TOWARDS A LOW ENERGY LTE CELLULAR NETWORK: ARCHITECTURES

Weisi Guo, Charles Turyagyenda, Hassan Hamdoun, Siyi Wang, Pavel Loskot, and Tim O'Farrell

Institute of Advanced Telecommunications, College of Engineering, Swansea University
Swansea, SA2 8PP, UK
phone: + (44) 1142225193, email: (w.guo, 514411, 476506, 515441, p.loskot, t.ofarrell) @swansea.ac.uk

ABSTRACT

One of the emerging challenges faced by industrialists and academics is reducing the energy consumption of cellular networks. The impact of the growing energy consumption, both to the environment and to the operational expenditure of operators can no longer be neglected. This paper introduces the Mobile VCE (MVCE) Green Radio project, and some of its investigation results regarding network architecture. The project has set itself a goal to reduce total energy consumption by 100-fold. This paper focuses on the optimization of architectures, with the aim of significantly reducing energy consumption, whilst maintaining or improving the quality of service (QoS).

1. INTRODUCTION

Traditionally, wireless 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 energy consumption, both from an operational expenditure (OPEX) point of view and from a climate change perspective. Over the past few years, operators and manufacturers have pledged to reduce carbon emissions of wireless networks by up to 50% by 2020. Typical cellular network in UK consumes approximately 40MW (one tenth of a standard coal power plant), and this is increasing with traffic volume. On average, the traffic volume has increased by more than a factor of 10 in the last five years and the associated energy consumption by 16-20%. The majority (~80%) of this energy is consumed in the base-stations and the backhaul of the radio access network (RAN) [1].

With this in mind, this paper investigates techniques to reduce operational energy consumption for a *multi-cell* and *multi-user* LTE cellular network. Specifically, the paper considers the impact of cell size, antenna tilt, network-coded relays and multiple-antenna (MIMO) techniques. This is done with the aid of energy reduction metrics that both measure the radio-transmission efficiency and operation energy consumption.

2. REVIEW OF CHALLENGES

Recent literature has extensively analyzed the performance and optimization of energy efficiency in cellular networks, especially with regard to improving either transmission performance or hardware efficiency. The areas considered include: hardware design [2], sleep mode operation [3], antenna tilt [4], scheduling and radio-frequency techniques [5]. A shared conclusion between our previous work [6] and existing literature [7] is that the greatest energy reduction is achieved by putting cells in a low energy sleep mode during periods of low activity load. Most existing work has tackled energy efficiency by considering only the part of the radio transmission power. In reality, a large proportion of energy consumption is taken up by a fixed overhead consumption. How this overhead affects optimization results is often unexplored, and a reasonable assumption is that it can significantly alter the existing conclusions drawn. It remains an open challenge in how to maximize sleep mode behaviour without sacrificing the QoS. Moreover, it is unclear what the combined optimization of the various energy reduction methods can produce.

2.1 Proposed Solutions

Therefore, whilst there is growing attention on how to optimize the energy efficiency of cellular networks in the past few years, this paper sets itself apart from most existing work by considering both the energy efficiency and the full operational energy consumption of the RAN. Some of the techniques introduced here have been previously considered for their throughput performance merits, but not from their energy consumption perspective. This paper introduces the following energy metrics: Energy Consumption Ratio (ECR), Energy Consumption Gain (ECG) and Energy Reduction Gain (ERG). The former measures the radio transmission (RF) energy efficiency of transmitting a bit of data, and the latter is a dimensionless figure of merit on the reduction in operation energy consumption. The paper is organized as follows. The RAN system model and simulation parameters are defined in Section 3, and the energy metrics are defined in Section 4. In Section 5 the paper analyzes the energy reduction from cell size, antenna height and downtilt optimization. In Sections 6 and 7, the effect on energy efficiency by network coding and MIMO are investigated respectively.

3. SYSTEM MODEL

The paper considers an LTE system that is modelled by our own proprietary Matlab simulator. The investigation considers the following architecture techniques and their potential energy reduction benefit: Cell Size, Antenna Height and Tilt, Network Code Relaying, and MIMO. This is illustrated in

Fig.1. The system model employs the COST231 HATA path-loss channel model with dense urban adjustment. Furthermore, the model also utilizes Rayleigh flat multi-path fading and a log-normal shadow fading model, with parameter details given in Table.1.

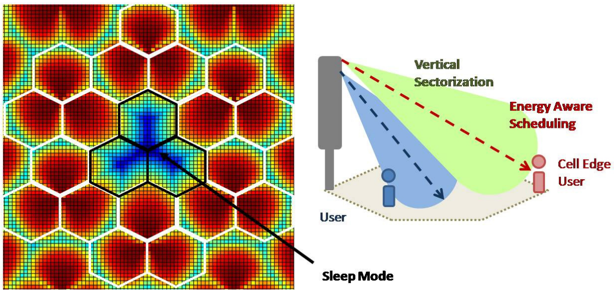

Fig. 1: Hexagonal Homogeneous Cell Deployment with Network Coded Relay, potentially allowing existing cells to enter a low energy consumption sleep mode.

Unless otherwise stated, the homogeneous cells each have three horizontal sectors and the antenna pattern used is: $A_{cell}(\theta)=-\min[12(\theta/\theta_{3dB,cell}), A_m]$, where $A_{bs} + A_{cell}(\theta)$ is the antenna gain (dB) at an angle θ from the azimuth plane. A_{bs} = 17.6dBi is the bore-sight gain and θ_{3dB}=75 degrees is the 3dB reduction point in the antenna pattern and A_m=20dBi. The users are modelled as randomly generated to have a constant average user density over the whole simulation area. The position of each user is random and in order to gain accurate results, each simulation is repeated many times. The scheduling is round robin (RR) and the traffic model is full load (*L*=1), unless otherwise stated. The throughput rate is derived from internal MVCE link-adaptation tables. Unlike some existing literature, it does not employ the Gaussian input upper-bound, which is inaccurate for high SINRs or low density modulation schemes [8]. The quality of service (QoS) is defined as the average down-link throughput achieved by 95% of users in a cell.

Parameter	Symbol	Value
Operating Frequency	f	2000MHz
Bandwidth	BW	20MHz
Simulation Area Radius	r_{sim}	4000m
Cell Radius	r_{cell}	200-1500m
BTS Antenna Height	H	5-40m
Antenna Down-tilt	T	0-15 degrees
Shadow Fading	σ_{shadow}	8dB
Number of Users	N_{UE}	256
QoS	R	1Mbit/s
User Antenna Height	H	1.5m
Path-loss	PL	COST 231 HATA
AWGN	n_0	4×10^{-21} W/Hz
User Noise Figure	n_{UE}	8dB
DSCH Power	P^{DSCH}	0.5 P^{max}
CSDRS Power	P^{CSDRS}	0.1 P^{max}

Table.1: System Parameters for Simulation and Theoretical Framework

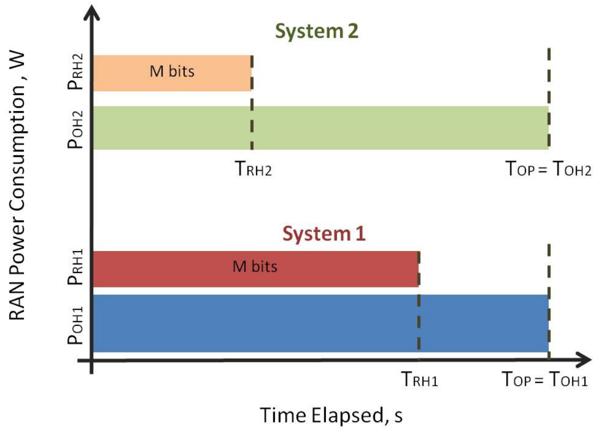

Fig. 2: Energy Model comparing 2 systems with a constant operational time T^{OP} and different RAN power consumption values for radio transmission P^{RF} and overhead P^{OH}.

4. ENERGY METRICS

4.1 Power Consumption

This paper considers cells operating in two modes. The ***Active Mode*** is when there are one or more users in any of a cell's sectors, the cell is in an active mode and consumes power which has both an element which scales with traffic load (***RF***) and an element which is static overhead (***OH***). A cell with some active sectors consume the same static overhead power, but inactive sectors do not consume their associated load-dependent RF power (i.e., load is zero). The ***Sleep Mode*** is when there are no users in a cell and its sectors, and the cell enters a sleep mode. The power consumed is entirely a fraction of the active mode's static overhead consumption. When in the active mode, the operational power consumed in system *i* with an average of N_i active heterogeneous cells is:

$$P^{OP}_{RAN,i} = \sum_{k=1}^{N_i} P^{OP}_{cell,i,k} = \sum_{k=1}^{N_i} (P^{RF}_{cell,i,k}(L) + P^{OH}_{cell,i,k}),$$

where $P^{OP}_{cell,i,k}$ for cell k is defined as the sum of the power owing to the radio transmission $P^{RF}_{cell,i,k}(L)$, which is a function of the traffic load (L={0,1}) and those owing to a static overhead $P^{OH}_{cell,i,k}$. For a cell with $K=3$ sectors, and each sector with $A=1$ antenna, the approximate operational power consumed is given by:

$$P^{OP}_{cell,i,k} = P^{RF}_{cell,i,k}(L) + P^{OH}_{cell,i,k} = 3\frac{P^{\max}_{cell} L}{\mu_{\Sigma}} + 487 \qquad (1)$$

where μ_{Σ}= 0.25 is the joint efficiency of the power amplifier and various radio head elements. The values in (1) are given for a $P^{\max}_{cell} = 40W$ cell sourced internally from Vodafone in the MVCE group, and is used as a reference point and corroborated with data from existing literature [9] and presented in Table.2.

	Macro	Micro	Micro	Pico
Cell Radius, m	> 1000	600-1000	400-600	<400
No. Sectors	3	3	3	3
Max. Power, W	40	20	10	6
RF Efficiency	0.25	0.35	0.31	0.28
RF Power, W	480	171	96	64
Overhead, W	490	375	290	126
Operational, W	**970**	**546**	**386**	**190**
Sleep Mode, W	245	188	145	63

Table.2: Power Consumption for Macro to Pico Cells

4.2 Energy Consumption Ratio (ECR)

The paper compares systems that transmit the same amount of data (*M* bits). Consider system (RAN *i*) with an average of N_i active homogeneous cells and serves a number of users. The total operational period of the RAN is the same as the period for which the static overhead power is kept on in the cells ($T_{RAN}^{OP} = T_{RAN}^{OH}$), as shown in Fig.2. The average throughput rate perceived by the RAN over its operational period is therefore defined as: $R_{RAN} = M / T_{RAN}^{OH}$. The ***Energy Consumption Ratio (ECR)*** is defined as the ratio between the radio-head power consumed (RF power) and the throughput rate. Therefore, the ECR for the RAN is the average ECR of each sub-carrier (*s*) in each cell sector (*n*):

$$ECR_{RAN,i}^{RF} = \frac{1}{S_i N_i} \sum_{n}^{N_i} \sum_{s}^{S_i} \frac{P_s}{\mu_\Sigma R_s} = \frac{1}{S_i N_i} \sum_{n}^{N_i} \sum_{s}^{S_i} \frac{P_s^{RF}}{R_s} \quad (2)$$

where R_s is the throughput of each sub-carrier given by the link adaptation table, and P_s is the transmit power per sub-carrier. The ECR or similar variants without the radio-head efficiency, is frequently used in literature. To include the operational energy, if one were to simply exchange P_{RAN}^{RF} with P_{RAN}^{OP}, one would be implying that all the operational energy scales with transmission load, which is incorrect. The ECR of a particular RAN only refers to the efficiency owing to the RF energy consumed to transmit M bits.

4.3 Energy Reduction Gain (ERG)

In order to accommodate the energy metric into a figure of merit that considers the full operation energy with idle states, the energy consumption model shown in Fig.2 is introduced. The total energy consumed by a system's RAN with N_i cells is a function of the powers and associated duration: $E_{RAN,i}^{OP} = \sum_{n}^{N_i} (P_{n,i}^{RF}(L) T_{RAN,i}^{RF} + P_{n,i}^{OH} T_{RAN,i}^{OH})$. In order to compare two systems, a useful metric is the ***Energy Consumption Gain (ECG)***, which is the ratio between the baseline old energy and new system's energy consumption, which is:

$$ECG = \frac{ECR_{RAN,1}^{RF} R_{RAN} + \sum_{n}^{N_1} P_{n,1}^{OH}}{ECR_{RAN,2}^{RF} R_{RAN} + \sum_{n}^{N_2} P_{n,2}^{OH}}, \quad (3)$$

The term T_{RAN}^{OH} is defined as the larger of the two systems' T_{RAN}^{RF} under comparison. The rationale is that given two systems of different performance but same data load (*M* bits), both have the same operational duration that allows both to finish transmitting the data load. To illustrate energy saving gains, a figure of merit called the ***Energy Reduction Gain (ERG)*** is defined as the following:

$$ERG = 1 - \frac{1}{ECG}, \quad (4)$$

which is usually expressed as a percentage. This is a measure of the energy saved in a new model compared to a baseline model as a percentage.

5. CELL DEPLOYMENT

5.1 Cell Size

A homogeneous cell deployment scenario is considered in order to gain insight into the trends which can reduce operation energy consumption. Therefore the results are not to be taken as universal values, but rather an indicator of the rationale for further investigation. Firstly, the relationship between cell radius and energy consumption is analyzed. The cell radius and the associated base station employed is determined by the average transmit power required to meet the target QoS throughput, and this is given previously in Table.2. This is regarded as the baseline model, with antenna height of 35m and down-tilt of 2 degrees throughout the different cell radius variations. The results for Energy Reduction Gain (ERG) figure of merit against the cell radius are shown in Fig.3, whereby the case of ERG with and without overhead energy is considered for the same QoS target. The theoretical lines are based on throughput rates derived from a basic theoretical framework based on work in [8] and our own approximations to the simulation model. However, that is beyond the scope and purpose of this paper.

When only the RF energy is considered, almost 100% energy reduction can be achieved with a small cell size deployment, compared with a large cell deployment scenario [6]. When the full operation energy is considered, the trends reverse and show that a RAN with larger cells can consume up to 80% less energy than one employing smaller cells. Considering the RF energy is still important for measuring the radio-head efficiency, and in the next sub-section the paper considers the joint optimization of the parameters: cell radius, antenna height and down tilt.

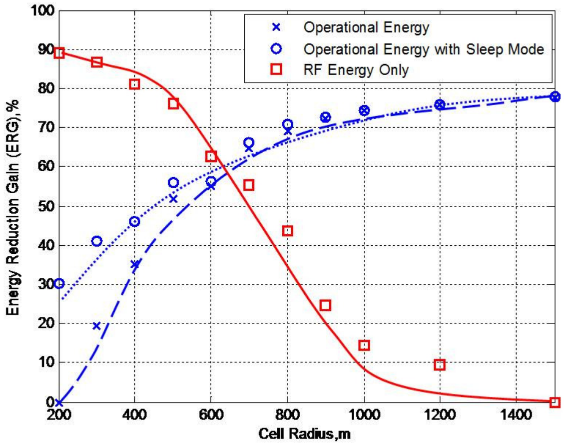

Fig. 3: Energy Reduction Gain (ERG) for different cell sizes, with: Only RF Energy, and Operational Energy considered. Symbols indicate simulation results and lines indicate theoretical framework.

5.2 Antenna Height and Down-tilt

The joint optimization of antenna height and down-tilt is presented in this section, and compared to a baseline performance (previously defined). In Fig.4, the results of Energy-Consumption-Ratio (ECR) is shown for different cell sizes with and without antenna parameter optimization. The analysis considers both singular and joint optimization of antenna height (5-40m with 5m increments) and down-tilt (0-12 degrees with 2 degree increments).

The results show that for large cell radius deployments, ECR efficiency gains of 60% can be made and up to 32% for smaller cell deployments. However, the gains in ECR are small for the singular cell height in the large cell scenario, because the baseline height of 35m is already near optimal for the down-tilt of 2 degrees. However, joint optimization affords more flexibility and from Fig.4, there is no doubt that the efficiency gain of joint optimization is better than that of singular optimization.

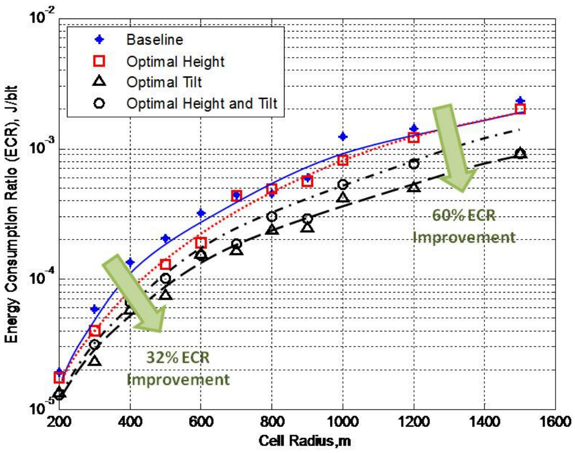

Fig. 4: Energy Consumption Ratio (ECR) for different cell sizes: with and without antenna height and tilt optimization.

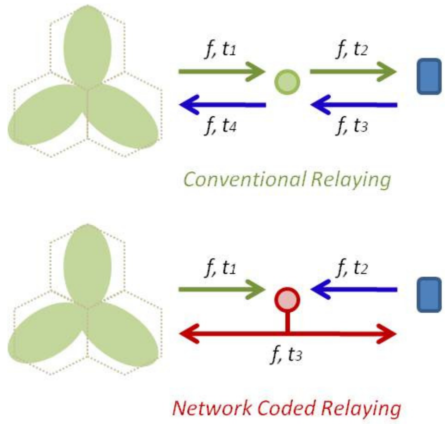

Fig. 5: Conventional and Network Coded (NC) Relaying between a basestation, relay and user (UE).

6. NETWORK CODED RELAYS

Relays are one of the key features in the LTE-Advanced architecture framework. A two-way relay channel is considered between the base-station (eNB) and the user (UE), as shown in Fig.5. Due to the orthogonality of LTE transmissions, the XOR based Network Coding (NC) is considered. The usefulness of the network coding is evaluated for various traffic load levels and geographical distances between the relay and basestation nodes.

The results in Fig.6 show that network coding can achieve ECR gains of 0.5-19% compared to conventional relaying. This is with and without sub-carrier division duplexing (SDD). The results indicate that the XOR based NC schemes are beneficial with respect to both the energy consumption reduced and the increased throughput performance. In terms of resource utilization, network coding with and without SDD yields 0.5-3.2% savings of cell resources utilized, therefore reducing both network interference and congestion. Furthermore, the work has demonstrated that network coding's gains are robust against varying channel and retransmission levels. This points the way for future research into multi-user relaying and more complex network coding schemes.

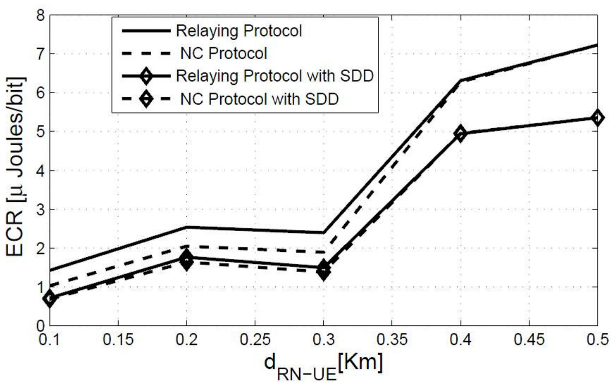

Fig. 6: Energy-Consumption-Ratio (ECR) for different relay to user (RN-UE) positions. Scenarios considered are: network coding, and sub-carrier division duplexing (SDD).

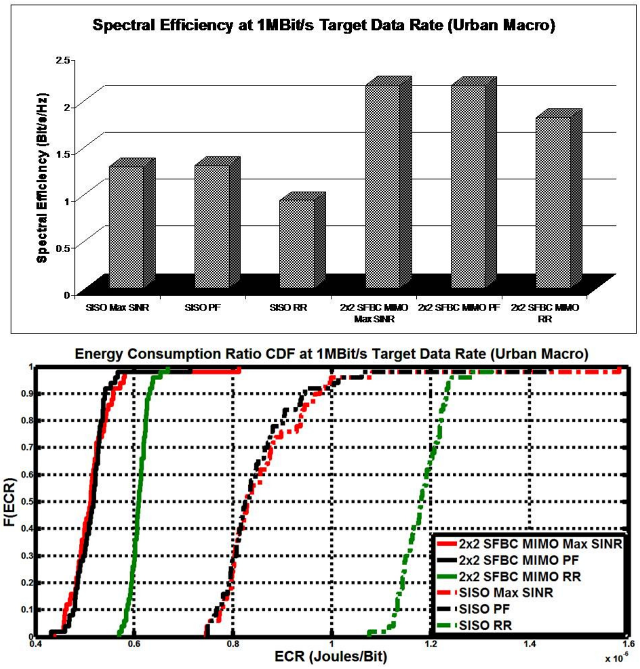

Fig. 7: Spectral-Efficiency and Energy-Consumption-Ratio (ECR) for various scheduling techniques in urban macro deployment.

7. MIMO: SPECTRAL EFFICIENCY AND ENERGY CONSUMPTION

An important element of implementing more efficient and better performing networks is the introduction of multiple-antenna radio techniques that exploit the benefits of diversity and multiplexing. The spectral efficiency and throughput performance of these schemes have been previously considered in literature. What is not apparent is whether spectrally efficient schemes are also energy efficient in delivering the required QoS target. The energy consumption ratio (ECR) is investigated for both single transceivers (SISO) and a 2x2 Alamouti scheme. The relationship between spectral efficiency and energy efficiency (ECR) is examined for the two scenarios.

The results are shown in Fig.7, for the following scheduling schemes: maximum receive SINR, round robin (RR), proportional fairness (PF). The analysis shows that spectrally efficient MIMO techniques are also energy efficient (ECR), producing gains of 39-49% for the different scheduling schemes investigated. Moreover, spectrally efficient techniques investigated here improve the QoS performance, whereby more users are scheduled and their associated throughput is increased. This was found to be the case for both urban macro and micro deployment.

8. CONCLUSIONS

This paper has demonstrated that significant energy reductions and improvements to radio transmission energy efficiency can be made by optimizing a network's parameters with the QoS as a constraint. The operational energy reductions (ERG) yielded by varying the cell radius have shown that, whilst smaller cells are more transmission energy efficient (ECR), larger cells consume up to 80% less operation energy than smaller cells. Moreover, the joint optimization of antenna height and tilt has yielded a 32-60% ECR improvement compared to a baseline setup. This has shown that increased system flexibility can allow designers to improve the transmission energy efficiency and operational energy consumption. The addition of network coded relays yielded up to 19% ECR improvements compared to conventional relaying techniques. Analysis in multiple antenna techniques showed that MIMO not only increased spectral efficiency and radio resource utilization, but also improved the ECR by 39-49% for a variety of scheduling schemes.

The relatively generic simulation setup employed has yielded results which are by no means universal, but they give a solid guideline to the direction of research and an idea of the gains that can be achieved

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] R. Rinaldi, and G.M. Veca, "The Hydrogen for Base Radio Stations" in *Proc. of 29th Int. Telecommunication Energy Conference*, Rome, Italy, September. 2007, pp. 288–292.
[2] K. Mimis, K. Morris and J. McGeehan, "A 2GHz GaN Class J Power Amplifier for Base-station Applications" in *Proc. of Radio Wireless Conference*, USA, January. 2011.
[3] H. Claussen, L. Ho and F. Pivit, "Leveraging Advances in Mobile Broadband Technology to Improve Environment Sustainability" in *Bell Labs Technical Journal*, vol. 15, pp. 97-116, USA, 2010.
[4] J. Niemela, T. Isotalo and J. Lempiainen, "Optimum Antenna Downtilt Angles for Macro-cellular WCDMA Network" in *EURASIP Journal of Wireless Communications Networking*, pp. 816-827. 2005.
[5] P. Marsch and G. Fettweis, "On Uplink Network MIMO under a constrained backhaul and imperfect channel knowledge" in *IEEE Int. Conf. on Comm.*, Germany, June. 2009.
[6] B. Badic, T. O'Farrell, P. Loskot and J. He, "Energy Efficient Radio Access Architectures for Green Radio: Large versus Small Cell Size Deployment" in *Proc. Vehicular Tech. Conf.*, USA, September. 2009.
[7] M. Marsan, L. Chiaraviglio, D. Ciullo and M. Meo, "Optimal Energy Savings in Cellular Access Networks" in *Proc. Green Communications*, Germany, June. 2009.
[8] D. Guo, S. Shamai and S. Verdu, "Mutual information and minimum mean-square error in Gaussian channels" in *IEEE Trans. on Information Theory*, April. 2005.
[9] G. Auer and V. Giannini, "Cellular Energy Efficiency Evaluation Framework" in *Proc. Vehicular Tech. Conf.*, Hungary, May. 2011