Dynamic Cell Expansion: Traffic Aware Low Energy Cellular Network

Weisi Guo, Tim O'Farrell
Department of Electronic and Electrical Engineering
University of Sheffield, United Kingdom
Email: {w.guo, t.ofarrell}@sheffield.ac.uk

***Abstract*—This paper addresses the challenge of designing a cellular network that can meet a dynamic range of offered traffic loads at a low energy level. Cellular networks are conventionally deployed to meet a high traffic load and can be energy inefficient at lower loads. The paper proposes a novel cell expansion technique that can reduce total energy consumption by up to 46% depending on the offered load. Dynamic cell expansion switches off a certain pattern of cell-sites in accordance with traffic load and allows neighbouring cells to compensate by expanding their coverage.**

A key novelty is achieving this via creating inner and outer cell regions using vertical sectorization and adaptively tilting outer cell antennas to expand and contract cell coverage. Furthermore, a management service is proposed to handle contention between competing cells. The gains achieved compared to existing techniques is 22% higher and the results of this paper can have a profound impact both on the operators' revenue and global environment, reducing up to 11 power plants world wide.

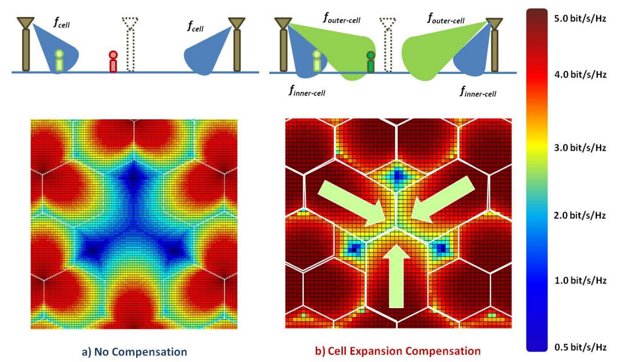


Fig. 1. Simulation plot of averaged received SINR with central cell-site switched off: a) without compensation by neighbouring cells, b) with compensation by neighbouring cells's dynamic expansion.

I. Introduction

Until recently, cellular networks have been primarily designed to meet the challenges of service quality. However, in the past decade, there is increasing attention on the importance of reducing operational energy and cost consumption, in order to increase commercial competitiveness and meet emission targets. In the past 5 years, the traffic volume has increased by more than a factor of 10 and the associated energy consumption by 20%. The majority (80%) of this energy is consumed in the outdoor cells of the radio access network (RAN) [1]. In terms of architecture, existing work has shown that the OFDMA based LTE is 60% more spectrally efficient than the SSMA based HSPA system. In the context of a LTE system, the challenge is: **how to reduce energy consumption for dynamic traffic loads?**

A. Review of Existing Work

During the course of a day, the urban traffic load can vary by up to 4-6 folds. It remains unclear how a single solution can dynamically satisfy the dynamic range, whilst consuming the least amount of energy across the variations. To an extent, this has been answered by the following work:

- **Reduction**: Switching high capacity MIMO down to SIMO to reduce energy consumption and capacity [2]. Switching multiple directional cells into single omni-directional cells [3].
- **Small-Net Sleep Mode**: Deploying a higher density of low power cells and switching off (sleep mode) those without users attached [4].
- **Reconfiguration**: Changing the cell coverage radius by several folds, but no detailed mechanism or analysis is given [5].

Most existing work on such areas assume: simplified or no inter-cell interference [6], employing the Shannon capacity expression without saturation limits; only radio transmission energy whilst neglecting the significant overhead energy [3]. Clearly these assumptions are fundamentally flawed, due to the fact that HSPA and LTE networks are interference limited and operate in regions that do not approach the Shannon bound. Furthermore, radio transmission power constitutes a small proportion of the total operational power consumption. These assumptions can significantly alter the existing results and conclusions drawn [7] [8].

B. Proposed Solution

In this paper, we propose an advanced LTE-Advanced radio architecture that employs the following operational progression:

1) Improve the cell's coverage flexibility by introducing inner and outer cells, this is achieved by antenna directionality and different frequency bands.
2) When the traffic load of a cell is reduced below a threshold, it has the opportunity to go into sleep mode and handover users to neighbouring cells. Neighbouring cells

978-1-4673-1881-5/12/$31.00 ©2012 IEEE

TABLE I
SYSTEM PARAMETERS FOR VCESIM SIMULATOR.

Parameter	Symbol	Value
LTE Operating Frequency	f_{LTE}	2600MHz
LTE System Bandwidth	BW_{LTE}	20MHz
Subcarrier Size	BW_{sc}	15kHz
Cell Radius	r_{cell}	200-1500m
Cell Max. Tx Power	P_{cell}	6-40W
Number of sectors per site	N_K	1,3,6
Number of antennas per sector	N_A	1,2
Antenna Pattern	$A(\theta)$	Equation (2)
Offered Traffic Rate	$R_{traffic}$	6-120 Mbit/s/km^2
UE Downlink QoS	R_{QoS}	1Mbit/s
UE antenna Height	H_{UE}	1.5m
Cell antenna Height	H_{cell}	10-35m
Pathloss Model	λ	WINNER II urban micro
AWGN (1 sided PSD)	N_0	6×10^{-17} W
Shadow Fading variance	σ_{sd}^2	9dB
Mobility Model	$Mobility$	Brownian Motion

expand their coverage using dynamic antenna tilting, as shown in Fig. 1.

3) Contention between which cell sleeps (contracts) and which compensates (expands) is managed by a centralized Sleep Mode Management (SMM) service.

The paper compares the proposed cell expansion technique with stand alone and combined existing methods in literature [2] [3] [4].

II. SYSTEM MODEL

A. Link Level and System Level Capacity

For an OFDMA system (such as LTE), the downlink received SINR ($\gamma_{s,i}$) in a sub-carrier s in cell i is calculated as a function of the transmit power ($P_{s,i}$), antenna gain (A), interference cells j, AWGN (N_0), log-normal shadowing ($\mathcal{S}$) and multipath fading gain (h):

$$\gamma_{s,i} = \frac{|h_k|^2 \lambda_i 10^{\frac{S_i + A(\theta_i)}{10}} P_{s,i}}{N_0 + \sum_{j=1, j\neq i}^{N_{cell}} |h_i||h_j| \lambda_j 10^{\frac{S_j + A(\theta_j)}{10}} P_{s,j}}, \quad (1)$$

where cells j are the co-frequency cells to cell i. The multipath and the Log-normal shadow fading parameters are modelled as $h \sim \mathcal{N}(0,1)$ and $\mathcal{S} = \mathcal{N}(0, \sigma_{sd}^2)$ respectively. The paper employs the appropriate adaptive modulation and coding scheme given by internal link level simulators and verified against [9]. All parameters values are given in Table I.

The system simulator is the **VCESIM**, which is an LTE dynamic system simulator developed at the University of Sheffield for industrial and academic members of the Mobile Virtual Centre of Excellence (MVCE). The combined system and link performance is validated against results in established simulators [9] and 3GPP standards [10]. The directional antenna pattern employed has the following gain (dB), for an angle θ_a on the azimuth and an angle θ_e on the elevation plane from the bore-sight direction:

$$A_{cell} = A_{bs} - \min[-A_a(\theta_a) - A_e(\theta_e)], \quad (2)$$

where $A_a(\theta_a) = \min[12(\frac{\theta_a}{\theta_{3dB,a}})^2, 25]$ and $A_e(\theta_e) = \min[12(\frac{\theta_e}{\theta_{3dB,e}})^2, 20]$. The bore-sight gain is $A_{bs} = 17.6$dBi and the 3dB beam-widths are: $\theta_{3dB,a} = 75^o$ and $\theta_{3dB,e} = 20^o$.

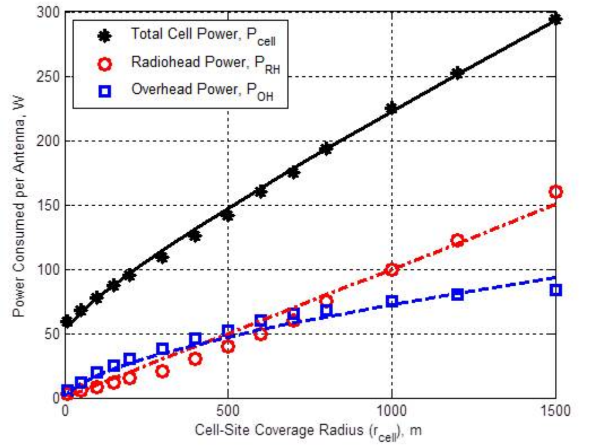


Fig. 2. Power Consumption Data variation with cell size, data from [11] and theory from expression (3).

B. Energy Consumption

A general power consumption model for a cell with N_A antennas is:

$$\begin{aligned} P_{cell} &= N_a(\frac{P_{max}}{\mu_{RH}} L + P_{cell}^{OH}) + P_{BH} \\ &\approx N_a(0.1 r_{cell} L + r_{cell}^{0.62} + 50), \end{aligned} \quad (3)$$

where the overhead power consumption is P_{cell}^{OH} and the back-haul power consumption per cell is typically $P_{BH} = 50W$. This has been further improved as a function of cell size (r_{cell}) to fit empirical data from [11], as shown in Fig. 2. The load of the cell is defined as the ratio between the offered traffic in the cell and the maximum achievable throughput of the cell: $L = \frac{R_{\text{traffic}}}{R_{\text{cell}}}$. The radio-head power can be defined as: $P_{cell}^{RH} = \frac{P_{max}}{\mu_{RH}} L$. In order to compare two systems, a useful metric is the Energy Reduction Gain (ERG), which is the percentage reduction in energy consumption when a *test* RAN is compared with a *reference* RAN:

$$\text{ERG}_{RAN} = 1 - \frac{N_{cell,test} P_{cell,test}}{N_{cell,ref.} P_{cell,ref.}}. \quad (4)$$

C. Energy Saving Bounds

The paper considers a certain research technique that can improve the capacity of each cell by a factor f. There are **two fundamental energy saving limits** that can be achieved:

- **Fixed Deployment:** the number of cells remains the same, but the load is reduced by a factor of $\frac{1}{f}$. The ERG achieved is:

$$\text{ERG}^{+}_{\text{RAN,Fixed}} = (\frac{f-1}{f})\Omega, \quad (5)$$

where $\Omega = \frac{\frac{P}{\mu_{RH}}}{P_{cell}}$. The bound approaches 40-60% for $f \to \infty$. Therefore, the bound is limited by the ratio between radio-head and total power consumption (Ω).

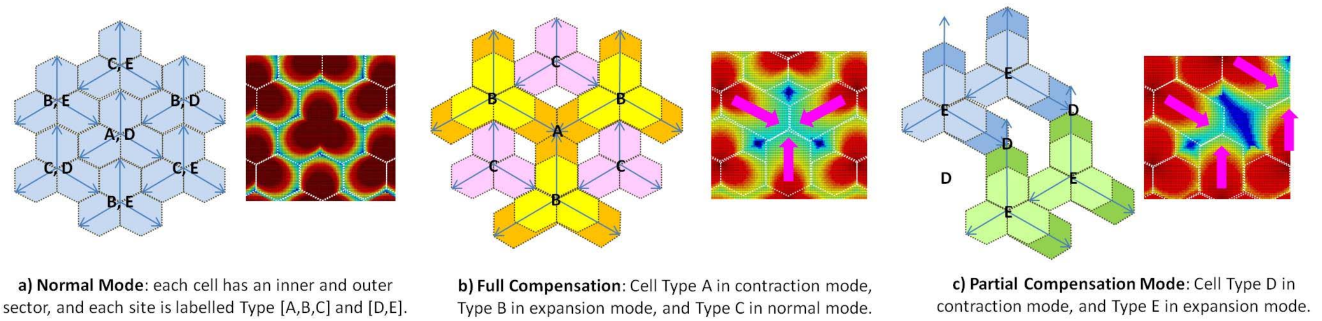


Fig. 3. Cell Expansion States: a) Normal Mode, b) Full Expansion Mode, and c) Partial Expansion Mode.

- **Re-Deployment:** fewer cells are needed to achieve the same load of $L = 1$. Assuming that the power consumption per cell is the same, the ERG achieved is:

$$\text{ERG}^{+}_{\text{RAN,Re-Dep.}} \sim \frac{f-1}{f}, \tag{6}$$

which approaches 100% for $f \to \infty$. Therefore, the bound is dependent on the capacity gain f.

The paper now considers dynamic cell expansion and compares its performance with other dynamic techniques.

III. Dynamic Cell Expansion

A. Introduction

The rationale of cell expansion as a low energy solution is that it switches off a percentage of cells, as well as reducing the interference of the network in that process. The cells can operate in the following modes:

1) **Normal**: all cells maximize the throughput of users within its traditional coverage area.
2) **Contract (Sleep)**: the cell is switched off and its users are passed to neighbouring cells, which must expand to compensate for the coverage loss.
3) **Expand**: the cell expands by tilting its outer cell antenna directionality towards the contracted cell area.

As shown in Fig. 1, the mechanism requires inner and outer cells to be implemented. This is achieved by deploying an additional vertical set of cell-sectors and adopting different antenna down-tilt angles. The outer cell-sectors are at $f_{\text{cell-outer}}$=800MHz and the inner cell-sectors are at $f_{\text{cell-inner}}$=2.6GHz. When 800Mhz is employed on the outer sectors (as opposed to 2.6GHz), the pathloss attenuation can be reduced by approximately 10dB, allowing better expansion of cell coverage, without increasing the interference unduely. The total bandwidth in all systems under comparison is kept constant for a fair spectral efficiency comparison.

B. Operation Mechanism

Each *cell-site* has two identities: $I_{full} = \{A, B, C\}$ and $I_{part} = \{D, E\}$. They are used to identify the role of the cells in various cell expansion roles. As shown in Fig. 3:

- Full Expansion: Cell type B is compensator for type A, and C is uninvolved. Likewise, A is the potential compensator for C. Therefore, a maximum of $\frac{1}{3}$ cells can be asleep at any one time.
- Partial Expansion: Cell type D and E are mutual compensators. Therefore, a maximum of $\frac{1}{2}$ cells can be asleep at any one time.

TABLE II
Cell Capacity for Various Operation Modes.

Mode	Capacity per Cell	Capacity Loss
Normal Mode (C_{norm})	67 Mbit/s	0%
Full Expansion ($C_{\text{exp,full}}$)	31 Mbit/s	54%
Full Contraction ($C_{\text{sleep,full}}$)	27 Mbit/s	69%
Partial Expansion ($C_{\text{exp,part}}$)	45 Mbit/s	33%
Partial Contraction ($C_{\text{sleep,part}}$)	16 Mbit/s	76%

The achievable capacity of a cell in various modes of operation is found via simulation results and presented in Table II. It can be seen that under full expansion, a reasonable parity between the capacity of the expanding and contracting cell is achieved (15% difference). Under partial expansion the throughput difference is 43%, because fewer compensating cells are involved. However, the tradeoff is that partial compensation can save up to 50% of the energy consumption.

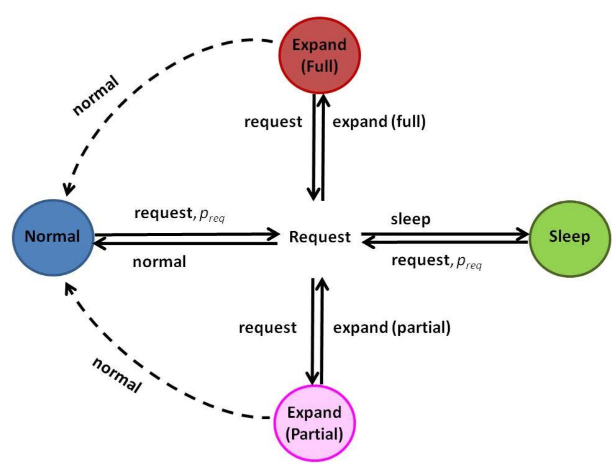
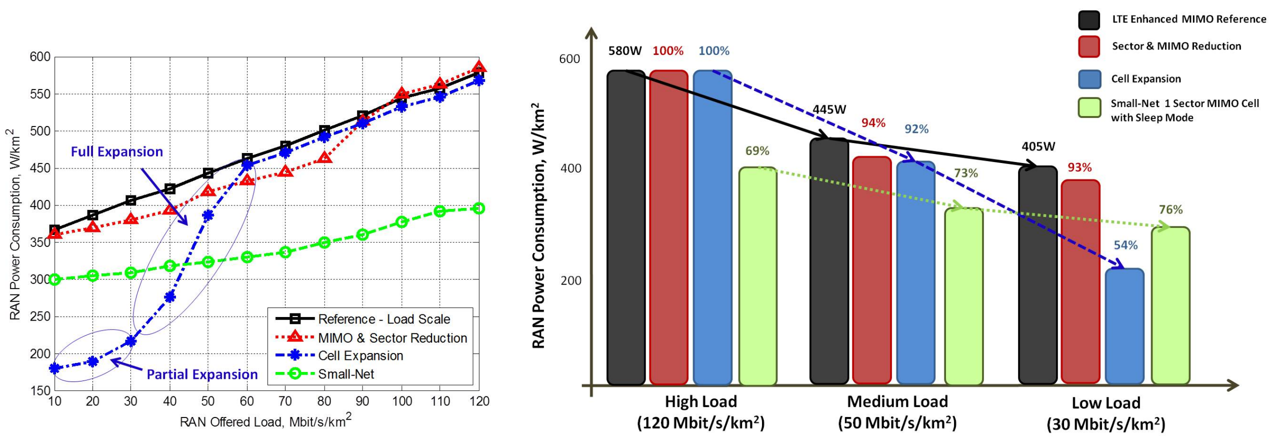


Fig. 5. Cell Expansion State Markov Model, controlled by the Sleep Mode Management (SMM).

C. Contention Mechanism

A dilemma arises when two adjacent cells that can potentially compensate each other, both wish to go to sleep. In order



a) Power Consumption vs. Capacity Tradeoff for a constant deployment.

b) Summary of Power Consumption with Dynamic Traffic Load

Fig. 4. Power-Capacity-Tradeoff and Energy Reduction Gains (ERG) for different deployment schemes.

to account for this potential conflict, a regional co-ordination must be performed so that the largest number of cell-sites can be put in sleep mode, whilst the traffic load is still met. The paper introduces a **Sleep Mode Management (SMM)** mechanism that controls the state of cells, as shown in Fig. 5.

- **Normal**: When the load of a cell is above a threshold ($L > C_{\text{sleep}}$) or the associated compensating cells have a load ($L > C_{\text{exp}}$), the cell operates in normal mode.
- **Request**: When the load of a single cell drops below a threshold ($L \leq C_{\text{sleep}}$), it can request to go into contraction / sleep mode. This is checked on a periodic basis. It doesn't mean the request is necessarily successful. The probability of the request transition shown in Fig. 5 is:

$$p_{\text{req}} = \sum_{m=0}^{C_{\text{sleep}}} \binom{M}{m} (\frac{1}{N_{cell}})^m (1 - \frac{1}{N_{cell}})^{M-m}, \quad (7)$$

  for a threshold of T and M users in N_{cell} cells. Note, request is not a state, but a command sent from the cell to the SMM.
- **Expansion and Contraction**: This request is processed by the SMM. A request to contract is successful if none of the compensating cells are requesting sleep mode, and that the load in the compensating cells is ($L \leq C_{\text{exp}}$). Full or Partial Cell Expansion occurs, depending on the traffic load.
- **Contention**: If one or more of the neighbouring cells are requesting sleep mode, contention exists. The solution that maximizes the number of cells in sleep mode, whilst satisfying the traffic load is found. This is done by considering each of the call identity categories ($I_{full} = \{A, B, C\}$, $I_{part} = \{D, E\}$) in turn and selecting the lowest energy solution.

IV. Cell Expansion Results

A. Uniform Load

Given a deployment that meets a high offered load target, the results in Fig. 4 show the energy reduction for **Dynamic Cell Expansion**. When compared with the *reference baseline* that scales radiohead energy consumption with load, the ERG values achieved compared to a reference technique are:

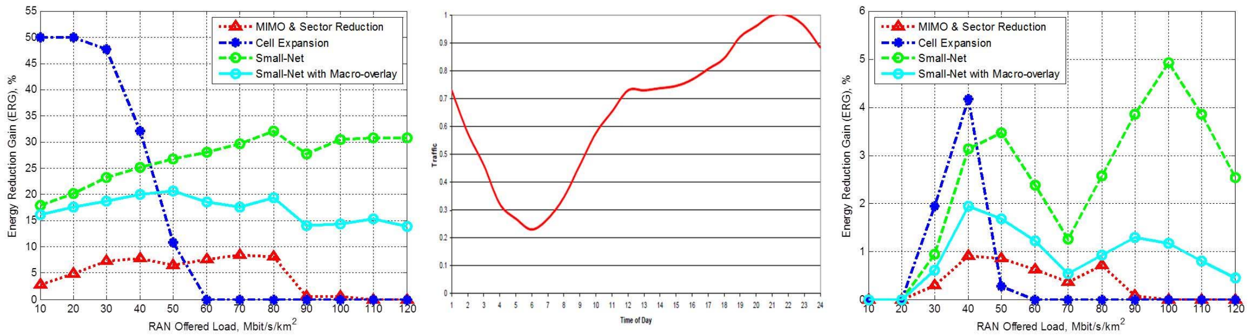
- **Antenna Reduction** [2] [3]: up to 7% relative to the reference and 30% relative to the peak consumption.
- **Small-Net with Sleep Mode** [4]: up to 31% relative to the reference and 22% to the peak consumption.
- **Cell Expansion**: up to 46% relative to the reference, 68% relative to the peak peak consumption, and 22% relative to the best alternative technique.

From Fig. 4, it can be seen that at medium to high loads, the energy consumption of the Small-Net solution is lower than cell expansion (25%). At loads below $L = 0.38$ (45 Mbit/s/km^2), the effect of cell expansion dramatically reduces the energy consumption of the network. The factors that have dominated cell expansions performance are: reduced interference and reducing the total operational energy of a cell by switching cells off. Fig. 6a shows the ERG results at each traffic load value over the course of a day. The impact of the cell expansion results compared to the reference system is that up to 11 power plants world wide can be saved, and this value is set to rise over the next decade. The paper now weights the results with typical traffic distributions over the coarse of a day.

B. Non-Uniform Load

In realistic circumstances, deploying Small-Net will require a macro-cell overlay. Deploying only pico-cells of 100m radius will not be plausible when a certain percentage of users are of high speed and handovers will become excessive. Fig. 6a considers the impact on the ERG for deploying small-net with a single macro-cell overlay. The results show a significant reduction in the ERG at medium and high loads. By weighting the results in Fig. 6a with the traffic distribution in Fig. 6b, the resulting ERG can be found in Fig. 6c. The key conclusions are as follows:

- **Dense Urban:** for traffic profiles that are predominantly of a medium-high level and with a low percentage of



a) ERG across the offered traffic load

b) Mean Urban Traffic Load Variation over a day.

c) Weighted ERG based on probability of traffic occurrence

Fig. 6. Energy Reduction Gains (ERG) for different deployment schemes under a realistic traffic profile distribution: a) ERG under uniform traffic distribution, b) Urban Traffic distribution [12], and c) weighted ERG according to urban profile.

high speed users, deploying Small-Net (dense pico-cells) with a macro overlay is the most energy efficient solution. Typical energy savings over a conventional deployment is 15-20% across all loads.

- **Sub-urban or Rural:** for traffic profiles that are predominantly of a low-medium level and with a high percentage of high speed users, deploying larger cells with cell expansion is the most energy efficient solution. Typical energy savings over a conventional deployment is 12-50% at low-medium loads.

What the paper has shown is that *cell expansion* is not the most energy-efficient solution across all traffic loads. It is however the most energy efficient architecture for traffic loads that contain either a high percentage of vehicular users or when the duration of low load times is very high, typical of sub-urban and rural traffic profiles.

V. Conclusions

This paper has considered the challenge of how to scale energy consumption with dynamic variations in the traffic load. A sleep mode management service is proposed to handle contention between cells. The proposed dynamic cell expansion technique was compared with solutions in existing literature using a dynamic system simulator that considers a multi-cell, multi-user, full interference urban environment. The conclusion to draw is that existing techniques of switching off antennas can only reduce the radio-head power consumption by up to 30%, an improvement of 7% over the reference. Our solution of switching off cells and expanding neighbouring cells can reduce energy consumption by up to **68%**, an improvement of 46% over the reference and an improvement of 22% over the best alternative technique. Cell expansion represents the most energy efficient solution for rural and sub-urban traffic distributions, whereas a dense deployment of pico-cells is shown to be more energy efficient for urban environments.

Acknowledgement

The work reported in this paper has formed part of the Green Radio Core 5 Research Programme of the Virtual Centre of Excellence in Mobile and Personal Communications, Mobile VCE. Fully detailed technical reports on this research are available to Industrial Members of the Mobile VCE. www.mobilevce.com

References

[1] G. Fettweis and E. Zimmermann, "ICT Energy Consumption - Trends and Challenges," in *Proc. IEEE Wireless Personal Multimedia Communications*, Finland, Sep. 2008.

[2] J. Christofferson, "Energy Efficiency by Cell Reconfiguration: MIMO to non-MIMO and 3-Cell Sites to Omni," in *Green Wireless Communications and Networks Workshop (GreenNet)*, May 2010.

[3] O. Holland, V. Friderikos, and A. H. Aghvami, "Energy efficient cross band spectrum management for mobile operators," in *Proc. IEEE Globecom*, Dec. 2010, pp. 2020–2040.

[4] W. Guo and T. O'Farrell, "Green cellular network: Deployment solutions, sensitivity and tradeoffs," in *Wireless Advanced (WiAd), IEEE Proc.*, London, UK, Jun. 2011.

[5] Z. Niu, Y. Wu, J. Gong, and Z. Yang, "Cell zooming for cost-efficient green cellular networks," in *Communications Magazine, IEEE*, Nov. 2010, pp. 74–79.

[6] F. Heliot, O. Onireti, and M. Imran, "An Accurate Closed-Form Approximation of the Energy Efficiency-Spectral Efficiency Trade-off over the MIMO Rayleigh Fading Channel," in *Communications Workshops (ICC), 2011 IEEE International Conference on*, Jun. 2011.

[7] A. Lozano, A. M. Tulino, and S. Verdu, "Optimal power allocation for parallel gaussian channels with arbitrary input distributions," in *Information Theory, IEEE Transactions on*, vol. 52, Jul. 2006, pp. 3033–3051.

[8] W. Guo, C. Turyagyenda, H. Hamdoun, S. Wang, P. Loskot, and T. O'Farrell, "Towards A Lower Energy LTE Cellular Network: Architecture," in *European Sig. Proc. Conf. (EUSIPCO)*, Sep. 2011.

[9] C. Mehlfuhrer, M. Wrulich, J. Ikuno, D. Bosanska, and M. Rupp, "Simulating the long term evolution physical layer," in *European Signal Processing Conference, EURASIP*, Aug. 2009, pp. 1471–1478.

[10] Ericsson, "Summary of Downlink Performance Evaluation," 3GPP TSG RAN R1-072444, Technical Report, May 2007.

[11] G. Auer, V. Giannini, I. Godor, P. Skillermark, M. Olsson, M. Imran, D. Sabella, M. Gonzalez, C. Desset, and O. Blume, "Cellular energy efficiency evaluation framework," in *Vehicular Technology Conference (VTC Spring), 2011 IEEE*, May 2011, pp. 1–6.

[12] NMIA, "WP2.D2.3: Energy Efficiency Analysis of the Reference Systems," National Media and Infocommunications Authority (NMIA) of Hungry, Technical Report, Dec. 2010.