

A Practical eNB Off/On Based Energy Saving Scheme for Real LTE Networks

Tong En *, Wang Ye **, Ding Fei **, Pan Zhiwen *, You Xiaohu *

* National Mobile Communications Research Laboratory, Southeast University, Nanjing, China

** Research and Development Center, China Mobile Group Jiangsu Co.,Ltd, Nanjing, China

{tongen, pzw, xhyu}@seu.edu.cn, {wangyesgs, dingfei}@js.chinamobile.com

Abstract—In this paper, a low-complexity practical energy saving algorithm by switching off/on some eNBs in a real dense urban scenario considering historical and real-time eNB load is proposed. First, eNBs are ranked according to their loads in an ascending order and the first eNB in the list with load decreasing and smaller than a low threshold is pre-selected as target switching off cell. Then, the effect of the target switching off eNB on neighbour eNBs is evaluated. The target eNB switches-off while the load of neighbour eNBs after the eNB switches off is smaller than another threshold. Since estimation of the additional load on the neighbour eNBs due to the switch-off eNB is of high complexity, a fast estimation algorithm considering the whole eNB load by a traffic load conversion coefficient is proposed. Third, the switching-off eNB can be switched on by the active eNBs in a distributed way. Simulation results show that the proposed energy saving scheme can save up to 24% energy consumption.

Keywords—energy saving, practical, real LTE network, switch off/on

I. INTRODUCTION

Recently, with the gradually commercialization of long term evolution (LTE) system and the rapid expansion of smart phones, there has been a dramatic increase in mobile data service. Meanwhile, it also results in more and more energy consumptions and CO₂ emissions. According to [1], by 2020, mobile cellular networks will contribute up to 4% of the total world CO₂ emission. Hence, it is urgent to save the energy consumption of mobile communication systems.

In LTE networks, the energy consumption caused by the Evolved Node B (eNB) is about 60%-80% of the total energy consumption [2], and once the eNBs are deployed, it is hard to modify the network topology for energy saving. Thus, switching-off/on the eNBs in light traffic conditions becomes a widely used approach. In Figure 1, a typical traffic load profile of an eNB in actual LTE network during one week is shown. Obviously, traffic peaks occur in business hours and the traffic of ordinary weekdays is higher than that in weekend. Nevertheless, the eNBs consume most of their peak power energy consumption even when they are in low traffic condition. It is shown that the tendency of traffic load in a period is regularity, so these data can be use to design the energy saving algorithm.

Now the energy saving scheme by switching on/off the

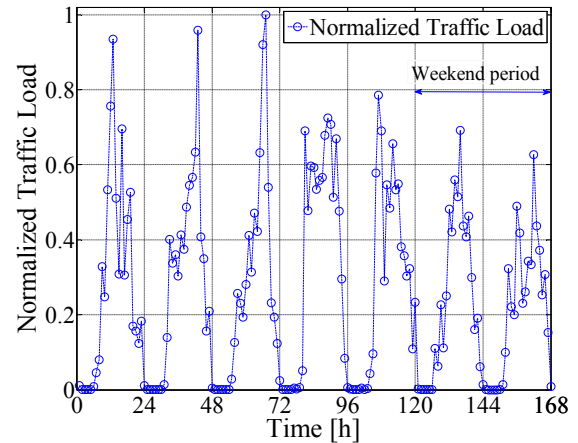


Figure 1. The normalized traffic load of an eNB during a week

eNBs has been attracted much attention recently [3]-[10]. In [3], a centralized entity in the network controls the switching off of the eNBs by the information pigged with signal overheads. However, the researchers paid little attention to the switching on schemes of the eNBs. In [4], an algorithm to switch on the eNB based on the location information of eNB and user equipments (UEs) when its load is larger than a fixed threshold is proposed. Further, in hexagonal and Manhattan model networks, dynamic BS switching strategies relying on a simple analytical model [5] for saving the energy consumption have been introduced [6]. And, considering the difference between traffic load of day-time and night, the load threshold is set dynamically and a distributed eNBs switching off/on algorithm is proposed in [7], and whether an eNB will switch off/on is decided by its neighbours based on its load impact factor. In addition, the scheme in [7] has been employed for macro/macro, macro/micro, macro/femto-cells are proposed in [8], [9], [10]). However, these algorithms are usually with high complexity since the traffic load changes dynamically and how to make good use of the historical traffic load of eNBs to select the switching-off eNB fast are not considered. Meanwhile, how to estimate the load impact on the adjacent eNBs accurately and quickly considering distance, number of eNBs, real time load is lacking.

In this paper, a practical algorithm for network energy saving for the real LTE cellular network in dense urban

commercial area is proposed. Based on the joint analysis of historical and real-time eNB load, a low complexity eNB switching-off scheme with a centralized entity is adopted and the switching-on scheme for sleeping eNBs is implemented by the active eNBs in a distributed way.

The rest of the paper is organized as following: In Section II, the system model is introduced. In section III, the practical and fast eNBs switching-off/on energy saving algorithm (PFSES) is proposed. Simulation results are given in Section IV, and the paper is concluded in Section V.

II. SYSTEM MODEL

A. Network Model

A real LTE cellular network in dense urban areas is chosen and the layout of eNBs in the $1\text{km} \times 1\text{km}$ area is shown in Figure 2. Usually, the distance between macro-eNB sites is more than 500m, and the coverage and capacity for UEs can be well guaranteed [11]. As can be seen in Figure 2, there are 13 eNBs in the 1km^2 area, and for each eNB, the neighbour eNBs can be found within 500m. Some eNBs will be switched off for better energy saving as its coverage and capacity can be guaranteed by its neighbour eNBs. The cell boundary of each eNB is obtained by Voronoi diagram through the Perpendicular Bisector Delaunay (PBD) method [12], [13], as shown in Figure 2 by solid line.

B. System Load

According to the Shannon theorem, the achievable rate for user k in eNB b is:

$$R_{b,k} = BW \cdot \log_2(1 + \text{SINR}_{b,k}) \quad [\text{bps}] \quad (1)$$

where BW denotes the system bandwidth; $\text{SINR}_{b,k}$ is the received signal to interference and noise ratio (SINR) of user k in eNB b :

$$\text{SINR}_{b,k} = \frac{P_b G_{b,k}}{\sum_{i \in \mathbf{B}_{\text{nei}}} P_i G_{i,k} + \sigma^2} \quad [\text{dB}] \quad (2)$$

where P_b is the transmit power of eNB b , and $G_{b,k}$ is the channel gain between eNB b and user k including the path loss and log-normal shadowing, where σ^2 is the noise power.

According to [14], traffic load for each user k served by the eNB b with the rate requirement r_k is defined as

$$\rho_k = \lceil r_k / R_{b,k} \rceil / N_b \quad (3)$$

where $\lceil x \rceil$ is the minimum integer larger than x , and $\lceil r_k / R_{b,k} \rceil$ is the number of TFRB allocated by eNB to user k , and N_b is the total number per second in TFRB of eNB.

C. Energy Consumption Model

The total input power P_b^{in} of eNB b is

$$P_b^{\text{in}} = \begin{cases} P_b^0 + \Delta p_b L_b P_b^{\text{max}}, & 0 < L_b < 1 \\ P_b^S, & L_b = 0 \end{cases} \quad (4)$$

where P_b^0 represents the minimal RF output power when the eNB is idling, P_b^S is the minimum system power consumption when the eNB is sleeping, Δp_b refers to the power amplifier

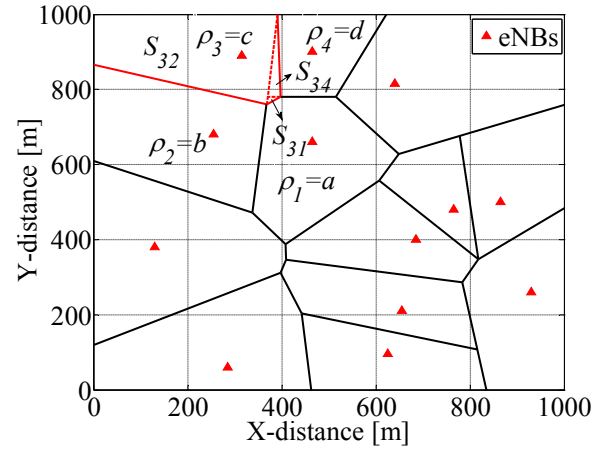


Figure 2. The eNBs layout in a dense urban area and the Voronoi diagrams for eNBs in solid line and an example for illustrating the effect of switching-off an eNB

TABLE 1. EARTH ENERGY CONSUMPTION MODEL PARAMETERS CONFIGURATION

$P_b^{\text{max}}(\text{W})$	Δp	$P_b^0(\text{W})$	$P_b^S(\text{W})$
40.00	14.20	780.00	450.00

efficiency, L_b is the load of eNB b , and P_b^{max} is the maximum transmit power. The parameters of energy consumption model for macro-eNBs are listed in Table 1.

An activity indicator $a_b(t)$ is introduced to represent whether the eNB b is sleeping or working.

$$a_b(t) = \begin{cases} 1, & b \text{ is working} \\ 0, & b \text{ is sleeping} \end{cases} \quad (5)$$

Then for an eNB, the total energy consumption is given by:

$$\begin{aligned} E_b(T) &= \int_{t \in T} P_b^{\text{in}} a_b(t) dt \\ &= \int_{t \in T} [(P_b^0 + \Delta p_b L_b P_b^{\text{max}}) a_b(t) + P_b^S (1 - a_b(t))] dt \end{aligned} \quad (6)$$

The total energy consumption in this area is computed as:

$$E_{\mathbf{B}}(T) = \sum_{b \in \mathbf{B}} E_b(T) \quad (7)$$

where $\mathbf{B}$ denotes the set of all eNBs.

Therefore, the energy saving ratio is defined as:

$$\text{Ratio}_{\text{ES}} = 1 - \frac{E_{\mathbf{B}}(T)}{\sum_{b \in \mathbf{B}} \int_{t \in T} (P_b^0 + \Delta p_b L_b P_b^{\text{max}}) dt} \quad (8)$$

III. THE PFSES ALGORITHM

In this section, the practical algorithm for eNB switching-off/on in dense urban commercial area is proposed. The algorithm consists of three parts: the pre-selection rule for switching-off eNB based on historical load record and real time load; the decision for switching-off eNB based on fast load prediction and its effect on system load and energy consumption; the eNB switching-on by neighbour eNBs.

A. Pre-selection of Switching-off eNB

It is found that the varying tendency of traffic load of each eNB is similar for all weeks. Hence history data can be used for designing the algorithm.

Firstly, the eNBs are ranked by the total load from small to big in a time window, and an execution order list **L** is generated initially in a central control entity. Then the eNB *b* for switching-off is selected by:

$$b = \arg \min_{b \in \mathbf{B}} \sum_{t \in T} \sum_{k \in A_b} \rho_k(t) \quad (9)$$

Secondly, for an eNB *b*, if both real-time load and historical load in the same period are decreasing and smaller than the system switching-off load threshold ρ^{off} , the variation in system load and energy consumption assuming switching-off it should be evaluated. If the historical load is larger than ρ^{off} , then this eNB *b* turns to a waiting list **L_{wait}**. The target switching-off eNB *b* is selected according to the list **L_{wait}** firstly in next time window. The detailed pre-selection rule is concluded as follow:

Pre-selection rule

Initializing: an execution order list **L** is generated;

1: For eNB *b*

2: If $\Delta traffic / \Delta t < 0$;

3: If $total_traffic_{now} < \rho^{off}$;

4: If $total_traffic_{history} < \rho^{off}$;

5: Estimate the variation of system load and energy consumption assuming switching-off it;

6: Else the eNB *b* turns to a waiting list **L_{wait}** for the next time window, and turn to step 1;

7: End if

8: Else turn to step 1;

9: End if

10: Else turn to step 1;

11: End if

12: In next time window, the eNB *b* is selected according to the list **L_{wait}** firstly;

13: If $\Delta traffic / \Delta t < 0$;

14: If $total_traffic_{next_window} < \rho^{off}$;

15: Estimate the variation of system load and energy consumption after switching-off it;

16: End if

17: Else turn to step 12;

18: End if

19: Else turn to step 12;

20: End if

B. Decision for Switching-off eNB

When the eNB *b* is switched off, as the UEs in it should handover to the adjacent eNBs, the adjacent eNBs need to serve the UEs in its own coverage area and guarantee the QoS requirements for the UEs handing over from the eNB *b*. The eNB *b* is bound to have an increasing effect on traffic load of other eNBs. Another system load threshold, ρ^{switch} , and the additional load caused by the switching-off eNB $\Delta\rho$ are introduced. If the predicted load of neighbor eNBs assuming switching off eNB *b* is less than ρ^{switch} , and the whole energy consumption predicted by (7) is lowered, eNB *b* will switch off. Then eNB *b* and its adjacent eNBs should be removed from the

execution order list **L**. This makes sure that only one of the eNB and its neighbour eNBs could be switched off simultaneously, preventing the users from the ping-pong effect caused by switching-off/on the eNBs frequently. The decision rule is concluded as follow:

Decision for switching-off rule

1: For the eNB *b* selected by Pre-selection rule;

2: If $\rho_{b_nei} + \Delta\rho < \rho^{switch}$;

3: If $\sum_{b \in (\mathbf{B}-b_{off})} U_b(T) < \sum_{b \in \mathbf{B}} U_b(T)$;

4: the eNB *b* switches-off, update the list **L**;

5: Else turn to Pre-selection rule;

6: End if

7: Else turn to Pre-selection rule;

8: End if

Thus how to estimate the $\Delta\rho$ quickly and accurately becomes the key point in the decision rule. $\Delta\rho$ is usually estimated by analyzing the traffic load for each UE which hand over to the other eNB in many practical networks [14]. However, on the one hand, the computational complexity for every UE is very high and increases with the numbers of UEs. On the other hand, it is impossible to get the information including the position and dynamic load of each UE accurately, and only the load of an eNB can be collected as shown in Figure 1. So estimation of the $\Delta\rho$ by the load of eNBs directly is an effective way.

Firstly, the traffic load of the eNB *b_i* within the coverage area *S_i* is assumed to be subject to uniform distribution, namely:

$$f(L_{b_i}) = \frac{1}{S_i} \quad (10)$$

Secondly, when the eNB *b_i* is switching off, its coverage area will be covered by neighbor eNBs with no coverage hole defined as:

$$S_i = \sum_{j=b_{nei}} S_{i \rightarrow j} \quad (11)$$

where *S_{i→j}* describes the additional coverage area caused by the switching-off eNB *b_i* using PBD method.

Thirdly, a traffic load conversion coefficient, *C_{load}*, describing the ratio of the load caused by the UEs in coverage *S_i* after switching-off eNB *b_i* to the original load is defined as:

$$C_{load} = \frac{\sum_{b_i \rightarrow b_{nei}} L_{b_i \rightarrow b_{nei}}}{L_{b_i}} \quad (12)$$

where *L_{b_i→b_j}*

 is the load of the UEs in *S_i* served by neighbour eNB *b_{nei}*.

Then the additional load $\Delta\rho$ is estimated as:

$$\Delta\rho_{i \rightarrow j} = \frac{\rho_i \times S_{i \rightarrow j} \times C_{load}}{S_i} \quad (13)$$

In Figure 2, a pictorial example is given to illustrate how to estimate the traffic load when an eNB is switched off. As can be seen, when the eNB *b₃* with a coverage area *S₃* and traffic load $\rho_3=c$ is selected to switch off, its load may bring positive impact on the adjacent eNBs *b₁*, *b₂*, *b₄*. Its coverage area will be separated by *b₁*, *b₂*, *b₄* by PBD method too, as:

$$S_3 = S_{3 \rightarrow 1} + S_{3 \rightarrow 2} + S_{3 \rightarrow 4} \quad (14)$$

So the additional load for b_1 is computed as:

$$\Delta \rho_{3 \rightarrow 1} = c \times S_{3 \rightarrow 1} \times C_{load} / S_3 \quad (15)$$

C. Decision for Switching-on eNB

If the network traffic increases, there would be a need to switch on some of dormant eNBs. However, the dormant eNB can't switch on by itself as it has no information about the current system load. Thus, it should be inspired by active eNBs. Active BSs exchange traffic load information over the interface between them (X2 interface in LTE) during normal network operation in a distributed manner.

Once both real-time load and historical load in the same period of an active eNB is in an increasing tendency and is more than ρ^{switch} , the last switched off neighbor eNB is informed to switch on. If the historical load is less than ρ^{switch} , another system load threshold ρ^{on} is introduced. If the real-time load of an active eNB is increasing over ρ^{on} latter, the last switched-off eNB will be waken up. The detailed decision for switching-on rule is concluded as follow:

Decision for switching-on rule

- 1: For the active eNB;
- 2: If $\Delta traffic / \Delta t > 0$;
- 3: If $total_traffic_{now} > \rho^{switch}$;
- 4: If $total_traffic_{history} > \rho^{switch}$;
- 5: the switching-off neighbor eNB b switches-on;
- 6: Else if $total_traffic_{now} > \rho^{on}$ in a period of time;
- 7: the switching-off neighbor eNB b switches-on;
- 8: End if
- 9: End if
- 10: End if
- 11: End if

The complexity of the proposed PESE algorithm is only $\mathbf{B}^2$ and it is much less than optimal exhaustive research algorithm what requires a $\mathbf{B}^k$ computational complexity [15].

IV. SIMULATION RESULTS AND ANALYSIS

A. Traffic load conversion coefficient

According to [16], the path loss model is:

$$PL = 128.1 + 37.6 \log_{10}(d_{BS,k} / 1000) + S \quad [\text{dB}] \quad (16)$$

where $d_{BS,k}$ is the distance between UE and the eNB in meter; S is the shadow fading in dB.

By using the algorithms in our previous research [17-18] for the real dense urban area shown in Figure 2, sets of simulated data of the total load in coverage S_i before and after switching-off eNB b_i are obtained. Thus, C_{load} can be computed as:

$$C_{load} = \frac{\sum_{k \in (b \rightarrow b_{nei})} \rho_k^{b_{nei}}}{\sum_{k \in b} \rho_k^b} \quad (17)$$

As the load is random in the real network, the C_{load} is also a random variable. Figure 3 depicts the cumulative distribution function (CDF) of C_{load} obtained by (17). Then by using Mean Square Error (MSE) method to quantitative analyse the

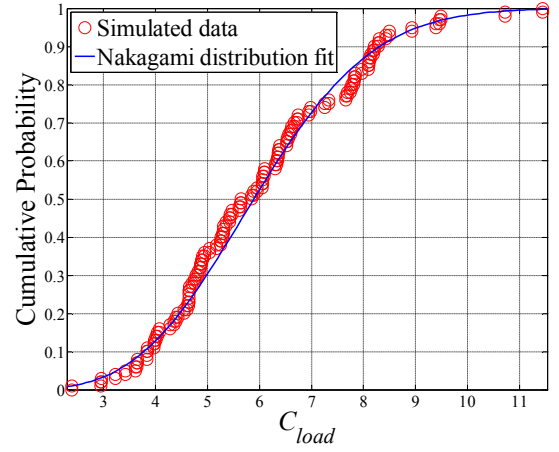


Figure 3. CDF of C_{load}

TABLE 2. STATISTICAL VALUES OF C_{load}

	Mean	variance	mu	omega
Nakagami distribution	5.98	3.10	2.99	38.93

accuracy between the measurement cumulative probability and the fit value, and the calculated MSE value for the Nakagami distribution fit depicted in Figure 3 is just 0.0253. It confirms that Nakagami distribution fits the C_{load} well, and the statistic parameters of C_{load} are given in Table 2. The mean value 5.98 indicates that it has a significant impact on the neighbor eNBs in the real dense urban area.

B. Energy saving results and analysis

Initially, the values of ρ^{off} , ρ^{switch} and ρ^{on} should be set appropriately in simulations. On one hand, with a low ρ^{off} value, eNBs operate in a conservative manner with a low system load on average. In this case, the UEs would experience less delay and call dropping probability, as the eNBs are more robust to the burst traffic arrivals. On the other hand, with ρ^{switch} and ρ^{on} value close to one, more energy saving could be achieved at the cost of slight performance degradation. Based on the traffic load profiles shown in Figure 1, the percentage of time that the traffic is below and over different percent of week peak during weekdays and weekends is acquired. The detail values are presented in Table 3. From the table, it is shown that during weekdays, about 33.2 percent of the time the traffic is less than 10 percent of the peak, while only 5.1 percent of the time the traffic is more than 70 percent of the peak. Meanwhile during the weekend the low traffic load period increases to 43.7 percent of the time and the high traffic load period declines to 4.0 percent of the time.

Hence, in the initial simulation, the threshold values is set at 0.7, 0.8, and 0.3, for ρ^{switch} , ρ^{on} and ρ^{off} . Figure 4 shows that 12.8% and 18 energy saving of the network can be achieved for weekday and weekend respectively, by researching all the real traffic profiles of eNBs as shown in Figure 2.

Then, the energy saving ratio during a week is studied for couples of ρ^{switch} and ρ^{on} with fixed interval between them, varying the ρ^{off} from 0.1 to 0.8. The results are shown in

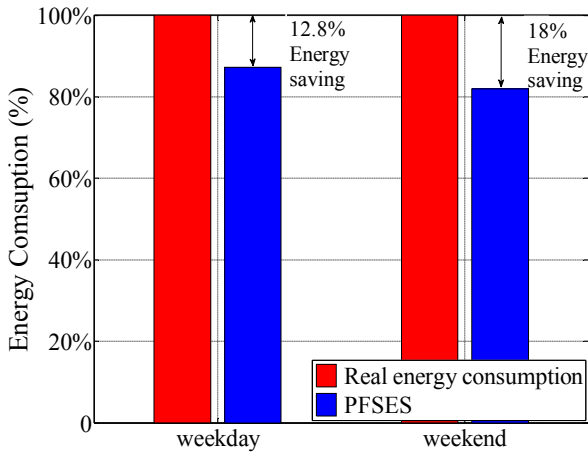


Figure 4. Energy saving ratio for weekday and weekend

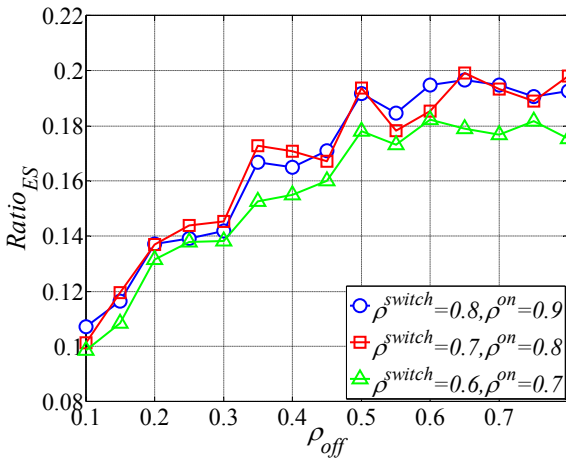


Figure 5. Energy saving ratio for fix interval between ρ^{switch} and ρ^{on}

TABLE 3. ANALYSIS OF TRAFFIC LOAD PROFILES FOR THE TYPICAL eNB DURING A WEEK

Threshold	Below x percent traffic load peak				Over x percent traffic load peak			
	5%	10%	20%	30%	70%	80%	90%	95%
Weekday	31.2%	33.2%	43.5%	53.6%	5.1%	3.4%	2.6%	0.25%
Weekend	39.8%	43.7%	54.5%	64.3%	4.0%	2.6%	1.8%	0.16%
Avarage	33.3%	36.3%	46.4%	56.5%	4.8%	3.2%	2.4%	0.2%

Figure 5. It can be clearly seen that the energy saving ratio increases as ρ^{off} increases. The limit and maximum value is about 19.6% when the ρ^{off} is larger than about 0.5. Moreover, for the same ρ^{off} , with the rising ρ^{switch} and ρ^{on} , the energy saving ratio increased slightly, e.g., the maximum energy saving ratio is about 18.0% when ρ^{switch} is 0.6, and nearly 19.6% when ρ^{switch} is 0.8. As only 4.8% of the time is more than 70 percent of the peak, the energy saving ratio is similar when ρ^{switch} is over 0.8.

Further, the energy saving ratio is analysed with varied intervals between ρ^{switch} and ρ^{on} . In the research, ρ^{switch} is fixed at 0.7 and ρ^{on} increases from 0.75 to 0.95 stepping by 0.05. From the results depicted in Figure 6, on the one hand, the energy saving ratio is improving with the increasing ρ^{on} when

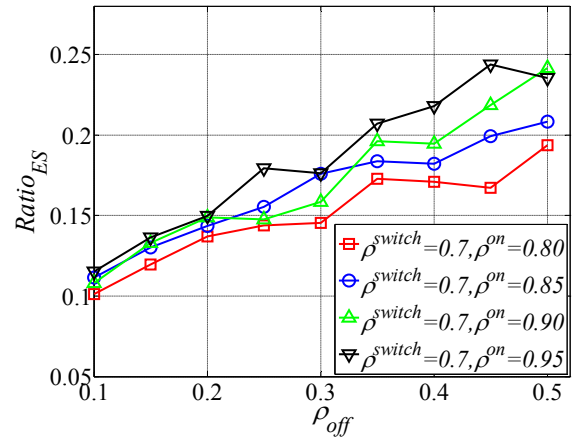


Figure 6. Energy saving ratio for varying intervals between ρ^{switch} and ρ^{on}

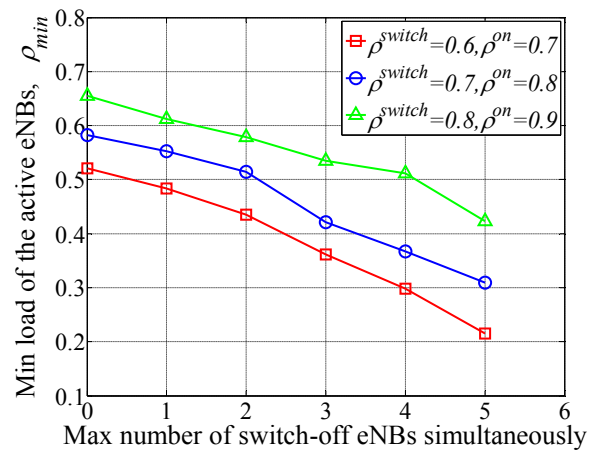


Figure 7. The maximum number of switching-off eNBs simultaneously

ρ^{off} is the same value. On the other hand, the energy saving ratio improves obvious when ρ^{off} is higher, (e.g. the energy saving ratio is 23.52% when ρ^{off} is 0.95 what is about 4.16% more than the condition when ρ^{off} is 0.7). It concludes that the higher ρ^{off} is, the more load is charged with the active eNBs adequately.

Finally, Figure 7 shows the maximum number of switching-off eNBs simultaneously with the minimum traffic load of the active eNB for the research area shown in Figure 2. In this study, the value of ρ^{off} is set as the minimum load of active eNBs in the area. It is shown that the maximum number of the switching off eNBs simultaneously increases as the min load of the active eNB falls down. And when ρ^{switch} rises, the load of minimum active eNBs increases too, (e.g. when ρ^{switch} is set at 0.8, the minimum load value for the active eNBs is 0.66). And in the area, owing to the location deployment of eNBs, the maximum switching-off eNBs number is 5 among 13 eNBs. It means that even in the night time, in order to ensure the capacity and coverage of the network, maximum 5 eNBs can be switched-off at the same time.

V. CONCLUSIONS

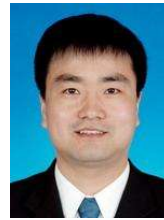
In this paper, a low-complexity practical energy saving algorithm by switching off/on some eNBs considering the historical and real-time load of eNB is proposed. First, eNBs are ranked according to its loads in an ascending order with a central controller and first eNB in the list with load decreasing and smaller than ρ^{off} is pre-selected as target switching off eNB. Then, the effect of the target switching off eNB on neighbour eNBs is evaluated by C_{load} conveniently. The eNB switches-off while the load of neighbour eNBs assuming switching-off an eNB is lower than ρ^{switch} . Third, the switching-off eNBs is switched on inspiring by the active eNBs in a distributed way. Finally, by varying different load thresholds, the simulation results show that the proposed energy saving scheme has a good performance in the urban commercial area.

ACKNOWLEDGMENT

This work is partially supported by National Major Project (2013ZX03001032-004), National 863 Program (2014AA01A702), National Natural Science Foundation (61221002), Jiangsu Province Key Technology R&D Program (BE2012165), and Huawei Corp., Ltd.

REFERENCES

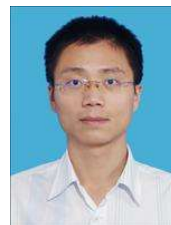
- [1] T. Chen, Y. Yang, H. G. Zhang, H. Kim, and K. Horneman, "Network energy saving technologies for green wireless access networks," *IEEE Wireless Communications*, vol. 18, no. 5, pp. 30-38, October 2011.
- [2] K. Son, H. Kim, Y. Yi, and B. Krishnamachari, "Toward energy-efficient operation of base stations in cellular wireless networks," a book chapter of *Green Communications: Theoretical Fundamentals, Algorithms, and Applications*. CRC Press, Taylor & Francis, 2012.
- [3] T. Han and N. Ansari, "On Greening Cellular Networks via Multicell Cooperation," *IEEE Wireless Communications*, vol. 20, no. 1, pp. 82-89, February 2013.
- [4] L. Saker, S. E. Elayoubi, R. Combes, and T. Chahed, "Optimal Control of Wake Up Mechanisms of Femtocells in Heterogeneous Networks," *IEEE Journal on Selected Areas in Communications*, vol. 30, no. 3, pp. 664-672, April 2012.
- [5] L. Chiaraviglio, D. Ciullo, M. Meo, and M. A. Marsan, "Energy Savings in Cellular Access Networks," in Proc. IEEE International Conference on Communications Workshops, 2009, pp. 1-5.
- [6] L. Chiaraviglio, D. Ciullo, and M. Meo, "Energy-aware UMTS access networks," in Proc. ITC'21, 2009, pp. 1-8.
- [7] E. Oh, K. Son, and B. Krishnamachari, "Dynamic Base Station Switching-On/Off Strategies for Green Cellular Networks," *IEEE Transactions on Wireless Communications*, vol. 12, no. 5, pp. 2126-2136, May 2013.
- [8] A. J. Fehske, F. Richter, and G. P. Fettweis, "Energy efficiency improvements through micro sites in cellular mobile radio networks," in Proc. GreenComm'09, pp. 1-5, Nov. 2009.
- [9] P. Rost and G. Fettweis, "On the transmission-computation-energy trade-off in wireless and fixed networks," in Proc. GLOBECOM'10, pp. 1394-1399, 2010.
- [10] M. A. Marsan and M. Meo, "Energy efficient management of two cellular access networks," in Proc. ACM'09, pp. 1-5, Nov. 2009.
- [11] Hiltunen. K, "Improving the Energy-Efficiency of Dense LTE Networks by Adaptive Activation of Cells", in Proc. IEEE International Conference, pp. 1150-1154, June. 2013.
- [12] D. Stoyan, W. S. Kendall, and J. Mecke, *Stochastic Geometry and Its Applications*, 2nd edition. Wiley, 1996.
- [13] J. S. Ferenc and Z. Neda, "On the size distribution of Poisson Voronoicells," *Physica A*, vol. 385, no. 2, pp. 518-526, Nov. 2007.
- [14] 3GPP TS 36.304 V10.7.0 Technical Specification Group Radio Access Network; Evolved Universal Terrestrial Radio Access (E-UTRA); User Equipment (UE) procedures in idle mode (Release 10). 3GPP, 2013.
- [15] S. Martello and P. Toth. *Knapsack Problems: Algorithms and Computer Implementation*. [M]. Wiley, U.K.: Chichester, 1990.
- [16] 3GPP TR 36.814 V9.0.0 Technical specification group radio access network; evolved universal terrestrial radio access (E-UTRA); further advancements for E-UTRA physical layer aspects (release 9). 3GPP, 2009.
- [17] E. Tong, Y. Wan, Z.W. Pan, X.H. You, "A Low Complexity Energy Efficiency Optimization Algorithm Based on Optimal Switching-off eNB Selection in LTE Networks," 6th International Conference on Wireless Communications and Signal Processing, 2014.
- [18] E. Tong, F. Ding, Z.W. Pan, X.H. You, "An energy minimization algorithm based on distributed dynamic clustering for long term evolution (LTE) heterogeneous networks," *SCIENCE CHINA Information Sciences*.



Tong En was born in Yangzhou city, China, on March 15, 1971. He received the M.S. in Nanjing University of Posts and Telecommunications. He is currently a Ph.D. candidate in School of Information Science and Engineering, Southeast University, Nanjing, China. He is currently a Deputy General Manager of the Data Service department and Director of the R&D center at China Mobile Group Jiangsu Co., Ltd, Nanjing, China. He has long been engaged in the research of mobile communication and the internet of things (IoT) related technologies, chaired or participated more than 10 mobile communication research projects. He was the winner of China Mobile innovation awards for many times and published nearly 20 academic papers.



Wang Ye was born in Yangzhou city, China, on January 3, 1987. He received the Ph.D. degree in Nanjing University of Posts and Telecommunications, China, in 2013. He is currently an Internet of things (IoT) and mobile network Researcher in the R&D Center, China Mobile Group Jiangsu Co., Ltd, Nanjing, China. His research interests include the internet of things, mobile communication and key techniques for integrated application between mobile communication and the internet of things (IoT).



Ding Fei was born in Taixing city, China, on August 30, 1981. He received the Ph.D. degree in the School of Instrument Science and Technology, Southeast University, Nanjing, China, in 2010. He is currently an Internet of things (IoT) and mobile network Researcher in the R&D Center, China Mobile Group Jiangsu Co., Ltd, Nanjing, China. His research interests include the internet of things, mobile communication and key techniques for integrated application between mobile communication and the internet of things (IoT).