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Energy Savings Using an Adaptive Base Station to Relay Station Switching Paradigm

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Abstract—Applying a Base Station (BS) sleep approach during low traffic periods has recently been advocated as a strategy for reducing energy consumption in cellular networks. The complete switching off of certain BS however, can lead to coverage holes and severe performance degradation in terms of off-cell user throughput, greater transmit power dissipation in both the up and downlinks, and more complex interference management. This paper presents a novel cellular network energy saving model in which certain BS rather being turned off are switched to Relay Station (RS) mode during low traffic periods. The switched RS and other shared RS deployed at the cross border of each cell are responsible for upholding the same *quality of service* (QoS) provision as when all BS are active. A centralised adaptive switching threshold algorithm is also introduced to undertake the switching decision, instead of using a fixed threshold. Simulation results confirm the new *BS-RS Switching* model using an adaptive threshold can reduce network energy consumption by more than half, as well as improving off-cell users' throughput.

I. INTRODUCTION

Despite cellular networks being one of the most fertile wireless communication areas, major concerns persist about the rapidly rising energy costs and inexorable growth in energy consumption, which have far exceeded predictions¹. The rise in wireless network energy consumption is reflected by increasing greenhouse gas emissions, which has been recognized as a serious threat to both environmental protection and sustainable development. The escalation of energy costs and growth in communications usage creates an urgent need to address the development of energy efficient communications. The cellular network is the largest factor contributing to the mobile industry's environmental impact with the emissions from the telecommunications business sector estimated at between 0.5% and 1% of the entire worlds carbon footprint [1].

In current cellular networks, *base stations* (BS) essentially operate in a 24 hours/7 day "always-on" mode, and are generally designed based on cell peak traffic loads, irrespective of either the time of day or traffic profile. Statistical results of energy consumption in cellular networks show that traffic load of cells during a day varies significantly both in the spatial and temporal domains [2], whereas BS are responsible for most of the energy consumption, ranging from 60% to 80% of the whole network energy consumption [3]. Due to the

significant spatial and temporal fluctuations of the traffic profile and "always-on" mode of BS operations, techniques to reduce energy consumption in network operation by either powering down or putting the BS to sleep during low traffic periods have been proposed in the literature [3]–[8]. BS sleeping techniques are only really feasible in cellular networks, however, if the neighboring BS are able to guarantee the service coverage of the cell that is put to sleep without degrading the *quality of service* (QoS) of the network.

In [9], [10], coordinated multi-point (CoMP) transmission has been used to improve network throughput while guaranteeing the service area. In [10], [11], *relay stations* (RS) have been deployed at the edge of cells for energy efficiency benefit. In [12], the authors proved that neighboring cells in BS sleep mode are unable to guarantee the service coverage area of switched-off cell even by increasing the transmit power without generating significant interference to neighboring cells. Indeed, they analyzed whether BS sleeping was in fact, a viable operational strategy for a number of key factors, including the ability to uphold BS synchronization i.e., CDMA2000, the possible inability to quickly power up/down equipment, and fulfilling government regulatory requirements such as E-911 localization [12]. In [13], three dimming techniques (coverage, frequency and service) have been proposed as an alternative to turning off a BS to conserve energy. Coverage and service dimming may not be a viable solution due to coverage gaps and the violation of "anywhere anytime" communication property which is essential in future generation mobile networks. Moreover, service degradation for energy saving is unacceptable in terms of emergency service provision. This is why cellular networks are designed based on it's peak traffic load although the peak load period is only a portion of whole day [2]. In considering the coverage problem in BS sleeping approaches as well as guaranteeing the same QoS as in normal BS mode, this paper introduces an energy efficient adaptive *BS-RS Switching* cellular network model where certain BS instead of being turned off, are adaptively switched to low-powered RS mode during low traffic period [14]. The rationale for switching from a BS to RS mode is to ensure the *mobile station* (MS) that would be served by sleep BS, are still be able to receive the same level of QoS. Six other RS are deployed at the edge of each cell to both improve cell edge user throughput and support

¹Gartner Inc. Research, 2011.

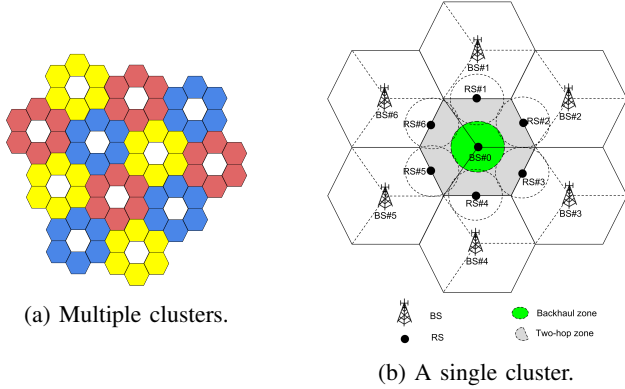


Fig. 1: An example of considered network model. The center BS is switched to relay mode that serves users in the green area and users in the gray zone in the off-cell are served by RS deployed at the edge of the cell.

coverage extension during any BS switched to RS mode. In previous BS sleeping solutions [2], [5], [7], [9], [10] and *BS-RS Switching* solution [14], the switching has been performed using a fixed traffic threshold. While this provides improved energy efficiency, it is neither traffic proportional nor does it fully exploit the potential energy savings. The proposed model presented in this paper together with the adaptive switching threshold algorithm can provide higher off-cell user throughput while reducing the network energy consumption by over 53%.

The remainder of the paper is organized as follows. In Section II, the *BS-RS Switching* model is formally introduced. In addition, both the relay selection and transmission strategies, and power consumption models are considered together with formulating the problem design. In Section III, the proposed centralized adaptive switching threshold algorithm is presented. Section IV provides an analysis of the energy saving simulation results using the proposed energy minimization strategy, while Section V provides some concluding comments.

II. SYSTEM MODEL

The network model is assumed to comprise a clustering arrangement illustrated in Fig. 1(a). Each cluster has a 7-hexagonal cell configuration (see Fig. 1(b)), with every cell of radius R . The BS is located at the center of a cell and $(N_{RS} - 1)$ RS are deployed at the edge of a cell at a distance $\sqrt{3}R/2$ from the center BS with two RS per sector, as shown in Fig. 1(b). Each RS is associated two adjacent BS whose edge the RS belongs to, so-called *shared-RS*. Assume that RS can work as either in-band or out-band relay mode. Neighboring BS will allocate frequency either in-band or out-band based on MS locations which we assume, are already known to the neighboring BS by means of pilot signal. MS located within its original coverage range are allocated to in-band while those MS located in the off-cell area are allocated to out-band frequency. The out-band frequency is the frequency globally assigned for the off-cell BS corresponding to the associated sector. Since this

model does not need to increase transmit power for coverage extension, this location based frequency allocation maintains the same interference level as would be provided when all BS are active.

Links between either RS and its serving BS are referred to as relay links i.e. BS-RS link, and links between RS and MS are referred to as access links. Relay links are considered as line of sight (LOS) as heights of BS and RS can reasonably be assumed to be high. MS are placed independently with uniform distribution throughout each cell. Each MS is associated with either a BS or a RS to which it receives the largest value of pilot signal strength based on long-term channel quality measurement.

In each cluster, the center BS can only be in sleep mode during its off-peak period, but switched to low-powered relay (RS) mode, so-called *switched-RS*. The remaining $(N_{BS} - 1)$ active neighboring BS in the cluster serve all the users within the off-cell area being assisted by both the *shared-RS* and *switched-RS*. The relay link between the BS and *shared-RS* is considered as wireless while the link between the BS and *switched-RS* is considered as a dedicated back-haul connection (possibly fast fibre connections) to which all BS are interconnected. The *switched-RS* is always off unless the corresponding BS goes into sleep mode. This implies the BS and the center (switched) RS will always operate in opposite modes, so if a center BS is active, then the RS will be in sleep mode and vice-versa. The coverage radius of each RS is assumed to be $R/2$ such that an entire cell can be covered with RS deployed as in Fig. 1(b).

A. Relay Selection and Transmission Strategies

The RS assists in communications between BS and MS by either *amplify-and-forwarding* (AF) or *decode-and-forwarding* (DF) the received signal. For relay transmission, the DF relay mode was applied which consists of two transmission phases/two time-slots. In the first phase, RS decodes its received signal whereas it re-encodes the decoded data and then transmits it in the second phase. Because we are considering the RS that can serve only off-cell when the center BS is switched to RS mode and the distance between BS and MS will be long, so it is assumed there is no direct path between the BS and off-cell MS. Moreover, for the *switched-RS*, the received signal over the dedicated connection is modulated and transmitted to off-cell MS located in the green zone only (see Fig. 1(b)), so this relay transmission is considered as a direct transmission. Each off-cell MS is served by a BS via a RS, which is associated to only one fixed BS (for example, $RS_1 \rightarrow BS_1$, $RS_2 \rightarrow BS_2$ and so on, as shown in Fig. 1(b)). The selection criteria for an off-cell MS to choose a RS is dependent upon the location of the MS, i.e., an off-cell MS chooses a RS a minimum distance-dependant path-loss.

If it is assumed that each cell has N_U users, then $(N_{BS} - 1)$ active BS need to jointly serve all $(N_U \cdot N_{BS})$ users within each cluster provided there are similar traffic intensities in all cells. Therefore, each BS will have to serve no more than $N_U / (N_{BS} - 1)$ handed over users via the RS, together

with its N_U users. If direct transmission is adopted, the transmit power $P_i^{(b)}$ from the BS b that guarantees a given minimum data rate r_i for user i must satisfy the rate equation, $r_i = W \log_2 \left(1 + \frac{\eta_0 P_i^{(b)} 10^{\xi_i/10}}{d_i^\alpha} \right)$, $\forall i = 1, 2, \dots, N_U$. We then have:

$$P_i^{(b)} = \frac{(2^{r_i/W} - 1) d_i^\alpha}{\eta_0 10^{\xi_i/10}} \quad (1)$$

where $\eta_0 = \frac{G_0}{N_0}$ includes the effect of the antenna gain G_0 and thermal noise N_0 . The signal attenuation at the distance d_i is given by $d_i^{-\alpha}$ where α is the path-loss exponent, and the shadow fading $10^{\xi_i/10}$ follows a lognormal distribution $\xi_i \sim N(0, \sigma^2)$. Assuming that the shadow fading is independent from each BS, then ξ_i are independent and identical distributed (i.i.d.). W is the channel bandwidth. When a BS b serves a MS i via a RS j associated to it with adopting DF relaying, the BS b transmit power, $P_j^{(br)}$ is then:

$$P_j^{(br)} = \frac{(2^{2r_i/W} - 1) d_j^\alpha}{\eta_1 10^{\xi_j/10}} \quad (2)$$

And the RS transmission power, $P_i^{(r)}$ is:

$$P_i^{(r)} = \frac{(2^{2r_i/W} - 1) d_{ji}^\alpha}{\eta_2 10^{\xi_i/10}} \quad (3)$$

where d_j and d_{ji} are distances from BS b to RS j in the first transmission phase and from RS j to MS i in the second transmission phase, respectively. η_1 and η_2 are defined similar to η_0 corresponding to the relay and access link, respectively. It needs to be noted that half-duplex relaying requires two time slots, so the rate for each hop is $2r_i$.

B. Power Model and Problem Formulation

A typical cellular network comprises three main elements: the core network, BS and MS. The BS consumes by far the most energy, as it includes operational units such as power amplifiers, baseband units, feeder networks and site cooling systems. The general relationship between the average total power consumption and the average radiated BS power can be expressed as [4]:

$$P_T = a_m \cdot P_t + P_f \quad (4)$$

where P_T and P_t respectively denote the average total consumed and transmission power, while a_m is a power scaling factor which reflects both amplifier and feeder losses. P_f models the fixed power components due to site cooling, signal processing hardware and battery backup systems, which is independent of the transmit power. The two power model parameters a_m and P_f in (4) are also dependent on the operating mode i.e., either BS (a_{bs} and P_f^{BS}) or RS (a_{rs} and P_f^{RS}) modes, where $a_{bs} > a_{rs}$ and $P_f^{BS} > P_f^{RS}$ [11]. The power consumption model for the seven-cell network with RS can be expressed as:

$$P_T = N_{BS}(a_{bs}P_t^{BS} + P_f^{BS}) + N_{RS}(a_{rs}P_t^{RS} + P_f^{RS}) \quad (5)$$

where N_{BS} and N_{RS} are the number of BS and RS including the center BS and *switched-RS*, respectively. Since RS also consumes a part of the total energy consumption, we replace a_{rs} and P_f^{RS} with ga_{bs} and gP_f^{BS} to influence the power consumption of RS in the proposed model. The factor g is the ratio of RS and BS energy consumption to reflect the actual cost of using the RS. So:

$$P_T = (N_{BS} + gN_{RS})P_f^{BS} + N_{BS}a_{bs}P_t^{BS} + N_{RS}ga_{bs}P_t^{RS} \quad (6)$$

Assume there are $(N_{BS} - 1)$ neighboring active BS that will always be active and $(N_{RS} - 1)$ RS (at the edge of the center cell) that are also active all the time. Let A_b and A_r denote the operation modes of all BS and RS (including the center BS and the *switched-RS*), respectively, where $A_b = 1$ and $A_r = 1$ for $b = 1, 2, \dots, N_{BS} - 1$ and $r = 1, 2, \dots, N_{RS} - 1$ whereas $A_{N_{BS}}, A_{N_{RS}} \in \{0, 1\}$ and $A_{N_{BS}} + A_{N_{RS}} = 1$ for the center (N_{BS} -th) BS and the switched (N_{RS} -th) RS. Also, let $m_b(t)$ denote the number of users served by a BS of which $m_r(t)$ users are served via a RS at time t . From(5), the energy savings problem of the *BS-RS Switching* technique that minimizes the network energy consumption with the minimum data rate and transmit power constraints can be formulated as:

$$\begin{aligned} \min_{A_{N_{BS}}, A_{N_{RS}}} P_T = & \sum_{b=1}^{N_{BS}} A_b(t)(a_{bs}P_t^{BS} + P_f^{BS}) \\ & + \sum_{r=1}^{N_{RS}} A_r(t)(a_{rs}P_t^{RS} + P_f^{RS}) \end{aligned} \quad (7)$$

$$s. t. \quad r_i \geq r_{min}, \quad \forall i = 1, 2, \dots, m_b(t),$$

$$\sum_i^{m_b(t)} P_i^{BS(b)} = P_t^{BS(b)} \leq P_{max}^{BS}, \quad \forall b = 1, 2, \dots, N_{BS},$$

$$\sum_j^{m_r(t)} P_j^{RS(r)} = P_t^{RS(r)} \leq P_{max}^{RS}, \quad \forall r = 1, 2, \dots, N_{RS},$$

$$A_b = 1 \text{ for } b = 1, 2, \dots, N_{BS} - 1,$$

$$A_r = 1 \text{ for } r = 1, 2, \dots, N_{RS} - 1,$$

$$\text{and } A_{N_{BS}}, A_{N_{RS}} \in \{0, 1\}, \quad A_{N_{BS}} + A_{N_{RS}} = 1,$$

where $P_t^{BS(b)}$, P_{max}^{BS} , $P_t^{RS(r)}$ and P_{max}^{RS} denote the total and maximum transmission powers of the BS b and RS r , respectively. r_i is the data rate of the i^{th} user and r_{min} is the minimum data rate requirement. The problem in (7) is a mixed integer linear programming problem, which is generally NP-hard. The optimal solution to (7) can be obtained by an exhaustive search, though this is computationally intensive. Thus, in the new *BS-RS Switching* model, the switching decision is made at fixed time intervals of period T_0 , based on the traffic variation between consecutive periods. The following section will present and analyze the adaptive *BS-RS Switching* algorithm under varied traffic loads. Once the *BS-RS Switching* decision has been made based on the proposed algorithm in

the following section, the problem in (7) becomes a linear programming problem, whose optimal result can be determined in linear calculation time.

III. ADAPTIVE *BS-RS Switching* STRATEGY

Existing BS switching techniques such as [2], [3], [5], [7], [9], [10] and [14] often use a fixed traffic threshold, which may not necessarily be optimal in terms of exploiting the available resources of neighboring BS. Intuitively, a higher switching threshold while maintaining the requisite QoS affords a longer interval for the BS to stay in either RS or sleep mode, thereby providing lower power operation and enhanced network energy savings. Moreover, the fixed switching threshold strategy to switch a BS to RS mode can not change to higher value even if neighboring BS are able to handle more traffic. Due to the inherent asymmetric traffic profile amongst BS, distribution of off-cell traffic to neighboring BS will not be uniform, so it is necessary to have an adaptive switching threshold. A novel adaptive BS switching strategy is proposed to dynamically find the best switching threshold and to distribute the handed-over traffic among neighboring active BS based on their current traffic load in a centralised manner. Let $\rho_b(t)$ be the traffic load of BS b at time t , where $\rho_{N_{BS}}(t)$ is the traffic load of the center BS. The center BS can switch its operation mode to RS mode only if the remaining $(N_{BS} - 1)$ BS are able to handle the center BS's traffic load $\rho_{N_{BS}}(t)$, being assisted by both the *shared* and *switched-RS*, with in this model, only the center BS being allowed to switch. Assume $\rho'_b(t)$ is the new traffic load of BS b after switching.

The centralized adaptive *BS-RS Switching* algorithm is detailed in Algorithm 1. It determines the center BS switching dynamically from the known network traffic profile information, which is periodically updated by the network. Since the traffic load fluctuates in spatial domain and it is assumed the switching decision holds for a certain period T_0 , so a tolerance margin δ is introduced in order to reduce the impact of sudden traffic changes.

IV. RESULTS ANALYSIS

In this section, we evaluate the performance of our proposed model compared with different BS operation modes by simulation. Table I details all the simulation environment parameters. We consider orthogonal frequency division multiple access (OFDMA) with 5MHz of carrier bandwidth, 300-subcarrier and subcarrier spacing of 15kHz. To evaluate the performance of the proposed switching model, we have used the approximated traffic profile for different cells. Fig. 2 shows the normalized traffic profile of the center cell averaged over a 10 minutes period using both a fixed and adaptive switching threshold levels. The fixed switching threshold was chosen = 0.5 as in [2] and [14].

To evaluate the energy savings achieved by the new adaptive *BS-RS Switching* model, the network power consumption performance is evaluated under three operation modes for a

Algorithm 1 Adaptive *BS-RS Switching*

Inputs: $A_b(t)$, $\rho_b(t) \forall b = 1, \dots, N_{BS}$ where N_{BS} -th BS is the center BS.

Outputs: $A_{N_{BS}}(t)$, $A_{N_{RS}}(t)$, $\rho_{th}(t)$, $\rho'_b(t)$ for $b = 1, \dots, N_{BS}$.

- 1: Compute $\rho_b^{ho}(t) = \rho_{max} - \rho_b(t)$ for $b = 1, \dots, N_{BS} - 1$
 - 2: **if** $\rho_{N_{BS}}(t) \leq \left(\sum_{b=1}^{N_{BS}-1} \rho_b^{ho}(t) - \delta \right)$ **then**
 - 3: $A_{N_{BS}}(t) = 0$, $A_{N_{RS}}(t) = 1$
 - 4: **if** $\rho_{N_{BS}}(t) \geq \rho_{th}(t-1)$ **then**
 - 5: $\rho_{th}(t) = \rho_{N_{BS}}(t)$
 - 6: **else**
 - 7: $\rho_{th}(t) = \rho_{th}(t-1)$
 - 8: **end if**
 - 9: $\rho'_b(t) = \rho_b(t) + \frac{\rho_{N_{BS}}(t) \cdot \rho_b^{ho}(t)}{\sum_{b=1}^{N_{BS}-1} \rho_b^{ho}(t)}$
 - 10: Optimize power allocation based on $\rho'_b(t)$ by solving problem (7).
 - 11: **else**
 - 12: $A_{N_{BS}} = 1$, $A_{N_{RS}} = 0$
 - 13: $\rho_{th}(t) = \rho_{N_{BS}}(t) - \delta$
 - 14: $\rho'(t) = \rho_b(t)$
 - 15: **end if**
-

TABLE I: Simulation Environment Parameters

Parameters	Value		
Carrier frequency	2 GHz		
Cell radius, R	750m		
RS location	$\sqrt{3}R/2$		
Cell sectoring	3 sectors/cell		
BS/RS max transmit power	43/37dBm		
BS-to-BS distance	1.5km		
RS coverage radius	$R/2$		
BS/RS/MS antenna gain	14/10/0 dBi		
BS/RS antenna height	30/30m		
Noise power	-141dBm/Hz		
Path-loss type (BS-RS links)	suburban, LOS (Type D) [15]		
Path-loss type (BS,RS-MS links)	suburban, NLOS (Type B) [15]		
Shadow std. deviation	8dB		
BS-MS/RS-MS link	Type B(suburban, terrain Type B)		
Power model parameters in eq. (5)	a	P_f	
	BS	21.45	354.44
	RS	7.84	71.50
Receiver sensitivity	-99dBm (MS), -103dBm (BS)		

whole day period: 'Always-on' BS (current cellular system), BS sleeping (with increased transmit power to maintain off-cell coverage) and *BS-RS Switching* model (switched a BS to RS) during a day, as shown in Fig (3). In this energy performance evaluation, the minimum rate requirement of $r_i = 122$ kbps is assumed for all users by transmit power control irrespective of their locations and BS operation modes and $g = 0.05$. All BS and RS are active all the time irrespective of their traffic loads in 'Always-on' mode, which consumes the most energy (100%). The power consumption in 'Always-on' mode is not depended on any threshold value, ρ_{th} , as no switching is allowed in this mode. However, both the BS sleeping and *BS-RS Switching*

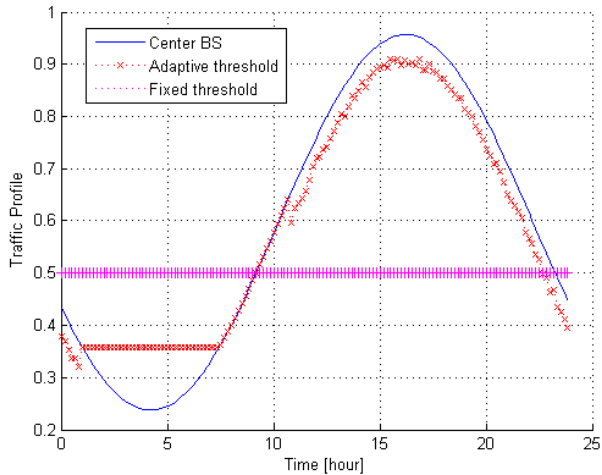


Fig. 2: Normalized traffic profile of the center BS with fixed and adaptive switching threshold levels.

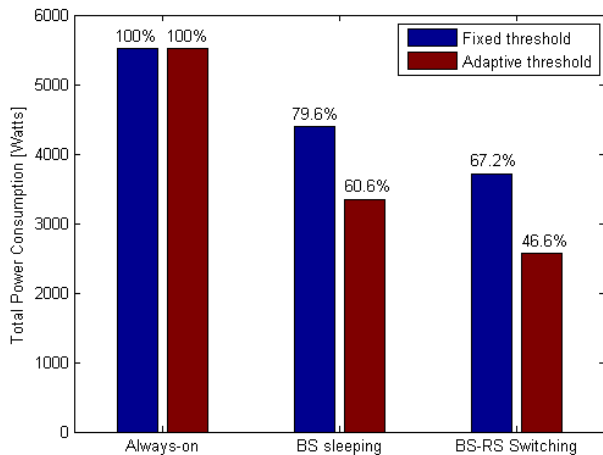


Fig. 3: BS energy consumption in different BS operation modes for a whole day period.

techniques reduce energy consumption while adaptive switching threshold performs better than a fixed switching threshold. In both switching strategies, *BS-RS Switching* outperforms BS sleeping technique so for the given 7-cell cluster arrangement, the energy saving percentage in different operation modes with the fixed and adaptive switching strategies is tabulated in Table II, which are calculated from Fig (3). Almost 40% energy saving is achieved with the *BS-RS Switching* technique with fixed threshold while further energy saving (53.4%) is also achieved with adaptive switching threshold.

The percentage of energy saving with different strategies discussed above is also depended on the amount of energy consumed by the RS. If the RS consumes less energy then additional savings are achievable by either turning-off or switch-

TABLE II: Energy saving percentages in different operation modes with fixed and adaptive switching threshold.

Switching algorithm	'Always-on' (%)	BS Sleeping (%)	BS-RS Switching (%)
Fixed-threshold	0	20.40	39.40
Adaptive-threshold	0	32.80	53.40

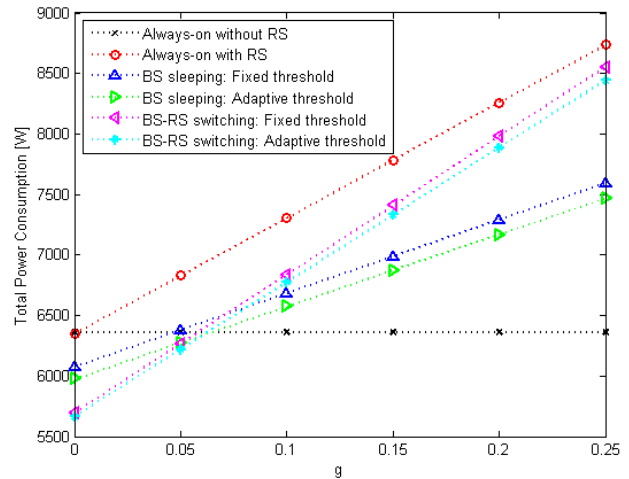


Fig. 4: Total energy consumption with the variation of g (the ratio of RS and BS energy consumption) for a certain period of time in a day.

ing a BS to RS. We compare the total energy consumption for different RS energy consumption levels, which we assumed a fraction g of BS energy consumption. We compare the total energy consumption based on eq. (6) shown in Fig 4 for a certain period of time. It can be seen that if RS consumes the amount of energy equivalent to $g = 1/14$ of the BS energy, then the total energy consumption of the *BS-RS Switching* model with adaptive switching strategy are almost same with that of the traditional cellular network ('Always-on') without RS. Moreover, BS sleeping model with fixed switching strategy requires RS to consume less energy (equivalent to $1/20$ of BS's energy) for achieving the same total energy ('Always-on': no RS). However, the 'Always-on' mode with RS consumes the most energy as expected.

Finally, the benefit of switching a BS to RS during off-peak times rather than turning off entirely a BS and concomitantly increasing the transmit powers of neighboring BS to serve off-cell users, is evidenced by the throughput curves displayed in Fig 5. These clearly show a significant improvement in off-cell user throughput with the *BS-RS Switching* model compared to that with BS sleeping. For example, off-cell users experience an average throughput about around 9bps/Hz with the adaptive *BS-RS Switching* model whereas it is only 5bps/Hz with BS sleeping technique at the BS transmit power of 40dBm. This

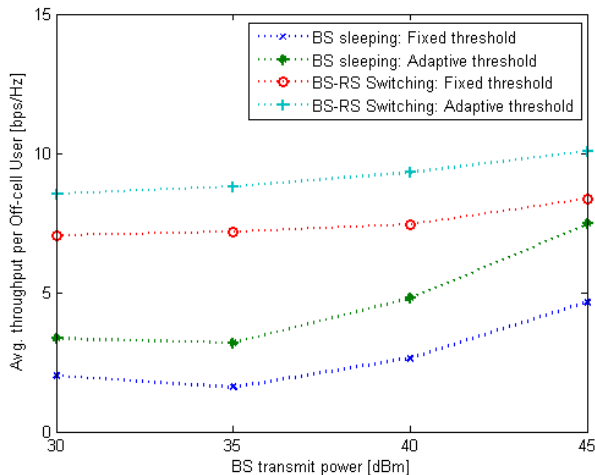


Fig. 5: Average throughput per off-cell user during off-peak period.

improvement is due to the service provided by the *switched-RS* to those users located in the green zone (Fig 1), which are most likely either in coverage hole or receive a worse signal quality when a BS goes into sleep mode. Moreover, the average off-cell user throughput improves further with the adaptive switching threshold compared to the fixed switching threshold. Hence, *BS-RS Switching* model with the adaptive switching threshold strategy performs very well in terms of network energy savings as well as maintaining better off-cell user experience.

V. CONCLUSION

The paper has proposed a new *BS-RS Switching* technique for energy savings where certain BS rather being turned off are switched to *relay stations* (RS) during low traffic period as well as a centralized BS switching algorithm based on adaptive switching threshold. We observed that a significant energy consumption reduction can be achieved using both *BS-RS Switching* and BS sleeping techniques during off-peak time by switching certain BS to RS mode and turning off certain BS, respectively. Moreover, the former reduces more energy consumption than the later technique while maintaining the minimum quality of service. In addition, the adaptive switching threshold performs better than a fixed switching threshold in both *BS-RS Switching* and BS sleeping techniques. As a consequence, the established *BS-RS Switching* technique, allied with the new adaptive threshold strategy represents a useful paradigm for green wireless communications.

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