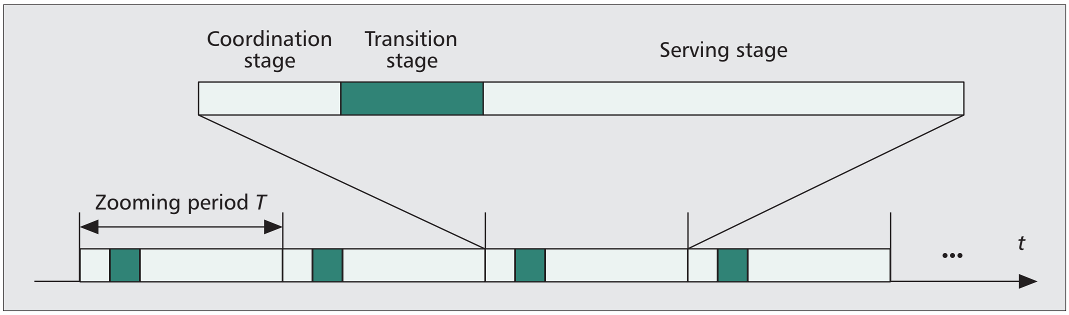

Figure 4. *The process of cell zooming algorithms.*

Cell zooming may also produce coverage holes. When cells zoom in and zoom our, some areas in the network are possible have no coverage. In order to provide service to newly arrival MUs, the neighboring cells need to zoom in so as to cover these areas.

variation pattern over time. Another similar work considers switching off some microcells at night hours while guaranteeing the blocking probability below a given target [5]. In these solutions, the sleeping pattern is fixed and the traffic intensity is assumed to be uniformly distributed over the whole network. In this article, we consider cellular networks with spatial and temporal traffic load fluctuations, and develop dynamic cell zooming algorithms for energy saving.

Consider a densely deployed cellular network in which the coverage of BSs overlaps and traffic load fluctuates over time and space. Assume there are M BSs, and all the BSs are assumed to have the same energy consumption. Each BS has two working modes: *active* mode with energy consumption P^a and *sleeping* mode with power consumption P^s, where P^a is usually much larger than P^s. MUs arrive at the network according to a Poisson process, and each MU will be associated with one BS upon its arrival. The sojourn time for each MU is exponentially distributed, and the rate requirement is fixed for each MU, denoted by r_i for MU i. The spectral efficiency is ω_{ij} when MU i is associated with BS j. Therefore the bandwidth needed is given by $b_{ij} = r_i/\omega_{ij}$. We assume the spectral efficiency is independent of the associations among other BSs and MUs. The total bandwidth for BS j is B_j. When a new MU arrives, if there is not enough bandwidth to be allocated, the MU will be blocked. We are interested in two objectives, minimizing the energy consumption and minimizing the blocking probability. If there are more cells working in sleep mode, more energy will be saved, however, it also leads to larger blocking probability. Therefore, there is a trade-off between the two objectives.

As the mode transition of BSs will last for a period of time, during which the cells cannot provide service to MUs, thus frequent mode transition is infeasible in practice. In our cell zooming algorithms, time is divided into cell zooming periods, and the length of each period is T. Each period consists of three stages: coordination stage, transition stage, and serving stage, as shown in Fig. 4. In the coordination stage, the CS collects necessary network state information for cell zooming, and makes decisions. Our proposed cell zooming algorithms will also work during this stage. In the transition stage, cells change their working modes, and complete the handoff process if needed. In the serving stage, cells fix their working mode, and provide service to current and newly arrival MUs in the network. We assume the length of coordination stage and transition stage are much shorter than serving stage, so the energy consumption depends on the work mode of cells in the serving stage.

Intuitively, in order to minimize the number of active BSs, traffic load should be concentrated to a few BSs so the left BSs under light load can be switched off. Following the intuition, two cell zooming algorithms are proposed. The first one is a centralized algorithm, in which all the channel conditions and user requirements in the network are collected by the CS, and resource allocation and cell zooming operations are performed in a centralized way. The second one is a distributed algorithm. Each MU will select the BS to be associated with by itself based on the information provided broadcasted by the BSs. Generally speaking, the centralized algorithm requires more signaling overhead, but can achieve better performance compared with the distributed one. The details of the two cell zooming algorithms are given as follows.

Centralized Algorithm

In the centralized cell zooming algorithm, MUs feed back channel conditions and rate requirements to the BSs during the coordination stage. The CS will collect all these information together with BSs' bandwidth limitation. After receiving updates from all the MUs and BSs, CS will generate a 0-1 matrix $\mathbf{X} = [x_{ij}]$, where $x_{ij} = 1$ means MU i is associated with BS j, otherwise $x_{ij} = 0$. As each MU can only be served by one BS, the sum of each column in $\mathbf{X}$ is 1. The main idea of the algorithm is to switch off the BSs under light load as far as possible. As there are many MUs which arrive during the serving stage, each active BS will reserve some bandwidth for the newly arrival MUs. Denote the proportion of bandwidth reserved in BS j as α_j, where $\alpha_j \in [0, 1]$. Initially, the idle bandwidth for BS j is given by

$$\tilde{B}_j = (1 - \alpha_j)B_j. \quad (1)$$

Denote the set of MUs associated with BS j as $\mathcal{M}_j$. The traffic load of BS j is given by

$$L_j = \sum_{i \in \mathcal{M}_j} \frac{b_{ij}}{B_j} \quad (2)$$

The detailed procedure of the algorithm is described as follows.

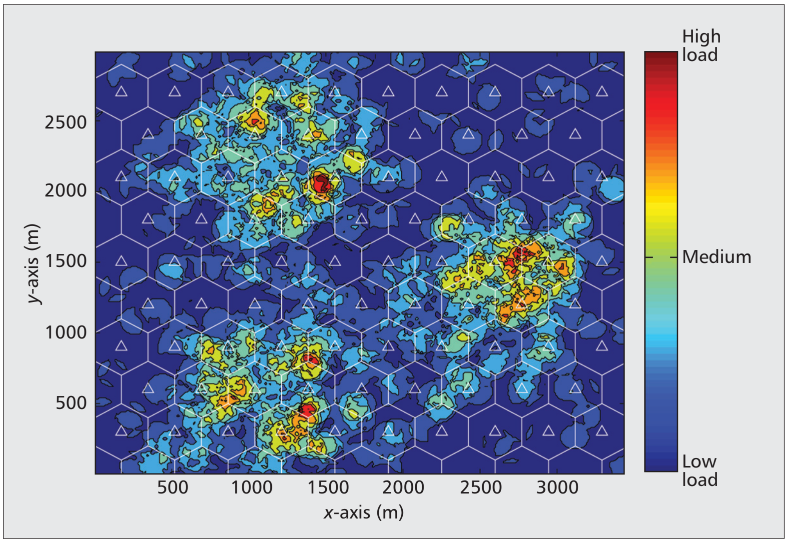

Figure 5. *Traffic distribution in the tested cellular network layout.*

- Step 1: Initialize all the L_j to be 0, and all the elements in matrix **X** to be 0.
- Step 2: For each MU i, find the set of BSs who can serve MU i without violating the bandwidth constraints, which means $L_jB_j + b_{ij} \le \tilde{B}_j$. If the set is empty, MU i is blocked. Otherwise, associate MU i with a BS j which has the highest w_{ij} in the set. Update L_j and **X** after each association.
- Step 3: Sort all the BSs by the ratio of L_jB_j to $\tilde{B}_j$ by increasing order. All the BSs with the ratio 0 will zoom in to zero and work in sleep mode in the following serving period. For other BSs, find the BS j with the smallest ratio, and re-association the MUs in $\mathcal{M}_j$ to other BSs in the network. If no MU is blocked, undate **X** and go to Step 3. Otherwise, output **X** and end the procedure.

Distributed Algorithm

To reduce the information exchange and signaling overhead, we also propose a distributed cell zooming algorithm, in which each MU will select the BS by itself according to the measured channel conditions and BSs' traffic load. In the distributed algorithm, BSs also reserve bandwidth for newly arrival MUs as in centralized algorithm. In practice, traffic load information and bandwidth reservation parameters can be obtained by broadcasting control signals from BSs. Intuitively, each MU will select the BS with high load and high spectral efficiency. We define a preference function if MU i is to be associated with BS j as

$$U(\omega_{ij}, L_j, \alpha_j)\begin{cases} \dfrac{\omega_{ij}(L_jB_j + b_{ij})}{\tilde{B}_j} & L_jB_j + b_{ij} \le \tilde{B}_j \\ 0 & L_jB_j + b_{ij} > \tilde{B}_j \end{cases}, \tag{3}$$

which means MUs prefer those BSs with high load and high spectral efficiency, but the load can not exceed a predefined threshold. The procedure of distributed cell zooming algorithm is described as follows:

- Step 1: Initialize all the L_j to be 0, and all the elements in matrix **X** to be 0.
- Step 2: For each MU i, find the set of BSs who can serve MU i without violating the bandwidth constraints, which means $L_jB_j + b_{ij} \le \tilde{B}_j$. If the set is empty, MU i is blocked. Otherwise, associate MU i with a BS j which has the highest $U(\omega_{ij}, L_j, \alpha_j)$ in the set. Update L_j and **X** after each association.
- Step 3: Repeat Step 2 until there is no undate of **X**, then output **X** and end the procedure.

In the distributed algorithm, no coordination among BSs is needed, therefore much signaling overhead is reduced. The distributed algorithm works in an iterative way. The convergency of the distributed algorithm is guaranteed if any two MUs take no action simultaneously. This is because the BS selection set of each MU is finite. After the algorithm converges, the BSs with no association will work in sleep mode during the serving stage.

Performance Evaluation

The proposed dynamic cell zooming algorithms are evaluated in a scenario with time-varying traffic distribution. The simulation layout is 10 by 10 hexagon cells wrapped up to avoid boundary effect (Fig. 5). The cell radius is set to 200m, and assume each BS can extend its coverage to at most 400m. We only consider pathloss for the channels between BSs and MUs, according to ITU microcell test environment [8]. Power consumption is 400W for BSs in active mode, and 10W for BSs in sleep mode. The bandwidth of each BS is 5MHz. MUs arrive in the network according to a Poisson process, and the average sojourn time of each MUs is 1 minute. To evaluate the algorithms in cellular networks with spatial traffic load fluctuations, 3 hotspots with relatively higher load than other areas are generated, as shown in Fig. 5. A new MU arrives in each hotspot with probability 5 percent respectively, and their locations follow normal distribution with mean at central point of each hotspot and standard deviation R. The others are uniformly placed in the whole area. The rate requirement of each MU is 122kb/s. The cell zooming period T is set to be 1 hour, and all the simulation results are averaged over 100 cell zooming periods.

In the simulation, we set the reservation parameters the same for all BSs with $\alpha_i = \alpha$, then tune the value of a and calculate the average energy consumption. When α increase, more bandwidth is reserved and the cell zooming algorithm becomes more conservative. This will result in more BSs working in the active mode, and less blocking probability can be achieved. Therefore by tuning α, we can leverage the trade-off between energy consumption and quality of service. The simulation results in Fig. 6 verify our analysis. For a given arrival rate, there is a trade-off curve of energy consumption versus outage probability for each algorithm. The figure also show that our algorithms can save a lot energy (the energy consumption is normalized to 100 if all the BSs are active). The centralized algorithm can achieve a better trade-off than distributed algorithm. We also compare the cell zooming algorithms with the static BS sleeping algorithm, which switches off 1/2 or 1/3 of all the BSs. The results show that our centralized algorithm perform better than the static algorithm. Our algorithms are also more flexible as they can freely leverage the trade-off between energy consumption and outage probability.

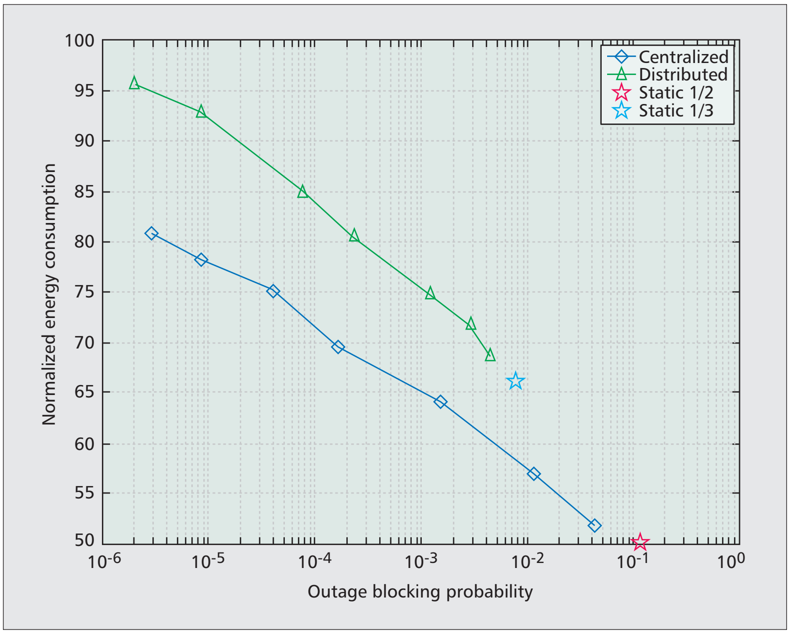

Figure 6. *Energy outage trade-off of centralized and distributed cell zooming algorithms.*

CONCLUSION

In this article, the concept of cell zooming is proposed, which is to adaptively adjust the cell size according to the traffic load fluctuations. Cell zooming can not only solve the problem of traffic imbalance, but also reduce the energy consumption in cellular networks. Techniques such as physical adjustments, BS cooperation, and relaying can be used to implement cell zooming. In the case study of cell zooming for energy saving, we show that the proposed cell zooming algorithms can leverage the trade-off between energy saving and blocking probability. The algorithms also save a large amount of energy when traffic load is light, which can achieve the purpose of green cellular network in a cost efficient way.

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