Progress In Electromagnetics Research C, Vol. 31, 153–168, 2012

DYNAMIC BASESTATION ANTENNA DESIGN FOR LOW ENERGY NETWORKS

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Abstract—A challenge faced by the information and communications technology (ICT) industry is the growing data volume and associated energy consumption. How to both meet a dynamic traffic demand at a consistently low energy consumption level is of importance from both commercial and climate change perspectives. This paper proposes a dynamic basestation concept that allows the number of active sectors to be adjusted in accordance with the traffic load. This is achieved through a novel switchable antenna design that can adjust the azimuth beam-width by using a tuneable reflector. Simulation and theoretical results show that the dynamic basestation can reduce the total operational energy of a cellular network by a peak of 75% and a mean of 38%.

1. INTRODUCTION

Over the past 5 years, the average communication data volume has increased by more than a factor of 10 and the associated energy consumption by at least 20%. Most of the wireless energy consumption is consumed by the outdoor cellular network's basestations (70%). This energy consumption growth has had a negative impact on both the carbon footprint and the profit margin of the wireless ICT industry. Globally, mobile network operators (MNOs) contributes to 0.5% of carbon emissions. Commercially, approximately a third of the operational and maintenance (O&M) bill of MNOs is attributed to energy consumption. Therefore, there is an urgency to reduce energy consumption of basestations, whilst maintaining coverage and capacity.

A promising solution to the challenge is to exploit the fact that mobile traffic is very dynamic, but the network coverage and capacity

Received 15 June 2012, Accepted 9 July 2012, Scheduled 18 July 2012

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is very static. By adapting the coverage and capacity in accordance to the traffic environment, significant energy can be saved [1].

A key consideration of basestation (BS) design is to maximize spectrum reuse. This is achieved by *sectorization*, so that a BS consists of multiple sectors with directional antennas. The azimuth beamwidth of the antennas pre-dominantly depends on the number of sectors. Generally speaking, the amount of bandwidth and the power consumption at the BS scales *linearly* with the number of sectors [2]. Typically, a network consisting of multiple BSs is deployed to meet an offered peak traffic rate [3]. In the temporal domain, the traffic intensity typically varies by 4 to 6 folds during the course of a day. In the spatial domain, the traffic intensity between BSs can vary by up to 10 folds.

The challenge addressed in this paper is how to design a dynamic BS that can meet the peak traffic demand, but consume the minimum amount of energy across the variations. The system level energy and capacity performance of this proposed BS is analyzed in the context of a multi-cell multi-user simulator.

1.1. Existing Techniques

Existing literature has proposed a variety of energy efficient techniques, which can be categorized into the following:

- *Offloading*: offloading a certain proportion of the data from high energy BSs to low energy nodes, i.e., from macro-BSs to relays [4]. The advantage of this technique is that the coverage pattern of the network has not changed dramatically, but the energy saved is not dramatic due to the fact that all existing infrastructure remains active and additional nodes are inserted [5].
- *Sleep Mode*: switch-off certain BSs that experience a low traffic demand [1]. The advantage of this technique is that by switching-off infrastructure, a significant amount of energy is saved. However, coordinating which BSs to switch-off, as well as predicting the subsequent coverage pattern is challenging.

In order to maximize the performance of the aforementioned techniques, generally some level of re-deployment of BSs and inter-node coordination is needed [6]. For cost reasons, there is a reluctancy for MNOs to implement extensive inter-BS coordination interfaces or to re-deploy the network. Therefore, a pragmatic energy-efficient solution must incorporate the following features:

(i) **Scalability**: significantly reduce energy consumption with lower offered traffic rate.

(ii) **Reliability**: not incur unexpected coverage changes and cause outages.

(iii) **Pragmatic**: does not require inter-BS coordination, network-wide control, or the installation of new network elements.

In order to achieve this, dynamic BS design and its application has been proposed before in various forms on a system level [7–9] and on an antenna design level [10–12].

To date, adaptive antennas for cellular networks have included designs for dual-band operation where the frequency band of operation can be electronically switched [13, 14] and designs which can be switched between omni-directional and sectorized radiation patterns [12, 15, 16]. The designs proposed in [15, 16] comprises high-gain collinear antenna surrounded by an active cylindrical frequency selective surface (FSS). By electronically controlling the state of the FSS a directive radiation pattern can be obtained that can be swept in the entire azimuth plane, or if the FSS is switched off omni-directional coverage can be provided. The disadvantage of this design and similar designs is that that resultant BS is *capacity-limited* as all users share the same RF feed regardless of the configuration.

1.2. Proposed Solution

One promising concept that can efficiently scale energy consumption with the traffic load, is to allow the BS to dynamically switch between:

- High Capacity-High Energy: multiple directional sectors, during periods of high traffic.
- Low Capacity-Low Energy: single omni-directional sector, during periods of low traffic.

Given that the offered traffic varies in time and space, a scalable radio-access-network (RAN) should consist of multiple BSs that have different number of sectors, that can change in accordance with the traffic environment. Each BS only needs to be aware of its own traffic load and does not need knowledge on the state of neighbouring BSs. Furthermore, no additional infrastructure or network-wide controller is required in the network. The antenna design itself doesn't save energy, but it enables the BSs to dynamically *sleep* and *wake* its sectors. The two primary BS designs considered in this paper are:

- **Reference BS**: 6-sector BS that maintains all the sectors as active across all traffic variations. The transmission energy consumption is scaled linearly with the offered traffic.

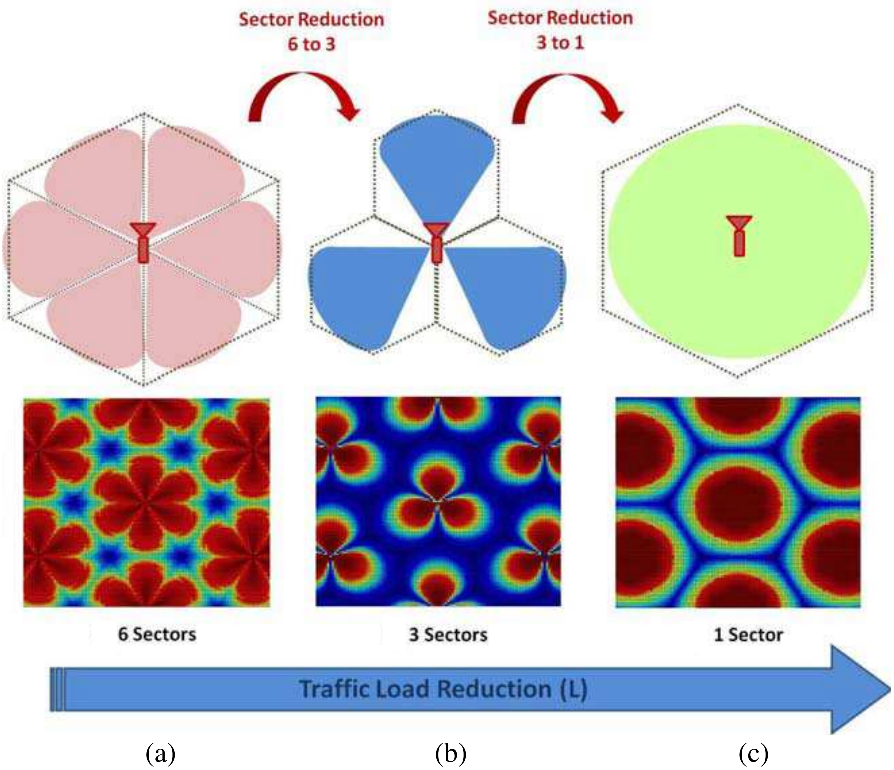

Figure 1. Dynamic BS's operational modes (top) and mean received SINR plots (bottom) across different traffic loads: (a) 6 sectors, (b) 3 sectors, (c) 1 sector.

- **Dynamic BS**: 6-sector BS that dynamically switches-off its sectors and adapts the antenna beam pattern in accordance, as shown in Figure 1.

In order to achieve this, the BS has to either switch between different antenna types or employ an adaptive antenna that can change its beam pattern.

Whilst this idea has been proposed before on a system-level [8, 9] and antenna-level [15, 16], to the best of our knowledge no joint-consideration in terms of energy-efficiency has been considered. Furthermore the proposed antenna design is novel and has the following benefits over existing designs:

- increased coverage due to adaptive beam-forming and gain control. To date, research has predominantly focused on the control of the elevation beamwidth and electrical down-tilt of antenna systems. This can be achieved by traditional amplitude and phase control of the antenna array [11, 17] or using time modulated linear arrays (TMLAs) where the main beam direction is controlled by altering the switch-on time sequence of each element in the array [18];

- lower transmit power requirements due to optimized transmission towards the user. This can include aspects of elevation beamwidth optimization but also azimuth beamwidth control for micro- or pico-BSs [19, 20];
- improved link quality due to spatial or polarization diversity gain. Presently, cellular RANs combine spatial diversity between BSs, and polarization diversity within a BS. Many examples of suitable antennas are available in the literature [21–23]. Current research focus is towards multiple-input multiple-output (MIMO) communication techniques which make use of multi-element antenna arrays at both the transmitter and the receiver of a radio link. MIMO has been theoretically shown to drastically improve the capacity over more traditional single-input single-output (SISO) or single-input multiple-output (SIMO) systems [24].

The paper's system and antenna integrated study considers multi-BS interference and total energy consumption. This paper demonstrates that the proposed adaptive antenna design is simple and significant energy can be saved compared to a reference BS design. The paper presents the dynamic BS design in Section 2 and how it incorporates into the network in Section 3. The theoretical relationship between traffic load and energy consumption, as well as theoretical bounds is shown in Section 4. The results for the energy saved is shown in Section 5.

2. DYNAMIC BS DESIGN

2.1. Reconfigurable Antenna Concept

The schematic for a reconfigurable directional to omni-directional antenna system is presented in Figure 2(a). This particular design is for a 3-sector to a 1-sector BS, which can be extended to multi-sectors such as that envisage in Figure 1. The design uses a combination of a radiating dipole and a folded reflector to provide the required beam reconfigurability. The reflector considered comprises of an array of 6 horizontal metallic strips of length, w, with three vertical strips equally spaced across each half of the reflector. The vertical strips provide the reconfigurability via an array of PIN diodes connected in series with the vertical strips:

- When the diodes are conducting, each face of the reflector appears as a continuous metallic sheet, due to the short electrical spacing of the vertical strips. Combined with the 120° folded reflector this provides the 75° azimuth beamwidth for the directional case.
- When the diodes are non-conducting, the reflector appears as a capacitive grating, which is partially transparent and hence provides the omni-directional beam pattern. In this case the radiating element is a centre fed dipole spaced a quarter wavelength, h, from the reflector.

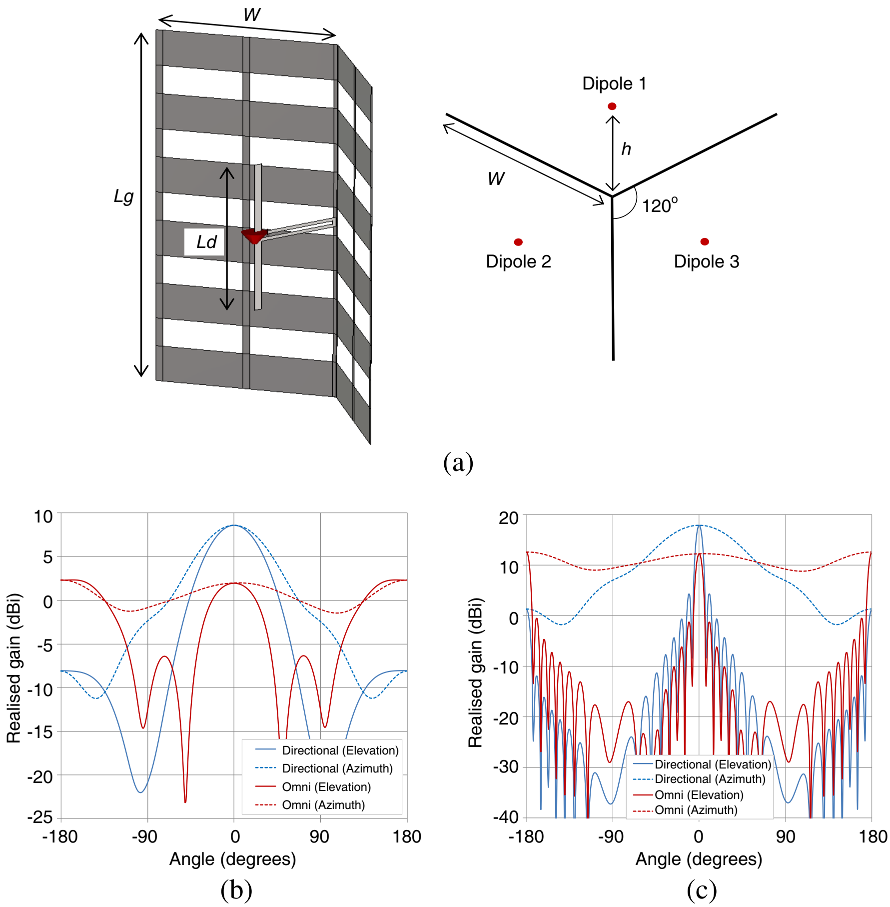

Figure 2. (a) Schematic of reconfigurable antenna; Azimuth and Elevation gain patterns for: (b) the 3-dipole; (c) 12 element antenna array.

The full 3-sector array would comprise of a further two dipoles rotated 120° apart and an additional reflector.

2.2. Antenna Simulation Plots

Electromagnetic simulations of the antenna were carried out using Computer Simulation Technology (CST) Microwave Studio, which is a commercial 3D full wave simulator, based on a Finite Integral (FI) technique. Simulations of the realised antenna gain patterns and antenna input match were carried out for the three dipole case and for a 12 element array to provide the required antenna gain. Figures 2(b) and 2(c) show the azimuth and elevation gain patterns for the two cases. In both cases the input match was better than −10 dB over frequency band of interest.

Figure 2(b) shows that with the antenna in the directional mode of operation the −3 dB beamwidth is 73° and 56° for the azimuth and elevation respectively, with a gain of 8.6 dBi. In the omni directional mode the elevation beamwidth is 100° and the azimuth beam is essentially omni-directional with a 2 dBi perturbation. Figure 2(c) shows patterns for the 12 element antenna array having similar azimuth performance as in Figure 2(b). The elevation beamwidth is 6.5°, with a gain of 17.5 dBi and 12 dBi for the directional and omni modes. The results meet the requirements for LTE BS deployments [25].

3. SYSTEM MODEL

The LTE dynamic simulator is the **VCESIM**, which has been developed at the University of Sheffield for industrial members of the Mobile Virtual Centre of Excellence (MVCE). It is a multi-cell multi-user interference limited simulator and is validated by *industrial sponsors Fujitsu and Nokia-Siemens Networks*, as well as benchmarking against 3GPP standard's performance [27]. The modeling parameter values are defined in Table 1 and is described in detail in our previous work [28]. The system level simulations employ the following key features:

- Monte-Carlo simulations for a multi-BS multi-user setup.
- Wrap-Around is implemented to create a spherical geographical area in order to eliminate edge effects [29].

For a BS with S sectors (typically, each sector has 1 antenna array), the **Load** (L_S) is defined as the ratio between the offered traffic rate R_{traffic} and the maximum capacity of the BS (R_S):

$$L_S = \frac{R_{\text{traffic}}}{R_S}. \tag{1}$$

Table 1. System and hardware parameters.

Parameter	**Symbol**	**Value**
System Parameters		
LTE Operating Frequency	f	2600 MHz
Number of BSs in RAN	N_{BS}	19
Interference Model		19 BS Wrap Around
Propagation Model	λ	WINNER II [25]
Antenna Pattern	$A(\theta)$	Figure 2
AWGN Power per Subcarrier	N_0	6×10^{-17} W
Shadow Fading Variance	σ_s^2	9 dB
Transmission Scheme		SISO
Traffic Load	R_{traffic}	0–120 Mbit/s/km^2 [26]
Hardware Parameters		
BS Coverage Radius	r_{BS}	200–1500 m
BS Transmit Power	P	5–40 W
Radiohead Efficiency	μ	0.2–0.3
Overhead Power	P_{OH}	25–95 W
Backhaul Power	P_{BH}	50 W
Radiohead Proportion	Ω	0.32–0.58
Sleep Mode Overhead Factor	η	0–1

A general model for the total operational power consumption P_{BS} for a BS can be broken down into a load dependent and independent parts [28]:

$$P_{\text{BS}} = S\left(\frac{P}{\mu}L_S + P_{\text{OH}}\right) + P_{\text{BH}} \approx S\left(0.1r_{\text{BS}}L_S + r_{\text{BS}}^{0.62}\right) + 50, \qquad (2)$$

where each parameter and its typical values are defined in Table 1. The load dependent aspect of the expression is known as the radiohead (RH): $P_{\text{RH}} = \frac{P}{\mu}L_S$ and the load independent is known as the overhead and backhaul ($P_{\text{OH}} + P_{\text{BH}}$). This expression can be expressed as a function of the BS coverage radius (r_{BS}), by using a curve-fitting approach on the empirical data from [2]. The fitting is accurate, as shown in Figure 3. The benefit of the modified expression is that there is now a relationship between BS coverage range (BS density) and power consumption.

When the sector of a BS is switched off and no-longer transmitting, the paper assumes the overhead power consumption associated with that sector remains at a faction η of the full value. The paper will consider the resulting gains that arise from different values of η, which

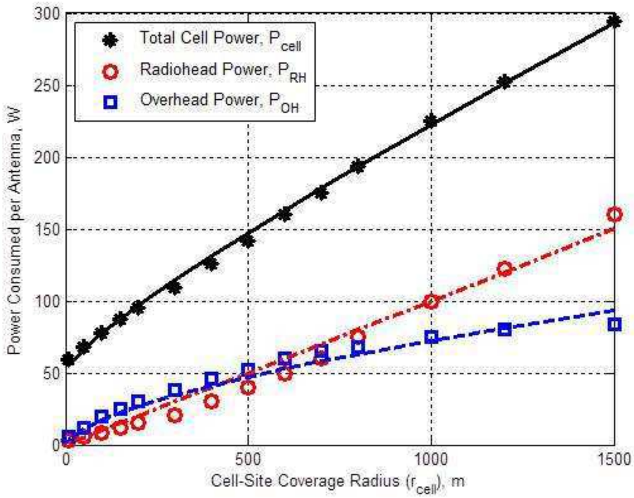

Figure 3. Power consumption per Sector's variation with BS coverage size: Data (symbols) from [2] and theory (line) from expression 2.

typically vary between 0 to 40% [26, 30].

4. ENERGY SAVING BOUNDS

4.1. Reference Bound

The paper defines the energy reduction gain (ERG) as amount of energy saved by a test setup in comparison with a reference setup. The paper first considers the maximum amount of energy that can be saved by the reference BS, as the offered traffic load (L) varies. The ERG achieved in comparison with peak load is

$$\mathrm{ERG}_{\mathrm{Ref.}} = 1 - \frac{P_{\mathrm{BS}}(L=1)}{P_{\mathrm{BS}}(L)} = (1-L)\Omega, \qquad \text{where:} \quad \Omega = \frac{\frac{P}{\mu}}{P_{\mathrm{BS}}}, \tag{3}$$

where for $L \to 0$, the energy saving approaches $\Omega = 30$–50%, depending on the BS technology (expression 2). Therefore, the energy saving gain relative to the peak consumption value is hardware-limited by the ratio between load dependent (radio-head) and total power consumption of the BS.

Table 2. Dynamic BS performance.

Sectors (S)	**BS Capacity (R_S)**	**Capacity per Sector**	Ψ
6	$R_6 = 52$ Mbit/s	8.7 Mbit/s	1
3	$R_3 = 41$ Mbit/s	13.7 Mbit/s	0.64
1	$R_1 = 28$ Mbit/s	28.7 Mbit/s	0.30

4.2. Dynamic Antenna Reduction Bound

The paper now considers the technique of antenna/sector reduction. Consider a dynamic BS with initially S sectors that yield a BS capacity of R_S, and a resultant load L_S, as defined in expression 1. Each stage of reduction to S' sectors also reduces the BS capacity to $R_{S'}$. The resulting load ($L_{S'}$) on the new BS configuration is:

$$L_{S'} = \frac{R_{\text{traffic}}}{R_{S'}} = L_S \frac{R_S}{R_{S'}}. \tag{4}$$

The ERG achieved relative to a peak load power consumption is:

$$\begin{aligned} \text{ERG}_{\text{Dynamic}} &= 1 - \frac{P_{\text{BS}}(L = 1, S)}{P_{\text{BS}}(L_{S'}, S')} \\ &= (1 - \Psi L_S)\Omega + \frac{S - S'}{S}(1 - \eta)(1 - \Omega) \\ \text{where:} \quad \Psi &= \frac{S' R_S}{S R_{S'}} = \frac{(R_S/S)}{(R_{S'}/S')}. \end{aligned} \tag{5}$$

The factor Ψ is effectively the ratio between the capacity per sector between a BS with S sectors and a BS with S' sectors. A low ratio ($\Psi < 1$) would mean that the loss in capacity per BS is low and there is in fact a gain in capacity per sector. The ERG is improved when the value of η is small.

For the considered case of a dynamic BS switching from $S = 6$ to $S' = 3$ to $S' = 1$ sectors, simulation has found the BS capacity and Ψ parameter for different number of sectors and they are presented in Table 2. The decision to switch between sector configurations is based on whether the new configuration's capacity can satisfy the offered traffic load. For an optimistic value of $\eta = 0$, the resulting ERG compared to peak load at each stage is:

$$\begin{aligned} \text{ERG}_{\text{Dynamic}} &= (1 - L_S)\Omega && \text{for: } R_{\text{traffic}} > R_{S'=3} \\ &= (1 - 0.64 L_S)\Omega + \tfrac{1}{2}(1 - \Omega) && \text{for: } R_{\text{traffic}} > R_{S'=1} \\ &= (1 - 0.30 L_S)\Omega + \tfrac{5}{6}(1 - \Omega) && \text{for: } R_{\text{traffic}} < R_{S'=1}. \end{aligned} \tag{6}$$

The bound approaches:

$$\text{ERG}_{\text{Dynamic}} \to \Omega + \frac{S - S'}{S}(1 - \Omega), \tag{7}$$

which is 88–91% for $L \to 0$, $S = 6$, $S' = 1$, $\eta = 0$ and $\Omega = 0.3$ to 0.5 (BS size and technology dependent). This is an improvement over the reference BS energy savings given in 3, which was limited by Ω = 30–50%. For a given load, the ERG is amplified by a low Ψ and a high Ω value. A low Ψ value results from achieving the greatest capacity with the lowest number of sectors active. A large Ω results from BSs that have a greater proportion of load dependent power consumption (typically large macro-BSs, as shown in Figure 3).

4.3. Summary

The most energy efficient dynamic BS design has the following properties:

- **Scalability**: reducing the number of sectors doesn't result in a severe loss in capacity (Ψ).
- **Low Overhead**: most of the power consumption of the BS is load dependent (Ω).

The scalability can be achieved with a strong omni-directional antenna design and the low-overhead can be achieved by reducing the power consumption of cooling and signal-processing units. When comparing the energy consumption of the dynamic and reference BSs, the ERG bound approaches $\frac{S-S'}{S}$ for $\eta = 0$ and $L_{S'} = 0$. The precise load dependent energy saving of the dynamic BS compared to the reference BS is examined in the next section's multi-cell RAN results.

5. RESULTS

5.1. Traffic Variation

The paper now considers how the power consumption value changes for each BS as the offered traffic varies. The results presented in Figure 4 are obtained using both theoretical expressions (lines) and accurate system simulation results (symbols). The model considers macro-BSs with a hardware factor of $\Omega = 0.5$ [2] and various values of the sleep-mode parameter η.

In comparison with the *reference BS*, the mean upper-bound energy saving of 44% ($\eta = 0$) and the lower-bound saving is 11% ($\eta = 1$). Furthermore, a larger (Ω) value will amplify the ERG improvements. It can be seen that for every η value, the energy saved is equal or greater than the reference system, for any offered traffic rate.

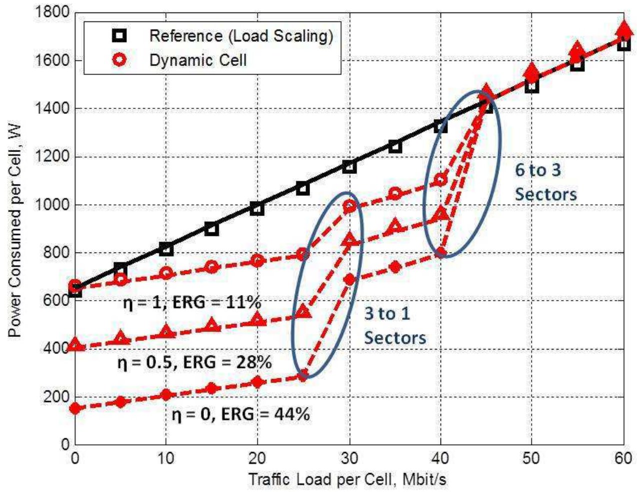

Figure 4. Power consumption variation with traffic load and η for a macro-BS ($r_{\text{BS}} = 1500\,\text{m}$, $\Omega = 0.5$). Simulation (symbols) and theory (lines).

5.2. Urban Traffic Model

The paper now considers how the traffic rate actually varies across the duration of a day. The typical data traffic intensity of a European urban area is dominated by long periods of low load (night and mornings) and short periods of peak traffic load (day and evenings) [26].

The results in Figure 5 show that the greatest energy saving is achieved at the lowest load times, which typically occur during the early hours of the morning (3–7 am), with an energy saving of 75% compared to reference. During the evening, the network is typically operating at full buffer and the associated energy saving compared to reference is none. Under the urban data traffic loads, the mean energy saving achieved is 38%.

It is worth noting that the multi-cell multi-user simulator considers a uniform but random distribution of traffic load. This means that at any particular instance, the BS are not all performing with the same operational mode (number of sectors active). In terms of sensitivity analysis, the underlying assumption is that when a sector is switched off, all or most of the overhead consumption can be switched off ($\eta \sim 0$). The lower bound of the energy savings is when $\eta = 1$ and the mean

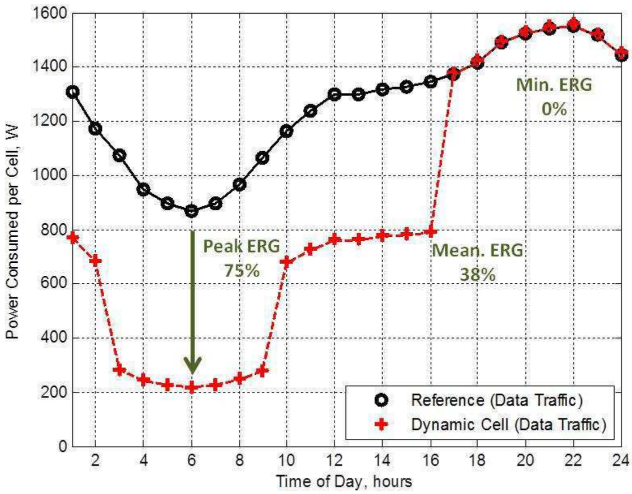

Figure 5. Power consumption variation with data traffic loads throughout a day. Simulation (symbols) and theory (lines).

lower-bound energy saving is 13%. A more general sensitive study has been performed in our previous work [28], whereby it was found that accurate interference and pathloss models were important. This is why a 19-BS interference wrap-around [29] and 3GPP pathloss models have been employed in the simulator, and a good match between simulation and theoretical results are observed.

6. CONCLUSIONS

By incorporating the novel antenna design, the paper has demonstrated how a cellular network can dynamically adjust its capacity and energy consumption in accordance to the traffic load. In comparison with the conventional BS design, the energy savings achieved reach a peak of 75% and a mean of 38% under a realistic traffic profile. The proposed solution is pragmatic in the sense that no additional deployment is needed, as well as no inter-node coordination or network wide control is required.

On a system level, the dynamic BS shows better scalability than the reference BS in terms of reducing energy consumption in accordance to the offered traffic, as well as not sacrificing the coverage pattern of the network significantly. On an antenna level, the proposed design has the potential to yield improved coverage, higher diversity and lower transmit power; when compared to existing dynamic antenna designs.

The paper has shown that an integrated system-and-antenna design has resulted in significant operational energy savings, which has a high impact on the future deployment of energy- and cost-efficient mobile communications.

ACKNOWLEDGMENT

The work papered in this paper has formed part of the Green Radio Research Programme of the Virtual Centre of Excellence in Mobile and Personal Communications, Mobile VCE. Fully detailed technical papers are available to Industrial Members of the Mobile VCE. www.mobilevce.com.

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