

# A Scalable Multimode Base Station Switching Model for Green Cellular Networks

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**Abstract**—Recently, *base station (BS) sleeping* has emerged as a viable conservation strategy for energy efficient communication networks. Switching-off particular BS during low-traffic periods requires the load to be sufficiently low so user performance is not compromised. There remain however, network energy saving opportunities during medium-to-high traffic periods if BSs operate in scalable fashion, which involves deploying multiple BSs with different power modes, *i.e.*, macro/microcells, which are co-located in each cell. In this paper, a new scalable *multimode BS switching* (MMBS) cellular model is presented where depending on the traffic load, each BS operates in multimode: *active, low-power* and *sleep*, so the model dynamically switches network capacity by dynamically switching modes to minimise energy consumption. Results corroborate that the MMBS model reduces energy consumption by more than 50% during low-traffic and up to 9% during high-traffic conditions, thereby significantly improving the energy efficiency compared with the *always-on* and existing *BS sleeping* approaches.

**Keywords**—*green cellular networks; base station sleeping; multimode switching; small-cell; energy efficiency; traffic load.*

## I. INTRODUCTION

The demand for cellular data traffic has grown dramatically in the past decade compelling operators to deploy *base stations* (BSs) more densely to ensure the requisite quality and coverage of services. The growing number of BSs has correspondingly increased network energy consumption with the corollary being higher greenhouse gas emissions and a related network carbon footprint. This issue has also become a major political, financial, environmental and social concern for network vendors and regulators alike, with innovative green network design strategies and solutions being demanded. Consequently, operators are actively investigating how best to reduce energy consumption by developing greener cellular networks.

Cellular BSs are principally designed from a peak-traffic load perspective, and operate in a 24/7 *always-on* mode. While BSs consume between 60%-80% of the total network energy [1], there is well-documented evidence of the wide traffic load variations which occur across the day in both spatial and temporal domains [2], with most BSs being under-utilized during off-peak periods [1]. Recently, *BS sleeping* techniques [1], [3], [4], [5], [6] have been considered as sustainable energy efficient solutions for green cellular networks. For example, in [1], static BS sleep patterns using a deterministic traffic profile are applied over a 24hr period, while dynamic BS switching algorithms [3], [7], [8], [9], which turn off certain BSs when the traffic load is low have been proposed for

unpredictable traffic patterns. An alternative energy-efficient *BS-RS* (relay station) *switching* technique is employed in [4] and [6], with certain BSs being turned off and switched to low-powered RS mode during low-traffic intervals. Despite the availability of many BS switching energy saving techniques, they are generally predicted on achieving savings only during low-traffic periods, though their operations can still be more energy efficient. The failure to achieve further energy savings based on traffic dynamics is due to the ineffective exploitation of spare network capacity. For example, to guarantee the coverage for a given traffic demand, there must be a certain number of active BSs within a given area even though the capacity of the active BS may not necessarily be able to meet such demand. This inevitably leads to BSs still being under-utilized while at the same time consuming high static power, which is independent of traffic conditions. It is the inherent high static power overheads incurred by BS which leads to the poor *energy efficiency* (EE) when operating under either low or medium traffic loads. To resolve this limitation and secure tangible energy savings, it is necessary to develop new architectures capable of scaling the network capacity in terms of user traffic demand.

This paper proposes a scalable *multimode BS switching* (MMBS) model which exploits latent opportunities to lower energy consumption by switching the BS from active to *low-power* (LP) mode when particular network conditions prevail. This contrasts with the existing dual-mode *BS sleeping* where switching between active and sleep modes occurs only when the traffic load is low, *i.e.*, lower than a predefined switching threshold. In scenarios when the traffic load of a BS is higher than the switching threshold, the BS is not allowed to switch to sleep mode. The decision is then made to change to an intermediate LP mode instead of staying in the active mode which expends much more static power. In these circumstances, a fraction of the traffic load is served by a LP mode BS which means the overall handover traffic to neighbouring BSs falls below the threshold. Pragmatically, this requires a LP micro BS ( $\mu$ -BS) to be co-located with the macro BS (MBS), though with the evolution of *next-generation* (XG) or all-in-one BSs which are smarter, more energy-aware and have a cognitive capability, such practical energy saving scalable multimode BS operation will become feasible.

The remainder of this paper is organized as follows. In Section II, the system model is detailed along with the traffic and power models, while Section III describes the new MMBS model for minimising the number of active BSs. Section IV presents a critical analysis of the energy saving performance of

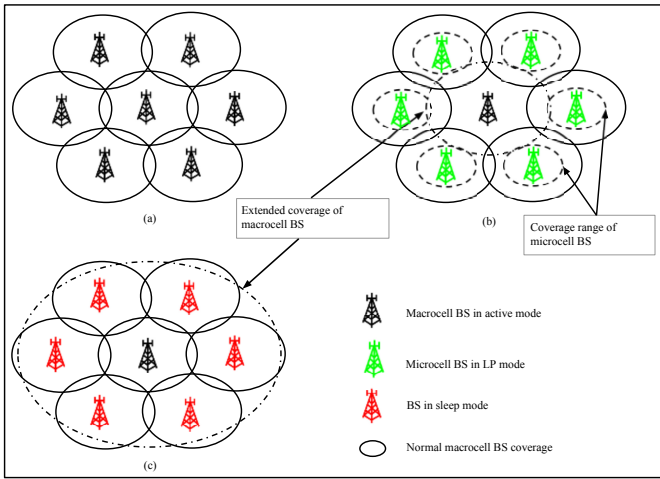


Fig. 1. Example energy saving network arrangements reflecting different traffic variations: (a) all BSs in active mode during peak-traffic; (b) Certain BSs in LP and others in active mode during medium-traffic periods; and (c) some BSs in sleep and active modes during low-traffic.

MMBS, with Section V providing some concluding comments.

## II. SYSTEM MODEL

### A. Network Model

A cellular network consisting a set of  $N$  MBS,  $\mathcal{B} = \{\mathcal{B}_1, \dots, \mathcal{B}_N\}$  is assumed in an area  $\mathcal{A}$ , with a  $\mu$ -BS also deployed and co-located with each MBS, which normally consumes lower static power than the MBS [10]. Both co-located MBS and  $\mu$ -BS cannot be in active mode simultaneously. This means if a MBS is active, then the corresponding  $\mu$ -BS must be in sleep mode and vice-versa, so the  $\mu$ -BS set can be denoted by the same set  $\mathcal{B} = \{\mathcal{B}_1, \dots, \mathcal{B}_N\}$ . If there are a set of  $M$  mobile stations (MSs)  $\mathcal{M} = \{1, \dots, M\}$  located within  $\mathcal{A}$ , then  $\mathcal{M}_b \in \mathcal{M}$  is the set of MSs associated with  $\mathcal{B}_b$  such that  $\mathcal{M} = \mathcal{M}_1 \cup \dots \cup \mathcal{M}_N$  and  $\mathcal{M}_i \cap \mathcal{M}_j = \emptyset$  for  $i \neq j$ . Each  $\mathcal{B}_b$  has an omni-directional antenna and is situated in the cell centre. It is further assumed every  $\mathcal{B}_b$  is connected to its neighbouring BS set  $\mathcal{N}_b$  via dedicated backhaul connections so it can share information on traffic load, location and maximal operational power without negligible delay.

In the MMBS model, each  $\mathcal{B}_b$  has three different operating modes: active, LP and sleep, with examples illustrating each being shown in Fig. 1. The operational time line (e.g. 24hr) is divided into  $N_T$  slots with each slot being of duration  $T_0$  so  $N_T \cdot T_0 = 24\text{hr}$  and the mode switching decision being taken once per slot. When active, the BS functions as a full-power MBS covering a large area and consuming high static power irrespective of the traffic load, while in sleep mode, the BS is completely turned off. In the new intermediate LP mode, the BS opportunistically operates as a  $\mu$ -BS covering a smaller area as evidenced by the uniform dashed circles in Fig. 1(b). During low-traffic periods, most of the BSs are in sleep mode while active BSs are responsible for service coverage by extending their range as shown in Fig. 1(c). Thus, a scalable cellular design is realised by the multimode switching, where the network capacity is scaled with respect to traffic demand. When  $\mathcal{B}_b$  switches from active to either LP or sleep mode, both the residual radio coverage and service provision of  $\mathcal{B}_b$

must be guaranteed by its active neighbours. The BS operating mode or *mode activity factor* (MAF)  $A_b(t)$  of  $\mathcal{B}_b$  at time  $t$  is defined as:

$$A_b(t) = \begin{cases} 0, & \text{Sleep mode} \\ 0.5, & \text{LP mode} \\ 1, & \text{Active mode} \end{cases} \quad (1)$$

Once the MAF of each  $\mathcal{B}_b \in \mathcal{B}$  is fixed, a particular MS  $m \in \mathcal{M}$  is associated with and served by the  $\mathcal{B}_b$  which provides the highest signal strength:

$$\mathcal{B}_b^* = \arg \max_{b' \in \mathcal{B}^{\text{on}}} g_{b'm} \cdot p_{b'm} \quad (2)$$

where  $\mathcal{B}^{\text{on}} \subset \mathcal{B}$  is the set of active BSs at any time instant,  $g_{b'm}$  is the channel gain from  $\mathcal{B}_{b'}$  to  $m$  including path-loss attenuation and shadow fading, and  $p_{b'm}$  is the transmit power of  $\mathcal{B}_{b'}$  for MS  $m$  such that  $\sum_{m \in \mathcal{M}_b} p_{b'm} = P_{tx,BS} \leq P_{max}^{BS}$ , where  $P_{tx,BS}$  and  $P_{max}^{BS}$  are the transmit power and maximum allowable transmit power of  $\mathcal{B}'_b$  respectively. Now, if a BS has maximum bandwidth  $W_{max}$  then each sub-channel has a bandwidth  $W = W_{max}/N_{RB}$ , where  $N_{RB}$  is the total number of *primary resource blocks* (PRBs) in each BS. The achievable throughput of  $\mathcal{B}_b$  is then:

$$R_b = W \cdot \sum_{m \in \mathcal{M}_b} \log_2 \left( 1 + \frac{g_{bm} \cdot p_{bm}}{\sum_{l \in \mathcal{N}_b} g_{lm} \cdot p_{lm}} \right) \quad (3)$$

where the term  $\sum_{l \in \mathcal{N}_b} g_{lm} \cdot p_{lm}$  is the interference power experienced by MS  $m$  from its direct neighbours  $\mathcal{N}_b$  and  $\sigma^2$  is the noise power. Therefore, the network EE in *bits per joule* can be derived using (3) as [4]:

$$\eta_{EE} = \sum_{b \in \mathcal{B}^{\text{on}}} \frac{R_b}{P_{T_b}} \quad (4)$$

where  $P_{T_b}$  is the total BS consumed power (see Section II.C).

### B. Traffic Model

Due to the highly dynamic temporal and spatial nature of cellular traffic, the call arrival process is modelled as time-inhomogeneous by multiplying a time-homogeneous Poisson process with a traffic intensity parameter  $\lambda$  and the rate function  $0 \leq f(t) \leq 1$  as shown in Fig. 2. This is a unit-less deterministic function and is normalized by the capacity of BS, *i.e.*, PRB. This shapes the traffic profile from constant traffic intensity into a time-varying profile in an analogous manner to typical traffic patterns in real cellular networks [2]. If the call arrives in cell  $\mathcal{B}_b$  according to a Poisson process with intensity  $\lambda$  calls/sec and constant service time  $h$  sec/call, then the normalized traffic load of  $\mathcal{B}_b$  at time  $t$  is [9], [11]:

$$\rho_b(t) = \frac{\chi_b h \delta_b f(t)}{N_{RB}}, \forall b = 1, \dots, |\mathcal{B}| \quad (5)$$

where  $\chi_b \sim Poi(\lambda)$  is a Poisson random variable with parameter  $\lambda$ ,  $\delta_b$  is the requisite number of channels (PRBs), with  $\rho(t) = \{\rho_1(t), \dots, \rho_{|\mathcal{B}|}(t)\}$  the set of traffic loads at time  $t$  and  $|\mathcal{B}|$  the cardinality of  $\mathcal{B}$ .

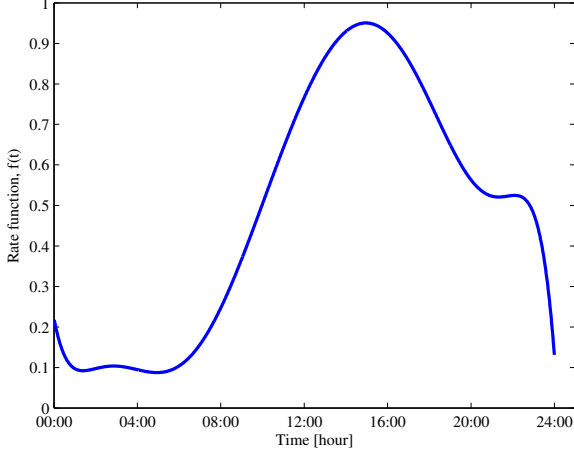


Fig. 2. The rate function  $f(t)$  for a time-inhomogeneous call generation.

### C. Power Consumption Model

The power consumed  $P_T(t)$  by each BS at time instant  $t$  can be expressed as [10]:

$$P_T(t) = a_{BS} \cdot P_{tx,BS}(t) + P_{f,BS} \quad (6)$$

where  $P_T(t)$  and  $P_{tx,BS}(t)$  respectively denote the average total consumed and transmission power of a BS at time  $t$ , while  $a_{BS}$  is a BS power scaling factor which reflects both amplifier and feeder losses.  $P_{f,BS}$  models the static power consumption which is independent of  $P_{tx,BS}(t)$  and is a lumped parameter which includes all electronic circuit power dissipation due to site cooling, signal processing hardware as well as battery backup systems, which are reliant on the BS type. Intuitively, smaller scale BSs such as  $\mu$ -BS will have lower  $a_{BS}$  and  $P_{f,BS}$  values compared with MBS as they do not require large power amplifiers or major cooling equipment [10].

Since the power consumption of  $\mathcal{B}_b$  depends on  $A_b(t)$ , and each  $\mathcal{B}_b$  can hold a single state (active/LP/sleep) at any time instant  $t$ , a generalised power consumption model of  $\mathcal{B}_b$  using (6) and the MAF  $A_b$  can be expressed as:

$$P_{T_b}(t, A_b) = \begin{cases} a_M \cdot P_{tx,M}(t) + P_{f,M}, & \text{if } A_b(t) = 1 \\ a_L \cdot P_{tx,L}(t) + P_{f,L}, & \text{if } A_b(t) = 0.5 \\ 0, & \text{if } A_b(t) = 0 \end{cases} \quad (7)$$

The power consumed in sleep mode is assumed to be zero, though in practice there will be a very small amount of energy expended in reactivating a BS, though this is negligible compared with the power consumed by the BS in active mode.

## III. MULTIMODE BS SWITCHING MODEL

The potential to diminish network energy consumption by employing either the new MMBS model or dual-mode (active/sleep) *BS sleeping* [3] will now be discussed.

In dual-mode arrangements,  $\mathcal{B}_b$  switches to sleep mode at a particular time instant provided its active neighbouring BSs are able to handle the additional load  $\rho_b(t)$ . This decision is

based on a switching threshold  $\rho_{th}$  with the criterion for a BS to switch from active to sleep mode being [3], [4]:

$$0 \leq \rho_b(t) \leq \rho_{th} \quad (8)$$

While existing BS switching techniques [1]–[5], [7]–[9], [11] operate only in dual-mode, this section introduces a MMBS model which assumes a LP  $\mu$ -BS is co-located with each MBS. When the load is greater than  $\rho_{th}$  during medium-to-high traffic periods,  $\mathcal{B}_b$  can still conserve energy by switching to LP mode, *i.e.*, the network is scaled to lower capacity according to current traffic demand. In these circumstances, if a portion of the load  $\rho'_b(t) = (\rho_b(t) - \rho_{th})$  is serviced by the  $\mu$ -BS and the rest  $(\rho_b(t) - \rho'_b(t))$  by active neighbouring BSs, this fulfils switching condition  $0 \leq (\rho_b(t) - \rho'_b(t)) \leq \rho_{th}$  and MBS is then switched to sleep mode. An alternative view is that if a portion of the traffic  $\rho'_b(t) = (\rho_b(t) - \rho_{th})$  in cell  $\mathcal{B}_b$  can be served by the corresponding co-located  $\mu$ -BS, and the remaining traffic  $(\rho_b(t) - \rho'_b(t))$  can be handed over to its neighbouring active MBSs, then the high-power consuming MBS can be switched to sleep. This is the rationale for co-locating  $\mu$ -BS deployment with each MBS. Using (1) and (8), the MAF  $A_b(t)$  of  $\mathcal{B}_b$  for the MMBS model can be expressed as:

$$A_b(t) = \begin{cases} 0, & 0 \leq \rho_b(t) \leq \rho_{th} \\ 0.5, & \rho_b(t) > \rho_{th} \ \& \ (\rho_b(t) - \rho'_b(t)) \leq \rho_{th} \\ 1, & \text{Otherwise} \end{cases} \quad (9)$$

In the MMBS model, coordination amongst BSs is needed, so two sets  $\mathcal{B}^{on}$  and  $\mathcal{B}^{off}$  are respectively maintained to track the total number of BSs in active mode and in either LP or sleep modes, with both sets being updated after each decision.

### A. The MMBS Algorithm

The various steps involved in this new multimode algorithm are summarised as follows, where without loss of generality the time index  $t$  is omitted:

**Step 1:** Each BS obtains the information for traffic loads of its entire neighbours  $\mathcal{N}_b$  through X2 interface.

**Step 2:** Each active BS  $\mathcal{B}_b \in \mathcal{B}^{on}$  checks if it satisfies (8).

**Step 3:** If satisfied,  $\mathcal{B}_b$  is switched off and the associated MSs  $\mathcal{M}_b$  are distributed among active  $\mathcal{N}_b$  with updating sets  $\mathcal{B}^{on}$ ,  $\mathcal{B}^{off}$ , and the MAF  $A_b$ .

**Step 4:** Otherwise, calculate traffic within  $\mu$ -BS coverage area and check the switching condition (9) for the remaining traffic  $(\rho_b - \rho'_b)$ .

**Step 5:** If (9) is satisfied for traffic load  $(\rho_b - \rho'_b)$ , *i.e.*,  $(\rho_b - \rho'_b) \leq \rho_{th}$ ,  $\mathcal{B}_b$  is switched to LP mode and  $\mathcal{B}^{on}$ ,  $\mathcal{B}^{off}$ , and  $A_b$  are updated. The load in  $\mathcal{B}_b$  is then served by both the LP mode  $\mu$ -BS and active neighbours  $\mathcal{N}'_b$ .

**Step 6:** Repeat Steps 2-5 until all BSs in  $\mathcal{B}^{on}$  are checked.

The corresponding MMBS model flowchart is given in Fig. 3, where  $sgn(x)$  is the sign function, with  $sgn(x) = 1$  when  $x > 0$  and zero otherwise. MMBS iterates  $|\mathcal{B}^{on}|$  times at each time instant and generates the corresponding  $A_b$  values for all BSs. To ensure the QoS, each off-cell MS will either achieve

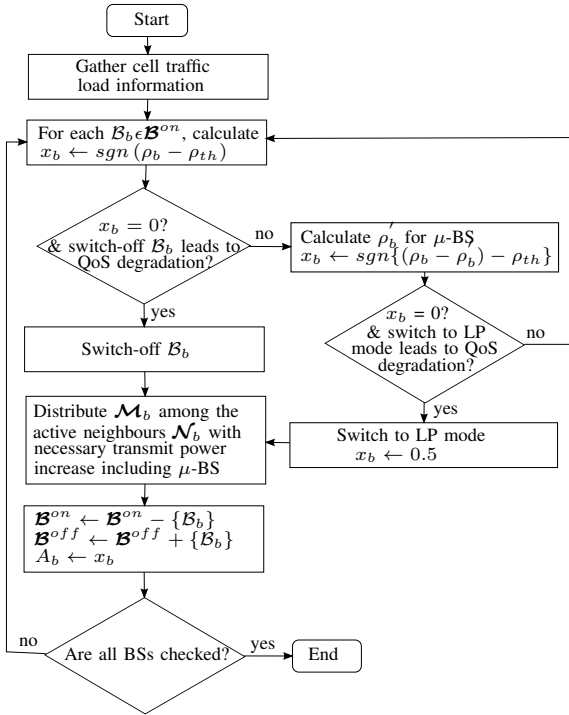


Fig. 3. Flowchart of the MMBS algorithm.

the minimum bit rate or be blocked, where it is reasonably assumed all BSs co-operate with each other and will serve any off-cell MS, provided they are not overloaded.

To return  $\mathcal{B}_b \in \mathcal{B}^{off}$  back from sleep to either LP or active mode, all neighbouring BSs continually monitor their traffic loads and by sharing load information decide whether the off-cell  $\mathcal{B}_b$  is to be reactivated to either LP or active modes. The priority is firstly to switch from sleep to LP rather than directly to active mode if (9) is satisfied, due to the lower static power consumed by LP mode  $\mu$ -BS. Once  $\mathcal{B}_b$  is either in active ( $A_b = 1$ ) or LP modes ( $A_b = 0.5$ ) at any time instant, the corresponding traffic load respectively reverts to either the original MBS or  $\mu$ -BS and its neighbours.

#### IV. RESULTS DISCUSSION

To critically evaluate the performance of the new MMBS model and compared with the existing *BS sleeping* model [3], a network comprising  $N = 25$  BSs in a suburban scenario is considered with an inter-side distance of 1.5km and the  $\mu$ -BS coverage radius set to 200m. Calls arrive according to (5) with the traffic intensity parameter =  $138.9 \times 10^{-3}$  calls/sec and the service time fixed at 180sec/call with  $\delta_b = 1$ PRB, which corresponds to a peak-time load of 25PRBs. Throughout the experiments, the rate function in Fig. 2 is used to generate the time-inhomogeneous traffic profile. To maintain the QoS, the target blocking probability is set to 1%, with a minimum bit rate requirement of 122kbps. The generated traffic is averaged over 15min intervals ( $T_0 = 15$ min) giving a total of  $N_T = 96$  time slots per day. The switching threshold is chosen as  $\rho_{th} = 0.6$  as in [3], while at least two neighbouring BSs are assumed to always be active to allow a BS to switch to either LP or sleep mode *i.e.*,  $|\mathcal{N}_b| \geq 2$ . All other simulation environment parameter settings are summarized in Table I, and

TABLE I. SIMULATION ENVIRONMENT PARAMETERS

Parameters	Settings		
Carrier frequency	2 GHz		
Channel bandwidth	5 MHz		
Max. BS transmit power (MBS/ $\mu$ -BS)	43/33 dBm		
Antenna gain (MBS/ $\mu$ -BS)	16/10 dBi		
BS antenna height	25 m		
Noise power	-141 dBm/Hz		
Path-loss (BS-MS links) [13]	Type B (non-light-of-sight, suburban, terrain Type B)		
Shadow standard deviation	8 dB		
Power model parameters in (7) [10]		$a$	$P_f$
	MBS	32.0	412.4
	$\mu$ -BS	5.5	22.6

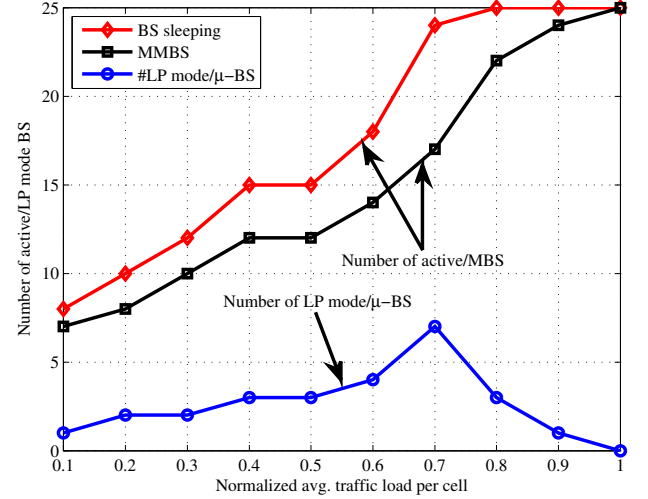


Fig. 4. Number of active and LP mode BSs per day.

are fully congruent with both the 3GPP/LTE [12] and IEEE 802.16 standards [13].

The motivation behind the MMBS model is to reduce the number of active BSs while providing the service coverage by means of LP mode  $\mu$ -BS. Results presented in Fig. 4 show that the number of active BSs increases with the normalized cell traffic load for both MMBS and *BS sleeping* cases. It is evident the number of active BSs is consistently lower for MMBS than with *BS sleeping*. For example, at a normalized cell traffic load of 0.7, MMBS requires only 17 active and 7 LP mode BSs to provide services in area  $\mathcal{A}$  in contrast to the *BS sleeping* model which needs 24 active BSs to provide similar service coverage. The results also confirm that in terms of energy conservation, the MMBS model is able to save considerably more energy due to the use of LP mode  $\mu$ -BS which does not consume high static power. Thus, BSs are under-utilized in *BS sleeping* under all traffic conditions as the model has to keep a higher number of active BSs than is actually required for the given traffic load. These results reveal there is more BSs in LP mode  $\mu$ -BS during the challenging medium-to-high traffic conditions, when BSs in *BS sleeping* model are under-utilized.

To comparatively evaluate the *area power consumption* (APC) performance (defined as the ratio of the average total consumed power to the corresponding network area measured in watts per  $\text{km}^2$  [10]) of MMBS with the *always-on* and *BS sleeping* strategies, Fig. 5 displays the respective APC values



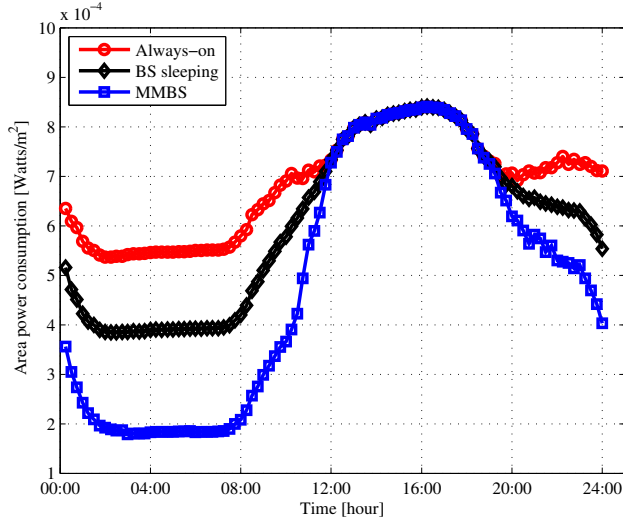


Fig. 5. APC comparison for the MMBS, *BS sleeping* and *always-on* models over a 24hr window.

for each strategy for each time-interval  $T_0$  throughout the day. The MMBS model consumed the least power per unit area (190 watts/km<sup>2</sup>) compared with 400 watts/km<sup>2</sup> for *BS sleeping* and 580 watts/km<sup>2</sup> for the *always-on* strategy during low-traffic periods. This saving is derived both from the lower transmit power required for microcell MSs and the reduced static energy consumed by the LP  $\mu$ -BS instead of the high-power MBS. The APC graph also reveals the *always-on* strategy is always highest during low-traffic periods, and that all three models consume the same energy per unit area (on average 790 watts/km<sup>2</sup>) during the peak-traffic period (12:00 to 7:00pm). It is important to stress that even when traffic load is higher than  $\rho_{th}$ , there are still opportunities for MMBS to change mode to LP  $\mu$ -BS and secure further energy savings. Conversely for *BS sleeping*, the transmit power of neighbouring BS has to be increased to extend the coverage area for off-cell MSs and the BS is prevented from being put to sleep until the necessary condition is upheld. This means a higher number of active MBS operates with *BS sleeping* than in the MMBS model.

The respective EE performances defined in (4) are given in Fig. 6, which shows the number of bits delivered per unit energy for each switching strategy. For low-traffic periods, there is a significant improvement in EE for both the MMBS and *BS sleeping* models, which is especially significant for the MMBS model, because the numerator term in (4) is increased due to the co-located  $\mu$ -BS being activated instead of completely switching off the BS. Another reason is that wherever possible, MMBS distributes off-cell MSs among active and LP mode  $\mu$ -BS, with the consequence that off-cell MSs served by the  $\mu$ -BS require lower transmit power while other off-cell MSs served by neighbouring active MBSs, incur comparatively higher transmit power. In contrast, in the *BS sleeping* all off-cell MSs are required to be served by neighbouring active MBSs that require higher transmit power to ensure the minimum QoS, due to the larger propagation distance between the off-cell MS and the neighbouring active BS. Thus, certain BSs are kept in LP rather than active mode, leading to lower energy consumption which translates into enhanced EE. To illustrate this point, the

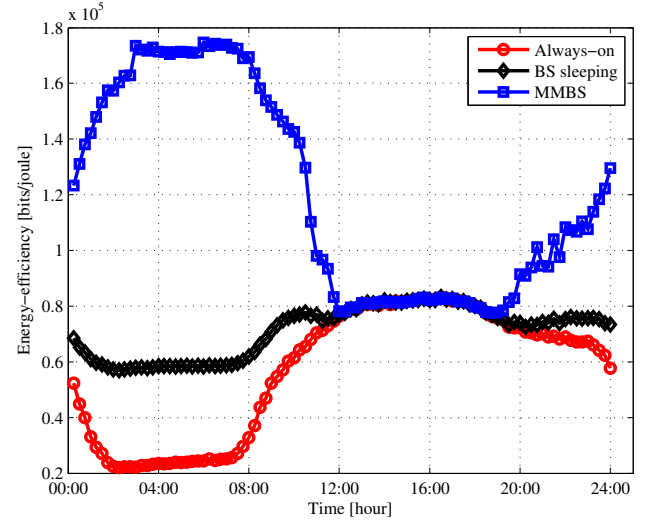


Fig. 6. EE performance comparison of the MMBS, *BS sleeping* and *always-on* models over a 24hr window.

EE for MMBS during low-traffic period is on average  $1.5 \times 10^5$  bits/joule higher than *BS sleeping* ( $6.5 \times 10^4$  bits/joule), *i.e.*, an over 56% EE improvement. As anticipated, the *always-on* strategy consistently gave the poorest EE performance during low-traffic periods, while for peak periods again no savings were feasible with all three strategies provided the same EE performance, an average  $8 \times 10^4$  bits/joule.

Fig. 7 compares the energy saving percentage of the MMBS and *BS sleeping* models relative to the *always-on* mode at various (normalized) traffic loads. The plots reveal a consistently higher percentage of energy savings achieved by MMBS (up to 55%) compared with *BS sleeping* (up to 52%), with the relative savings being greater at higher normalized traffic loads, which is an advantageous feature of the MMBS model. No savings are obtained by *BS sleeping* when the normalized traffic load is greater than 0.6 because this is the value used in the simulations as the switching threshold,  $\rho_{th}$ . The key finding to highlight from this analysis is that MMBS still saves energy even when the normalized traffic load is higher than  $\rho_{th}$ , with  $\approx 7\%$  saving being achieved for loads of 0.7 and even  $\approx 3\%$  at 0.8. The reason for this is a proportion of the traffic is still able to be off-loaded to the switched  $\mu$ -BS rather than being kept in active mode, with the corollary that the handed-over traffic load drops below the threshold.

Fig. 8 plots the respective blocking probabilities averaged over 15min intervals across a 24hr time window. The average blocking performance for MMBS and *BS sleeping* is consistently below the 1% target at  $\approx 0.3\%$  and  $0.4\%$  respectively. Interestingly, if the low blocking tolerance for the network is relaxed, then further energy savings are feasible by employing a higher value. This would mean a higher number of active BSs can then be switched to either LP or sleep mode so translating into larger energy savings.

In introducing multimode switching, the number of switching instances will intuitively increase and there will be some additional costs incurred compared to the existing dual-mode *BS sleeping*, although in general, the switching energy cost

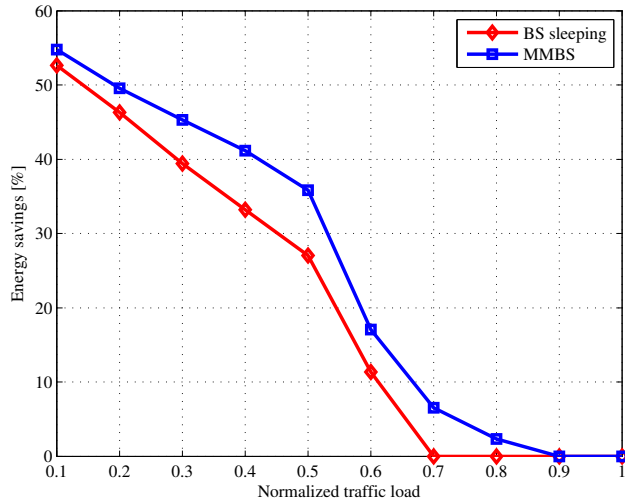


Fig. 7. Comparison of the percentage of energy savings for the MMBS and *BS sleeping* relative to the *always-on* mode.

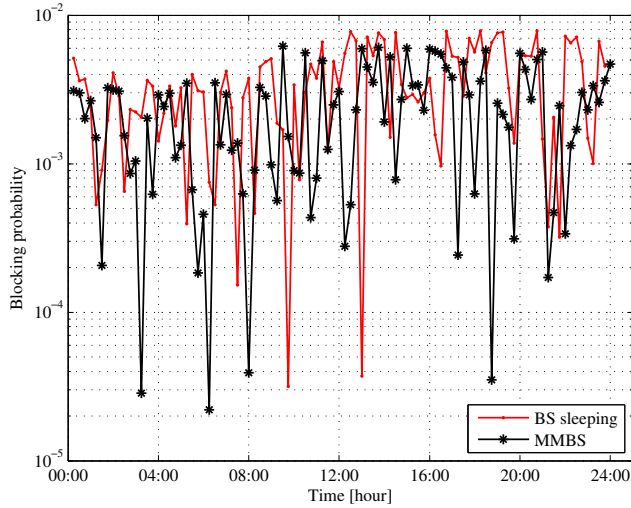


Fig. 8. Blocking probability variations averaged over 15min intervals over a 24hr window.

has been ignored in the overall network energy consumption for both models. Analysis reveals the MMBS model switches an extra 10% of BS into either LP or sleep modes, thereby resulting in greater energy savings. Conversely, the total number of switching instances for MMBS increases by less than 12%, with a correspondingly small increase in the total energy consumed. When this is pragmatically judged against both the improved EE performance (Fig. 6) and overall network energy savings (Fig. 7) achieved, the MMBS model represents a notably superior solution compared to *BS sleeping*, especially at high traffic loads, while only experiencing a small overhead in the overall energy consumed per switching.

## V. CONCLUSION

This paper has presented a new scalable MMBS model for enhanced EE in green cellular networks. The approach is

founded on the assumption that each BS acts in a scalable fashion so it can switch from high-power active (MBS) to LP ( $\mu$ -BS) mode. Depending on current traffic conditions, when BSs change operating modes, priority is given to switching firstly to sleep mode and then to the new LP mode, so the BS becomes scalable in terms of power consumption. While there may be debate about the cost of deploying multiple BSs (MBS/ $\mu$ -BS) in each cell, the quantitative results confirm up to 55% energy savings are feasible across the day with superior APC and EE performance compared with the *always-on* and *BS sleeping* models. When offset against the one-off deployment expenditure, this is noteworthy. Furthermore, on average over 9% energy savings are feasible during medium-to-high traffic conditions by MMBS in contrast to *BS sleeping* which cannot conserve any energy during such periods. The scalability of the solution also means higher energy saving percentages are envisaged with more switching modes *i.e.*, macro/micro/pico and sleep, though a commensurate higher switching overhead will be incurred. Moreover, the MMBS model provides impetus to vendors to design and implement smarter scalable XG BS designs which more effectively adapt their operating modes to current traffic loads to reduce energy consumption.

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