Energy Savings through Dynamic Base Station Switching in Cellular Wireless Access Networks

Eunsung Oh
Department of Electrical Engineering,
University of Southern California,
Los Angeles, CA, 90089
e-mail:eunsung.oh@usc.edu

Bhaskar Krishnamachari
Department of Electrical Engineering,
University of Southern California,
Los Angeles, CA, 90089
e-mail:bkrishna@usc.edu (see: http://anrg.usc.edu)

***Abstract*—Reducing the energy consumption of cellular wireless access networks is not only beneficial for the global environment but also makes commercial sense for telecommunication operators. Since access networks are designed to support peak time traffic, the utilization of base stations can be very inefficient during off-peak time because the traffic profile is time varying. We study the dynamic switching of base stations (BS) to reduce the energy consumption considering the time varying characteristic of the traffic profile. We show via analysis that the mean and variance of traffic profile and the BS density are the dominant factors that determine the amount of energy saving that can be achieved. Simulations using ideal and real traffic profiles are used to quantify the potential savings from dynamic BS switching in a realistic setting.**

***Index Terms*—energy-aware operation, green communication, green cellular, dynamic base station switching**

I. INTRODUCTION

Nowadays, the transmitted multimedia data and energy consumption are the key issues in information and communication technology (ICT) communities. The amount of transmitted data increases approximately by a factor of 10 per every 5 years, which corresponds to an increase of the associated energy consumption by 20% per year; and currently, 3% of the world-wide energy is consumed by the ICT infrastructure which causes about 2% of the world-wide CO_2 emissions [1]. Among the main ICT sectors, 37% of the total ICT emissions are due to the telecommunication infrastructure and devices [2]. The base station (BS) is the main component of the cellular telecommunications infrastructure. Energy consumption of the BS amounts to nearly $850W$, with the energy needed to transmit from the antennas amounting only up to $40W$ and the rest expended even in case of idle operation[3].

Observing the traffic profile in real cellular-based wireless access networks, it can be modeled as a periodic sinusoidal profile, as shown in Fig. 1[1]. This is consistent also with the data presented in [4]. The traffic profile during the day time period (11 am - 9 pm) has higher value than that of the night time period (10 pm - 9 am). And, there is a difference in the traffic profile observed on a normal weekday and on a weekend/holiday period. Because BSs are planned to support the day time traffic, infrastructures of access networks are under utilized during the night time and the weekend period. This is why effective dynamic BS planning (switching off redundant base-stations) can save energy consumption.

A few related works on BS planning have considered the daily traffic profile [5], [6], [7]. The first work shows the possibility of energy saving of BS switching-on/off planning by simple simulations [5]. Marsan *et al.* studied the BS switching strategy using a simplified analysis and showed simulation results for several switching-off BS ratios [6]. The research has also been extended to the overlay network environment with the proposal of BS switching strategies based on the utility balance of two networks [7]. Also, the BS switching strategy based on a snapshot approach not considering the traffic profile, has been proposed. In [8], BS switching algorithms are presented, illustrating the relationship between energy saving by BS switching-off and QoS, i.e. outage probability. However, these prior works do not analyze the dominant factor for minimizing the energy consumption

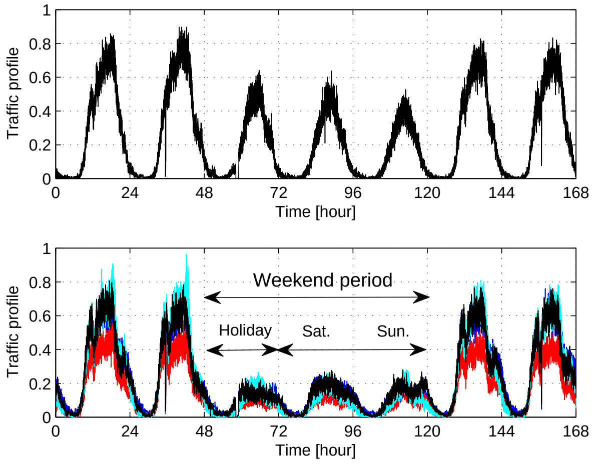

Fig. 1. Normalized traffic profile during one week. The figures show the center BS (Top) and neighboring BSs (Bottom).

---

[1] The real traffic data used in this paper was obtained from a cellular operator in a metropolitan urban area. The data captures voice call information from 5 BSs, one central BS and its neighboring 4 BSs over the course of one week. The data is measured with a resolution of one second. We normalize the values of load by a constant value to show the relative change.

based on the BS switching.

In this paper, we investigate the design of energy efficient wireless access networks based on switching BSs. First, we suggest a basic distributed BS switching strategy, and, by the first-order analysis, explore the factors affecting energy savings. We find that the traffic profile and the BS density are key factors.

II. SYSTEM MODELS AND PROBLEM FORMULATION

A. System Models and Assumptions

The system model and the associated assumptions used in this paper are summarized below:

1) The number of channels is C, and all channels are orthogonal. The channels are randomly allocated to each active user equipment (UE). The same radio channel is reused in every BS.
2) BSs are uniformly placed in an area with mean density p_{BS} and minimum inter site distance (ISD). UEs are randomly generated around BSs. A sample deployment is shown in Fig. 2.
3) The call arrival process of a BS b at time t is modeled as a Poisson process with mean arrival rate $\lambda_b(t)[call/sec]$ [4]. And, it is assumed that there is a constant service time, $h[sec/call]$, for each call.
4) The traffic profile of a BS b, $\rho_b(t) = \lambda_b(t) \cdot h$, is a time varying function with $D = 24h$ time period. Assuming that the overall system is homogeneous in statistical equilibrium, the subscript is ignored, $\rho(t)$.
5) BSs only know the approximated sinusoidal traffic profile with mean, M, and variance V, i.e. $\bar{\rho}(t) = V \cdot \cos(2\pi(t+\phi)/D) + M$.
6) Data is retransmitted when losses occur.

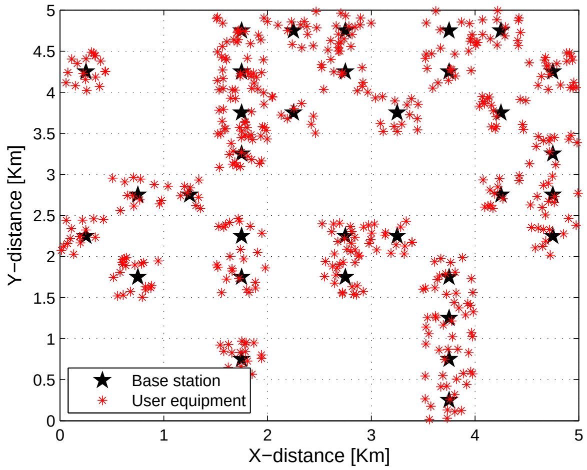

Fig. 2. Sample deployment of BSs and UEs in $5Km \times 5Km$ with $p_{BS} = 1.1547BS/Km^2$ that is the hexagonal cellular system BS density at $1Km$ ISD.

B. Problem Formulation

The energy saving problem in access networks is formulated to minimize the energy consumption of BSs considering the system requirements, as follows:

$$\begin{aligned} &\min_{A_b} \sum_{b\in\mathbf{B}} \int_t^{t+D} E_{BS} A_b(t)dt \\ &s.t \quad Pr_b^{Bloc}(t) \le Pr_{req}^{Bloc}, \quad \forall b, t, \end{aligned} \tag{1}$$

where $\mathbf{B}$ is the set of BSs in networks, and E_{BS} is the BS energy consumption per unit time. $A_b(t)$ is the activity function of a BS b at time t, $A_b(x) \in \{0, 1\}$ $\forall x \in \{t, t+D\}$, that is determined by the BS switching strategy.

Since we assume retransmission, there is no data loss, and therefore the blocking probability is used as the quality of service (QoS) requirement. In the constraint, $Pr_b^{Bloc}(t)$, Pr_{req}^{Bloc} are the blocking probability of a BS b at time t and the minimum requirement, respectively. Pr_{req}^{Bloc} is set the peak blocking probability when the BS switching strategy is not applied.

III. BASIC ALGORITHM FOR SWITCHING BSS

To reduce the computational complexity and the information exchange, we consider a distributed BS switching strategy. Each BS only knows the number of neighboring BS, $|\mathbf{N_b}|$. We assume the traffic profile is modeled as the sinusoidal with D period time, thus the BS switching-off and on each occur only once during D period time.

A. The BS switching-off strategy

If the BS b is switched off at time t_b^{off}, UEs served by the BS b are handed over to the neighboring BSs, $\mathbf{N_b}$. The handover traffic of a neighboring BS by the BS b's switched off is approximated as $\bar{\rho}(t_b^{off})/\mathbf{N_b}$ because we assume that UEs are randomly positioned in serving area[2]. Considering the handover traffic, the cell traffic of the neighboring BSs are calculated as

$$\bar{\rho}_n(t_b^{off}) = \bar{\rho}(t_b^{off}) \cdot (1 + 1/|\mathbf{N_b}|), \quad n \in \mathbf{N_b}, \tag{2}$$

when the BS b is switched off at time t_b^{off}. Therefore, the BS b is switched off when it is satisfied

$$\bar{\rho}(t) \cdot (1 + 1/|\mathbf{N_b}|) < \rho_{th}, \tag{3}$$

where ρ_{th} is the switching threshold. If the switching threshold is set at a higher value, more energy is saved but the blocking probability is also increased, and *vice versa*. Considering the constraint, the switching threshold is established to minimize the energy consumption.

---

[2] By defining some information exchange procedure similar to RTS/CTS or the tie-breaking rule, it can be neglect that two or more BSs which have same neighboring BS are switched off at same time.

B. The BS switching-on strategy

During the switching-off period, the BS does not exchange the information from networks. The BS is switched on only considering the approximated sinusoidal traffic profile

$$\bar{\rho}(t) > \rho_{th}. \tag{4}$$

Assuming the homogeneous traffic condition, BSs are switched on at same time, $t^{on} = t_b^{on},\ \forall b \in \mathbf{B}$.

IV. FIRST-ORDER ANALYSIS OF ENERGY SAVING

In this section we discuss a rough first-order analysis for the maximum amount of energy saving under the described BS switching strategy, which gives an insight into the key factors affecting the energy saving.

Let us define the energy saving ratio as

$$S = 1 - \frac{\sum\limits_{b\in\mathbf{B}} \int_t^{t+D} A_b(t)dt}{|\mathbf{B}| \cdot D}, \tag{5}$$

where $|\mathbf{B}|$ is the number of BSs in networks. The second term of the right part in (5) means the average BS switching-on duration. Therefore, the energy saving ratio can be written as the expected BS switching-off duration,

$$\begin{aligned} S &= \frac{1}{D} \cdot E\left\{t^{on} - t_b^{off}\right\}, \\ &= \frac{1}{D} \cdot \left[E\left\{t^{on}\right\} - E\left\{t_b^{off}\right\}\right], \end{aligned} \tag{6}$$

where $E\{\cdot\}$ refers to the expected value.

Assuming the traffic profile is sinusoidal as shown in Fig. 3, (6) is rewritten as

$$S = \frac{1}{D} \cdot \left[2 \cdot E\left\{t^{on}\right\} - D - \delta\right], \tag{7}$$

where δ is the time gap from ρ_{th} to $\rho_{th}(1 - 1/|\mathbf{N_b}|)$ at the BS switching-off strategy. If the number of neighboring BS is increasing (the BS density, p_{BS}, is increasing), the value is decreased.

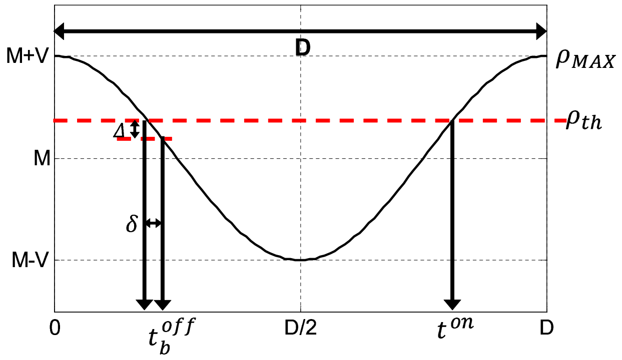

Fig. 3. First-order cell load with mean M and variance V, $\rho(t) = V \cdot \cos(2\pi t/D) + M$ where $\phi = 0$.

TABLE I
SIMULATION PARAMETERS

Parameter	Value
BS transmission power	$43dBm$
Noise power	$-176dBm/Hz$
UE required data rate	$256Kbps$
Transmission mode	M-QAM with $BER = 10^{-6}$ [9]
Channel model	path-loss with exponent 4
	log-normal shadowing with $8dB$ std.

From two observation: 1) the blocking probability is a monotonic increasing function of the traffic load, 2) the peak traffic load is occurred at time t^{on} during the switching-off period, we can obtain the equation to maximize the energy saving while satisfying the QoS constraint,

$$\rho(t^{on}) \cdot \left(1 + E\left\{1/|\mathbf{N_b}|\right\}\right) = \rho_{MAX}. \tag{8}$$

Using the cosine inverse function, $acos(\cdot)$, t^{on} is calculated as

$$t^{on} = D - \frac{D}{2\pi} acos\left(\frac{1 - \frac{M}{V}X}{1 + X}\right), \tag{9}$$

where $X = E\left\{1/|\mathbf{N_b}|\right\}$.

Substituting (9) into (7), the energy saving ratio is expressed as

$$S = 1 - \frac{1}{\pi} acos\left(\frac{1 - \frac{M}{V}X}{1 + X}\right) - \delta. \tag{10}$$

To clarify the expression, we apply the Taylor series expansion

$$\begin{aligned} S &= 1 - \frac{1}{\pi}\left\{\frac{\pi}{2} - \frac{1 - \frac{M}{V}X}{1 + X} - \frac{1}{6}\left(\frac{1 - \frac{M}{V}X}{1 + X}\right)^3 - \cdots\right\} - \delta \\ &\approx \frac{1}{2} + \frac{1}{\pi}\frac{1 - \frac{M}{V}X}{1 + X} - \delta \end{aligned} \tag{11}$$

The energy saving ratio of (11) is the function of the traffic parameters, (M, V), and the number of neighboring BS, $|\mathbf{N_b}|$ because δ is also the function of $|\mathbf{N_b}|$. From (11), we can see that the energy saving is increased when the ratio of traffic, M/V and the number of neighboring BS have higher value. It means, for instance, that the greatest energy savings are likely to be realized in urban commercial areas (since such an area is likely to show both high traffic variance between day time and night time as well as high BS density).

V. NUMERICAL RESULTS

The system considers frequency division multiple access (FDMA) with 30 channels, a $10MHz$ bandwidth and a $2.3GHz$ radio frequency. The method used is Monte Carlo simulation. Simulation parameters are summarized in Table I.

To evaluate the performance of BS switching strategy we used the real traffic profile in Fig. 1. The approximated sinusoidal traffic profile is estimated for four different cases to minimize the least square estimation error as shown in Fig. 4.

Fig. 5 illustrate the average peak blocking probability of the weekday BS 0 case versus the switching threshold ρ_{th}. The average peak blocking probability is divided flat and increasing regions by the switching threshold. During the flat region, the average peak blocking probability is obtained at the peak traffic time, so we say the region is the traffic dominant region. The increasing region of the average peak blocking probability can be described the switching dominant region because the average peak blocking probability is increased by the switching strategy. In our simulations, the switching threshold is determined the maximum value of the traffic dominant region to maximize the energy saving without decreasing the system performance.

Fig. 6 show the simulation results versus the four difference traffic and the BS density. In this figure, we used the ideal traffic profiles, i.e. Fit 1 $\sim$ 4 illustrated in Fig. 4. At each BS density, the energy saving ratio has the similar value with less than the 1% difference. That is because the traffic ratio of each traffic is same to $M/V = 1$. Also, by increasing the BS density, the energy saving ratio is improved. The results are consistent with the analysis presented in the previous section. The solid line in Fig. 6 is the result of (11). It presents the similar slope with the simulation result but there is a gap between the absolute values. In practice, the number of neighboring BS is dynamically changed by the switching-off action at each time, unlike the analysis result which assumes a constant number of neighboring BS.

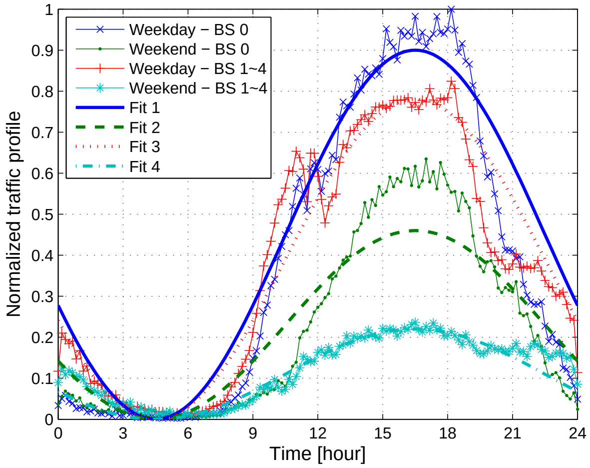

Fig. 4. Normalized traffic profile of four different cases. The traffic profiles are averaged over 10 minute slots.

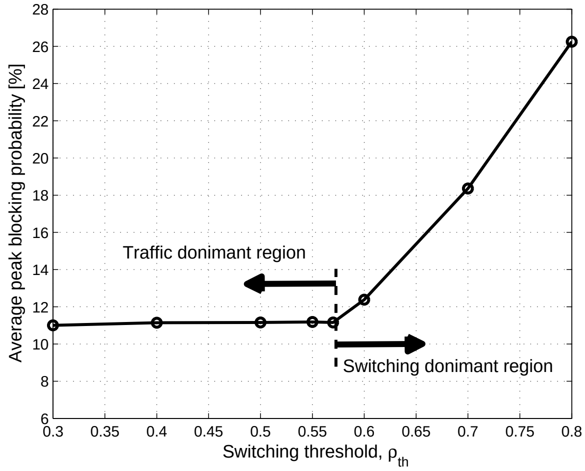

Fig. 5. Average peak blocking probability of the weekday BS 0 case versus the switching threshold, ρ_{th}

TABLE II

RESULTS USING REAL TRAFFIC PROFILES WITH $p_{BS} = 1.1547 BS/Km^2$

Case	**Energy saving [%]**	**Switching-on time (t^{on})**
Weekday - BS 0	16.04	11.7h
Weekend - BS 0	16.41	12.0h
Weekday - BS 1$\sim$4	13.13	10.3h
Weekend - BS 1$\sim$4	16.91	12.5h

The results using the real traffic profile are expressed in Table II. As with the results using the ideal traffic profile, each case has the similar energy saving ratio except the result of the third case (Weekday - BS 1$\sim$4). That is because, as per the traffic profile of the third case in Fig. 4, the real traffic has larger value than the estimated traffic during 9$\sim$12 hour which includes the switching-on time. In addition, the difference of the maximum value between the real and estimated traffic profile has the large value at the second case (Weekend - BS 0) but the energy saving ratio of the second case has the similar value comparing the other cases. From that it can be seen that the slope is more important than the maximum value in estimating the traffic profile because the slope directly determines the switching-on/off time.

VI. Conclusion

In this paper, we investigated the basic BS switching strategy for saving energy in cellular wireless access networks.

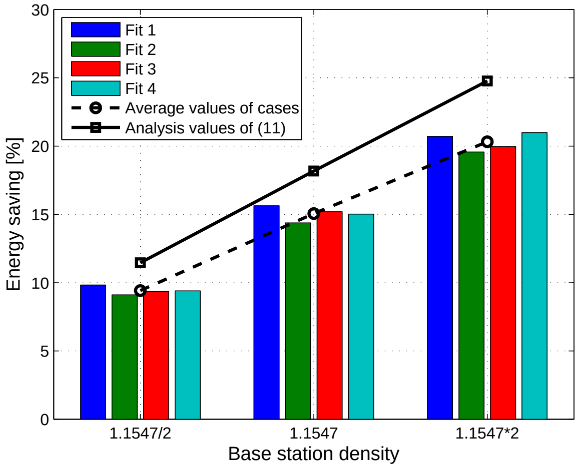

Fig. 6. Energy saving at each traffic versus the BS density using the ideal traffic profile

From the first-order analysis we showed the amount of energy saving is dependent upon the traffic ratio of mean and variance and the BS density. This was verified by simulation results using the ideal and real traffic profile. The results provide a guideline on how to manage the BS resources so as to obtain energy saving.

Several extensions of the results presented in this paper are possible. First of all, more research in heterogeneous traffic conditions among BSs is needed. Second, while we considered the time varying characteristic of the traffic profile it could be studied considering the other characteristic, i.e., geographical patterns. Third, our research should be extended to more sophisticated dynamic network topologies such as hierarchical cell structure networks.

ACKNOWLEDGMENT

The work of Dr. Oh was partially supported by the National Research Foundation of Korea Grant funded by the Korean Government (NRF-2009-352-D00205).

REFERENCES

[1] “An inefficient truth,” Global Action Plan, Tech. Rep., Dec. 2007. [Online]. Available: http://www.globalactionplan.org.uk/

[2] “Enabling the low carbon economy in the information age,” SMART 2020, Tech. Rep., Jun. 2008. [Online]. Available: http://www.theclimategroup.org/

[3] “Node B specification sheet,” Motorola, 2007. [Online]. Available: http://www.motorola.com/

[4] D. Willkomm, S. Machiraju, J. Bolot, and A. Wolisz, “Primary users in cellular networks: A large-scale measurement study,” in *Proc. of IEEE DySPAN*, Chicago, IL, Oct. 14-17, 2008, pp. 1–11.

[5] L. Chiaraviglio, D. Ciullo, M. Meo, M. A. Marsan, and I. Torino, “Energy-aware UMTS access networks,” in *Proc. of WPMC Symposium*, Lapland, Finland, Sep. 8-11, 2008, pp. 1–5.

[6] M. A. Marsan, L. Chiaraviglio, D. Ciullo, and M. Meo, “Optimal energy savings in cellular access networks,” in *Proc. of IEEE ICC Workshop*, Dresden, Germany, Jun. 18, 2009, pp. 1–5.

[7] M. A. Marsan and M. Meo, “Energy efficient management of two cellular access networks,” in *Proc. of ACM SIGMETRICS workshop*, Seattle, WA, Jun. 15, 2009, pp. 1–5.

[8] S. Zhou, J. Gong, Z. Yang, Z. Niu, and P. Yang, “Green mobile access network with dynamic base station energy saving,” in *Proc. of ACM MobiCom*, Beijing, China, Sep. 20-25, 2009, pp. 1–3.

[9] A. Goldsmith and S. Chua, “Variable-rate variable-power MQAM for fading channels,” *IEEE Trans. Commun.*, vol. 45, no. 10, pp. 1218–1230, Oct. 1997.