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Traffic-and-Interference Aware Base Station Switching for Green Cellular Networks

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Abstract—*Base station* (BS) *sleeping* in cellular networks has emerged as a promising solution for more energy efficient communications, concomitant with lowering the network carbon footprint. Switching off specific BS entirely however, can lead to coverage holes and severe performance degradation. To avoid coverage holes, the transmit power of neighbouring BS must be commensurately increased, which can cause higher interference to other cell users. Recently a *BS-RS* (relay station) *switching* model has been proposed where the BS changes operating mode to a RS during off-peak periods rather than being completely turned off. This paper presents a *traffic-aware* and *traffic-and-interference aware* switching strategy for both the *BS sleeping* and *BS-RS switching* paradigms, which dynamically establishes the conditions for a BS to alter its working mode. The switching is based upon a dynamic traffic threshold allied with the received BS interference level. Analysis corroborates both new algorithms significantly improve network energy efficiency, while upholding the requisite *quality of service* provision.

Keywords—green cellular networks; base stations; relay station; interference-aware; traffic-aware; base station switching.

I. INTRODUCTION

The last decade has witnessed extraordinary growth in cellular networks, with the introduction of smart phones and other high-end devices like the Android, iPad, Kindle and gaming consoles spawning a raft of data intensive applications. The corresponding explosion in data demand has forced operators to increase the deployment density of *base stations* (BSs), though this rapid data growth has commensurately contributed to higher energy consumption and larger carbon footprints. In 2008 for instance, server farms and core telecommunications infrastructure were responsible for around 3% of the total worldwide electricity consumption with BS and backhaul networks consuming just 0.33% [1], which have inexorably increased over the last five years. The corollary is that both energy consumption and related greenhouse gas emission levels have become major political, economic, environmental and social issues for vendors and regulators alike, with innovative energy efficiency network design strategies and solutions being mandated. In existing cellular networks, it is customary for the BS to be *always-on*, with their design being predicated on peak cell traffic loads, irrespective of either the load profile or time of day. Despite significant latent spatial and temporal traffic fluctuations, the continual operating mode of BS means they are generally responsible for 60-80% of the total network energy consumption [2].

Various *BS sleeping* schemes [2–6] have been proposed with the aim of reducing this high energy consumption by turning off certain BSs during periods of low traffic. These are only feasible however, if neighbouring BSs can guarantee the coverage of the cell put to sleep without compromising the *quality-of-service* (QoS). Cell zooming [3] for instance, where neighbouring cells either expand or shrink their coverage enable other cells to be put to sleep during low traffic periods, though successfully managing *inter-cell interference* (ICI) is paramount for this solution to be viable. In [2], static BS sleep patterns based upon a deterministic traffic profile are applied over a 24-hour time window, while [4] initiates BS switching based on traffic variations and the distance between the BS and *mobile stations* (MSs). In [5], BS are dynamically turned off one-by-one by considering the network impact of the extra load incurred by neighbouring BSs. Interestingly the opposing view is expressed in [7] that *BS sleeping* may neither be viable or energy efficient due to the higher transmission power other BS must employ and the inevitable capacity/coverage degradation. Extending coverage by increasing the transmit power of neighbouring cells can significantly impact the ICI in certain areas of the network. By taking cognisance of the coverage in *BS sleeping* approaches and ensuring analogous QoS to normal BS mode, the authors recently proposed [6] an energy efficient *BS-RS* (relay station) *switching* model where certain BS instead of being turned off, are switched to a low-power RS mode during low-traffic intervals.

A recurrent feature in these energy saving strategies is they do not consider the influence of interference in choosing which BS to turn off. This provided the motivation to investigate the nexus between the best BS selection to be switched off and interference. This paper presents a new *dynamic traffic-aware* (DTA) and a *dynamic traffic-and-interference-aware* (DTIA) BS switching algorithm which can be seamlessly incorporated in both *BS sleeping* and *BS-RS switching* models to determine the best BS set to be kept active at any instant. Using either traffic information (DTA) or a combination of traffic load and received BS interference (DTIA), the switching mechanisms not only turn off particular BS to conserve energy, but choose the best BS set which decreases off-cell MS energy consumption, while critically upholding the requisite QoS.

The rest of the paper is organized as follows. In Section II, the system model is described along with the channel, traffic and power models, while Section III introduces the DTA and DTIA algorithms for minimizing the number of active BS. Section IV presents a rigorous performance analysis of DTA

and DTIA, with Section V making some concluding comments.

II. SYSTEM MODEL

A. Network and Channel Models

A cellular network comprising a regular hexagonal grid arrangement of N cells (BSs) is considered. The set of BS, $\mathcal{B} = \{\mathcal{B}_1, \cdots, \mathcal{B}_N\}$, lie within a two-dimensional area $\mathcal{A}$, with M MSs, denoted by $\mathcal{M} = \{1, \cdots, M\}$ located in $\mathcal{A}$. $\mathcal{M}_b$ is the set of MSs associated with $\mathcal{B}_b$ i.e. $\mathcal{M} = \mathcal{M}_1 \cup \cdots \cup \mathcal{M}_N$ and $\mathcal{M}_i \cap \mathcal{M}_j = \phi$ for $i \neq j$. Each BS has an omni-directional antenna and is situated in the cell centre. It is assumed each $\mathcal{B}_b$ is connected to its neighbouring BS set, $\mathcal{N}_b$ via a dedicated backhaul connection so it can cooperatively share information. For *BS-RS switching*, each cell has a low-powered RS, $\mathcal{R}_b \in \mathcal{R} = \{\mathcal{R}_1, \cdots, \mathcal{R}_N\}$, co-located with the BS, which is named as the *switched*-RS [6].

Each $\mathcal{B}_b \in \mathcal{B}$ is characterized by a *mode activity factor*, $A_b(t)$ at time t, with $\mathcal{B}_b$ being in either *active* $A_b(t)=1$ or *dormant* mode[1] $A_b(t)=0$, and with a BS and the *switched*-RS operating in reverse modes (active/sleep). When $A_b(t)=0$ for $\mathcal{B}_b$, the corresponding $\mathcal{M}_b$, referred to as the *off-cell* MSs, are redistributed amongst neighbouring BSs, $\mathcal{N}_b$. A MS, $m \in \mathcal{M}$ is associated with and served by the BS $\mathcal{B}_b^*$ which provides the strongest signal strength:

$$\mathcal{B}_b^* = \arg \max_{b' \in \mathcal{B}^{on}} g_{b'm} \cdot p_{b'm} \quad (1)$$

where $\mathcal{B}^{on} \subseteq \mathcal{B}$ is the set of active BS at any time instant, g_{bm} is the channel gain between $\mathcal{B}_b$ and MS m and includes both path-loss and shadow fading, and p_{bm} is the transmit power of $\mathcal{B}_b$ for m so that $\sum_{m \in \mathcal{M}_b} p_{bm} \leq P_{\max}^{BS}$, where $P_{\max}^{BS}$ is the peak BS transmit power. If every active BS has a maximum bandwidth W_{max}, then each sub-channel will have a bandwidth $W = W_{max}/N_{RB}$, where N_{RB} is the total number of *primary resource blocks* (PRB) in each BS. The achievable throughput of $\mathcal{B}_b$ is then:

$$R_b = W \cdot \sum_{m \in \mathcal{M}_b} \log_2 \left(1 + \frac{g_{bm} \cdot p_{bm}}{\sum_{l \in \mathcal{N}_b} g_{lm} \cdot p_{lm} + \sigma^2} \right) \quad (2)$$

where the term $\sum_{l \in \mathcal{N}_b} g_{lm} \cdot p_{lm}$ is the interference received at m from its direct neighbouring cells, and σ^2 is the noise power. Using (2) and the total power consumption of $\mathcal{B}_b$, the network *energy efficiency* (EE) in *bits per joule* can be derived as [6]:

$$\eta_{EE} = \sum_{b \in \mathcal{B}^{on}} \frac{R_b}{P_{T_b}} \quad (3)$$

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[1]When a BS changes from active to either sleep (*BS sleeping*) or RS mode (*BS-RS switching*), it switches from *active* to *dormant* mode.
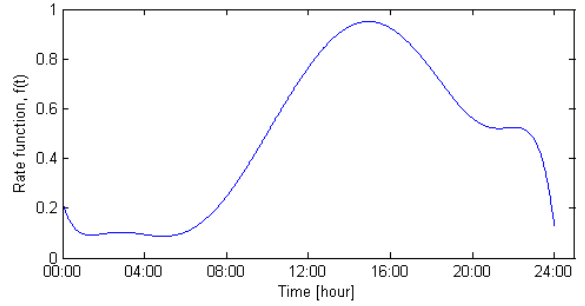

Figure 1: A rate function for time-inhomogeneous Poisson model.

where P_{T_b} is the total power consumption of $\mathcal{B}_b$ which will be described in Section II. C.

B. Traffic Model

Due to the highly dynamic temporal and spatial nature of cellular traffic [2], the call arrival process is modelled as time-inhomogeneous by multiplying a time-homogeneous Poisson process with a traffic intensity parameter λ and the rate function $0 \leq f(t) \leq 1$ shown in Figure 1, which closely reflects traffic patterns in real cellular networks [5]. If the call arrives in cell $\mathcal{B}_b$ according to a Poisson process with intensity λ_b [calls/sec] and constant service time h [sec/call], then the normalized traffic load of $\mathcal{B}_b$ at time t is:

$$\rho_b(t) = \frac{X_b h \delta_b f_b(t)}{N_{RB}}, \qquad \forall b = 1, \cdots, |\mathcal{B}| \quad (4)$$

where $X_b \sim Poi(\lambda_b)$ is a Poisson random variable with parameter λ_b, δ_b is the required number of channels (PRB) and N_{RB} is the total number of PRB in each BS, with $\boldsymbol{\rho}(t) = \{\rho_1(t), \cdots, \rho_{|\mathcal{B}|}(t)\}$ being the set of traffic loads at time t.

C. Power Consumption Model

The total power consumed by $\mathcal{B}_b$ in the *BS-RS switching* model can be expressed as a linear relationship [8], where without of generality, the index t has been omitted:

$$\begin{aligned} P_{T_b} &= P_{T,bs} + P_{T,rs} \\ &= A_b \cdot \left(a_{bs} \cdot P_{tx}^{BS} + P_f^{BS} \right) + (1 - A_b) \cdot \left(a_{rs} \cdot P_{tx}^{RS} + P_f^{RS} \right) \end{aligned} \quad (5)$$

where $P_{T,bs}$ and $P_{tx}^{BS} \leq P_{\max}^{BS}$ are respectively the average total consumed and transmission power of $\mathcal{B}_b$, a_{bs} is a scaling factor that reflects both amplifier and feeder losses and P_f^{BS} is the fixed power components which are independent of the transmission power. The corresponding parameters for $\mathcal{R}_b$ are signified as $P_{T,rs}$, $P_{tx}^{RS} \leq P_{\max}^{RS}$, a_{rs}, and P_f^{RS} respectively, while $a_{bs} > a_{rs}$ and $P_f^{BS} > P_f^{RS}$ [8]. When $A_b(t) = 1$, $\mathcal{B}_b$ is active so the second term in (5) which accounts for $\mathcal{R}_b$ is zero. Moreover, since there is no *switched*-RS in the BS sleeping model, the second term, $P_{T,rs}$ in (5) will not exist.

From the MS power consumption standpoint, the main constituent is transmit power, which increases with distance from the BS due to path-losses and shadowing effects. It is assumed each MS is capable of autonomously adapting its transmit power according to the LTE specification [9]. The total MS power consumption within a cell, $\mathcal{B}_b$ is expressed as:

$$P_{T_b,UL} = \sum_{m \in \mathcal{M}_b} P_{tx}^{(m)} \qquad (6)$$

where $P_{tx}^{(m)} \leq P_{max}^{MS}$ is the MS transmit power and P_{max}^{MS} the maximum transmit power.

III. BS SWITCHING STRATEGY

The aim of BS switching is to minimize the number of active BSs during low traffic periods so reducing energy consumption. This section describes the dynamic BS switching strategy used in the new DTA and DTIA algorithms within both the *BS sleeping* and the *BS-RS switching* models.

In switching active BS to dormant mode, the key challenge is deciding when the traffic load is sufficiently low that user performance can still be adequately maintained after the mode change. The basis of DTA switching is that when the traffic load of $\mathcal{B}_b$ falls below a threshold ρ_{th}, it can switch to dormant mode, provided the active neighbouring BSs $\mathcal{N}_b$ can handle the extra traffic from $\mathcal{B}_b$. The value of ρ_{th} has been empirically shown to be in the range 0.5 to 0.6 [5],[6]. Switching based on traffic load alone however, may not lead to the best BS set being made dormant because no cognisance is made of MS locations, which can lead to high interference in other cells. The DTIA algorithm assimilates interference into the BS switching, with each $\mathcal{B}_b$ comparing both the traffic load and received interference with active neighbours $\mathcal{N}_b$, with the requisite information being exchanged between neighbouring BSs by means of an X2 interface.

A. DTA and DTIA switching algorithms

Each $\mathcal{B}_b \in \mathcal{B}^{on}$ co-operatively acquires instantaneous traffic load and received interference power information from users in their neighbouring cells. Represented as $\mathbf{w} = \left\{ w_1, \cdots, w_{|\mathcal{B}^{on}|} \right\}$, a weighted vector is formed of all the normalized received interference power at each BS in $\mathcal{B}^{on}$. A utility function for each $\mathcal{B}_b$ is now defined which encompasses the impact of both traffic and interference:

$$\mathcal{U}(\mathcal{B}_b) = \begin{cases} \dfrac{\rho_b}{w_b}, & \text{if } \rho_b \leq \rho_{th} \\ \infty, & \text{otherwise} \end{cases} \qquad (7)$$

When $\rho_b > \rho_{th}$, $\mathcal{B}_b$ cannot be switched to dormant mode so $\mathcal{U}(\mathcal{B}_b)$ is set to ∞. Also as $0 > w_b \geq 1$, a small w_b gives greater emphasis to the received BS interference component in DTIA switching, while conversely when $w_b = 1$, interference is not

considered and DTIA reverts to the DTA algorithm. Since each $\mathcal{B}_b$ shares their status amongst its neighbours $\mathcal{N}_b$, the $\mathcal{B}_b^*$ with the lowest $\mathcal{U}(\mathcal{B}_b^*)$ in (7) is switched to dormant mode (Line 5-6) in Algorithm 1, with the corresponding MSs $\mathcal{M}_b$ associated with $\mathcal{B}_b^*$ being redistributed among $\mathcal{N}_b$ (Line 8) in accordance with Algorithm 2. When all $\mathcal{M}_b$ have been successfully reassigned to their neighbours, $\mathcal{B}_b$ is switched to dormant mode ($A_b(t)=0$) and its status updated in (Lines 10-12).

Algorithm 1: BS SWITCHING (ACTIVE TO DORMANT MODE)

1: **Inputs:** $\boldsymbol{\rho}$, ρ_{th}, $\mathcal{M}$, $\mathcal{B}$, $\mathbf{w}$. **Outputs:** A_b.
2:    Initialize $\mathcal{B}^{on} \in \mathcal{B}$, $\mathcal{M}_b \in \mathcal{M}$, $\forall \mathcal{B}_b \in \mathcal{B}^{on}$.
3:    Calculate: $\mathcal{U}(\mathcal{B}_b)$, $\forall \mathcal{B}_b \in \mathcal{B}^{on}$ by eq. (7).
4:    **for** each $\mathcal{B}_b \in \mathcal{B}^{on}$ **do**
5:       Exchange status (ρ_b, A_b, w_b) among $\mathcal{N}_b$.
6:       Find $\mathcal{B}_b^* = \arg \min_{\mathcal{B}_b' \in \mathcal{N}_b \cup \{\mathcal{B}_b\}} \mathcal{U}(\mathcal{B}_b')$.
7:       **if** $\mathcal{B}_b^* = \mathcal{B}_b$ **then**
8:          Distribute all $\mathcal{M}_b$ among $\mathcal{N}_b$ by Algorithm 2.
9:       **end if**
10:      **if** $\mathcal{M}_b = \phi$ **then**
11:         $A_b \leftarrow 0$, $\rho_b \leftarrow 0$, $w \leftarrow \infty$, $\mathcal{B}^{on} \leftarrow \mathcal{B}^{on} - \{\mathcal{B}_b\}$
12:         Update status (ρ_b, A_b, w_b).
13:      **end if**
14:   **end for**

The distribution of users from $\mathcal{B}_b^*$ to $\mathcal{N}_b$ is described in Algorithm 2, where every $m \in \mathcal{M}_b$ is assigned to the $\mathcal{B}_n^* \in \mathcal{N}_b$ with the maximum signal strength as long as the traffic load ρ_n of $\mathcal{B}_n^*$ is less than the maximum ρ_{max} permitted without compromising the QoS (Lines 3-9). Any MS in $\mathcal{M}_b$ unable to hand over to an active neighbouring BS is blocked (Line 11).

Algorithm 2: USER DISTRIBUTION OF A BS AMONG NEIGHBOURS

1: **while** $\mathcal{M}_b \neq \phi$ **do**
2:    Select a MS, $m \in \mathcal{M}_b$.
3:    Find $\mathcal{B}_n^* = \arg \max_{b' \in \mathcal{N}_b} g_{b'm} \cdot p_{b'm}$.
4:    **if** $\rho_n \geq \rho_{max}$ **then** // ρ_{max} is max. load served by each BS
5:       $\mathcal{N}_b = \mathcal{N}_b - \{\mathcal{B}_n\}$. // $\mathcal{B}_n$ has no capacity to serve m.
6:    **else**
7:       Associate m to $\mathcal{B}_n$. // m is now handed over to $\mathcal{B}_n$
8:       $\mathcal{M}_b = \mathcal{M}_b - \{m\}$.
9:    **end if**
10:   **if** $\mathcal{N}_b = \phi$ **then**
11:      MS in $\mathcal{M}_b$ are blocked and $\mathcal{M}_b \leftarrow \phi$
12:   **end if**
13: **end while**

To return $\mathcal{B}_b$ back to active mode, all neighbouring BSs must monitor their traffic loads and cooperate with each other to make the decision for the off-cell BS, $\mathcal{B}_b$ and request it be made active again when the following condition is upheld:

$$\rho_b > \rho_{th} \qquad (8)$$

Once $\mathcal{B}_b$ is active ($A_b(t)=1$), the corresponding traffic load reverts to the original BS $\mathcal{B}_b$.

IV. SIMULATION RESULTS

To analyse the performance of the DTA and DTIA energy-efficient algorithms in both *BS sleeping* and *BS-RS switching* models, a simulation layout of 5 by 5 hexagon cells was used with an inter-side distance of 1.732km and switching threshold ρ_{th} =0.6 [5]. λ_b was assumed to be 138.9×10^{-3} calls/sec, the service time was set at 180sec with δ_b =1PRB, which corresponds to a peak-time load of 25 PRBs, while the time-inhomogeneous traffic used the rate function displayed in Figure 1. All other simulation environment parameter settings are summarised in Table I and are fully congruent with the 3GPP/LTE standard [9].
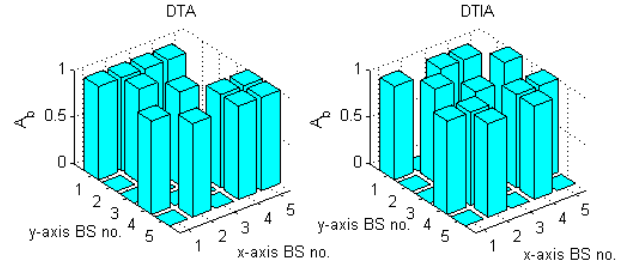
Figure 3(a) compares the performance of DTA and DTIA in terms of the average number of active BSs over a 24-hour period, with the normalized traffic load being averaged in 15-minute slots. The plots confirm that DTIA is able to maintain more BSs in dormant mode in the early morning while conversely more BSs are active in the evening compared to DTA, though the average number of active BS across the day is the same for both algorithms, so they consume the same P_f^* in (5). Figure 3(b) contrasts the selected BS sets chosen to be dormant at a specific time instant (11.00am) for DTA and DTIA respectively. While both have 12 active BSs, the chosen BS sets are very different. The important point to stress is that the DTIA BS set selection which remains active is better than for DTA because those BSs which incur the highest interference are given priority to switch to dormant mode hence leveraging better off-cell users' link quality. This is apparent in the higher throughput of off-cell users and the lower transmission energy consumption.

TABLE I: SIMULATION ENVIRONMENT PARAMETERS

Parameters	Value		
Carrier frequency	2 GHz		
Channel bandwidth	5 MHz		
Max. transmit power (BS/RS/MS)	43/24(or 30)/23 dBm		
Antenna gain (BS/RS/MS)	16/10/0 dBi		
BS/RS antenna height	32m		
Noise power	-141 dBm/Hz		
BS-MS/RS-MS & BS-RS links	Type B (NLOS) & D (LOS) (suburban, terrain Type B) [10]		
Shadow standard deviation	8 dBm		
Receiver sensitivity	-99dBm(MS),-103dBm (BS)		
Power model parameters in (5)		a	P_f
	BS	21.45	354.44
	RS	7.84	71.50
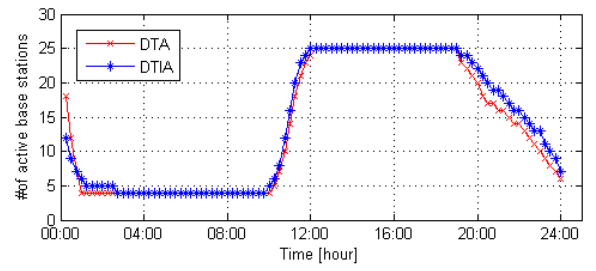
(a)

(b)

Figure 3: (a) Average number of active BS over a 24-hour interval; (b) DTA and DTIA comparison of the set of active BSs – snapshot at 11:00am.

Figure 4 compares the corresponding EE (3) performance for DTA and DTIA over an entire day. While the former considers only traffic load using ρ_{th} for switching, DTIA turns dormant those BSs suffering the highest interference first, so overall network interference is attenuated and EE improved during low traffic load periods. For example, the EE for DTIA in the morning period (1:00am to 11:00am) is nearly 22% higher than for DTA. Furthermore, by predicating the selection of the best active BS set upon the received interference of each BS, overall network throughput is enhanced. Figure 4 also confirms *BS-RS switching* consistently performs better than the *BS sleeping* model using both the DTA and DTIA algorithms. This is because by switching to RS mode, the distance between the neighbouring BSs which are serving the off-cell MSs is reduced, so lowering the transmission power consumption. Similarly as Figure 5 corroborates, the off-cell user throughput for off-cell MSs is improved by the *BS-RS switching* model
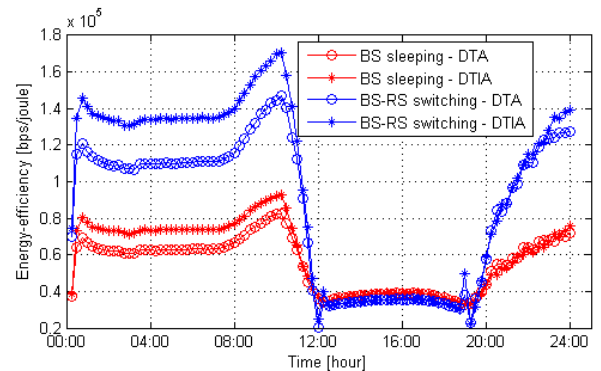

Figure 4: EE performance comparison of energy-saving BS switching techniques over a 24-hour window.
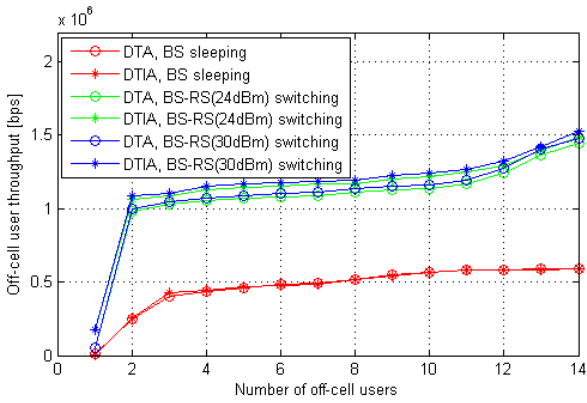
Figure 5: Average off-cell MS throughput verses the number of off-cell users.

with 24*dBm* and 30*dBm* power classes of RS being used. The reason for this is the shorter distance between the BS and off-cell MSs by the *switched*-RS. Note, also DTIA achieves a further small performance enhancement; from typically 1Mbps to ≈1.1Mbps when the number of off-cell users is 2 or more.

Figure 6 presents the cumulative average blocking probability for every switching decision occurrence during the day with the results confirming DTIA provides a consistently
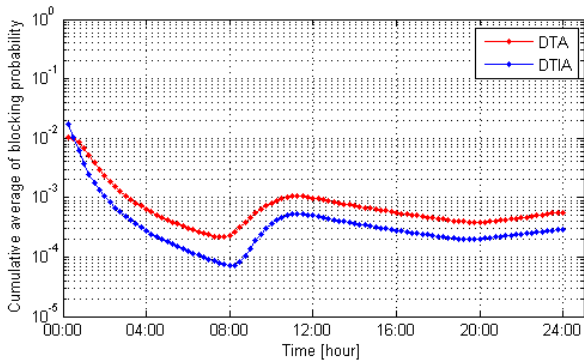

Figure 6: Cumulative average blocking probability for one full day for the DTA and DTIA algorithms.
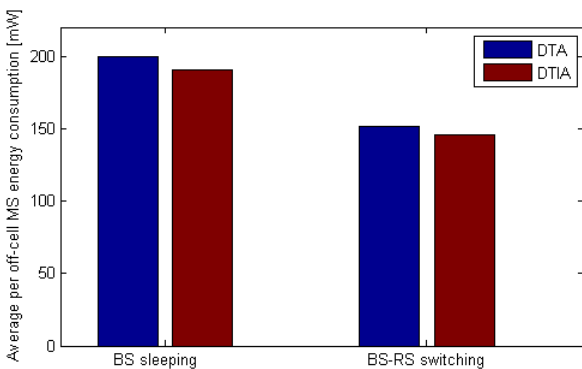

Figure 7: Average per off-cell MS energy consumption with the *BS sleeping* and *BS-RS switching* models for DTA and DTIA.

lower blocking probability than DTA, due to the better choice of BS to remain active during the low-peak traffic periods. Finally, Figure 7 contrasts the energy reduction performance for off-cell MSs achieved by DTIA and DTA, with the former providing a more than 5% improvement. The graphs also inculcate that better energy savings (≈30%) are achieved using the *BS-RS switching* model, which is ultimately manifest in an enhanced quality uplink between the BS and MS.

V. CONCLUSION

This paper has presented a *dynamic traffic-aware* (DTA) and *dynamic traffic-and-interference aware* (DTIA) switching strategy to change the operating mode of certain *base stations* (BSs) to dormant to conserve energy, while retaining the best selection of active BS which uphold the desired *quality-of-service*. For DTA, BS switching is founded on the traffic load profile of each BS and uses a preset threshold, while DTIA in contrast, incorporates received BS interference power along with traffic load to manage the switching decision. DTIA by virtue of choosing the better BS set to remain active affords improved network energy efficiency, and while DTA and DTIA use the same number of active BS on average, they are dissimilar sets. Both new switching algorithms have been seamlessly integrated into the *BS sleeping* and *BS-RS* (relay station) *switching* models, with the latter consistently providing superior performance for off-cell mobile station throughput and energy efficiency.

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