Environmental and Economically Sustainable Cellular Networks

Weisi Guo, Siyi Wang and Tim O'Farrell

Department of Electronic and Electrical Engineering, University of Sheffield, Sheffield S10 2TN, UK; e-mail: {w.guo, siyi.wang, t.ofarrell}@sheffield.ac.uk

Received 2 February 2012; Accepted: 10 April 2012

Abstract

The Information and Communications Technology (ICT) infrastructure is recognized as a key enabler to the growth of the global economy. With increased data transfer, there is an unprecedented growth in the associated energy consumption, carbon emissions and operational cost of ICT. In order for operators to increase competitiveness, the challenge is how to satisfy the growing data demand, whilst reducing the energy consumption and costs. This paper considers the wireless cellular network for both outdoor and indoor environments. Novel and theoretical bounds are presented for energy and cost savings.

Investigation results show that with careful redesign of the cellular network architecture, up to 60–70% reduction in energy consumption and 25% in OPEX can be achieved for indoor and outdoor environments. Furthermore, a detailed sensitivity analysis is also presented, which is novel and beneficial to future researchers.

Keywords: energy efficiency, wireless communication, cellular network, cost efficiency.

Journal of Green Engineering, Vol. 2, 273–283.

Figure 1 Energy consumption of (a) ICT and (b) wireless communications as of 2008–2010. A single UK cellular network typically consumes 40 MW. (c) Operational Expenditure (OPEX) of a typical 3G cellular network.

1 Introduction

A recognized key enabler in the modern economy is digital information exchange. The volume of data exchanged in ICT has increased by a factor of 10 over the past 5 years and the associated energy consumption by 20% [1]. One of the most challenging aspects of the ICT infrastructure is the wireless access network, which constitutes 14% of ICT energy consumption (Figure 1a). The global cellular network consists of over 3 million cells and 1.5 billion subscribers. Roughly 70% of the wireless ICT energy consumption is consumed by the outdoor network (Figure 1b), which includes 60TWh of electricity (20 million households). The utility bill is over $10 billion and 40 MT of CO_2 is directly attributed, with a further 500 MT indirectly attributed. Many operators are also pledging to reduce carbon emissions [2].

1.1 Challenges and Solutions

Currently, many operators are considering upgrading their 3rd generation High-Speed-Packet-Access (HSPA) network with the 4th generation Long-Term-Evolution (LTE) network. This is primarily due to the higher spectral efficiency and increased bandwidth of 4G LTE, which amounts to a higher throughput rate [3]. However, it is unclear what the most cost and energy efficient deployment of 4G LTE is. Given an existing LTE reference network deployment [4], the key research questions addressed are:

- *Fundamental Saving Bounds* for energy consumption and operating costs.
- *Outdoor and Indoor* architecture design that achieves the same capacity, but with lower energy consumption and operating costs.

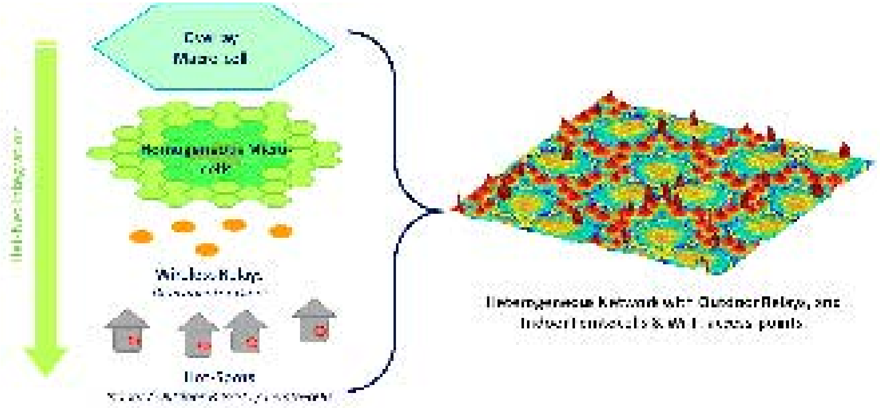


Figure 2 Simulation framework: Heterogeneous network's average received signal-to-interference-plus-noise ratio (SINR).

- *Sensitivity analysis* on each modeling parameter and propose beneficial research directions.

Existing work has primarily focused on specific techniques and their impact on transmission energy efficiency [5–7]. Analysis that considers interference, complete power consumption models and capacity saturation have been lacking [8]. This paper presents fundamental energy and cost saving bounds and demonstrates how savings change with different modeling parameters in order to suggest beneficial areas of research.

2 System Setup

2.1 Monte Carlo Simulation

The simulation results are produced using the MVCE's *VCESIM*, which is a proprietary LTE dynamic system simulator developed at the University of Sheffield for industrial members of the Mobile Virtual Centre of Excellence (MVCE), as demonstrated in Figure 2. The simulator emulates a heterogeneous network of outdoor cells and indoor access-points. Further details of simulation parameters are given in [9].

2.2 Power Consumption

A general power consumption model for a cell is a function of the transmit power (P), load factor (L), radio-head efficiency (μ_{RH}), over-head power

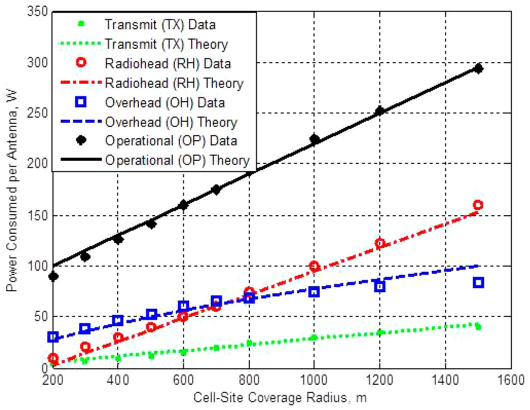


Figure 3 Power consumption variation with cell size with data from [10] and theory from expression (1).

($P_{\mathrm{cell}}^{\mathrm{OH}}$) and backhaul power ($P_{\mathrm{BH}}$):

$$P_{\mathrm{cell}} = \frac{P}{\mu_{\mathrm{RH}}} L + P_{\mathrm{cell}}^{\mathrm{OH}} + P_{\mathrm{BH}} \approx 0.1 r_{\mathrm{cell}} L + r_{\mathrm{cell}}^{0.62} + 50, \tag{1}$$

where the radio-head power can be defined as: $P_{\mathrm{cell}}^{\mathrm{RH}} = (P_{\max}/\mu_{\mathrm{RH}})\rho$. The load factor is defined as the ratio between the offered traffic rate and maximum achievable cell capacity: $L = R_{\mathrm{offered}}/R_{\mathrm{cell}}$. Using empirical data from [10], the expression can be shown to be a function of the cell coverage radius (r_{cell}), as shown in Figure 3.

2.3 Operational Cost

As shown in Figure 1c, the electricity bill accounts for up to 16% of the total operational expenditure (OPEX). Global annual electricity bills ($10 billion) make up 45% of the operational and maintenance bills ($22 billion). The OPEX is dominated by the following: site leasing costs ($\wp_{\mathrm{cell,rent}}$), backhaul rental ($\wp_{\mathrm{BH}}$) and electricity bills ($\wp_{\mathrm{bill}}$). The annual OPEX can be written as:

$$\mathrm{OPEX} = N_{\mathrm{cell}}(\wp_{\mathrm{cell,rent}} + N_{\mathrm{BH}}\wp_{\mathrm{BH}} + E_{\mathrm{cell}}\wp_{\mathrm{bill}}), \tag{2}$$

where N_{BH} is the number of back-hauls per cell, E_{cell} is the energy consumed by the cell [11, 12].

3 Energy and Cost Saving Bounds

3.1 Energy Saving Bound

The paper defines the energy reduction gain (ERG) as

$$\mathrm{ERG} = 1 - \frac{P_{\mathrm{cell,reference}}}{P_{\mathrm{cell,test}}}.$$

Given a *Fixed Deployment* of cells, the paper considers a certain technique that can improve the capacity of each cell by a factor f, which reduces the load of the improved cells by $L = 1/f$. The ERG achieved is:

$$\mathrm{ERG}^{+}_{\mathrm{RAN,Fixed}} = (\frac{f-1}{f})\Omega, \qquad (3)$$

where $\Omega = (\frac{P}{\mu_{\mathrm{RH}}})/P_{\mathrm{cell}}$. The bound approaches 40–60% for $f \rightarrow \infty$. Therefore, one can conclude that for a fixed deployment of cells that have a capacity gain of f, the energy saving gain bound is limited by the ratio between radio-head and total power consumption (Ω).

Given a *Re-Deployment* of higher capacity cells, fewer cells are needed to achieve the same offered load. Assuming that the power consumption change per cell is negligible, the resulting ERG achieved is:

$$\mathrm{ERG}^{+}_{\mathrm{RAN,Re-Dep.}} \sim \frac{f-1}{f}, \qquad (4)$$

which approaches 100% for $f \rightarrow \infty$. Therefore, one can conclude that for a re-deployment of cells, the energy saving is dependent on the capacity gain. The ERG simulation results (symbols) and bounds (lines) are shown in Figure 4a. The simulation results approach their respective bounds when the capacity gain is large $f > 10$.

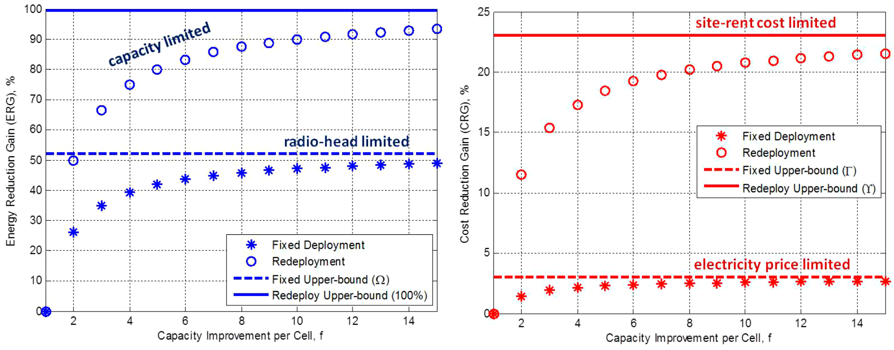
3.2 Cost Saving Bound

The paper defines the cost reduction gain (CRG) as

$$\mathrm{CRG} = 1 - \frac{\mathrm{OPEX}_{\mathrm{reference}}}{\mathrm{OPEX}_{\mathrm{test}}}.$$

Given a *Fixed Deployment* of cells, the CRG is:

$$\mathrm{CRG}^{+}_{\mathrm{RAN,Fixed}} = (\frac{f-1}{f})\Gamma, \qquad (5)$$



a) ERG as a function of capacity improvement

b) CRG as a function of capacity improvement

Figure 4 Energy and cost savings as a function of capacity improvement: symbols indicate simulation results and lines indicate theoretical bounds.

where

$$\Gamma = \frac{\wp_{\text{bill}}\frac{P}{(f\mu_{\text{RH}})}}{\text{OPEX}}t.$$

Over a period of a year ($t = 8760$ hours), the saving is approximately 3% for $f \to \infty$. Therefore, one can conclude that the cost saving gain bound is limited by the ratio between electricity price and the total OPEX: $\wp_{\text{bill}}/\text{OPEX}$.

Given a *Re-Deployment* of higher capacity cells, the paper assumes that each cell needs proportionally more back-hauls. The CRG is:

$$\text{CRG}^{+}_{\text{RAN,Re-Dep.}} \sim \left(\frac{f-1}{f}\right)\Upsilon, \tag{6}$$

where $\Upsilon = \wp_{\text{cell,rent}}/(\wp_{\text{cell,rent}} + N_{\text{BH}}\wp_{\text{BH}})$. The CRG approaches 26% for $f \to \infty$. Therefore, one can conclude that the cost saving gain bound is limited by the ratio between cell site rental price and the total OPEX. The CRG simulation results and bounds are shown in Figure 4b.

4 Green Cellular Network

4.1 Outdoor Network

The paper analyzes the outdoor and indoor networks separately, but does consider their mutual interference. The overall Heterogeneous RAN (Het-Net) has the following elements (Figure 2): micro-cells, wireless Decode-and-Forward (DF) relays and indoor femto-cell access-points (FAPs). All the

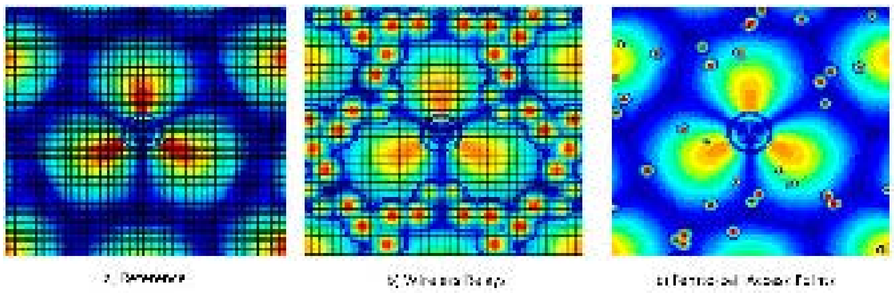


Figure 5 Average received SINR for: (a) reference homogeneous, (b) Het-Net with relays, (c) Het-Net with FAPs.

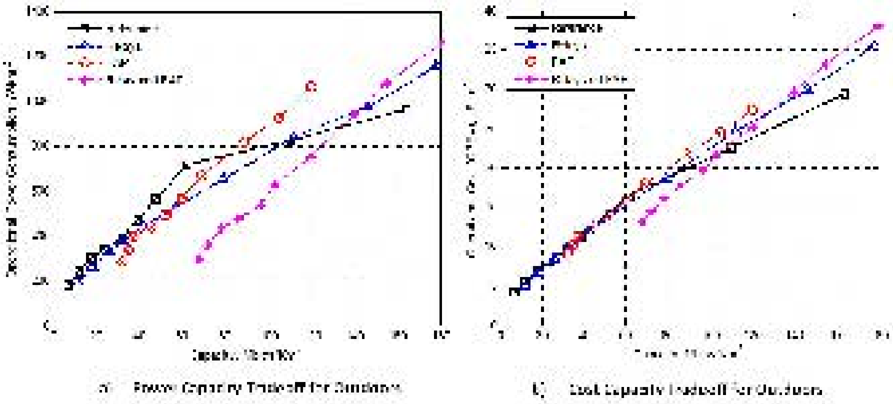
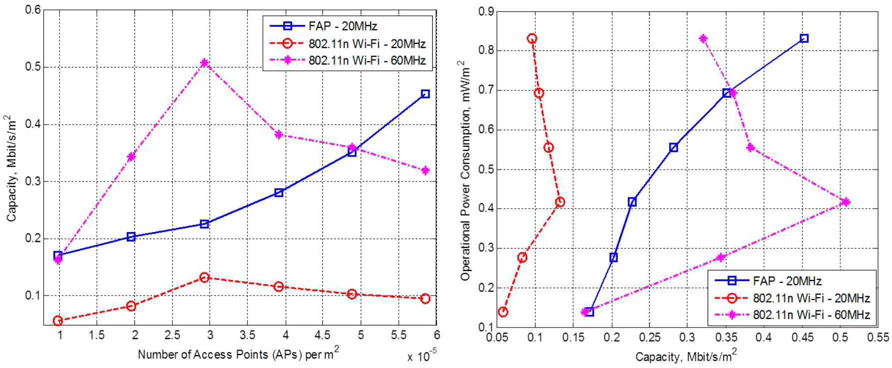


Figure 6 Power, cost and capacity tradeoff for outdoor networks.

elements are co-frequency and mutually interfere with each other. An example of the outdoor average received SINR map is shown in Figure 5. The reference network considered is a homogeneous deployment of micro-cells [3]. The paper introduces heterogeneous elements in the form of 6 relays per cell [12] and 10 FAPs per square km.

The results in Figure 6 show the tradeoff between increasing capacity (through higher cell density) and the associated higher power consumption and OPEX. By introducing heterogeneous network elements, the tradeoff can be both improved and deteriorated. In general, the conclusion is as follows:

- For low-medium traffic loads (30–60 Mbit/s/km^2), a heterogeneous RAN of macro-cells with wireless relays and/or FAPs is more beneficial than a homogeneous deployment.



a) **Capacity as a function of Access Point Number** b) **Power Capacity Tradeoff for Indoors**

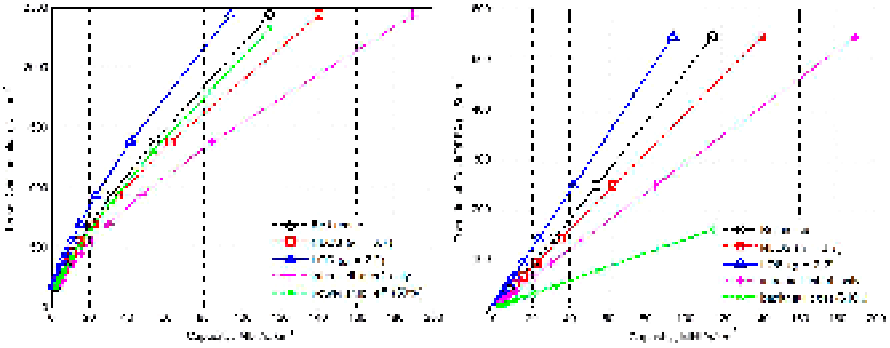
Figure 7 Power and capacity tradeoff for indoor networks.

- For high traffic loads (80–120 Mbit/s/km^2), a homogeneous RAN of pico-cells is more beneficial than a Het-Net.

The rationale behind this is that as the cell-size decreases, the interference caused by relays and FAPs becomes more substantial. Therefore, the green strategy should be to either adopt large cell Het-Nets or small cell Homogeneous Networks. For a target capacity of 70 Mbit/s/km^2, up to 60% operational energy and 25% OPEX can be saved by employing a Het-Net approach. This approaches the theoretical limits for energy cost savings shown previously.

4.2 Indoor Network

In the indoor scenario, the paper considers a large office or commercial area. A number of APs are deployed to achieve a certain capacity density and consume a certain power density. The results in Figure 7a show that for a 20 MHz channel, the FAP offers a superior performance to 802.11n, primarily due to a better adaptive modulation and coding scheme. However, the 802.11n can employ up to 60 MHz of bandwidth in reality, and therefore can always deliver a superior capacity-power-tradeoff, as shown in Figure 7b. As the number of APs increases, increased interference can cause a deterioration in average capacity. This causes the effect that for a given capacity requirement, some tradeoff curves exhibit two power consumption values. Between 60–67% energy can be saved by deploying the right number and type of indoor AP.



(a) Power Capacity Tradeoff Sensitivity Results (b) Cost Capacity Tradeoff Sensitivity Results

Figure 8 Power and capacity tradeoff for indoor networks.

5 Sensitivity Analysis

In the sensitivity analysis, the paper examines the impact of the following:

- Interference: full interference or only intra-cell interference.
- Pathloss Model: pathloss exponent of 2.2 (LOS) or 3.7 (NLOS) [4].
- Power Model: power amplifier efficiency (35 or 50%) [13].
- OPEX Model: backhaul rental cost ($10000 or $40000) [12].

The values are chosen based on existing literature and research on energy efficiency and cellular network modeling. The impact of the parameter values is shown in Figure 8. The results show that in terms of power consumption, the effect of interference modeling has the greatest impact, whereas backhaul cost has the greatest impact on OPEX results. These two areas represent the most promising areas of research for sustainable cellular network design.

6 Conclusions

The paper has demonstrated theoretical and simulation results for the achievable energy and cost savings of a cellular network. In terms of energy saving, the lower-bound is limited by the radiohead consumption (40–60%), and the upper-bound is limited by the capacity gain (up to 100%). In terms of cost saving, the lower-bound is limited by the electricity price (3%), and the upper-bound is limited by the site rental costs (25%).

The simulation results showed that the proposed outdoor and indoor heterogeneous network can reduce energy consumption by 60-70% and OPEX by 25%. This approaches the theoretical bounds and can provide the foundation to a sustainable green architecture. Furthermore, the sensitivity analysis has shown that interference mitigation and backhaul rental costs are the most promising areas of research for energy and cost efficient sustainable cellular networks.

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 *Proceedings of IEEE Wireless Personal Multimedia Communications*, Finland, September 2008.

[2] Sustainability Report 2010-2011. Vodafone Group Plc, Technical Report, 2011.

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

[4] 3GPP. TR36.814 V9.0.0: Further Advancements for E-UTRA Physical Layer Aspects (Release 9). 3GPP, Technical Report, March 2010.

[5] C. Xiong, G. Li, S. Zhang, Y. Chen, and S. Xu. Energy- and spectral-efficiency tradeoff in downlink OFDMA networks. *IEEE Transactions on Wireless Communications*, 10(1):3874–3885, November 2011.

[6] S. Tombaz, A. Vastberg, and J. Zander. Energy and cost efficient ultra-high capacity wireless access. In *Proceedings of IEEE Green Net Workshop*, May 2011.

[7] 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 *Proceedings of 2011 IEEE International Conference on Communications (ICC)*, June 2011.

[8] Y. Chen, S. Zhang, S. Xu, and G. Li. Fundamental trade-offs on green wireless networks. *IEEE Communications Magazine*, 49(6), June 2011.

[9] W. Guo and T. O'Farrell. Green cellular network: Deployment solutions, sensitivity and tradeoffs. In *Proceedings of IEEE Wireless Advanced Conference (Wi-Ad)*, London, UK, June 2011.

[10] 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 *Proceedings of 2011 IEEE Vehicular Technology Conference (VTC Spring)*, pp. 1–6, May 2011.

[11] A. Furuskar, M. Almgren, and K. Johansson. An infrastructure cost evaluation of single- and multi-access networks with heterogeneous traffic density. In *Proceedings of IEEE Vehicular Technology Conference*, May 2005.

[12] E. Lang, S. Redana, and B. Raaf. Business impact of relay deployment for coverage extension in 3GPP LTE-advanced. In *Proceedings of IEEE International Conference on Communications (ICC)*, June 2009.

[13] K. Mimis, K. Morris, and J. McGeehan. A 2GHz GaN class J Power Amplifier for Basestation Applications. In *Proceedings of IEEE Symposium for Radio and Wireless (RWS)*, Phoenix, USA, January 2011.

Biographies

Weisi Guo graduated from the University of Cambridge with BA, MEng, MA and PhD engineering degrees. He is currently a wireless communications research assistant at the University of Sheffield, with research interests in: energy efficiency, cooperative techniques, self-organizing networks, and cellular architectures. He has published over 30 papers and journals and is the author of the VCESIM LTE System Simulator.

Siyi Wang graduated from the University of Leeds and is currently a PhD student at the University of Sheffield. His research interests include: indoor-outdoor network interaction, small cell deployment, and theoretical frameworks for complex networks.

Tim O'Farrell is the Chair in Wireless Communication at the University of Sheffield and the Academic Coordinator of the MVCE Green Radio Project. His research activities encompass resource management and physical layer techniques for wireless communication systems. He has led over 18 major research projects and published over 230 research outputs, including 8 patents.