Energy-Efficient Cellular Network Planning under Insufficient Cell Zooming

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***Abstract*—With rapid growth of cellular systems, energy consumption has become a critical issue. The existing cellular network planning is performance-oriented, whose objective is to satisfy peak traffic requirements, without too much considerations on energy efficiency. Unfortunately, real-world traffic profiles have indicated that in most time, most of the cells are in low utilization. Switching off certain cells in low traffic period for some time is proved energy-efficient. To switch off cells, remaining operating cells need to extend their coverage by cell zooming to guarantee service. However, such zooming might be insufficient, depending greatly on cell configurations.**

In this paper, we consider energy efficiency in cellular network planning. We introduce a new parameter for traffic estimation, which is low traffic time ratio τ. In order to switch off more cells for insufficient cell zooming, two solutions are feasible: to deploy smaller but more cells or to implement coverage extension technologies. We focus on former solution to determine cell configurations and propose an evaluation method to determine whether certain cell deployment is energy-efficient and how much energy it could save, compared with traditional planning. It is shown that when cell zooming ratio is reaching sufficient for certain switching-off scheme, deploying more cells could be more energy-efficient. Also, after exceeding the threshold, the larger the parameter τ is, the more energy-efficient our solution is.

I. Introduction

In recent years, due to prevalent application and rapid growth of cellular networks, energy consumption of cellular networks has become a critical issue and keeps scaling up with increasing traffic demand. Energy saving for cellular networks has drawn increasing attentions and much work has been done in this area for greener communications. In development of new generation cellular networks, such as LTE, energy consumption issue has been regarded as one of the major concerns.

Previously, energy consumption of base station (BS) equipments has been intensively investigated, mainly concerning the consumption by devices and supporting system, e.g. power supply and cooling system. Data from manufacturers [5] indicates that energy consumed for radio transmission part only constitutes a small fraction of total energy consumption. Hence, a feasible approach to improve energy efficiency is switching off BSs rather than merely adjusting transmit power. Lately, work [1] [2] introduced analysis from perspective of whole network, by switching off fraction of BSs in low traffic period, i.e. night zone. Work [3] extended the discussions with real traffic profile and dynamic control.

Previous work is done in operation stage, in which available configurations of cells could not be changed, and has assumed that sufficient cell zooming could provide service for area originally served by cells that are switched off. However, insufficient cell zooming that prevents switching off more cells is not considered. To combat insufficient cell zooming, little work has been done to discuss whether it is energy-efficient to adjust deployment in network planning stage. One feasible solution is to deploy smaller but more cells: on one hand, it would increase energy consumed in high traffic period since more cells are operating; while on the other, it could not only switch off more fractions of cells in low traffic period but also increase low traffic time ratio, thus improve energy efficiency. Another feasible solution is to introduce coverage extension technologies (CET) other than increasing transmit power , such as relay and cooperative multi-point transmission.

In this paper, we focus on the former solution and consider cellular network planning for cases in which traffic is uniformly distributed in space but time-varying. We propose an evaluation method to investigate deployments for insufficient cell zooming. Our analysis indicates that under certain circumstances, adjusting deployment to switch off more fractions of cells in network for operation stage is energy efficient.

II. System Model and Problem Formulation

A. System Model and Assumptions

System model and associated assumptions used in this paper are summarized below:

- Channel model is Walfisch-Ikegami model [6]. For each user, we compute the path loss PL[dB], only considering large-scale effect of channel.

$$\mathrm{PL}\,(d) = \alpha \log_{10} d + C_d \tag{1}$$

  where d is the distance between a user and a BS, C_d is coefficient of the other factors irrelevant of distance, α is attenuation coefficient. For LOS (line-of-sight) case, α is 26 while for NLOS (non-LOS) 38 (lower bound) [6]. For planning, we fix α to 38.
- Cells are deployed in uniform hexagons (shown in white in Fig.1). During high traffic period, all cells are active to provide service; while during low traffic period, some cells would be switched off to save energy. We use

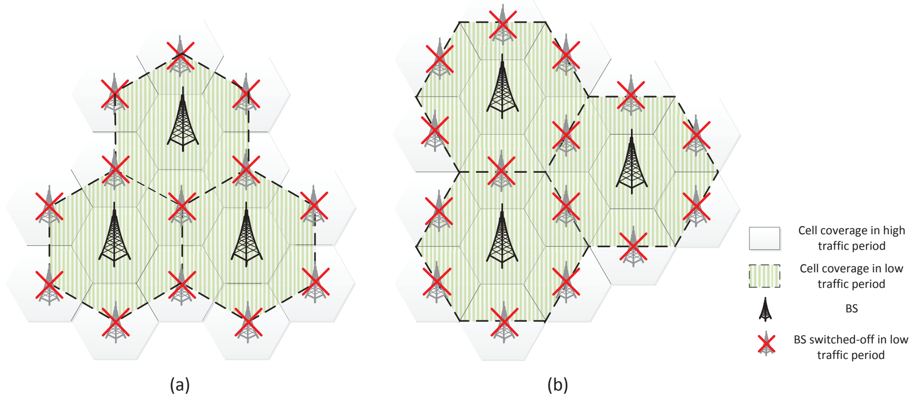

Fig. 1. Possible switching-off schemes for cell zooming by increasing transmit power.
(a) (2,3)-off scheme. Possible only for cells equipped with omnidirectional antenna, since cell direction changes after switching-off.
(b) (3,4)-off scheme. Possible for cells equipped with either omnidirectional or directional antenna, since cell direction does not change.

(m, n)-off to indicate m cells switched off out of n active cells.
For different cell settings, possible switching-off schemes are different. For cells using omnidirectional antenna, we list two possible schemes with smallest possible n as demonstration in Fig.1. However, for cells using sector antenna, $(3, 4)$-off scheme in (b) is feasible as well, whereas $(2, 3)$-off scheme in (a) infeasible. Area in green indicates new cell coverage in $(2, 3)$, $(3, 4)$-off scheme respectively. In this paper, we consider cells with omnidirectional antenna, but we could easily extend the analysis to cells with sector antenna in same approach. For cell zooming by increasing transmit power with omnidirectional antenna, (2,3)-off scheme is the scheme with smallest possible n.

- System is interference-limited. Since deployment is uniform, signal-to-interference-and-noise (SINR) ratio of place (x, y) is only subject to its relative location in cell and transmit power P_T of the BS.

$$\text{SINR}(x, y) = \frac{g(x, y)P_T}{P_T \sum_i g_i(x, y) + P_N} \tag{2}$$

where g is transmit gain and P_N is the power of noise.

- Traffic arrival process is modeled as a Poisson process with mean arrival rate changing with time t in time domain, uniformly distributed in space domain. Traffic arrival rate per unit area is $\lambda(t)$ [bits/second/m^2]. For users located at (x, y), service rate is subject to both received signal SINR and service unit of that cell, μ_j(SINR)[bits/second]. For cell j, effective traffic intensity ρ_j follows:

$$\rho_j(t) = \iint_{S_j} \frac{\lambda(t)}{\mu_j\left(\text{SINR}(x, y)\right)} dxdy \tag{3}$$

where S_j is the area served by cell j.
Maximum arrival rate per area $\lambda_{\max}$ follows:

$$\lambda_{\max} = \rho_{j,\max} \left(\iint_{S_j} \frac{1}{\mu_j\left(\text{SINR}(x, y)\right)} dxdy \right)^{-1} \tag{4}$$

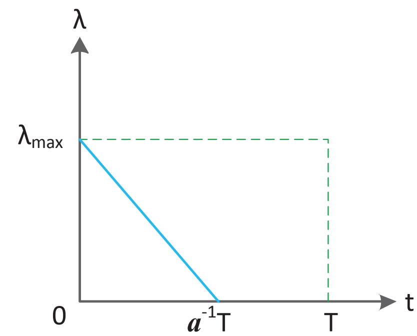

Fig. 2. Trapezoidal traffic pattern.

where $\rho_{j,\max}$ is the maximum traffic intensity that could be served by cell j.
Traditionally, cellular network planning only consider the peak traffic $\lambda_{\max}$ from traffic perspective. However, for energy-efficient planning, we also need to know how long the low traffic period is in one day, which is the foundation of energy saving. For uniformly distributed traffic, low traffic time ratio τ is related to traffic intensity:

$$\tau = \frac{1}{T} \int_{\rho(t) \le \rho_0} dt \tag{5}$$

We employ trapezoidal traffic pattern [1] to describe the variation of traffic. In one day (T), traffic arrival rate $\lambda(t)$ changes with time t as in Fig.2. Traffic variance parameter a indicates traffic variance: $a \to 0$ illustrates traffic is time invariant while $a \to \infty$ opposite. Time in which traffic arrival rate is lower than threshold λ_0 is:

$$\frac{\int_{\lambda(t) \le \lambda_0} dt}{T} = 1 + a^{-1} \left(\frac{\lambda_0}{\lambda_{\max}} - 1 \right), a \in [0, \infty) \tag{6}$$

- Each BS could equally provide service for traffic intensity $\rho_{\max}$. Deployment given by traditional planning, which satisfies peak traffic, is as follows: the number of BSs is N, with per BS coverage area S and power P_0.
- User equipment is served by cells with largest SINR, i.e. cell selection by user is unavailable. When some cells are

switched off or on, transition cost (e.g. handover) is not considered.

B. Problem Formulation

Cells need to change their configurations (on-off state, transmit power) by cell zooming to enable different (m, n)-off schemes for the network. For different schemes, power and/or resource consumption is different.

In [1] [2], guarantee of coverage and quality of service is achieved by cell zooming, which could not hold for all cases. By cell zooming [7], we refer to adjusting cell configurations (including transmit power, et cetera) to extend coverage. Cell zooming by only adjusting transmit power will result in scale-up of transmit power, but maximum transmit power of a particular BS is regulated. Hence merely increasing transmit power to extend coverage could reach limit, which disables the feasibility to switch off cells while maintaining coverage.

We arrange feasible switching-off schemes, or (m, n)-off schemes, in ascending order of value m/n. Specially, we define 0^{th} scheme as that all cells are active; $k_{\max}(k_{\max} \geq 0)$ is the index of last feasible scheme for current planning (due to limitation of maximum transmit power). For the k^{th} feasible switching-off scheme: define parameters for single cell, coverage area $S^{(k)}$, total power consumption $P^{(k)}$ and transmit power $P_T^{(k)}$; define parameters for the network, number of active cells $N^{(k)}$ and the set of active cells $A^{(k)}$; define $\lambda^{(k)}$ as the threshold of traffic arrival rate per area, below which k^{th} feasible switching-off scheme could be used.

During planning, given the traffic and coverage constraint, we shall minimize the energy consumption of the whole network $E_{network}$ for one day (T):

$$\begin{aligned} \min \quad & E_{network} = \int_T P(t)dt = \sum\nolimits_k N^{(k)} P^{(k)} t^{(k)} \\ s.t. \quad & \rho_j^{(k)}(t) \leq \rho_{\max}, \forall j \in A^{(k)}, \lambda(t) \leq \lambda^{(k)} \end{aligned} \tag{7}$$

where $P(t)$ is the total power of network changing with time t, $t^{(k)}$ is the duration for k^{th} feasible switching-off scheme.

For simplicity, we consider that the network only use the ${k_{\max}}^{th}$ switching-off scheme and make comparison between traditional planning and our energy-efficient planning. In traditional planning, cell parameters are not optimized to save energy, hence it might happen that a cell could not zoom to enable certain switching-off scheme. We define zooming sufficiency ratio $\eta_{(m,n)}$ for (m, n)-off scheme: if $\eta_{(m,n)} \geq 1$, zooming is sufficient for the scheme; otherwise insufficient.

$$\eta_{(m,n)} = \frac{S_{\max}}{\frac{n}{n-m} S} = \frac{(n-m) S_{\max}}{nS} \tag{8}$$

where $S_{\max}$ is the area of maximum coverage by cell zooming.

Our method unifies analysis of both sufficient and insufficient zooming for certain switching-off schemes. We'll investigate the threshold for both situations, focusing on insufficient situation. Coverage extension by cell zooming could be categorized into two implementations: by increasing transmit power or by introducing CET. The former method is investigated in this paper. Given the zooming sufficiency and resource consumption in the switching-off scheme, we could decide whether to keep the result of traditional planning, or to deploy smaller but more cells to enable the switching-off scheme, as shown in Fig.3.

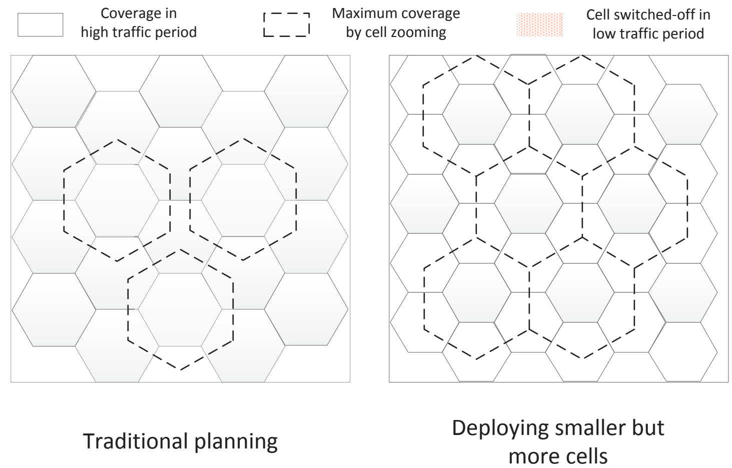

Fig. 3. Solution for insufficient cell zooming in (2,3)-off scheme. Traditional planning could not enable (2,3)-off scheme, while deploying smaller but more cells could.

III. Cell Zooming by Increasing Transmit Power

Obviously, cells could not zoom to infinity due to constraint of transmit power. After traditional planning, we would obtain index of last feasible scheme $k_{\max}$. We could decide whether it is energy efficient to deploy smaller but more cells to enable $k^{th}(k > k_{\max})$ switching-off scheme, say (m, n)-off scheme.

Denote x as maximum zooming ratio by increasing transmit power for cell size determined in traditional planning.

$$x = \frac{S_{\max}^{\text{Tx}}}{S} \tag{9}$$

where $S_{\max}^{\text{Tx}}$ is the area of maximum zooming by increasing transmit power.

Correspondingly, zooming sufficiency is:

$$\eta_{(m,n)} = \frac{(n-m)x}{n} \tag{10}$$

A. Traffic in Planning

For zooming by increasing transmit power, we only need to consider impact of traffic arrival rate per area $\lambda(t)$, rather than traffic intensity $\rho(t)$ in [1]. Proof is simple. Consider a relative location (rR, θ) in a cell, where R is cell radius, r is the relative ratio, θ is the direction. Due to geometric similarity, if we keep boundary power of the cell unchanged, i.e. gP_T remains constant, from (2) SINR of that location is same regardless of R. Therefore, increasing transmit power will not affect SINR distribution in cells. In other words, in uniformly distributed traffic case, we do not need to further consider service rate distribution in cells, but rather traffic arrival rate per area.

Therefore, for cell zooming by increasing transmit power:

$$\tau = \frac{1}{T} \int_{\lambda(t) \leq \frac{\lambda_0}{x}} dt \tag{11}$$

where ρ_0, λ_0 is the threshold of traffic intensity and traffic arrival rate per area for low traffic period respectively.

B. Network Energy Saving

Although reducing cell size could potentially reduce number of cells active during low traffic period and increase low traffic time ratio, it also requires more BSs in the area during high traffic period, which counteracts the effort to save energy. In all, given traffic variance and zooming ratio x for traditional planning, criterion exists for cell size.

Compare the energy-efficient planning with traditional planning in terms of energy consumed in one day. Deployment of traditional planning is unable to use (m, n)-off scheme but able to use ${k_{\max}}^{th}(m_0, n_0)$-off scheme. $E_{(m,n)}, E_{(m_0,n_0)}$ are the energy consumption (using switching-off schemes) for energy-efficient and traditional planning respectively. E_0 is the energy consumption for traditional planning without using any switching-off schemes.

$$E_{(m,n)} \leq E_{(m_0,n_0)} \tag{12}$$

where

$$E_{(m_0,n_0)} = (1 - \frac{t}{T})E_0 + \frac{t}{cT}\left[(1 - c^{-\frac{\alpha}{20}})\frac{P_T^{\max}}{P_0} + 1\right]E_0 \tag{13}$$

$$E_{(m,n)} = \frac{n\,(1-\tau)}{(n-m)x}E_0 + \frac{\tau}{x}\left[(1 - x^{-\frac{\alpha}{20}})\frac{P_T^{\max}}{P_0} + 1\right]E_0 \tag{14}$$

with

$$c = \frac{n_0}{n_0 - m_0} \tag{15}$$

$$E_0 = NP_0T \tag{16}$$

Maximum transmit power $P_T^{\max}$ is fixed by regulators. Comparison of energy consumption against low traffic time ratio for different switching-off schemes is shown in Fig.4 for (2,3)-off scheme (sufficient zooming) and (3,4)-off scheme (insufficient zooming, solved by deploying smaller but more cells), with traditional planning as baseline. To be energy efficient, we could obtain the threshold for low traffic time ratio in deploying smaller cells, as shown in Fig.5. It makes sufficiently small difference (less than 10%) for typical $P_T^{\max}/P_0$ ratio [4] [5], such that analysis could be applied to different BSs without difficulty. It also confirms the energy saving performance would hold unless transmit power weighs sufficiently heavy in the total power consumption of BS. In later discussions, difference of maximum transmit power is disregarded.

To compare with [1], in which cell zooming is always sufficient, we listed results of (2,3)-,(3,4)-off schemes under trapezoidal traffic model (6). Network energy consumption against inverse of traffic variance parameter a^{-1} is shown in Fig.6. We could observe that around 50%, optimal solution is not (3,4)-off, in which largest number of cells are switched off, but rather (2,3)-off. Additionally, if zooming is sufficient, $(n-1, n)$-off schemes achieve better performance with larger n if both traffic variance (between high and low traffic periods) and low traffic time ratio are sufficiently large.

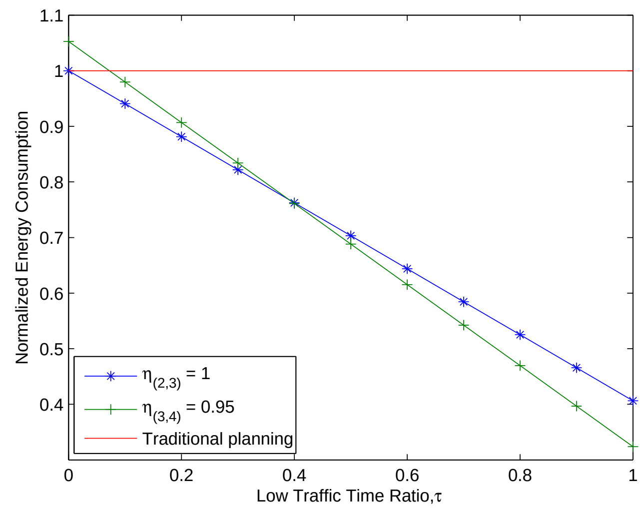

Fig. 4. Energy consumption comparison for different switching-off schemes: (2,3)-off scheme (sufficient zooming) and (3,4)-off scheme (insufficient zooming solved by deploying smaller but more cells). Maximum transmit power ratio $P_T^{\max}/P_0 = 25\%$. Zooming ratio x is 3.8.

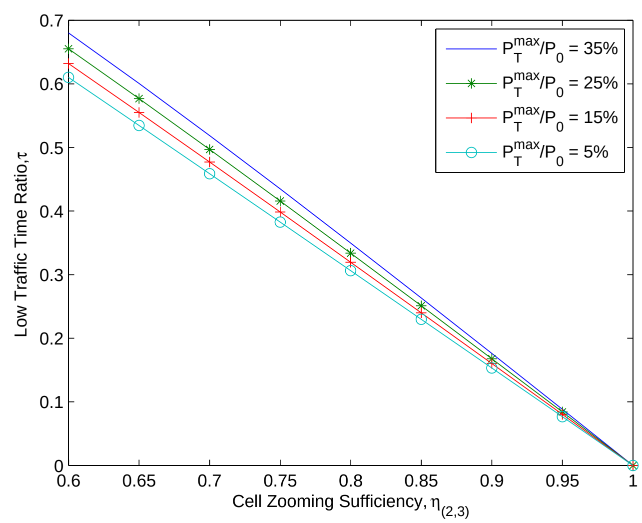

Fig. 5. Threshold for low traffic time ratio τ in deploying smaller cells for (2,3)-off scheme.

For cases that result of traditional planning has insufficient cell zooming for certain switching-off scheme, if cell zooming ratio is reaching sufficient or low traffic time ratio is large enough, it would be beneficial to deploy more cells to enable this scheme. The thresholds for each feasible scheme are shown in Fig.7. It is observed that if results of traditional planning are insufficient for any switching-off schemes, thresholds of low traffic time ratio are not as strict as those with feasible scheme(s). In other words, deploying smaller but more cells to improve deployment that already has feasible switching-off scheme shall satisfy stricter conditions.

Finally, we plot the thresholds against cell zooming ratio to better illustrate conditions applicable for energy-efficient network planning in Fig.8.

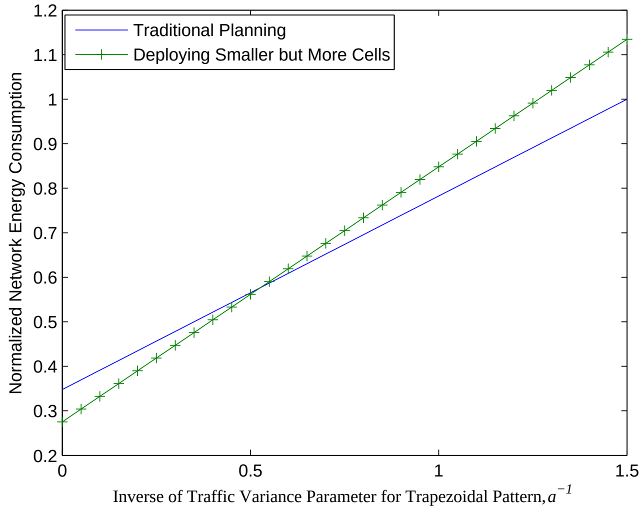

Fig. 6. Comparison of network energy consumption for different traffic variance parameter a of trapezoid traffic model. Here, zooming ratio $x = 3.8$, indicating traditional planning is sufficient for (2,3)-off scheme, but insufficient for (3,4)-off scheme. Deploying smaller but more cells is more energy-efficient when traffic variation is larger.

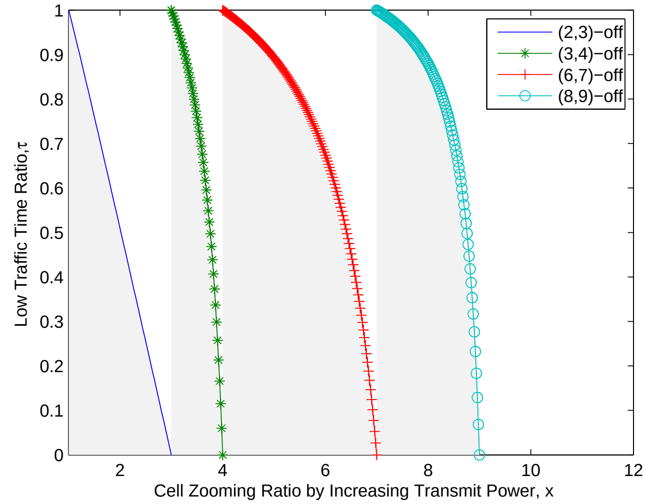

Fig. 8. Comparison of threshold for low traffic time ratio τ against cell zooming ratio x for different schemes. Grey area indicates that traditional planning is energy-efficient, while white area indicates that deploying smaller but more cells is energy-efficient.

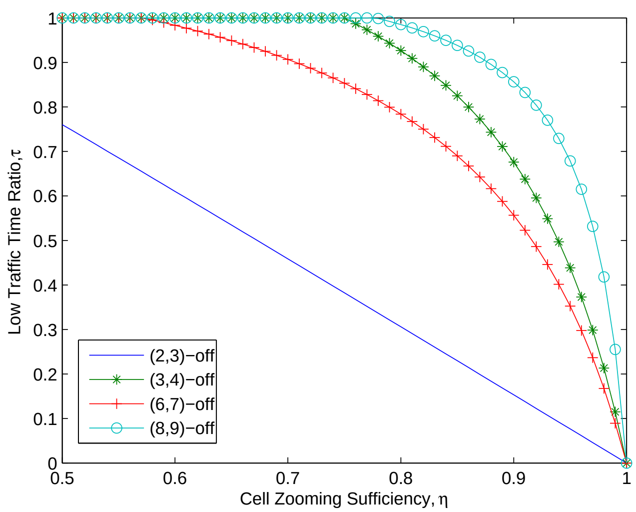

Fig. 7. Comparison of threshold for low traffic time ratio τ against cell zooming sufficiency $\eta_{(m,n)}$ for different schemes.

IV. Conclusion

We have considered energy saving in cellular network planning stage. An evaluation method is proposed to determine whether or not to adjust deployment obtained from traditional planning in order to switch off more cells, which normally requires remaining active cells to extend their coverage to certain extent. This requirement could be achieved with cell zooming by increasing transmit power. Even if cell zooming is insufficient, it is still possible to deploy smaller but more cells to increase energy efficiency if cell zooming ratio is reaching sufficient and low traffic time ratio is larger than certain threshold.

Our results indicate that in planning stage, given the traffic estimation, we might adjust deployment (cell number and cell configurations) such that the network is energy-efficient in operation stage. This improvement originates from traffic variation and zooming ability of cells. Particularly, benefit of energy-efficient network planning is significant if no cells could be switched off in deployment of traditional planning. The analysis in the paper is done focusing on cells equipped with omnidirectional antenna; fortunately, the method could easily be extended to situations with sector antenna.

The discussion is based upon the assumption of uniformly distributed traffic and does not include real traffic profile either in spatial or time domain. However, evaluation method could be extended to incorporate real traffic pattern. We did not investigate influence of solutions by CET. Moreover, this paper considers traffic requirements as hard constraints, which could be relaxed to trade-off energy-efficiency.

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