Dynamic Base Station Switching-on/off Strategies for Green Cellular Networks

Eunsung Oh, *Member, IEEE,* Kyuho Son, *Member, IEEE,* and Bhaskar Krishnamachari, *Member, IEEE*

***Abstract*—In this paper, we investigate dynamic base station (BS) switching to reduce energy consumption in wireless cellular networks. Specifically, we formulate a general energy minimization problem pertaining to BS switching that is known to be a difficult combinatorial problem and requires high computational complexity as well as large signaling overhead. We propose a practically implementable switching-on/off based energy saving (*SWES*) algorithm that can be operated in a distributed manner with low computational complexity. A key design principle of the proposed algorithm is to turn off a BS one by one that will minimally affect the network by using a newly introduced notion of *network-impact*, which takes into account the additional load increments brought to its neighboring BSs. In order to further reduce the signaling and implementation overhead over the air and backhaul, we propose three other heuristic versions of SWES that use the approximate values of network-impact as their decision metrics. We describe how the proposed algorithms can be implemented in practice at the protocol-level and also estimate the amount of energy savings through a first-order analysis in a simple setting. Extensive simulations demonstrate that the SWES algorithms can significantly reduce the total energy consumption, e.g., we estimate up to 50-80% potential savings based on a real traffic profile from a metropolitan urban area.**

***Index Terms*—Energy saving, base station switching on/off, green cellular networks;**

I. INTRODUCTION

A. Motivation

Recently, there has been an explosion in mobile data [2], which is mainly driven by smart-phones that offer ubiquitous Internet access and diverse multimedia applications. However, this also brings ever-increasing energy consumptions and carbon footprint to the mobile communications industry. In particular, the whole information and communication technology (ICT) sector has been estimated to contribute to about 2 percent of global CO_2 emissions, and about 1.5 percent of global CO_2 equivalent (CO_2e^1) emissions in 2007 [3], [4]. A quantitative study in [5] estimated the corresponding figure for cellular networks to be 0.2 and 0.4 percent of the global CO_2e emissions in 2007 and 2020, respectively. Note that while the overall ICT footprint will less than double between 2007 and 2020, the footprint of cellular networks is predicted to almost triple within the same period.

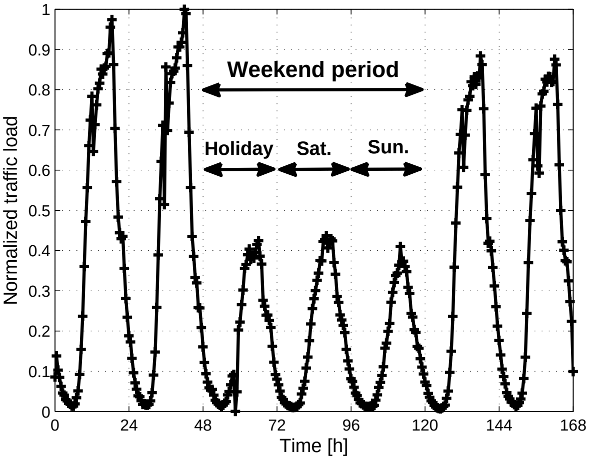

Fig. 1. Normalized real traffic load during one week that are recorded by an anonymous cellular operator. The data captures voice call information over one week with a resolution of one second in a metropolitan urban area, and are averaged over 30 minute time-scale.

With increasing awareness of the potential harmful effects to the environment caused by CO_2 emissions and the depletion of non-renewable energy sources, it is more critical than ever to come together to develop more energy-efficient systems in all industries, and of course, telecommunication systems is not an exception. From the economical perspective of cellular network operators, it is also important because a significant portion of their operational expenditure goes to pay the electricity bill. For instance, it is estimated that the cellular network operational expenditure for electricity globally will increase up to $22 billion in 2013 [6].

The focus of this paper is on reducing the power consumption at base stations (BSs) that account for heavy energy usage, e.g., about 60-80% of the total energy consumption [7], [8] in cellular networks. Energy reduction in BSs can be achieved in many ways: from hardware design (e.g., more energy efficient power amplifiers [9] and natural resource for cooling [10]) to topological management (e.g., the deployment of relays and/or micro BSs [11]–[13]), and so on. In this paper, we concentrate on the switching-on/off based dynamic BS operation for potential energy saving, which allows the system to entirely turn off some underutilized BSs during low traffic periods.

We shall start with a motivational example in Fig. 1 that shows a real traffic profile from a cellular wireless access

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E. Oh is with the Department of Electrical and Computer Engineering, Hanseo University, Korea (e-mail: eunsung.oh78@gmail.com).

K. Son and B. Krishnamachari are with the Department of Electrical Engineering, Viterbi School of Engineering, University of Southern California, Los Angeles, CA 90089. (e-mail: {kyuhoson, bkrishna}@usc.edu).

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[1] CO_2e is the internationally recognized measure of greenhouse emissions. When an organization calculates its greenhouse emissions these are reported as though they were equivalent to a given volume of CO_2.

network. It can be easily seen that the traffic profile of the nighttime is much lower than that of the daytime. It is also observed that there is a slight difference between the traffic profiles of ordinary weekdays and weekend/holiday. Note that this result is consistent with the data presented in [14]. Since the operators need to deploy their BSs to support the peak time traffic, it is inevitable that the BSs are under-utilized most of other times, especially, at night and on weekends. Note, however, that BSs consume most of their peak power consumption even when they are in little and no activity [15]. This explains why potential energy savings can be achieved by dynamically switching on/off BSs.

B. Main Contribution

The traffic profile is temporally (as well as spatially) varying and there are thus certain periods of time (and locations) where BSs are under-utilized. In order to manage the BSs in an energy-efficient manner, our research is concerned with two basic questions:

(Q1) *When and which BSs should be switched on/off?*
(Q2) *What are important parameters to be considered for determining the switching decision?*

The key contributions of our work are summarized below:

- *Algorithm design:* The general problem of energy saving with BS switching is formulated as a combinatorial problem. To optimally solve this complex problem, a central controller is required. In our work, we introduce a concept of the *network-impact* for a specific BS, which is defined as how much the switching-off of this BS will affect the network. The network-impact is composed of deterministic parameters at each BS such as internal (own) and external (neighboring BS's) system load[2], and overall system parameters such as he traffic profile and threshold. Motivated by this, we modify the energy saving problem as a BS selection problem which has linear computational complexity, and propose a distributed switching-on/off based energy saving (SWES) algorithm without a central controller.
- *Practical implementation:* To make the proposed SWES more practical, we further present three heuristic algorithms, which can be operated with only partial feedback or even without feedback. We empirically verify that the performance gap between heuristic algorithms and the optimal exhaustive search algorithm minimizing the total energy consumption is less than 10% in a real traffic condition. Moreover, we consider other implementation issues: i) a collision resolution protocol for control message exchange to prevent two or more BSs from shutting down simultaneously, and ii) a hysteresis to mitigate the inefficient repetition of switching off and on due to the high variation of the system load. The implementation of the proposed algorithm is also comprehensively described at the protocol-level.

C. Prior Work

Energy-efficient design of cellular wireless networks has recently received significant attention [1], [7], [8], [11], [12], [16]–[23]. In [16], the authors suggested the possibility of energy saving by dynamic BS operation based on BS switching related with the traffic profile. As an extension, they studied BS switching strategies based on a simple analytical model [8]. However, these works are only focused on ideal networks such as hexagonal and Manhattan model network, and they have just introduced that the energy consumption could be saved by dynamic BS switching algorithms. Our own prior work [1] also provides a similar analysis of the energy savings with a simple switching policy. In addition, the BS operation concept considering the network sharing among networks, i.e. macro/macro, macro/micro, macro/femto-cells, are proposed in [11], [12], [17]. However, these studies also show how much energy saving can be achieved rather than presenting operating algorithms.

Basic concepts of the dynamic BS operation issues are summarized in [7], [20], and some algorithms are proposed in [21]–[23]. In [21], [22], the authors researched about the energy efficient operation based on the cooperation transmission in multi-hop systems. Niu *et al.* proposed the cell zooming considering the BS cooperation and relaying in cellular systems [23]. However, these works are not concerned with the implementation in practice. Our work fills the voids of the previous work in that: i) we propose practical and distributed online algorithms for the dynamic BS operation, ii) consider the implementation difficulty such as information feedback, and iii) also provide the better understanding of important parameters that potentially bring us significant energy saving.

The remainder of this paper is organized as follows. In Section II, we formally describe our system model and general problem. In Section III, we propose the distributed SWES algorithm and further design three heuristic algorithms by taking into account practical implementability. In Section IV, by first-order analysis, we explore the factors affecting energy savings. In Section V, we demonstrate the performance of the proposed algorithms under the ideal and real traffic profiles. Finally, we conclude the paper in Section VI, and future works are described in Section VII.

II. SYSTEM DESCRIPTION AND PROBLEM FORMULATION

A. System Description

1) Network Model: We consider a wireless cellular network where the set of BSs, denoted by $\mathbf{B}$, lies in the two-dimensional area $\mathcal{A}$. Our focus is on downlink communication as that is a primary usage mode for the mobile Internet, i.e., from BSs to user equipments (UEs).

2) Traffic Model: The packet-based traffic model is used for our our analysis and simulations. We assume the traffic arrival rate of UE located x at time t is modeled as an independent Poisson distribution with mean arrival rate $\lambda(x,t)$. Its average requested file size is assumed to be an exponentially distributed random variable with mean $1/\mu(x,t)$. Note that this captures spatial traffic variability by setting different arrival rates or file sizes for different users. The traffic load of UE is then defined as

$$\gamma(x,t) = \lambda(x,t)/\mu(x,t) \quad \text{[in bps]}. \tag{1}$$

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[2] The concept of internal and external system load is described later in Section III-A.

TABLE I
SUMMARY OF NOTATIONS

$\mathcal{A} \subset \mathbb{R}^2$	Consideration region
$x \in \mathcal{A}$	Location in continuous space
$b \in \mathbf{B}$	BS index
$\mathcal{A}_b \subset \mathcal{A}$	Coverage of BS b
$\mathbf{B}_t^{\text{on}} \subseteq \mathbf{B}$	The set of active BSs at time t
$\mathbf{N}_b$	The set of neighboring BSs of BS b
$\lambda(x,t)$	Traffic arrival rate of location x at time t
$1/\mu(x,t)$	Average file size of location x at time t
$\gamma(x,t)$	Traffic load of location x at time t, $\gamma(x,t) = \lambda(x,t)/\mu(x,t)$
$s_b(x,t)$	Service rate at location x from BS b at time t, $s_b(x,t) = BW \log_2(1 + SINR_b(x,t))$
$\rho_b(t)$	System load of BS b at time t, $\rho_b(t) = \int_{\mathcal{A}_b} \gamma(x,t)/s_b(x)dx$
ρ^{th}	System load threshold
E_{BS}	Operational expenditure of BS per unit time
$\mathbf{a}_t$	The set of BS activity indicators at time t, $\mathbf{a}_t = \{a_1(t), \cdots, a_{\lvert\mathbf{B}\rvert}(t)\}$
ρ_t	The set of the system load at time t, $\rho_t = \{\rho_1(t), \cdots, \rho_{\lvert\mathbf{B}\rvert}(t)\}$

From the perspective of UE, it is worthwhile mentioning that the traffic load can be interpreted as *QoS (quality of service) requirement* because it is the amount of traffic the user should receive for its satisfaction.

3) BS Selection Rule: A UE located $x \in \mathcal{A}$ is associated with and served by the BS which provides the best signal strength,

$$b = \arg \max_{i \in \mathbf{B}_t^{\text{on}}} \ g(i,x) \cdot P_b, \tag{2}$$

where $\mathbf{B}_t^{\text{on}} \subseteq \mathbf{B}$ is the set of active BSs at time t, $g(b,x)$ is the average channel gain from BS b to UE at location x including the path loss and other factors such as slow fading (e.g., log-normal shadowing), and P_b is the transmission power of BS b.

4) Channel Model: Assuming the physical capacity is modeled as Shannon capacity[3], the service rate of UE at location x from BS b at time t is calculated as

$$s_b(x,t) = BW \cdot \log_2 \left(1 + SINR_b(x,t)\right), \tag{3}$$

where BW denote the system bandwidth; $SINR_b(x,t)$ is the received signal to interference and noise ratio (SINR) at location x from BS b at time t that is given by

$$SINR_b(x,t) = \frac{g(b,x) \cdot P_b}{\sum\limits_{i \in \mathbf{B}_t^{\text{on}} - \{b\}} g(i,x) \cdot P_i + \sigma^2}, \tag{4}$$

where σ^2 is the noise power.

5) System Load: In order to guarantee the QoS of UE, a BS should assign a certain amount of resource (e.g., time or frequency) depending on user's traffic load as well as its service rate. From the perspective of system, the system load of BS b at time t is defined as the fraction of resource to serve the total traffic load in its coverage[4],

$$\rho_b(t) = \int_{\mathcal{A}_b} \frac{\gamma(x,t)}{s_b(x,t)} dx, \tag{5}$$

where $\mathcal{A}_b$ represents BS b's coverage (i.e., the set of UEs locations served by BS b). The system load denotes the fraction of time required to serve the total traffic load in his coverage. Our notation is summarized in TABLE I.

B. General Problem Formulation

In this paper, we aim at proposing a BS switching algorithm that minimizes the total energy expenditure in cellular networks during T. Our objective function is given by

$$U(\mathbf{a}) = \sum_{b \in \mathbf{B}} \int_0^T E_{BS} \cdot a_b(t) dt, \tag{6}$$

where E_{BS} is the BS power consumption; $a_b(t) \in \{0,1\}$ is the activity indicator of BS b at time $t \in [0,T)$, that is determined by the BS switching strategy, and $\mathbf{a}$ is a vector of the activity indicators of all BSs during T.

In general, our energy saving problem considering the BS switching can be formulated as:

$$\begin{aligned} \min_{\mathbf{a}} \quad & U(\mathbf{a}) \\ \text{s.t.} \quad & 0 \leq \rho_b(t) \leq \rho^{th}, \ \forall b \in \mathbf{B}, \ \forall t \in [0,T). \end{aligned} \tag{7}$$

Note that we introduce a system load threshold ρ^{th} (≤ 1) on the system load to balance trade-offs between the system stability/reliability and the energy efficiency as shown in the constraint of the problem formulation (7). For example, with a low threshold value, BSs operate in a conservative manner with a low system load on average (i.e., large spare capacity). As a result, users would experience less delay. We can also expect less call dropping probability since the BSs become more robust to bursty traffic arrivals. On the other hand, with a high threshold value close to one (i.e., a loose threshold), more energy saving could be achieved at the cost of slight performance reduction.

Remark: At any given time instance t, the energy minimization problem in (7) becomes to determine the set of active BSs subject to the system load constraint. Note that the problem can be reduced from a vertex cover problem which is NP-complete [26]. Finding an optimal solution to this problem faces two difficulties: First, theoretically, it requires high computational complexity for finding the optimum active BS set among $2^{\lvert\mathbf{B}\rvert}$ on/off combinations, and it also needs a centralized controller which requires information from all BSs in practice. In this paper, we will deal with these two

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[3] Instead of Shannon's formula, we may use a limited set of modulation and coding scheme (MCS). However, it will not affect our final algorithms. We may also introduce the minimum SINR level to capture coverage holes.

[4] Even though we do not explicitly address here, many factors affecting the system load, e.g., channel variation (fading or dynamic inter-cell interference), user arrival/departure, and mobility [24], [25]. It is worthwhile mentioning that our final algorithms in Section III work well under such dynamics as long as BSs can measure the system load.

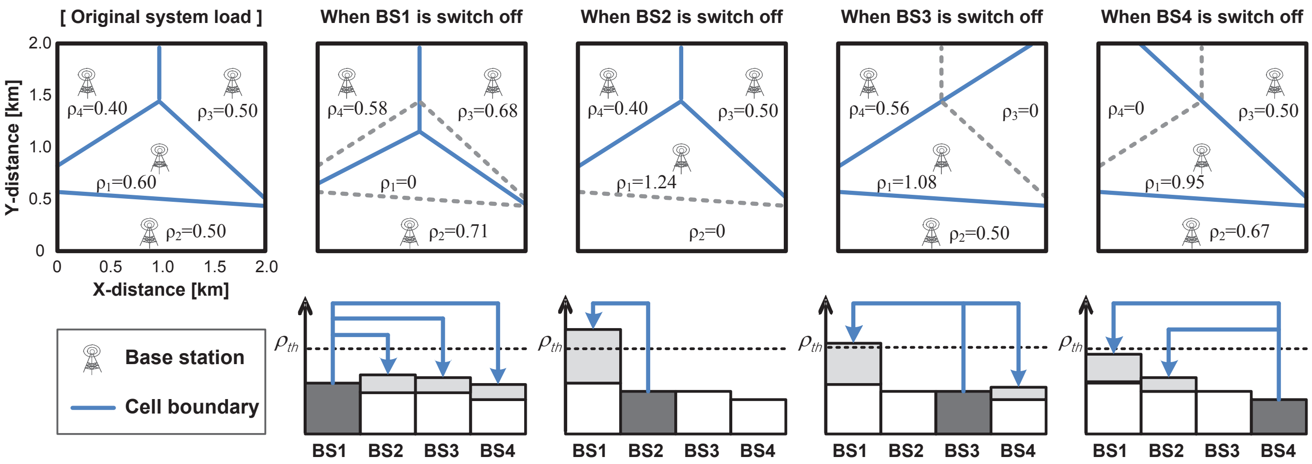

Fig. 2. An illustrative example of the effect of the system load by the switching-off BS.

difficulties, and present practically implementable distributed algorithms. To keep our notation simple, we suppress the time slot index t throughout the paper.

III. The Proposed SWES Algorithm

Since BSs are typically deployed on the basis of peak traffic volume and stayed turned-on irrespective of traffic load, it is possible to save huge energy by switching off some under-utilized BSs during off-peak times. In this section, we shall start by discussing the effect of switching off one BS. Based on the lesson learned from this simple case, we propose a sequential (continuous) algorithm, called SWES, in which BSs get turned on/off one by one while ensuring users' QoS. We also describe how the proposed algorithm can tackle with several implementation issues.

A. Design Rationale: A Notion of Network-impact

Let us consider a simple case in which one BS is turned off. Apparently, this would result in an increase in the system load of neighboring BSs. This is not only because those UEs originally associated with the switched-off need to be transferred to the neighbors, but also because they will expect lower service rates $s_b(x)$ due to farther distances between the UEs and their new serving BSs. However, on the other hand, turning off a BS may bring positive impact on the system load due to reduced inter-cell interference, in particular, some UEs originally associated with neighboring BSs will see potentially higher service rates $s_b(x)$.

In Fig. 2, we provide a pictorial example to illustrate how the traffic loads are transferred to neighboring BSs when a BS is switched off. As can be seen, when BS 1 is turned off, the total system load decreases because the effect of reduced interference is more dominant. However, in most cases such as when switching off BS 2, 3, or 4, the total system load increases.

Now let us examine the possibility whether a particular BS can be turned off or not. We define the set of neighboring BSs of BS b by $\mathbf{N}_b$, and further denote by $n \in \mathbf{N}_b$ the neighboring BS providing the best signal strength (except BS b) to the UE at the location $x \in \mathcal{A}_b$ as follows:

$$n = \arg\max_{i\in\mathbf{N}_b} g(i,x)\cdot P_b \quad \text{for } x\in\mathcal{A}_b. \tag{8}$$

Note that the BS n can be interpreted as the BS to which the traffic loads will be transferred after turning off BS b. The BS b will be able to switch off only if all its neighboring BSs satisfy the following feasibility constraint:

$$\underbrace{\int_{\mathcal{A}_n}\frac{\gamma(x)}{s_n(x)}dx}_{\rho_n} + \underbrace{\int_{\mathcal{A}_{b\to n}}\frac{\gamma(x)}{s_n(x)}dx}_{\rho_{b\to n}} \le \rho^{th}, \quad \forall n\in\mathbf{N}_b, \tag{9}$$

where $\mathcal{A}_{b\to n}$ is the coverage of UEs who will be handed over from BS b to neighboring BS n when the BS b is switched off. In (9), the original system load ρ_n is defined as the internal system load of BS n, and the system load increment by the neighboring BS's switched off $\rho_{b\to n}$ is the external system load from BS b to BS n.

In our example of Fig. 2, either BS 2 or 3 should not be switched off because that will make the system load of BS 1 to exceed the threshold by the external system load. Considering the system load of neighboring BSs after switching-off, only BSs 1 and 4 are the only possible candidate to be switched off. Taking into account that turning off BS 1 sets aside larger spare rooms (for additional traffic in the near future) than BS 4, it would be better to choose BS 1.

To quantify how the system load of network (more precisely, neighboring BSs) are affected by the switching-off process, we introduce a notion of *network-impact* taking into account the additional load increments brought into its neighboring BSs, $\rho_{b\to n}$ in addition to the original load, ρ_n, in (9). Mathematically, the network-impact for the decision of the switching-off BS b is defined by[5]

$$\textbf{SWES}_{(1,1)}: \quad F_b = \max_{n\in\mathbf{N}_b}\left(\rho_n+\rho_{b\to n}\right), \quad \forall b\in\mathbf{B}^{\text{on}}. \tag{10}$$

Here, we take the maximum over the neighboring BSs $n \in \mathbf{N}_b$ in a conservative way; since it will select the worst BS having the smallest spare room for upcoming traffic demands of future. It should be mentioned that the network-impact may

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[5] In SWES$_{(x,y)}$, the subscript indicates the usage of external and internal information, ρ_n and $\rho_{b\to n}$, for calculating the network-impact at each BS, respectively. $x = 1$ [resp. $y = 1$] represents that the external [resp. internal] information is used for calculating the network-impact, and the network-impact calculation does not use the external [resp. internal] information in order to reduce feedback burden when $x = 0$ [resp. $y = 0$]. We discuss this further in the next section.

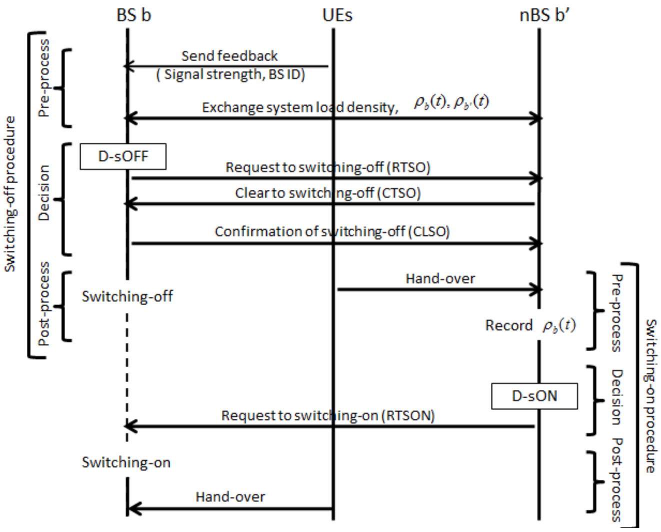

Fig. 3. Switching off/on procedures.

be modeled in other ways too, such as the average system load of neighboring BSs, $\frac{1}{|\mathbf{N}_b|}\sum_{n\in\mathbf{N}_b}\{\rho_n+\rho_{b\to n}\}$, and the increment of the overall system load, $\sum_{n\in\mathbf{N}_b}\rho_{b\to n}-\rho_b$.

Our proposed SWES algorithm switches off the BS which has the least network-impact, as follows:

$$b^* = \arg\min_{b\in\mathbf{B}^{\text{on}}} F_b. \tag{11}$$

This operation repeats until there is no active BS whose neighbors would satisfy the feasibility condition given in (9). Note that it has very low computational (linear) complexity with $|\mathbf{B}|$ sets, but requires a central controller for implementation.

Remark: The system load is a simple yet powerful metric capturing the network-impact that depends on the traffic loads as well as neighboring environment, e.g, the number of, the distance to, and the loads of the neighboring BSs. So there exist some works in literature [1], [8], [25], where the authors proposed similar forms of switching on/off algorithms based on the system load (or sometimes called the utilization) in slightly different formulations. However, our key contribution here is to focus on developing the distributed algorithm, which differentiates this paper from the existing works only proposing centralized algorithms.

B. Algorithm Description

In this section, we propose a distributed BS switching algorithm and suggest its protocol-level implementation.

1) Switching-off Algorithm: The decision criterion (i.e., network-impact) defined in (10) only depends on information for a BS and its neighboring BSs. Thus, it is possible that the switching-off decision can be localized as a problem at each BS. The proposed distributed switching-off algorithm is simple: the system information such as signal strength and system load are periodically shared among BSs and UEs, and each BS determines whether it should be turned off or not. Note that the proposed algorithm does not require the centralized controller.

The switching-off algorithm involves three parts as shown in Fig. 3.

(a) Pre-processing state: In typical cellular networks such as 3GPP(-LTE) and IEEE 802.16(e/m) [27], UEs periodically feedback information about the received signal strengths for resource management. If a BS b turns off, then users in its coverage will move the second best BS (i.e., the best BS after turning off the current serving BS b). To this end, the UE reports its second best signal strength along with the BS ID. This information is also used to calculate how much additional load increment brought to its neighboring BSs would be. As presented later, the feedback can be further reduced at the cost of slight performance loss in energy saving.

The system load is shared among neighboring BSs periodically (say, every several minutes) and/or when the abrupt system load change occurs.

(b) Decision state: Each BS first calculates the network-impact (10) based on information received from its users and neighboring BSs. Then, it determines whether or not it can be turned off as follows.

Switching-off decision

- If $F_b < \rho^{th}$, then send the request to switching-off to neighboring BSs, $\mathbf{N}_b$.

In distributed operation, it might be possible that two or more BSs with overlapping neighbors simultaneously switch off and consequently could lead to overload in the neighbors. To prevent such a confliction, each BS first broadcasts RTSO (request to switching-off) and only switches off when it receives CTSO (clear to switching-off) from all its neighboring BSs.[6] Prior to switching-off, the BS informs its neighbors of the confirmation, i.e., confirmation of switching-off (CLSO).

(c) Post-processing state: The BS b turns off only if it received CTSO from all neighboring BSs. Accordingly, UEs served by the switching-off BS are transferred to the neighboring BS who provides the second best signal strength. This is a similar procedure to the conventional hand-over except that a group of UEs should be handed over at the same time. There has been an abundant of research on the group hand-over. Most of them are targeted to support passengers on mass transportation such as buses or trains. The key of efficient group hand-over is to predict/prepare the hand-over a priori. One of the state-of-the-art group hand-over techniques such as [28], [29] could be used together with our switching off algorithm to efficiently support the group hand-over. Note that the control signaling (e.g., RTSO/CTSO and CLSO) related to the switching-off decision, may be used to trigger the group hand-over in advance.

2) Switching-on Algorithm: One way to implement the switching-on algorithm could be to reverse the switching-off algorithm. The basic concept of the switching-on algorithm is that the BS should be switched on when the system load reaches the same value that the BS was originally switched off. However, the turned-off BS cannot make a switching-on decision by itself because it does not have information about the current system load. This is why our switching-on process needs to rely on neighboring BSs. Before a BS is turned off, the BS and its neighboring BSs exchange the information about the switching-off status, i.e., RTSO and

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[6] This is similar to the classical hidden terminal problem for medium access.

TABLE II

SUMMARY OF PROPOSED SWES ALGORITHMS

Algorithm	The network-impact	External Information from neighboring BSs	Internal Information from serving UEs
$\text{SWES}_{(1,1)}$	$\max_{n\in\mathbf{N}_b}(\rho_n+\rho_{b\to n})$	Required, ρ_n	Required, $\rho_{b\to n}$
$\text{SWES}_{(1,0)}$	$\max_{n\in\mathbf{N}_b}\left(\rho_n+k\cdot\frac{\rho_b}{\lvert\mathbf{N}_b\rvert}\right)$	Required, ρ_n	Not required
$\text{SWES}_{(0,1)}$	$\max_{n\in\mathbf{N}_b}(\rho_b+\rho_{b\to n})$	Not required	Required, $\rho_{b\to n}$
$\text{SWES}_{(0,0)}$	$\left(1+k\cdot\frac{1}{\lvert\mathbf{N}_b\rvert}\right)\cdot\rho_b$	Not required	Not required

CTSO. Therefore, the neighboring BSs are known when and under what conditions (e.g., the current system load) the BS goes to turn off.

Similar to the switching-off algorithm, the switching-on algorithm also involves three parts as follows:

(a) Pre-processing state: The pre-processing state of the switching-on algorithm is operated with the post-processing state of the switching-off algorithm. Once a BS (say, BS b') receives CLSO from one of its neighbors (say, BS b), it knows that BS b will be switched off. After BS b is switched off, BS b' records own system load including the hand-over traffic from BS b.

(b) Decision state: When the system load of BS b' reaches the recorded system load when its neighboring BS b was switched off, BS b' wakes up BS b by sending the request to switching-on (RTSON). If multiple system loads have been recorded for several neighboring switched-off BSs, then the last recorded system load is considered. Therefore, the last switching-off BS is the first to be switched on. Let $\rho^{re}_{b'b}$ be the recorded system load of BS b' when BS b was switched off. The decision for the switching-on is determined as follows:

Switching-on decision

- If $\rho_{b'} > \rho^{re}_{b'b}+\epsilon$, then send the request to switching-on to the neighboring BS b which was switched off.

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where $\epsilon > 0$ is a small constant value.

(c) Post-processing state: If a BS receives RTSON, then the BS wakes up. Accordingly, UEs located in its possible serving area re-select their serving BSs (i.e., hand-over) based on the best signal strength.

Note that if the traffic pattern varies at the same rate over space, then our switching-on process is simply a reverse operation of switching-off process. So the switching-on algorithm based on the recorded system load works pretty well. When it comes to the case of traffic pattern without such a nice property, the switching order of BSs may change. Even in this scenario, it works okay but is not as much effective as the previous scenario.

C. Heuristics Considering Practical Implementation

To determine the BS switching, several feedbacks from UEs and neighboring BSs are required. As the feedback information may reduce the system performance and increase the difficulty for practical implementation, we discuss how to effectively reduce the feedback information in this section.

1) The hand-over system load: UEs basically send feedback information about the received signal strength from the served BS for adaptive modulation [27], but additional feedbacks, such as the second best signal strength and its associated BS ID, are required to calculate the hand-over system load. The additional information may increase the system burden (e.g., more than 6 bits per each channel is required for the full channel state feedback for adaptive modulation [30]).

One way to reduce the feedback is to approximate the hand-over system load as follows:

$$\rho_{b\to n}\to k\cdot\frac{\rho_b}{\lvert\mathbf{N}_b\rvert},\tag{12}$$

where k is the compensation factor which depends on the deployment of the BS and neighboring BSs. When the network is assumed to have a homogeneous deployment such as ideal hexagonal cellular networks, the factor is estimated as one. Based on the approximation of (12), the network-impact to decide the switching-off BS can be modified as

$$\textbf{SWES}_{(1,0)}\textbf{:}\quad F_b=\max_{n\in\mathbf{N}_b}\left(\rho_n+k\cdot\frac{\rho_b}{\lvert\mathbf{N}_b\rvert}\right),\quad\forall b\in\mathbf{B}^{\text{on}}.\tag{13}$$

2) The system load of neighboring BSs: Compared to the hand-over system load, the amount of feedback for the system load among BSs is not a main problem as it could be exchanged via high-speed wired backhaul. However, it might increase the system burden to implement such a message exchange in practice. So we also propose a way of reducing this overhead by simply predicting the system load of neighboring BSs as follows:

$$\rho_n\to\rho_b.\tag{14}$$

This approximation holds when the traffic loads are homogeneously distributed. It may not hold for the case of the inhomogeneous traffic loads; however, the error will be small because users' traffic patterns are likely to change continuously rather than abruptly in a spatial domain. Using this, the network-impact for decision the switching-off BS can be rewritten as:

$$\textbf{SWES}_{(0,1)}\textbf{:}\quad F_b=\max_{n\in\mathbf{N}_b}(\rho_b+\rho_{b\to n}),\quad\forall b\in\mathbf{B}^{\text{on}}.\tag{15}$$

Combining the approximations in (12) and (14) together, the network-impact can be calculated without information feedback as follows:

$$\textbf{SWES}_{(0,0)}\textbf{:}\quad F_b=\left(1+k\cdot\frac{1}{\lvert\mathbf{N}_b\rvert}\right)\cdot\rho_b,\quad\forall b\in\mathbf{B}^{\text{on}}.\tag{16}$$

It should be mentioned that the simplest heuristic algorithm, SWES$_{(0,0)}$, is exactly the same as the one proposed in our own prior work [1].

Our proposed SWES algorithms are summarized in Table II. As discussed earlier, the required information is different depending on which network-impact is used to determine the switching-off BS. In practice, the operators can choose one of the algorithms taking into account their infrastructure condition (e.g., wired BS-BS connection and wireless BS-UE connection) and system performance (e.g., feedback burden and loss in data rate).

D. Other Implementation Issues

There are several other issues for practical implementation. In our algorithms, the switching-off BS and its neighboring BSs exchange the message such as RTSO, CTSO and CLSO. This message exchange can prevent the possibility that multiple BSs which have same neighboring BS are switched off at the same time for guaranteeing the QoS of the neighboring BS. However, with a synchronous operation where these messages can be exchanged at the same time, the SWES algorithms might operate inefficiently. For example, BSs A and B send RTSO to the same neighboring BS C simultaneously, and BS C responses CTSO to BS B. But, suppose that BS B will be not switched off by the other neighboring BS of BS B which is not connected with BS A (say, BS D). In this case, both BSs A and B cannot be switched off. To mitigate this problem, we assume the network operates asynchronously. For implementing the algorithms with a synchronous operation, additional processes to prevent the collision of message exchange are required such as RTSO with waiting (e.g., BSs A and B send RTSO with random waiting time) or multi-step CTSO (e.g., BS D responses CTSO to BS A when CLSO from BS B is not reached until random waiting time) similarly with classical solutions for mitigating the collision at the protocol design site [31].

Another issue arises from the system load that is likely to fluctuate. Due to the high variation of the system load, BSs might repeat switching off and on in an inefficient way, similar to the ping-pong effect [32] in hand-over. To resolve this problem, we introduce a hysteresis margin Δ_h for practical implementation. The system load threshold for the switching off and on BS can respectively be rewritten as,

$$\begin{cases} \rho^{th} \rightarrow \rho^{th} - \Delta_h/2 & \text{for the switching-off} \\ \rho_{ji}^{re} \rightarrow \rho_{ji}^{re} + \Delta_h/2 & \text{for the switching-on.} \end{cases} \qquad (17)$$

While the decision strategy with the hysteresis margin decreases the amount of energy saving by the low system load threshold, it may reduce the inefficient switching off and on. Therefore, the tradeoff between the inefficient switching and the energy saving should be considered to determine an appropriate hysteresis margin.

IV. FIRST-ORDER ANALYSIS

The analysis for the amount of energy saving is challenging because the required parameters for analysis such as the BS deployment are dynamically changing during the switching process. In this section, we develop a rough first-order analysis under the simple BS switching strategy, i.e., SWES$_{(0,0)}$, which gives an insight into key factors affecting the energy saving.

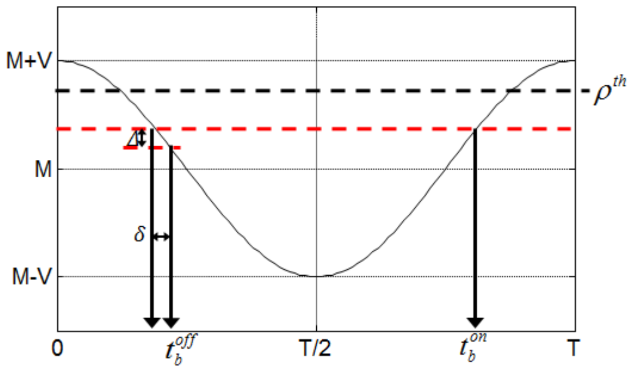


Fig. 4. First-order cell load modeling: $\rho(t) = V \cdot \cos(2\pi t/T) + M$ with mean M and variance V.

Let us define the energy saving ratio as

$$S = 1 - \frac{\sum_{b\in\mathbf{B}} \int_0^T a_b(t)dt}{|\mathbf{B}| \cdot T}, \qquad (18)$$

where $|\mathbf{B}|$ is the total number of BSs in networks. The second term of the right part means the average BS switching-on duration. The energy saving ratio in (18) represents how long BSs are switched-off during time T (i.e., one day), thus it can be rewritten as the time duration,

$$S = \frac{1}{T} \cdot \left[t_b^{on} - t_b^{off} \right], \qquad (19)$$

where t_b^{on} and t_b^{off} are the switching-on time and the switching-off time of the ordinary BS b, respectively [1]. Assuming the traffic profile is sinusoidal as shown in Fig. 4, (19) can be rewritten as follows:

$$S = \frac{1}{T} \cdot \left[2 \cdot t_b^{on} - T - \delta \right], \qquad (20)$$

where δ is the time gap with $(1 - k/|\mathbf{N}_b|)$ at the BS switching-off strategy. If the number of neighboring BS is increasing, the value is decreased.

From the observation that the peak traffic load occurs at time t_b^{on} during the switching-off period, we can obtain the equation to maximize the energy saving while satisfying the QoS constraint,

$$\rho(t_b^{on}) \cdot \left(1 + E\left\{k/|\mathbf{N_b}|\right\}\right) = \rho^{th}. \qquad (21)$$

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

$$t_b^{on} = T - \frac{T}{2\pi} acos\left(\frac{\frac{1}{V} \cdot \rho^{th} - \frac{M}{V}(1+X)}{1+X} \right), \qquad (22)$$

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

Substituting (22) into (20), the energy saving ratio is expressed as

$$S = 1 - \frac{1}{\pi} acos\left(\frac{\frac{1}{V} \cdot \rho^{th} - \frac{M}{V}(1+X)}{1+X} \right) - \frac{\delta}{T}. \qquad (23)$$

To clarify the expression, we apply the Taylor series expansion

$$\begin{aligned} S &= 1 - \frac{1}{\pi}\left\{\frac{\pi}{2} - \frac{\frac{1}{V}\cdot\rho^{th} - \frac{M}{V}(1+X)}{1+X} - \cdots\right\} - \frac{\delta}{T} \\ &\approx \frac{1}{2} + \frac{1}{\pi}\frac{\frac{1}{V}\cdot\rho^{th} - \frac{M}{V}(1+X)}{1+X} - \frac{\delta}{T}. \end{aligned} \tag{24}$$

The energy saving ratio is the function of the traffic parameters such as M and V, and the number of neighboring BS, $|\mathbf{N}_b|$ because δ is also the function of $|\mathbf{N}_b|$. From (24), the large energy saving is expected when the traffic parameters have low values and the number of neighboring BS is large. For example, much energy savings are likely to be realized in urban commercial areas during the nighttime at weekend.

Note that, despite the simplification, the calculation of the amount of energy saving (24) is challenging because there are a couple of unknown parameters δ and X dynamically changing during the BS switching process. In addition, there is a gap between the real-world traffic profile and ideal sinusoidal signal that we assumed in our analysis. For example, as shown in Fig. 1, the shape of traffic profile on weekday is broader than that of the sinusoidal signal, and has sharper on weekend. Our first-order analysis could establish a simple relationship between the amount of energy saving and some factors such as traffic profile and BS deployment. However, a more thorough analysis, which can consider the dynamics of the BS switching process and the characteristics of the real environment, remains still open.

V. NUMERICAL ANALYSIS

For our simulations, we consider a real 3G network topology consisting of 18 BSs in the area of $5 \times 5\text{km}^2$, which is a part of the topology considered in Fig 6. of [33]. We also adopt the wrap-around technique to avoid edge effects [34]. A traffic load is assumed to be spatially homogeneous and varies by scaling the traffic arrival rate. With the increasing of traffic arrival rate, if the system load for any BS reaches ρ^{th}, then we treat this point as *relative system load* = 1. In our simulation, the threshold value ρ^{th} for the proposed SWES algorithms is set at 0.6 considering the system reliability. In order to apply the real traffic profile in Fig. 1 to our simulation, the traffic load at peak traffic time is normalized as the relative system load is equal to one. We used the typical values of transmission power and operational energy for BS per unit time given in [13], i.e., P_i = 20W and E_{BS} = 865W, respectively. The other parameters for our simulations including the channel propagation model and BS characteristics follow the suggestions in the IEEE 802.16m evaluation methodology document as urban macro model (e.g., the modified COST 231 Hata path-loss model) [34].

A. Energy Saving by the SWES Algorithm

Fig. 5 shows the amount of energy savings for different algorithms under synthetic traffic profiles, i.e., varying the relative system load from zero to one. We also include the performance of optimal exhaustive search as a reference. As can be seen in Fig. 5, the lower relative system load are, the higher energy savings can be expected.

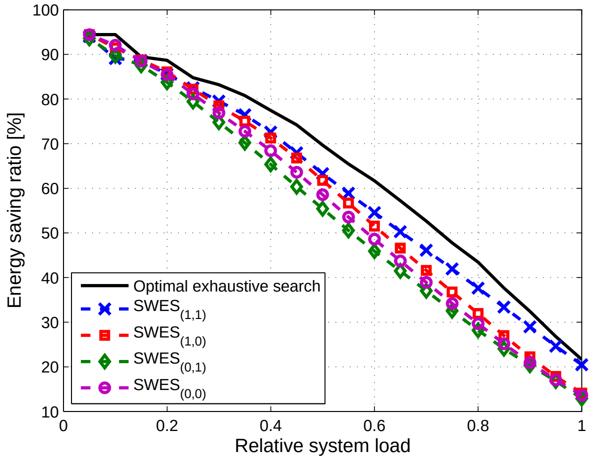
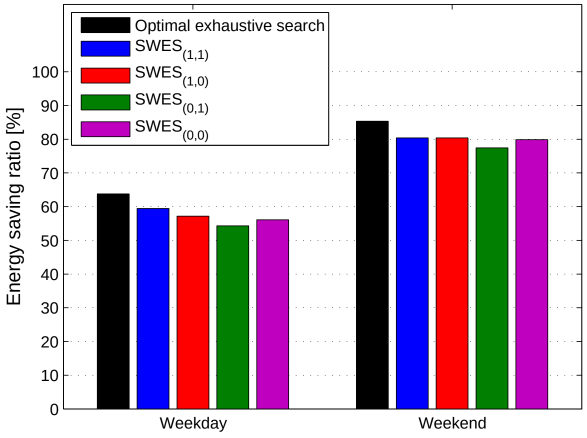
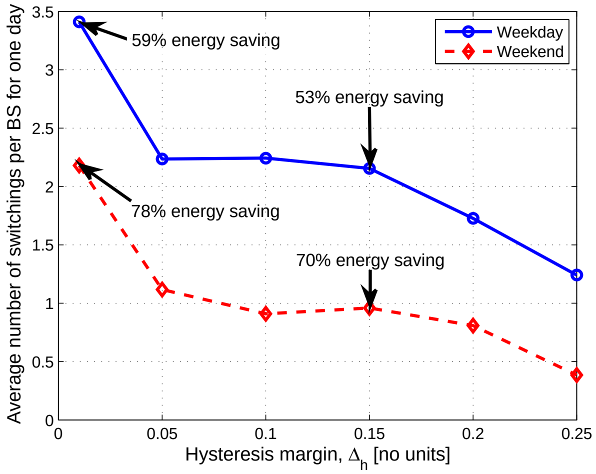


Fig. 5. Comparison of energy saving of SWESs using synthetic traffic profile.



(a) Energy saving ratio on weekday and weekend



(b) Effect of hysteresis margin

Fig. 6. Comparison of energy saving of SWESs using real traffic profile.

Compared to the energy consumption of the optimal exhaustive search, SWES$_{(1,1)}$ with full feedback information consumes at most 8% more energy for all the system load than the optimal algorithm. It is noteworthy that such a simple distributed algorithm with linear complexity can obtain

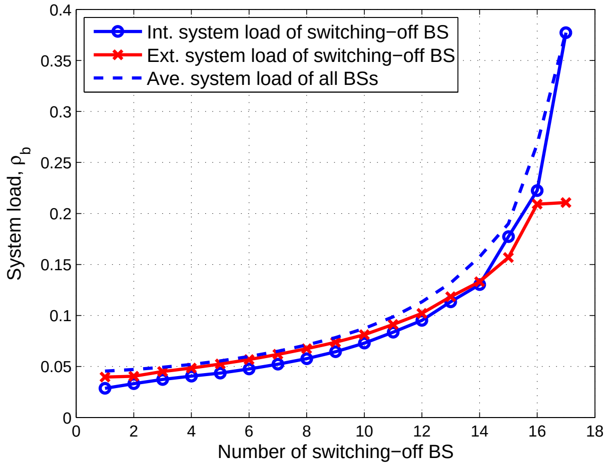
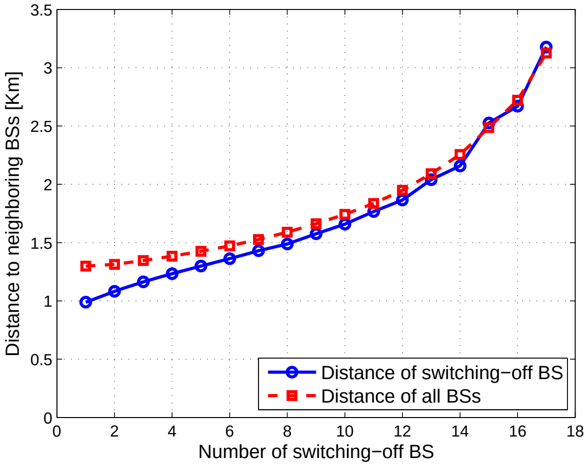


Fig. 7. Change of the average system load through the switching-off process for SWES$_{(1,1)}$.

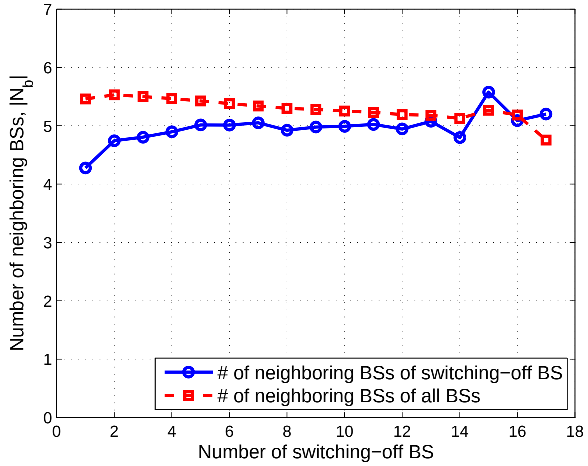
a similar performance to the centralized optimal algorithm that exhaustively searches the 2^{18} number of all on/off BS combinations. The other proposed algorithms with the partial feedback perform well when the relative system load is small; however, the performance gaps to the optimum become large, especially when the relative system load is close to 1. Their trends are almost similar and there are about 4-5% of performance gaps between SWES$_{(0,1)}$, SWES$_{(1,0)}$ and SWES$_{(0,0)}$. The compensation factor k is required for SWES$_{(1,0)}$ and SWES$_{(0,0)}$ algorithms to capture the effect of the signal strength degradation when traffic loads are transferred from the switched-off BS to neighboring BSs. For our simulation, we simply assume that the compensation factor is equal to one. If a more accurate method to estimate k is available, we may be able to further improve the performance.

Now let us consider a real traffic profile given in Fig. 1 to have more realistic results. Fig. 6(a) shows the amount of energy savings during one day under the real traffic profile when hysteresis margin is zero. As can be seen, large energy savings are expected, e.g, about 55% and 80% of reduction during weekday and weekend, respectively. Moreover, the performance gap between proposed SWES algorithms and the optimal exhaustive search is less than 10%. This is because for a significant portion of time the traffic load during one day is low (Based on the traffic load profiles in Fig. 1, the time portion when the traffic is below 10% of peak during the day is about 30% in weekdays and about 43% in weekends, respectively [20].) and the performance gap for such periods is relatively small, according to Fig. 5.

The effect of hysteresis margin is also investigated for SWES$_{(1,1)}$ in Fig. 6(b). As the hysteresis margin Δ_h increases from 0.01 to 0.25, we can prevent BSs from switching on/off too frequently due to the high variation of the system load over time. However, this leads to a small loss in energy saving. Therefore, it is important for system designers to choose an appropriate hysteresis margin to result in a good tradeoff between energy saving and system stability.



(a) Average distance from a BS to its neighboring BSs.



(b) Average number of neighboring BSs of the switching-off BS and that of all BSs

Fig. 8. Change of BS topology characteristics through the switching-off process for SWES$_{(1,1)}$.

B. Characteristics of the SWES Algorithm

The amount of energy saving of SWES is tightly related to the system load, which depends on the internal system load, the external system load, and the other environments between them such as the number of neighboring BSs and the distance among BSs. Figs. 7 and 8 show some trends of several important parameters as the switching-off process[7] goes on. Starting at the very low system load (=0.04), BSs are turned off one by one by the SWES algorithm.

Fig. 7 illustrates three average system loads through the switching-off process, where Int. and Ext. system loads of switching-off BS represent the average system load of the switching-off BS and its neighboring BSs, respectively. And Ave. system load depicts the average system load of all BSs in the network. The average system load of the switching-off BS and its neighboring BSs have lower values than that of all BSs. It means that a BS with the low internal and external system load is switched off earlier because the network is

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[7] Here we plot the results only for SWES$_{(1,1)}$, but the other results also show similar trends.

less impacted by the BS's switching-off than the other BSs' switching-off. The average system load of the switching-off BS is slightly lower than that of its neighboring BSs at the initial switching process, but the opposite results is shown at the end of the process. This implies that in the low system load region the internal factor of the switching-off BS has more network impact while the external factor by neighboring BSs becomes important in the high system load region.

Figs. 8(a) and 8(b) show (a) the average distance from a BS to its neighboring BSs and (b) the average number of neighboring BSs, respectively, which can express the relationship between the operation of switching-off algorithm and the BS topology. In both figures, we plot the average distance/number for the switching-off BS and all BSs. The average distance from the BS to neighboring BSs monotonically increases because the density of active BSs decreases. In particular, the average distance of the switching-off BS to its neighboring BSs has lower values than that of all BSs, which can be interpreted as follows: the switching-off BS in the high BS density area has less impact to the network than that in the low BS density area. On the other hand, however, the average number of neighboring BSs remains almost the same (e.g., the variance is less than one) through the switching-off process. This is because the coverage of each BS increases even if the BS density is reduced. The average number for the switching-off BS is slightly lower than that of all BSs since the system load of the BS increases due to interference from the neighboring BSs as the number of neighboring BSs increases. In brief, the distance between BSs is more dominant factor than the number of neighboring BSs in designing the network-impact for the BS switching.

VI. CONCLUSION

In this paper, we focused on the problem of BS switching for energy savings in wireless cellular networks. In particular, we suggested a design principle based on the newly introduced concept of network-impact. Taking into account the implementation difficulty, the computational complexity and the amount of feedback information problems, we proposed several SWES algorithms. Furthermore, our proposed algorithms are designed to be online distributed algorithms that could be operated without any centralized controller. Finally, 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 deployment. We empirically showed that the proposed simple algorithms can not only perform close to the optimal exhaustive algorithm but also can achieve significant energy savings up to 80%.

VII. FUTURE WORK

Although recent papers have started to investigate the green cellular operation issue, we are still at an early stage of this research. Therefore, we would like to encourage the community to give it greater attention by addressing several extensions and open problems for future study.

- One possible extension is to consider more realistic power consumption model for BS that depends on its utilization, instead of fixed power consumption model used in most of previous work, including this paper as well. For example, in another study [25], we introduced a model that can capture both utilization proportional power consumption and fixed standby power consumption.
- Another extension can be to consider heterogeneous networks, consisting of different types of BSs, such as macro, micro, femto BSs and even WiFi APs, which may have different transmission powers (related to coverage and capacity) as well as total operational powers and even work at different frequency bands. In such heterogeneous networks, it becomes more technically challenging to make an entire system operating energy-efficiently because the degree of controllability increases.
- Although we only focus on downlink communication in this paper, some aspects of our work can be applied to the uplink as well. Nevertheless, it would be interesting to develop a dynamic BS switching algorithm that considers downlink and uplink traffics jointly.
- This paper considered a simple signal strength based BS association; however, it must be coupled with turning on/off of BSs. Note that an association scheme concentrating traffic loads to a subset of BSs rather than distributing them among all the BSs (i.e., the most of conventional association schemes) may bring potential gains because it could allow us turn off the other BSs.

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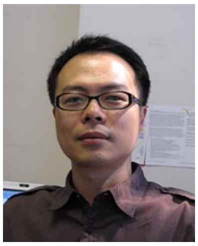

Eunsung Oh (S’03-M’09) Eunsung Oh received his B.S., M.S. and Ph.D. degrees in Electrical Engineering at Yonsei University, Seoul, Korea, in 2003, 2006 and 2009, respectively. From 2009 to 2011, he was a post-doctoral researcher in the Department of Electrical Engineering at the University of Southern California’s Viterbi School of Engineering. From 2011 to 2012, he was a senior researcher at Korea Institute of Energy Technology Evaluation and Planning, Korea. From 2012 to 2013, he was a research professor in the Department of Electrical Engineering at Konkuk University, Korea. He is currently a assistant professor in the Department of Electrical and Computer Engineering at Hanseo University, Korea. His main research interests include the design and analysis of algorithms for green communication networks and smart grid.

Kyuho Son (S’03-M’10) Kyuho Son received his B.S., M.S. and Ph.D. degrees all in the Department of Electrical Engineering from Korea Advanced Institute of Science and Technology (KAIST), Daejeon, Korea, in 2002, 2004 and 2010, respectively. From 2004 to 2005, he was a visiting researcher at Wireless Networking and Communication Group in the Department of Electrical and Computer Engineering at the University of Texas at Austin. From 2010 to 2012, he was a post-doctoral research associate in the Department of Electrical Engineering at the University of Southern California, CA. He is currently a senior engineer at T-Mobile, USA. His current research interests lie in the design, analysis and optimization of green networks and smart grid, with a focus on energy-efficiency and renewable energy. He is a founding member of TSGCC (Technical Subcommittee of Green Communications and Computing) within IEEE Communications Society.

Bhaskar Krishnamachari Bhaskar Krishnamachari received his B.E. in Electrical Engineering at The Cooper Union, New York, in 1998, and his M.S. and Ph.D. degrees from Cornell University in 1999 and 2002 respectively. He is currently an Associate Professor and a Ming Hsieh Faculty Fellow in the Department of Electrical Engineering at the University of Southern California’s Viterbi School of Engineering. His primary research interest is in the design and analysis of algorithms and protocols for next-generation wireless networks.