Energy Consumption of 4G Cellular Networks: A London Case Study

Weisi Guo, Siyi Wang, Tim O'Farrell, Simon Fletcher¶
University of Sheffield, NEC Telecom Modus¶, United Kingdom
Email: {w.guo, siyi.wang, t.ofarrell}@sheffield.ac.uk, simon.fletcher@emea.nec.com¶

***Abstract*—This paper presents the results of a joint investigation conducted between academia and industry. The investigation focused on modeling and reducing the energy expenditure of a 4G LTE network in a London case-study area, using data sets from an existing 3G network deployment. In the first part of the paper, different multi-cell network modeling approaches were compared, including: stochastic and linear geometry, hexagonal cell layout with wrap-around, and realistic network topology. The impact of terrain and clutter is also examined. It was found that they had a similar performance profile (80%) correlation, and a back-off factor to translate theoretical to measured results can account for most of the differences. The second part of the paper focuses on effective techniques that can be used to reduce energy consumption. Sleep mode and heterogeneous networks are combined and an ERG of 15-46% is achieved.**

I. Introduction

A. Motivation

Mobile data has grown exponentially over the past few years. Currently the mobile data usage is in excess of 1 Exabyte (1×10^{18}) per year. In fact, mobile data has grown by over 5-fold in the last 2 years (2010-2012), and is set to grow by another 5-fold in the years leading up to 2015. There is a direct relationship between the growth of mobile data demand and the associated energy consumption in wireless networks. Most of that consumption is expended in the basestations of the cellular network. Given the low data profit margins in cellular networks, there is genuine motivation to cut costs by reducing energy consumption. Furthermore, there is motivation to reduce the carbon footprint of the ICT sector by 50%.

B. Contribution

Low energy cellular network technologies has been researched extensively over the past few years by major global projects, i.e., Mobile VCE [1], EARTH [2]...etc. What has been lacking is an integration of cross-layer research techniques and a translation of that integration onto a realistic network topology. In this paper, the investigation considers two promising cross-layer energy efficient technologies and their impact on a realistic cellular network in London:

- Sleep Mode: effective at reducing energy consumption for networks that operate with varying traffic loads [3];
- Heterogeneous Network (HetNet):able to grow network wide capacity and improve local coverage in an energy efficient manner [4] [5].

In order for future researchers to repeat this investigation with other research techniques, the paper also compares the following different modelling approaches: Monte-Carlo Simulation of Hexagonal Cells with Wrap Around [6], Monte-Carlo Simulation of London Area, Stochastic Geometry [7], and Linear Geometry [5].

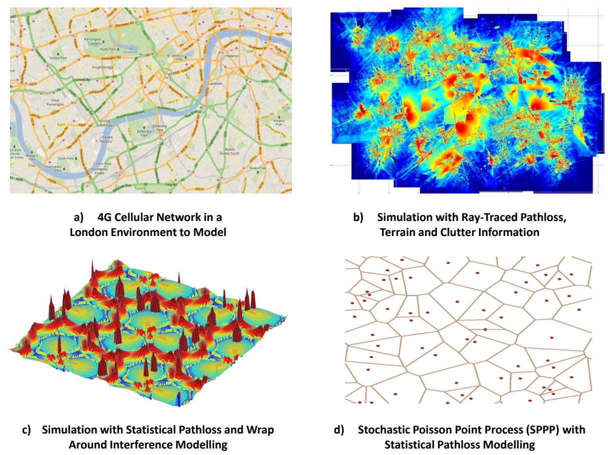

Fig. 1. Cellular network modeling methods: a) London Terrain; b) simulation of a realistic environment; c) simulation of hexagonal cells with wrap-around; d) stochastic geometry representation of a multi-cell network.

The novel contribution of the paper is that it yields realistic energy consumption and saving results for a realistic network, and presents future researchers with an indication of the accuracy of different modeling approaches.

II. Network Modelling

In order to optimize the cellular network performance, one has to first characterize the network's performance. In current literature, different performance modeling approaches have been taken to characterize the network performance:

- *Monte-Carlo Simulation of Hexagonal Cells with Wrap Around*: yields network upper-bound performance and can include realistic antenna patterns [6];
- *Monte-Carlo Simulation of London Area*: realistic performance with ray-traced pathloss models and terrain-clutter effects (Fig. 1a);
- *Stochastic Geometry*: yields closed-form mathematical expressions of multi-cell performance with full interference modeling, but without antenna patterns and the effects of capacity saturation (Fig. 1d) [7]. The average

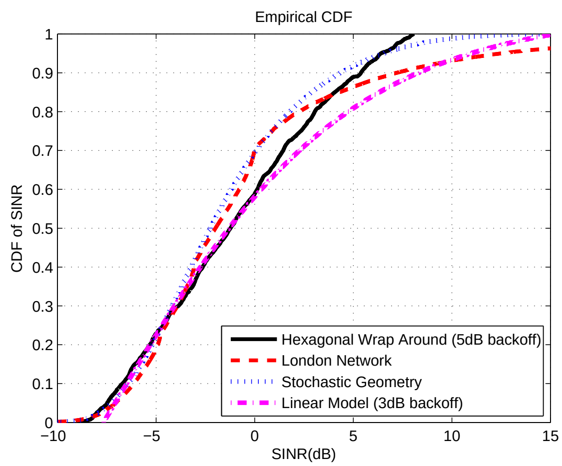

Fig. 2. CDF Plot of the network-wide SINR levels for different modeling approaches.

capacity ($\overline{C}$) achieved is expressed as [8]:

$$\overline{C} = \int_0^{\infty} \Big(1 + Q(\alpha,\zeta)\Big)^{-1} \mathrm{d}\zeta$$

$$\text{where: } Q(\alpha=4,\zeta) = \sqrt{2^{\zeta}-1}\left[\frac{\pi}{2} - \mathrm{atan}(2^{\zeta}-1)^{-\frac{1}{2}}\right], \tag{1}$$

where α is the pathloss distance exponent, and ζ is a dummy variable.

- *Linear Geometry*: yields closed-form mathematical expressions of multi-cell performance with capacity saturation (C_s) and dominant interference modeling and antenna patterns [5]. The capacity (C) profile as a function of user-cell distance (x) can be expressed as:

$$C(x) = \begin{cases} C_s & 0 < x \leq \frac{2r}{1+(2^{C_s}-1)^{\frac{1}{\alpha}}} \\ \log_2[1 + (\frac{x}{2r-x})^{-\alpha}] & \frac{2r}{1+(2^{C_s}-1)^{\frac{1}{\alpha}}} < x \leq r \end{cases}, \tag{2}$$

where r is the cell radius and this can be expanded to model a heterogeneous network as well [5].

Fig. 2 shows the cumulative distribution function (CDF) plot of the received signal-to-interference plus noise ratio (SINR) across the multi-cell network for different modeling approaches. The simulation parameters and settings are given in Table I. From the results, it can be observed that if the realistic London simulation model is taken as a reference, the other models with a *back-off factor* of 5-7dBs are quite accurate in comparison. This is especially the case for the low to medium SINR range, which is where the performance is more of interest and requires improvement. The relative merits of each modeling technique are beneficial for different purposes. Specific realistic challenges typically warrant the usage of simulation based approaches, where custom features can be added. Stochastic models can yield macro-feature insights, such as the impacts of cell density, transmit power and pathloss. However, they are not able to demonstrate the singular performance issues of a single cell or show the effects of custom modifications. The linear model for a single cell, provides a balance between the two aforementioned approaches and is more customizable than stochastic geometry, and can produce results faster than simulations. Furthermore, it was found that the impact of terrain and clutter is low (maximum of 2-3dBs) difference on the SINR profile. Based on these results, different research techniques can be modelled using the approach that best suits the research needs.

III. London Case Study

A. London Area

The network data is from a 3G radio-access-network (RAN), consisting of 96 macro-basestations (macro-BS) covering an area of 6 km × 9 km. This is used to infer the performance of a 4G RAN with BS deployed co-site to the 3G RAN. A full list of system parameters is given in Table I. The BS configuration, location, and ray-traced pathloss information was extracted from an Atoll Forsk coverage simulator and imported into a proprietary system-level dynamic simulator called VCEsim. An example of the SINR map of the London Area plotted in the VCEsim simulator, using the imported cell and pathloss data can be found in Fig. 1c.

B. Metrics

The paper defines the following metrics with regard to RAN performance and traffic:

- Cell Throughput (Mbit/s/cell): the throughput achieved that is averaged across the cell coverage area.
- RAN Throughput (Mbit/s/km^2): the throughput achieved that is averaged across the RAN coverage area.
- Outage Probability: the coverage probability is the chance that a user in the coverage area is equal to or above a certain SINR threshold, and the outage probability is the probability that it is below the threshold.
- Traffic Rate (Mbit/s/cell): the intensity of packet-switched data that is demanded in the coverage area of a cell.

The following key formulas and assumptions are used to calculate the power and energy consumption of the RAN. The operational power consumption of a basestation (BS) n at time t is defined as:

$$P_{\text{operational},n,t} = N_{\text{s},n} N_{\text{a},n} [\frac{P_{\text{tx},n,t}}{\mu_{\text{amp},n}} \left(\frac{R_{\text{traffic},n,t}}{C_{\text{cell},n}}\right) + P_{\text{overhead},n}] + P_{\text{backhaul},n}, \tag{3}$$

which for a macro-BS has the following approximate values: $N_{\text{s}} = 3$ sectors, $N_{\text{a}} = 1$ antenna, $P_{\text{tx}} = 40$W, $\mu_{\text{amp}} = 0.3$ is the radio-head efficiency, $P_{\text{overhead}} = 150$W, and $P_{\text{backhaul}} = 50$W. The load is defined as the ratio between the traffic intensity and the maximum cell capacity ($\frac{R_{\text{traffic}}}{C_{\text{cell}}}$). A single macro-BS therefore has a fully loaded power consumption of 900W. The Low-Power-Nodes (LPNs) have a similar power consumption model, with the parameters: $N_{\text{cell}} = 1$, $N_{\text{a}} = 1$, $P_{\text{tx}} = 1$mW to 5W, $\mu_{\text{amp}} = 0.1$, $P_{\text{overhead}} = 10$W, and $P_{\text{backhaul}} = 20$W. At full load, a LPN can consume between 30 to 80W. Typical values are given in Table I.

TABLE I
SYSTEM PARAMETERS

Parameter	*Value*
London Area Considered	6 km × 9 km
Simulation Resolution	10 m × 10 m
Statistical Pathloss Model	3GPP WINNER II
Deterministic Pathloss Model	PACE 3G
Number of BSs	96
Number of LPNs	10 per BS
Transmission Technology	SISO
BS Antenna Pattern	[9]
BS Antenna Height	20-40m
BS Transmit Power	40W
BS Full Load Power Consumption	300W per Sector
BS Zero Load Power Consumption	150W per Sector
BS Sleep Mode Power Consumption	75W per Sector
LPN Transmit Power	1mW to 5W
LPN Full Load Power Consumption	25W
LPN Zero Load Power Consumption	15W
LPN Sleep Mode Power Consumption	5W
LPN Antenna Height	5m
Traffic Data Type	Packet-Switched Intensity
Traffic Data Sample Size	15 minutes over 2 days
SINR Outage Threshold for QoS	-4dB (0.6 Mbit/s/cell)
Log-Normal Shadow Fading Variance	9dB
Multi-path Fading Model	Independent Rayleigh

The energy consumption of a RAN is derived from examining the variation of power consumption of all cells over a period of time (T):

$$E_{\text{operational},T,N} = \sum_{t}^{T} \sum_{n}^{N} P_{\text{operational},t,n}, \quad (4)$$

where typically the time interval t is given in 15 minute steps in accordance with the traffic resolution of each cell n.

The energy reduction gain (ERG) is a comparison between a test and reference system over the same time period T and with potentially a different set of cells, and is given as:

$$\text{ERG}_{\text{operational}} = 1 - \frac{E_{\text{operational,test},T,N_{\text{test}}}}{E_{\text{operational,reference},T,N_{\text{reference}}}}, \quad (5)$$

which is usually expressed as a percentage.

IV. RESEARCH TECHNIQUE: SLEEP MODE

A. Traffic Threshold

The paper considers the application of sleep mode [3], whereby certain cells are switched off when the traffic inside a cell drops below a traffic load threshold. The paper defines a traffic threshold τ_t at time t in terms of the mean network traffic:

$$\tau_t = f \times \frac{1}{N_{\text{BS}}} \sum_{n=1}^{N_{\text{BS}}} R_{\text{traffic},n,t}, \quad (6)$$

where $R_{\text{traffic},n,t}$ is the 3G packet-switched (PS) data traffic intensity on a certain cell n. The factor f is a calibration factor which determines the aggressiveness of the sleep mode functionality. Operationally, a cell will enter sleep mode if the traffic intensity falls below the network-wide threshold:

$$R_{\text{traffic},n,t} < \tau_t. \quad (7)$$

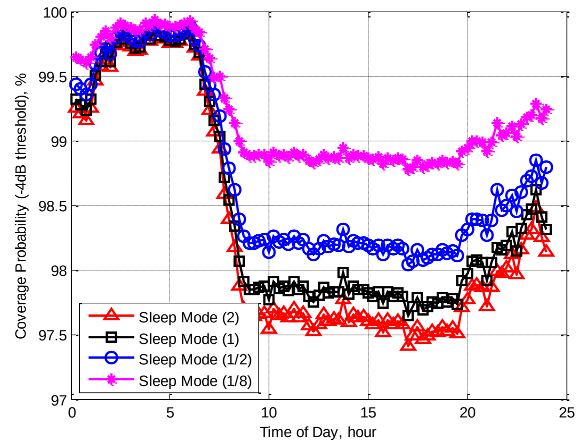

Fig. 3. Coverage Probability for SINR Threshold of -4dB (0.6 Mbit/s/cell) in London Area, for different Sleep Modes.

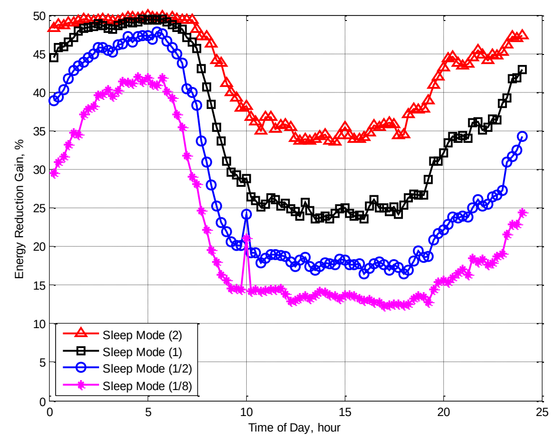

Fig. 4. ERG for London Area, with different Sleep Modes.

With regard to different traffic thresholds τ_t, the following metrics are considered:

- Coverage Probability (%): the percentage of area that has a received signal power above a certain minimum threshold required for acceptable data throughput (-4dB, 0.6 Mbit/s/cell) [9].
- Throughput (Mbit/s): the mean throughput achieved across the RAN under the assumption of one UE/cell.
- Energy Reduction Gain (ERG, %): the operational ERG achieved for the number of cells switched off.

It is worth mentioning that because the data was taken for a particular day in the year, the traffic intensity at the beginning and at the end of the day may not be the same. The sleep mode threshold τ_t is varied by a traffic value that is uniform across all cells. This is valued at a fraction of the mean traffic across all samples in the week. In the results, the report considers a number of values for f.

B. Results

The coverage and throughput results found are that: whilst sleep mode increases mean cell-UE distance, it improves the

SINR by reducing interference. For a given coverage threshold for the RAN across the day, one can find the most suitable sleep mode threshold. That is, one doesn't need to worry too much about coverage issues (at least for outdoor users). A mean SINR improvement of 2.8dB is experienced across the London region by increasing the Sleep Mode % from 20 to 50. Note, this says nothing yet about the spectral efficiency, throughput or radio resource blocks available. At no sleep mode ($f = 0$ in expression (6)), the coverage % is approximately 98% across the modeled area. For different sleep mode thresholds (f), the resulting coverage results are presented in Fig. 3.

The operational energy reduction gain (ERG) results for different sleep mode thresholds are presented in Fig. 4. The ERG achieved vary between 12 to 50% depending on the sleep mode threshold adopted and the time of the day. The concept is that for a given minimum coverage probability to achieve, the operator can use the results to find the sleep mode threshold that achieves the greatest energy saving, without sacrificing the QoS. The conclusion with sleep mode is that due to the high cell density of the London area, there is sufficient confidence of being able to switch cells off, whilst maintaining and actually improving coverage (outdoor). Whilst, this leads to a reduction in radio resources, during times of low load, this can lead to an energy reduction gain of 12-50%, depending on the time of the day. This broadly agrees with the conclusions drawn in the uniform hexagonal cell case [3], which arrived at a similar range of ERGs: 5-42%.

V. Research Technique: Heterogeneous Network

A. LPN Deployment

The heterogeneous network scenario considers the London baseline deployment of macro-BSs, with the following underlay of outdoor in-band low-power-nodes (LPNs), with the following LPN parameters:

- Transmit Power: 3 cases of 1mW, 1W and 5W are tested
- Location: random, and articulated deployment from an industrial source
- Deployment Area: 2km × 2km centered on Green Park and a wider 6km × 6km centered on Oxford Street.

The LPNs are deployed at a density of 7-9 LPNs per macro-BS coverage area. For the 2km × 2km area centered on Green Park, approximately 12 macro-BSs and 100 LPNs are considered. For the 6km × 6km area centered on Oxford Circus, approximately 60 macro-BSs and approximately 510 LPNs are considered. In order to speed-up the analysis of HetNets, the LPNs employ a statistical pathloss model (WINNER II) as opposed to generating an individual deterministic pathloss for each LPN.

B. Results

The results in Fig. 5 show that for the same LPN density, using an articulated deployment can achieve a significantly greater RAN coverage profile (SINR) and also throughput density improvement. The random deployment case has in fact introduced interference in areas that do not need LPNs,

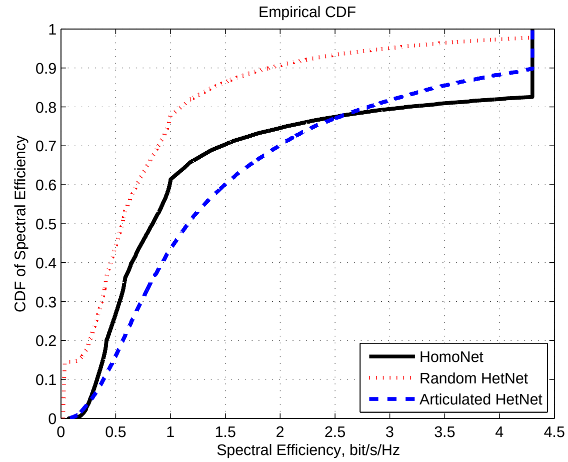

Fig. 5. HetNet Deployment Analysis: CDF of spectral efficiency in the London Area for a density of 8 LPNs per BS.

and as such, one can observe a significant increase in the proportion of areas that experience a capacity of below 0.5 bits/s/Hz (10 Mbits/s/cell) from 27% to 34%. The articulated deployment however has improved the coverage profile by reducing that from 27% to 16%. The articulated deployment case has improved the mean RAN throughput by approximately 200%. The large difference in results is explained by the fact that the articulated LPN deployment targets areas of poor coverage. This is an example of planned deployment being superior to anarchic deployment of LPNs. The assumption underlying the articulated LPN location data is that it is placing LPNs in regions of poor SINR coverage. Further the random deployment has not attempted to improve throughput in a more deterministic way.

The energy reduction gain (ERG) depends on:

1) the reduction in radio-head transmission energy in the macro-BSs
2) the LPNs' energy consumption value

If item (1) is greater than item (2), the ERG of the proposed HetNet is strictly positive. Otherwise, whilst the overall system capacity may have improved, the energy consumption under the current traffic model, has also increased. The results from Fig. 5 leads to the following energy saving results: the random HetNet deployment consumes 20% extra energy for a 10% capacity improvement; the articulated HetNet deployment consumes 6% extra energy for a 200% capacity improvement. Given that the traffic volume will continue to grow in the future, it is worth deploying HetNets to meet capacity growth and the investigation has demonstrated that whilst it doesn't reduce the energy consumption, intelligent deployment can lead to a small energy consumption increase.

VI. Integration of HetNet and Sleep Mode

A. Configuration

In this section, we consider the potential performance impact of integrating the previously considered techniques of sleep mode and heterogeneous network deployment. The rationale for this integration is that in baseline homogeneous

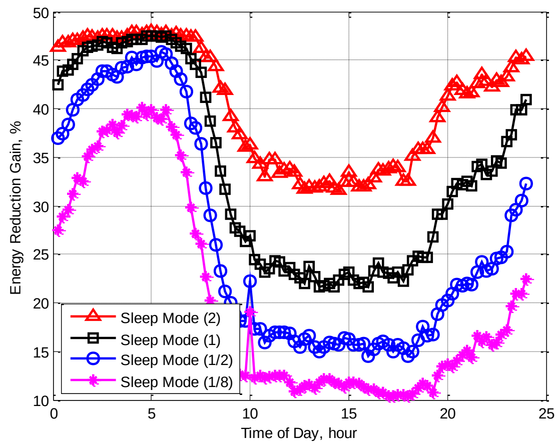

Fig. 6. HetNet Deployment with Sleep Mode's ERG results.

network deployment, the sleep mode traded off energy saving with outage probability. By deploying LPNs in a heterogeneous network configuration, the hypothesis is that the network is able to tradeoff more energy for a lower level of outage. The heterogeneous network scenario considers the London baseline deployment of macro-BSs, with the following under-lay of outdoor in-band low-power-nodes (LPNs), with the parameters given in Table I.

B. Results

Previously, it was found that sleep mode achieved a tradeoff between energy saving and outage probability. Heterogonous LPN network elements deployed at strategic places also improved the coverage and capacity of the RAN. By integrating the two techniques together, it was found that compared to sleep mode in a homogeneous network, the achievable energy saving has been decreased for the same sleep mode threshold. This is shown in Fig. 6. This is because the addition of LPNs has increased the RAN power consumption.

However, the outage probability for each given Sleep Mode threshold has been decreased. That is to say, for a target maximum outage probability across the RAN, the combined HetNet and sleep mode technique can achieve a higher ERG. For a target coverage probability of 98%, the Homogeneous RAN Sleep Mode can achieve an ERG variation of 12-42% depending on the time of the day. For a target coverage probability of 98%, the Homogeneous RAN Sleep Mode can achieve an ERG variation of 15-46% depending on the time of the day, yielding an improvement of 3-4%. That is to say, a more aggressive sleep mode threshold can be employed in the Heterogeneous case, due to the fact that LPNs can compensate for a potential loss in coverage. The results show that whilst the synergy of HetNet and Sleep Mode is not significant, accumulating different energy saving techniques can lead to higher energy saving gains.

VII. Conclusions

The paper first analyzes different multi-cell modelling approaches. Compared to a realistic London environment, hexagonal cell modeling's received SINR is 5-7dBs more optimistic. However, the shape of SINR profiles for a variety of modelling approaches are similar and a back-off factor can be used to yield 80% correlation between the performance profiles. The second part of the paper characterizes the tradeoff between energy saving and coverage probability using up-to-date traffic data. The results show that for a certain minimum coverage threshold, a sleep mode threshold that yields the lowest energy consumption can be found. The energy savings achieved are 13-42%, and the key result is that increasing the number of cells in sleep mode also reduces the interference, and improves the coverage probability across the area. The third part of the paper analyzed the energy saving potential of low-power-nodes (LPNs) deployed in a heterogeneous configuration and integrated this technique with sleep mode. It was found that random deployment can degrade the network-wide capacity, but articulated deployment can significantly improve the capacity. The combined solutions yielded an energy saving of 15-46% in a realistic London scenario.

Acknowledgement

The work reported in this paper has formed part of the EPSRC Knowledge Transfer Account and Green Radio Core 5 Research Programme of the Virtual Centre of Excellence in Mobile and Personal Communications, Mobile VCE. The authors would like to acknowledge the invaluable support given by: John Turk, David Lister, Eric Murray of Vodafone; Sunil Vadgama and Mythri Hunukumbure of Fujitsu. Fully detailed technical reports on this research are available to Industrial Members of the Mobile VCE. www.mobilevce.com

References

[1] C. Han, T. Harrold, S. Armour, I. Krikidis, S. Videv, P. Grant, H. Haas, J. Thompson, I. Ku, C.-X. Wang, T. A. Le, M. Nakhai, J. Zhang, and L. Hanzo, "Green radio: radio techniques to enable energy-efficient wireless networks," in *Communications Magazine, IEEE*, vol. 49, Jun. 2011, pp. 46–54.
[2] EARTH, "WP2.D2.3: Energy Efficiency Analysis of the Reference Systems," Energy Aware Radio and Network Technologies (EARTH), Technical Report, Dec. 2010.
[3] W. Guo and T. O'Farrell, "Green cellular network: Deployment solutions, sensitivity and tradeoffs," in *Wireless Advanced (WiAd), IEEE Proc.*, London, UK, Jun. 2011.
[4] C. Khirallah and J. Thompson, "Energy and cost impact of relay and femtocell deployments in LTE-Advanced," in *Communications, IET*, vol. 5, Dec. 2011, pp. 2617–2628.
[5] W. Guo and T. O'Farrell, "Relay deployment in cellular networks: Planning and optimization," in *Selected Areas in Communications (JSAC), IEEE Journal on*, vol. 30, Nov. 2012.
[6] A. Dinnis and J. Thompson, "The effects of including wraparound when simulating cellular wireless systems with relaying," in *Vehicular Technology Conference, IEEE*, Apr. 2007, pp. 914–918.
[7] M. Haenggi, J. G. Andrews, F. Baccelli, O. Dousse, and M. Franceschetti, "Stochastic geometry and random graphs for the analysis and design of wireless networks," in *Selected Areas in Communications (JSAC), IEEE Journal on*, vol. 28, Sep. 2009, pp. 1029–1046.
[8] S. Wang, W. Guo, and T. O'Farrell, "Two Tier Networks with Frequency Selective Surface," in *IEEE International Conference on High Performance Computing and Communications (HPCC)*, Jun. 2012.
[9] 3GPP, "Further Advancements for E-UTRA Physical Layer Aspects (Rel.9)," 3GPP TR36.814v9, Technical Report, Mar. 2010.