Energy Efficiency of Heterogeneous Networks in LTE-Advanced

Chadi Khirallah*, John S. Thompson* and Dejan Vukobratović †
*Institute for Digital Communications, School of Engineering, the University of Edinburgh, U.K, {c.khirallah@ed.ac.uk}
†Department of Power, Electronics and Communication Engineering, the University of Novi Sad, Serbia.

***Abstract-* Traditionally mobile operators have met the surge in mobile data traffic and the growing number of rural subscribers by deploying more macro base stations. This increases overall energy consumption, operational costs and carbon footprint of cellular networks. In this paper we investigate solutions for reducing the number and size of active macro cells following traffic load conditions in both homogeneous and heterogeneous networks. Results are presented as overall energy reduction gains for homogeneous macro-only and micro-only networks and heterogeneous joint macro-relay and micro-relay networks, using long-term-evolution-advanced technology. Results show that reducing the number of active cells using sleep mode at base stations, in low to medium traffic load conditions, combined with the deployment of small cells offer energy gains in both homogeneous and heterogeneous networks, but the most significant gains are observed in heterogeneous networks.**

I. INTRODUCTION

The staggering increase in mobile broadband data traffic as a result of higher customer usage of data intensive devices (e.g., smart phones, laptops, 3G dongles), and the growing number subscribers (over 5 billion by 2015 [1]), with almost 60-80% of new subscribers located in rural areas (i.e., off-electricity grid), are placing great financial, economic and ecological challenges on mobile network operators (MNOs).

Traditionally, MNOs have met any increase in data traffic or coverage extension, beyond electricity grids, by deploying more macro base stations (BSs). However, this solution increases overall energy consumption, operational expenditure costs (e.g., fossil fuel and electricity bills) and leads to adverse effects on the environment through increased carbon footprint (CO_2 emissions) [2].

To this end, MNOs need to seek alternative solutions to increasing the number of macro BSs (termed, enhanced NodeB (eNBs), in 3GPP). Such solutions are not only energy and cost efficient but also meet the challenge of reducing carbon footprints in mobile cellular networks.

Long term evolution-advanced (LTE-advanced) [3] offers MNOs an innovative “green radio” solution of deploying heterogeneous networks (HetNets) that combine high power-consumption macro eNBs, mainly used to ensure outdoor coverage, with low power-consumption micro, pico and femto BSs and relay nodes (RNs)[1]. The latter are deployed for throughput enhancement, in high user density areas (or hotspots), and coverage extension to users located close to problematic cell-edge areas [4].

Deploying small BSs as energy-efficient replacements to macro eNBs, opens the possibility to the use of alternative energy sources (solar and wind power) that are potentially more sustainable and cost-effective, and lowers CO_2 emissions in mobile cellular networks [2], [5]. On the other hand, wireless relaying is proposed for LTE-Advanced as a promising technique to increase the data fairness across a macro cell and improve system coverage. RNs target user equipments (UEs) suffering from poor channel conditions and low data rates, by mitigating shadowing, high pathloss, and fading channel impairments. Another key relay deployment scenario would be in rural or beyond electrical-grid public areas, where coverage extension using battery and/or solar-powered relays may be more energy efficient than deploying additional macro cell eNBs powered by fossil fuel and using costly wired backhaul links. In [6] we show that compared to homogeneous macro-only networks (HoNets), joint macro-relay networks reduce the overall energy consumption and cost in cellular networks.

Other promising energy reduction techniques such as cell-zooming and sleep mode deployments at BSs, target reducing energy consumption in the radio access network (RAN), which can contribute over 80% of the overall energy consumption in cellular networks [7]. These techniques adjust the BS power-consumption based on daily traffic load patterns that vary significantly between peak and quiet hours [8]. Therefore, adjusting the cell size, by varying the BS transmission power level according to traffic load conditions [9], or reducing the number of active macro cells by switching off part of the network macro BSs in low to medium traffic load conditions [10], may offer high energy gains in cellular networks.

The motivations of this paper are to investigate the energy impact of reducing the number and size of active BSs (macro, micro or relay) in HoNets and HetNets following

[1] A relay node is a well-developed BS that serves a small number of users and connects to its donor macro eNB using a wireless backhaul link (part of the macro eNB spectrum). A Micro BS is smaller in size and coverage area and consumes less power than the macro BS [10], and do not consume the macro eNB spectrum resources.

978-1-4673-0682-9/12/$31.00 ©2012 IEEE

traffic load conditions. Then we address questions related to the best topology for future cellular networks, in terms of hybrid deployment of large and small cells, and the way energy consumption varies with traffic load patterns in green BSs architectures using sleep modes. Moreover, since the radiated radio frequency power is not a realistic measure of actual energy consumption in cellular networks, we provide overall RAN energy consumption calculations and analyses using suitable operational power and embodied energy models and energy metrics, based on those introduced in [6].

The paper is structured as follows: Section II describes the methodology used to replace macro eNBs with RNs and micro BSs. Section III presents operational power and embodied energy models and energy metrics for macro, micro and relay BSs. Section IV provides numerical comparison of energy consumption in baseline macro- or micro-only networks and macro-relay or micro-relay networks for different traffic load conditions and inter-site-distances (*ISD*s). Finally, Section V concludes the paper.

II. Methodology of Replacing Macro eNBs

A. *Replacing macro eNBs with relays*

Iso-performance curves plot the relation between the density of macro eNBs and that of RNs in different combinations of eNBs and RNs (in a joint macro eNB-RN cells) that offer similar network performance. These curves provide numerous exchange ratios defined as the number of RNs required to replace one macro eNB. In this paper, we use three exchange ratios, introduced in [11], to analyze overall energy consumption in three HetNet scenarios, with high, medium and low number of RNs deployed per joint cell. Each cell combines one macro eNB of transmit power equal to 120 W, and a different number of RNs (M_{RN}) of transmit power equal to 0.25, 2, or 7 W (refer to Table 1).

The exchange ratio (R) between RNs and eNBs in HetNets is a function of M_{RN} (per joint cell) and the *ISD* ratio of the baseline and HetNet *ISD*s, and is given by:

$$R = M_{\mathrm{RN}} \frac{(ISD_{\mathrm{Base}}/ISD_{\mathrm{HetNet}})^2}{1-(ISD_{\mathrm{Base}}/ISD_{\mathrm{HetNet}})^2} \tag{1}$$

Table 1 chosen exchange ratios and the corresponding increase in *ISD*s (i.e., coverage extension) in joint macro eNB-RN networks.

Network scenario	**Parameter**			
	max. tx. power (W)	**Exchange ratio**	**M_{RN} (cell)**	**Coverage extension (%)**
Baseline (macro-only)	120 (eNB)	N.A	0	0
HetNet (joint macro-relay)	0.25 (RN)	28.9	36	50
	2 (RN)	12.9	36	95
	7 (RN)	8.5	9	44

Table 1 provides the chosen exchange ratios R = 28.9, 12.9, and 8.5, proposed in [11] (refer to table 2 in [11]), and the corresponding increase in *ISD* from ISD_{Base}= 500 m to ISD_{HetNet} = 750, 975, and 720 m, in joint macro-relay cells using (1).

B. *Replacing macro eNBs with micro BSs*

In cellular networks the relation between the radiated and received signal power is given as:

$$P_{\mathrm{rx}} = P_{\mathrm{tx}} + K + 10\gamma\log_{10}(d), \tag{2}$$

where P_{tx}, P_{rx} are the transmit and receive powers in (dBm), and K is a constant that accounts for several parameters such as the BS and mobile antenna gains, heights and patterns, in addition to shadowing and outdoor-to-indoor penetration losses [12]. For simplicity of calculation, we assume that K = 1 (0 dB) for users located outdoor in flat terrain cells (i.e., no penetration loss), line-of-sight conditions (i.e., no shadowing between BSs and UEs), and for the use of omni-directional antennas. The scalar γ is a constant pathloss exponent with value typically between 2 (free space propagation) and 4 (scattering environment) [10], and d is the propagation distance. Hence, for K = 0 dB, (2) becomes:

$$P_{\mathrm{rx}} = P_{\mathrm{tx}} \cdot (d)^{-\gamma} \tag{3}$$

Similar to replacing macro eNBs with RNs, a number of small cells (e.g., micros) are used to replace the coverage offered by one macro cell.

Based on (3), the ratio between transmission power levels of BSs in the baseline cell and reduced-size cell is given by:

$$\frac{P_{\mathrm{tx}}^{\mathrm{r}}}{P_{\mathrm{tx}}^{\mathrm{Base}}} = \left(\frac{ISD_{\mathrm{r}}}{ISD_{\mathrm{Base}}}\right)^{\gamma}, \tag{4}$$

where ISD_{Base} and ISD_{r} are inter site distances of the baseline cell (e.g., macro, or macro-relay) and reduced-size cell, respectively, and $(ISD_{\mathrm{r}}/ISD_{\mathrm{Base}})^{-\gamma}$ is the reduction factor in the baseline BS transmission power due to reducing the cell size.

Table 2 shows estimated reductions in transmission power levels, using (4), for macro BSs and RNs, as a result of reducing the cell size (i.e., coverage area). For example, in HetNet scenarios, and based on the number of RNs deployed per joint macro-relay cell, three power reduction factors 4.3, 11 and 3.7 are used to scale the macro eNB transmit power (120 W) to 27.9, 10.9, and 32.4 W, respectively, for ISD_{Base} = 750, 975 and 720 m, and ISD_{r} = 500 m. On the other hand, for the HoNet scenario ISD_{Base} = 500 m and ISD_{r} = 250 m, is used, and the reduction factor is 12.21. Note that the pathloss exponents for the RN and eNB are chosen as γ_{RN} = 2.2 and γ_{ma} = 3.6 [12].

Table 2 estimated reduction in the transmission power values for different types of BSs due to reducing the cell size.

<table>
<tr><th rowspan="2">Network scenario</th><th colspan="6">Parameter</th></tr>
<tr><th colspan="2">Baseline cell max. tx power (W)</th><th colspan="2">Reduction factor</th><th colspan="2">Reduced-size cell tx. power (W)</th></tr>
<tr><td>HoNet (macro-only)</td><td colspan="2">120 (macro)</td><td colspan="2">12.21</td><td colspan="2">9.8 (micro)</td></tr>
<tr><td rowspan="4">HetNet (joint macro- or micro-RN</td><td>macro</td><td>RN</td><td>macro</td><td>RN</td><td>micro</td><td>RN</td></tr>
<tr><td rowspan="3">120</td><td>0.25</td><td>4.3</td><td>2.4</td><td>27.9</td><td>0.1</td></tr>
<tr><td>2</td><td>11</td><td>4.3</td><td>10.8</td><td>0.47</td></tr>
<tr><td>7</td><td>3.7</td><td>2.2</td><td>32.4</td><td>3.2</td></tr>
</table>

III. POWER MODELS AND ENERGY METRICS

A. *Base station Operational Power (Op) Models*

The operational power (Op) models for macro eNBs and RNs are based on models introduced in [7][2], however, the macro eNB models are updated to include the energy consumption of wired backhaul links.

The Op model for the macro eNB describes the relation between the eNB maximum transmission power ($P_{\text{RF max}}^{\text{ma}}$) and the required operational power as:

$$P_{\text{Op}}^{\text{ma}} = \alpha_{\text{ma}} P_{\text{RF max}}^{\text{ma}} L + \sigma_{\text{ma}} + \lambda_{\text{ma}}, \tag{5}$$

where α_{ma} = 2.85 is a constant chosen based on the available energy-efficiency figures for state-of-the-art power amplifiers, antenna duplexer, and unit power supply. The scalar L is the value of the traffic load, σ_{ma} = 557 W is the sum of the power consumption by the transceiver (baseband and radio) and cooling sections. Finally, λ_{ma} = 45 W is the power consumption due to the use of Fibre Ethernet network end (backhaul link) for macro eNB [17], [18].

The RN Op consumption model is similar to that of the macro eNB, however, the static power consumption part in the RN model (σ_{RN}) is obtained by scaling down σ_{ma} by the ratio of $P_{\text{RF max}}^{\text{RN}}$ and $P_{\text{RF max}}^{\text{ma}}$. The RN Op model is given by:

$$P_{\text{Op}}^{\text{RN}} = \alpha_{\text{RN}} P_{\text{RF max}}^{\text{RN}} L + \sigma_{\text{RN}}, \tag{6}$$

where $\alpha_{\text{RN}} = \alpha_{\text{ma}}$ for similar base station elements in macro eNB and RNs.

Like in the case of RNs, the micro Op model is similar to that of the macro eNB, however, the static part of the micro Op model (σ_{mi}) is obtained by scaling down σ_{ma} by the ratio the micro and macro transmit powers. This choice is made to provide some simple and plausible trends for how the power consumption of BSs may scale with RF power, but these models can clearly be adjusted to fit actual BS products. The micro Op model is given by:

$$P_{\text{Op}}^{\text{mi}} = \alpha_{\text{mi}} P_{\text{RF max}}^{\text{mi}} L + \sigma_{\text{mi}} + \lambda_{\text{mi}}, \tag{7}$$

where the backhaul power consumption for a micro BS, due to the use of an asymmetric-digital-subscriber- line (ADSL) network connection, is λ_{mi} = 10 W [18].

Table 3 shows the estimated Op consumption of a macro, micro and relay BSs, using Op models provided in (5), (6) and (7), respectively. Op consumption values are presented for BSs operating in the active or sleep (switch-off) modes. For example, in the sleep mode we set the loading factor L to zero (zero load) in equations (5), (6) and, (7). For comparison reasons we include $P_{\text{Op}}^{\text{ma}}$ and $P_{\text{Op}}^{\text{RN}}$ values obtained using power models in [13], and [19], respectively, for a macro eNB and RN operating in the active mode. From Table 3, and based on Op values, it is clear that the proposed operational power models are similar to those widely available in the green radio literature.

The operational models in (5), (6) and (7) ignore any possible increase in signaling overhead due to: (i) increased handover messages with traffic-offload from macro to microcells, or from switch-off cells to active cells, and (ii) relay deployments. This assumption is justified taking into consideration the following arguments:

- Active neighboring cells are able to offload traffic from switch-off cells while maintaining a similar quality-of-service. This results in fewer handover messages;
- Energy loss during handover periods is minimal compared to potentially high energy savings due to sleep mode schemes [20];
- In HetNets the size of the signaling overhead depends on the number of relays simultaneously scheduled in a sub-frame (per cell), and we assume that only one relay is scheduled for service per sub-frame and no coordination or cooperation is allowed between relays);
- RNs are only active when serving UEs, otherwise, RNs and their signalling overhead are switch-off and BSs can use all available resources for UE scheduling [21].

Table 3 numerical values of the operational power as a function of the transmit power for different types of BSs.

<table>
<tr><th rowspan="3">Base station</th><th rowspan="3">Tx. power (W)</th><th colspan="3">Operational Power (W)</th></tr>
<tr><th colspan="2">Proposed model</th><th>Reference model</th></tr>
<tr><th>Active (L=1)</th><th>Sleep (L=0)</th><th>Active</th></tr>
<tr><td>Macro</td><td>120</td><td>944</td><td>602</td><td>1317 [13]</td></tr>
<tr><td>Micro</td><td>10.8</td><td>91</td><td>60</td><td>91.8 [13]</td></tr>
<tr><td>Relay</td><td>2</td><td>15</td><td>9.3</td><td>8 [19]</td></tr>
</table>

[2] These models are derived based on research on state-of-the-art base stations [13] and information on equipment available from several MNOs, telecom vendors [14], 'EARTH' [15] and 'Green Radio' [16] projects.

B. Base stations Embodied Energy Models

Embodied energy is defined as the energy consumption during the entire lifecycle of a product [22]. In [23] authors follow a detailed breakdown of energy costs - the "deep dive" approach and suggest that embodied energy of a macro or micro BSs, calculated over 10-year lifecycle, only contributes up to 10% of their total power consumption. For a similar proportion, the embodied energy of a customer-grade relay represents almost 20% of its total energy consumption considering a 5-year lifecycle.

C. Energy Metrics

Total energy consumption in a HoNet or HetNet is calculated from the total operational power $P_{\mathrm{Op}}^{\mathrm{Tot}}$ and embodied energy $E_{\mathrm{Em}}^{\mathrm{Tot}}$ of all BSs in the network given by:

$$P_{\mathrm{Op}}^{\mathrm{Tot}} = N_{\mathrm{ma}} \times P_{\mathrm{Op}}^{\mathrm{ma}} + M_{\mathrm{RN}} \times P_{\mathrm{Op}}^{\mathrm{RN}} + N_{\mathrm{mi}} \times P_{\mathrm{Op}}^{\mathrm{mi}}, \tag{8}$$

$$E_{\mathrm{Em}}^{\mathrm{Tot}} = N_{\mathrm{ma}} \times E_{\mathrm{Em}}^{\mathrm{ma}} + M_{\mathrm{RN}} \times E_{\mathrm{Em}}^{\mathrm{RN}} + N_{\mathrm{mi}} \times E_{\mathrm{Em}}^{\mathrm{mi}}, \tag{9}$$

where N_{ma}, N_{mi}, and M_{RN} are the total number of macro, micro and relay BSs in the network, $P_{\mathrm{Op}}^{\mathrm{ma}}, P_{\mathrm{Op}}^{\mathrm{mi}}$ and $P_{\mathrm{Op}}^{\mathrm{RN}}$ are the operational powers of macro, micro and relay BSs, respectively, while $E_{\mathrm{Em}}^{\mathrm{ma}}, E_{\mathrm{Em}}^{\mathrm{mi}}$ and $E_{\mathrm{Em}}^{\mathrm{RN}}$ are the equivalent embodied energy per second of macro, micro and relay BSs.

The energy reduction gain (ERG) (expressed in percent) is derived from (8) and (9), as the ratio of total energy consumption for a baseline macro-only network and that of a HetNet [6], [7]:

$$\mathrm{ERG}\% = \left(1 - \frac{\left(E_{\mathrm{Op}}^{\mathrm{Tot}} + E_{\mathrm{Em}}^{\mathrm{Tot}}\right)_{\mathrm{HetNet}}}{\left(E_{\mathrm{Op}}^{\mathrm{Tot}} + E_{\mathrm{Em}}^{\mathrm{Tot}}\right)_{\mathrm{Base}}}\right) \times 100[\%], \tag{10}$$

where $E_{\mathrm{Op}}^{\mathrm{Tot}}$ is the operational energy that is equivalent in value to the operational power assuming numerical calculations over a one second period.

IV. Numerical Results and Discussions

The overall energy consumptions for four cellular networks (see Table 4) that offer similar coverage area are evaluated and compared. First, a baseline homogeneous macro-only network that consists of 19 macro cells (active mode L =1), with ISD_{Base}=500 m and $P_{\mathrm{RF\,max}}^{\mathrm{ma}} = 120$ W. Second, a homogeneous micro-only network that consists of 76 micro cells, with ISD_{mi}=250 m and $P_{\mathrm{RF\,max}}^{\mathrm{mi}} = 10.8$ W. Third, two joint macro-relay and micro-relay HetNets that combine different numbers of macros, micros, and RNs. The chosen transmission power values of different BSs are given in Table 2.

Table 4 provides the number of active base stations (macros, micros, RNs) in the four network scenarios that varies according to the assumed traffic load value L = 20, 50, 100% (low, medium and high traffic load conditions).

To ensure similar coverage between the four networks, each macro cell in the baseline network offers a similar coverage area to four micro cells in the micro-only HoNet, while four macro cells are replaced by one joint macro-relay cell with 36 cell-edge RNs in the HetNet scenario. Also the coverage of each joint macro-RN cell can be replaced by four joint micro-RN cells. For example, 19 macros offer similar coverage to 76 micros as shown in Table 4.

Table 4 numbers of active and switch-off BSs in evaluated networks under different traffic load and *ISD* values.

Network scenario	**Traffic Load value *L* (%)**	**Num of eNB (M_{eNB})**		**Num of eNB (M_{RN})**	
		Active	**Sleep**	**Active**	**Sleep**
Baseline (macro-only) ISD_{Base}= 500m	100	19	0	0	0
	50	10	9	0	0
	20	4	15	0	0
HoNet (micro-only) ISD_{mi} = 250 m	100	76	0	0	0
	50	38	38	0	0
	20	16	60	0	0
HetNet (joint macro-RN) ISD_{HetNet}= 500, 974m	100	7	0	144	0
	50	4	3	72	72
	20	2	4	36	108
HetNet (joint macro- and micro- RN) ISD_{HetNet}= 250, 500m	100	16 (micro), 3 (macro)	0	576	0
	50	8 (micro), 2 (macro)	8 (micro), 1 (macro)	288	288
	20	4 (micro), 1 (macro)	12 (micro), 2 (macro)	144	1728

A. ERGs in joint macro-relay networks using sleep mode

This section investigates the energy impact of switching off BSs in macro-only and macro-relay networks, under varying traffic load conditions. Traffic loads are non-equally distributed and vary significantly during different periods of the day [8]. Table 5 shows an example of three traffic load values (given as a percentage of the total network traffic) that can be served by different fraction of cells (given as a percentage of the total number of cells) in three periods of the day. For example, we assume that 90% of the total network traffic load can be contributed by almost 30% of the network active cells during the peak hours (evening), and only 10% of network cells during the quiet hours (e.g., 7am). This suggests that depending on the time of the day almost 70-90% of total active cells may be serving only 20-50% of the total traffic load, and could be switched-off to save energy.

Table 5 fractions of active cells that contribute to different percentage of the total network traffic for three periods of the day.

Traffic load (%)	Percentage of active cells (%)		
	Evening (Peak-time)	Midday	Early Morning (Quiet-time)
90	30	22	10
50	30	30	30
20	40	48	60

Figure 1 shows potential operational ERG values, calculated using (10) (ignoring embodied energy), due to switching off base stations in the baseline macro-only and joint macro-relay networks, under traffic load conditions given in Table 5. It is clear that switching off BSs (eNBs, RNs) in both networks is expected to reduce energy consumption compared to the baseline macro-only network with all BSs in the active mode operation (no sleep mode). Nonetheless, the HetNet scenario results in higher ERGs equal to 57-59%, during peak and quiet traffic load periods, respectively, compared to ERGs equal to 16-25% in the macro-only network. This is due to the proposed relay energy consumption model (in (6)) that is more scalable with the traffic load values than the eNB energy model given in (5).

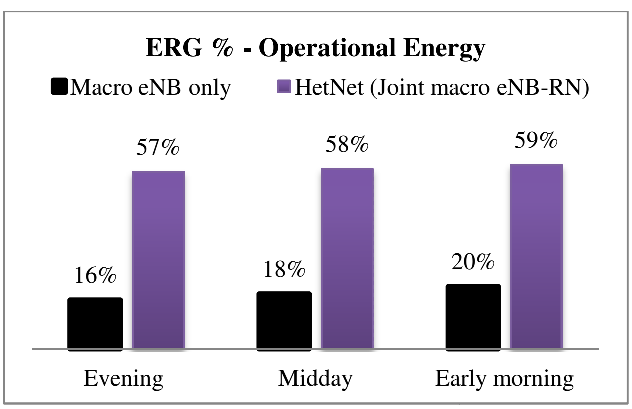

Figure 1 an operational ERG comparison of a macro-only and macro-relay networks using traffic load profiles in Table 5.

B. ERGs for sleep mode and small cell deployments

Figures 2 and 3 show combined energy benefits of switching-off active cells and reducing cell area, in macro–only, micro-only, macro-RN and micro-RN networks as a function of traffic load values. The integration of the two techniques results in significant operational ERGs equal to 61-70% for the micro-only network, and ERGs equal to 62-79% for the micro-RN network. These figures are for comparisons with macro-only and macro-RN networks, with no sleep mode at BSs[3]. Similar values are shown for total ERGs, calculated using (10) (including both the operational and embodied energy).

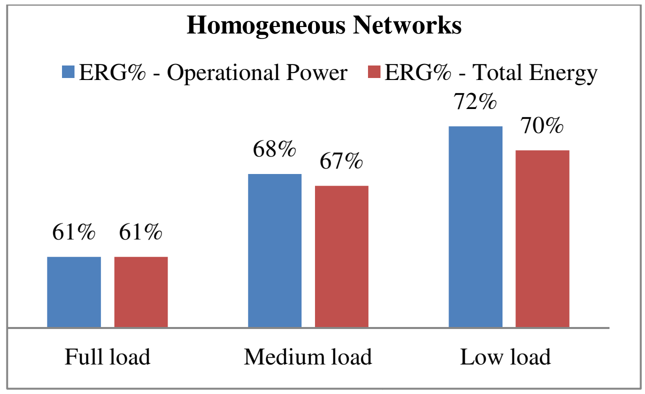

Figure 2 Operational and total ERG comparisons of a macro-only and micro-only HoNets under different traffic load conditions.

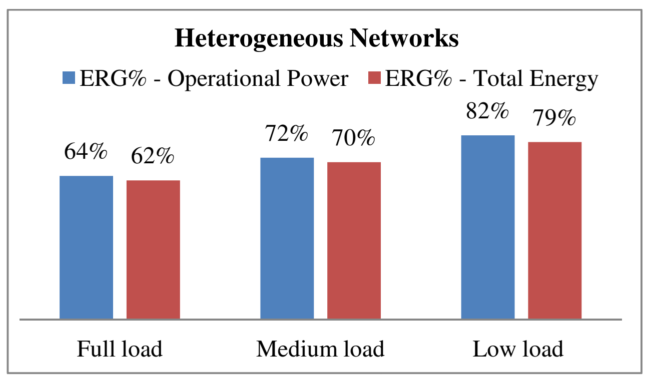

Figure 3 Operational and total ERG comparisons of a macro-relay and micro-relay HetNets under different traffic load conditions.

V. CONCLUSIONS

This paper investigates the energy benefits of reducing the macro cell size and implementing a sleep mode at the base station on overall the energy consumption in LTE-Advanced HoNets and HetNets. Results obtained show that reducing the number of active cells using sleep mode at BSs offers

[3] The baseline scenario is similar to that in current LTE networks with macro base stations "always on" even in low traffic conditions to deliver signaling messages (control overhead).

energy gains in both HoNets and HetNets. However, the most significant gains are observed in HetNets, with ERGs of 50-61% compared to modest ERGs of 0-25% in HoNets. This is attributed to the proposed micro and relay power models that scale power consumption with traffic load values. Additionally, the integration of sleep mode at BSs and deployment of small cells results high energy saving for both HoNets and HetNets. In summary, the best topology for future mobile cellular networks will be in the form of HetNets that mix large and small cells and RNs, and deploy green BSs that implement sleep mode, and is able to adjust power consumption with traffic load conditions.

ACKNOWLEDGEMENT

The work reported has formed part of the Green Radio Core 5 Research Programme of the Virtual Centre of Excellence (VCE) in Mobile and Personal Communications (www.mobilevce.com). This research is funded by the Industrial Companies who are members of Mobile VCE and by the UK EPSRC under Grant Numbers EP/G060584/1, EP/G06041X/1, EP/G062420/1 and EP/G064105/1. We would like to acknowledge the GR members and specially Tim Harrold and Simon Armour (Bristol University) and both David Lister (Vodafone) and Simon Fletcher (NEC) for their valuable feedback and useful comments.

REFERENCES

[1] Alcatel-Lucent, "Eco-sustainable Wireless Solutions: Leveraging the value of green," www.alcatel-lucent.com.

[2] A. Fehske, et al., "The global footprint of mobile communications: The ecological and economic perspective," *IEEE Comms. Mag*., vol.49, no.8, pp.55-62, Aug. 2011.

[3] A. Ghosh, et al., "LTE-Advanced: next generation wireless broadband technology," *IEEE Wireless Comms.*, vol. 17, no. 3, pp. 10-22, June 2010.

[4] T. Beniero, et al., "Effect of Relaying on Coverage in 3GPP LTE-Advanced," In Proc. IEEE VTC-Spring, Barcelona, Spain, April 2009.

[5] S. Matthews, et al., "Planning Energy-efficient and Eco-sustainable Telecommunications Networks," Bell Labs Technical Journal 15(1), 215–236, 2010.

[6] C. Khirallah, J. S. Thompson, and H. Rashvand, "Energy and Cost Impact of Relay and Femtocell deployments in LTE-Advanced," *IET Comms.*, vol. 5, Issue 18, 16 Dec. 2011.

[7] S. McLaughlin, et al., "Techniques for improving cellular radio base station energy efficiency," *IEEE Comms. Mag.*, vol. 18, Issue 5, Oct. 2011.

[8] H. Holma, and A. Toskala, LTE for UMTS, OFDMA and SC-FDMA Based Radio Access, John Wiley & Sons Ltd, 2009.

[9] Z. Niu, Y. Wu, J. Gong, Z. Yang, "Cell Zooming for Cost-Efficient Green Cellular Networks," *IEEE Comms. Mag.*, vol. 48, no. 11, pp. 74-79, Nov. 2010.

[10] F. Richter, J. Albrecht, P. Marsch, and G. Fettweis, "Traffic Demand and Energy Efficiency in Heterogeneous Cellular Mobile Radio Networks," In Proc. IEEE VTC-Spring, Taipei, Taiwan, May 2010.

[11] E. Lang, S. Redana, and B. Raff, "Business Impact of Relay Deployment for Coverage Extension in 3GPP LTE-Advanced," In Proc. IEEE ICC Workshops, Dresden, Germany, June 2009.

[12] 3GPP TR 36.814 V2.0.0, Further Advancements for E-UTRA Physical Layer Aspects, March 2010.

[13] O. Arnold, et al., "Power consumption modeling of different base station types in heterogeneous cellular networks," Future Network and Mobile Summit, Florence, Italy, June 2010.

[14] G. Fischer, "Next-Generation Base Station Radio Frequency Architecture," Bell Labs Technical Journal, vol. 12, no. 2, pp. 3-18, 2007.

[15] EARTH project deliverable, D2.3, www.earth.eu.

[16] The Green Radio Project Core 5, http://mobilevce.com.

[17] Cambridge Broadband Networks, "LTE Traffic Webinar: Backhaul on Demand", Oct. 2010.

[18] European Union, Code of Conduct on Energy Consumption of Broadband Equipment, Version 3. 18, Nov. 2008.

[19] M. Dohler, Y. Li, Cooperative Communications: Hardware, Channel and PHY, Wiley-Blackwell, Feb. 2010.

[20] M. A. Marsan, et al., "Switch-Off Transients in Cellular Access Networks with Sleep Modes," In Proc. IEEE ICC, Kyoto, Japan, June 2011.

[21] R1-092451, "Control structure for Relay Type 1 nodes", NEC Group, July 2009.

[22] Emmenegger M., et al., "Life Cycle Assessment of the Mobile Communication System UMTS: Towards ECO-efficient Systems," The International Journal of Life Cycle Assessment, vol. 11, no. 4, pp. 265-276, July 2006.

[23] L. T. Jyrki, and S. O. Hans, "Energy efficiency of cellular networks," In Proc. WPMC Conference, Finland, Sept. 2008.