Energy Efficiency of Relay deployment in LTE-Advanced

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Abstract— **Multi-hop relaying deployment are expected to offer coverage extension and throughput enhancement to fulfill the staggering increase in mobile broadband traffic, while reducing the total energy consumption in heterogeneous cellular networks, namely joint macro basestation-relay networks. This paper investigates the impact of relay deployment in long term-evolution advanced (LTE-Advanced), as a substitute for the traditional high-power macro basestation, on the total operational power and embodied energy of joint macro basestation-relay networks, with different basestations and relay nodes deployments densities. All joint networks are assumed to have similar service level to that of a baseline macro-basestation only network. Results obtained show that joint macro basestation-relay networks are more energy efficient than the baseline network, with energy reduction gain up to 58% for medium relay deployment density of 12 relay nodes per macrocell.**

Index Terms— **LTE-Advanced, operational power, embodied energy, heterogeneous networks.**

I. Introduction

The staggering increase of mobile broadband data traffic as a results of higher customer usage of data intensive devices (e.g., smart phones, laptops, 3G USB dongles), has presented mobile network operators (MNOs) with high increase in energy consumption of cellular networks. Such increase results in higher mobile network operational expenditure (e.g., electricity bills) and leads to adverse effect on the environment as increased CO_2 emissions.

Traditionally, MNOs are forced to deploy more high power macrocell basestations in order to meet the surge in traffic demands. However, the deployment of such basestations – termed enhanced node basestations (eNBs) – which are both expensive and non-energy efficient. To this end, MNOs have started to seek innovative techniques and architectures that are able to deal with the data traffic growth while reducing energy consumption in cellular network.

Long term evolution-advanced (LTE-advanced) [1] offers MNOs an innovative “green radio” solution of deploying heterogeneous networks (HetNets) that combine high power macrocell eNBs, that ensures umbrella coverage mainly for outdoor users, with low-power relay nodes (RNs) deployed for improving user throughput (dense area, hotspots), or for coverage extension (close to cell-edge) [2].

Wireless relaying is proposed for LTE-Advanced as a promising technique to increase the data fairness across a macrocell and improve system coverage. Relays target user equipments (UEs) suffering from poor channel conditions and low data rates, by mitigating shadowing, high path-loss, and fading channel impairments. Another key relay deployment scenario would be in rural or off electrical-grid public areas, in which coverage extension using low power wireless relays may be more energy efficient than simply using a macrocell eNB, powered by fossil fuel, and a wired backhaul.

Several recent works, such as [3], mainly investigate the enhanced technical performance of joint macro eNB-RN networks, under the assumption that relay deployments would also result in reduced total energy consumption in joint networks. This is due to their low transmit power (e.g., 20-38 dBm for RNs), compared to those of a eNB (e.g., 46 dBm/cell-sector) [4]. However, this inference ignores the effect of increased number of RNs deployed on the joint network operational power. It also neglects the embodied energy, defined as the additional energy consumption in manufacturing, commissioning and disposal of a product, and O&M costs. This may undermine any promised improvement in the technical performance due to relay deployments. In [5] authors propose replacing the high power macro eNBs with a number of RNs that offer similar service level (cell-edge throughput). However, this approach may not be accurate for energy consumption calculations, since it overlooks a major part of energy consumption that is spent by the donor eNB to carry traffic to RNs over relay links.

This paper presents a novel and realistic approach to investigate the energy efficiency of relay deployment in LTE-Advanced based on:

- The energy consumption of the entire radio access network (RAN) using energy models of the network components which account for the main power supply, power amplifier, transceiver, cable loss, and cooling systems;
- Suitable operational and embodied energy models and energy metrics to produce estimated energy consumption figures for eNB and RN;
- Evaluation of energy consumption is conducted using two operational energy models that give the lower (optimistic) and upper (pessimistic) energy consumption bounds.

The paper is structured as follows: Sections II describe the methodology used to compare energy consumption of a baseline macro eNB only network with those of joint macro eNB-RNs networks. Section III presents the numerical calculation using the proposed operational power and embodied energy models in addition to energy calculation metrics. Section IV presents the numerical results and relevant discussion. Finally, conclusions are drawn in Section V

II. Methodology of substituting macrocell base stations with relay nodes

In order to investigate the energy and cost impacts of relay extensions to LTE-Advanced, we compare four different deployment densities of mixtures of eNBs and RNs; a baseline macro eNB only network, and three joint macro eNB-RN networks, with different numbers of eNBs and RNs (per macrocell). All networks offer users similar service level (e.g., cell-edge throughput [3]). The optimum number of RNs deployed in a macrocell varies according to the RN transmit power, and can be obtained using the following algorithm [3] and [6]:

- Generate the indifference or iso-performance curves that represent a set of potential combinations of eNBs and RNs, in a joint deployment, that offer the same performance (e.g., 10%-tile of the throughput cumulative-distribution-function (CDF));
- Using iso-performance curves calculate the optimum exchange ratio between the number of RNs deployed per macrocell and the corresponding reduction in the number of eNBs in a joint macro eNB-RN network compared to that in a baseline macro eNB only network.

Figure 1 shows an example of substituting a set of four traditional macrocells, of four macro-centered eNBs, with one joint macrocell that combines one macro-centered eNB and 36 cell-edge RNs per cell-sector. In this scenario the coverage area of the joint macrocell equals four times that of the baseline macrocell, i.e., the inter-site-distance (ISD) of the joint macrocell is double that of the baseline macrocell.

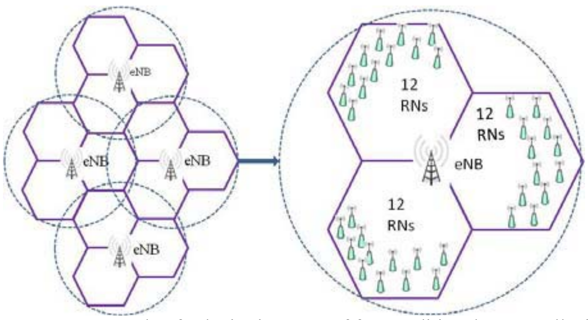

Figure 1: an example of substituting a set of four traditional macrocell of four eNBs with one joint macrocell that combines one eNB and 36 RNs.

III. Numerical calculations

In this section we first present the energy models and energy metrics that are used to evaluate the total energy consumption (both embodied and operational) for joint macro-relay networks. Then we draw a comparison between:

- Four macrocell deployments, that offer cell-edge users a similar throughput, a baseline macro eNB only network and three joint macro eNB–RN networks, with different numbers of RNs per macrocell (29, 12, and 9 RNs as proposed in [3] and [5]),

A. Operational power and Embodied energy models

In this paper we deploy a macro eNB operational power (Op) model based on recent studies of basestation energy efficiency presented in [7] and [8]. This model maps the power supply (i.e., input power) of a macro eNB to its maximum output power and offers the choice of estimating the upper (pessimistic) or lower (optimistic) power consumption bounds for the macro eNB. The pessimistic Op consumption model is given by:

$$P^{\mathrm{eNB}}_{\mathrm{Op}} = \lambda P^{\mathrm{eNB}}_{\mathrm{RFmax}} + \sigma, \quad (1)$$

where λ is linearly dependent on the maximum transmit power of eNB ($P^{\mathrm{eNB}}_{\mathrm{RFmax}}$) and is related to the power amplifier (PA) efficiency, while σ represents the static part of Op in (1) that mainly accounts for the power loss due to signal processing, power supply, and air conditioning [8] at the basestation. On the other hand, the optimistic Op model is given by:

$$P^{\mathrm{eNB}}_{\mathrm{Op}} = \beta L P^{\mathrm{eNB}}_{\mathrm{RFmax}} + \rho P^{\mathrm{eNB}}_{\mathrm{RFmax}} + \theta L + \gamma, \quad (2)$$

where β, ρ, and θ are constants with values linearly dependent on $P^{\mathrm{eNB}}_{\mathrm{RFmax}}$ and / or eNB traffic load L, while γ is fixed and independent of the radio frequency (RF) chain and the transceiver power loss. In this paper the power model parameters are chosen as λ = 2.85, σ = 577 Watts [W], β = 2.42, ρ = 0.00115, θ = 0.0121, and γ = 37 W, and the system load L = 1 (i.e., full load).

In regard to RN power consumption models, Dohler in [9] presents a typical RN Op consumption model, for both battery or non battery operated UMTS relays, as:

$$P^{\mathrm{RN}}_{\mathrm{Op}} = \left(P^{\mathrm{RN}}_{\mathrm{RFmax}} \big/ \varepsilon\omega \right) + k, \quad (3)$$

where ε = 0.3 is the PA efficiency, ω = 0.85 is the efficiency of the battery voltage stabiliser, while k = 0.195 W is the average power loss in the transmit/receive chain.

However, due to the unavailability of RN power consumption models for LTE and LTE-Advanced, within the green radio literature, we introduce a new RN operational power model[1] based on scaling down the static components in (1) and (2) (i.e., σ and γ) by the ratio of RN transmit power to eNB transmit power. This assumes that for consistency both the RN and the eNB should consume similar operational power for the same transmit power. Hence, the pessimistic and optimistic Op consumption models for RN are given by:

$$P^{\mathrm{RN}}_{\mathrm{Op}} = \lambda P^{\mathrm{RN}}_{\mathrm{RFmax}} + \left(P^{\mathrm{RN}}_{\mathrm{RFmax}} \big/ P^{\mathrm{eNB}}_{\mathrm{RFmax}} \right) \times \sigma, \quad (4)$$

$$P^{\mathrm{RN}}_{\mathrm{Op}} = \beta L P^{\mathrm{RN}}_{\mathrm{RFmax}} + \rho P^{\mathrm{RN}}_{\mathrm{RFmax}} + \theta L + \left(P^{\mathrm{RN}}_{\mathrm{RFmax}} \big/ P^{\mathrm{eNB}}_{\mathrm{RFmax}} \right) \times \gamma. \quad (5)$$

Table 1 shows the numerical values of $P^{\mathrm{eNB}}_{\mathrm{Op}}$ and $P^{\mathrm{RN}}_{\mathrm{Op}}$ obtained for $P^{\mathrm{eNB}}_{\mathrm{RFmax}}$ = 46 dBm using (1) and (2), and for $P^{\mathrm{RN}}_{\mathrm{RFmax}}$ = 24, 33, 38 dBm using (4), (5) and the RN Op consumption

[1] This model is proposed purely for numerical convenience and may offer different results to those obtained from real relay equipment.

model in (3). From Table 1, the UMTS RN Op model represents an average Op consumption model that lies in between our proposed relay pessimistic and optimistic operation power models.

Node	Num RNs per cell	RFmax [dBm]	Operational power [W]		
			Pessimistic	*Optimistic*	*UMTS RN [9]*
eNB	-	46	919	350	-
RN	29	24	2	0.7	1.03
	12	33	15.3	5.5	6.85
	9	38	48.3	17.3	21.3

Table 1: numerical values of P^{eNB}_{Op} and P^{RN}_{Op} obtained for P^{eNB}_{RFmax} = 46 dBm and P^{RN}_{RFmax} = 24, 33, 38 dBm and RN power consumption model in [9].

In order to make a fair comparison between the baseline macro eNB only network and the joint eNB-RN network we need to consider the total energy consumption including both the operational power and embodied energy. The latter is defined as the energy consumption during the entire lifecycle of a product (i.e., from raw material extraction to transportation, manufacturing, installation, etc) [10]. In [11], presented in 2008, Edler derives the yearly CO_2 emissions per user based on the expected embodied energy and operational power[2] of a typical basestation and mobile handset in wireless cellular network. The total energy consumption of eNB is broken down to almost 30% embodied energy and 70% Op contribution, compared to 70% embodied energy and 30% Op contribution for the mobile handset, due to the typical 2-year lifecycle of the handset compared to the 10-year eNB lifecycle.

On the other hand, according to [12] the embodied energy of an eNB, calculated over 10-year lifecycle, only contributes up to 10% of the total eNB power consumption. Assuming a similar proportion, the embodied energy of a customer-grade RN would represent almost 20% of the total energy consumption considering a 5-year lifecycle[3] for RNs. Table 2 shows the assumed values for the lifecycle and embodied energy (as a fraction of the total energy consumption) of a macro eNB and a customer-grade RN according to [12].

	Lifecycle [years]	Embodied energy as a % of the total energy consumption
eNB	10	10%
RN	5	20%

Table 2: assumed values for the lifecycle and embodied energy parameters for a macro eNB (carrier-grade) and a customer-grade RN according to [12].

[2]For numerical convenience all energy and cost calculations assume that eNB/RN operate over a one second period; hence, the value of the operational energy, given in [Joule], and that of the operational power, given in [Joule/sec], is the same.

[3] A 5-year lifecycle is expected for customer-grade equipment such as that of wireless LAN (WLAN) access points.

B. Energy Metrics

The total energy consumption of a joint macro basestation-relay network[4] is calculated as the sum of the total operational power P^{Tot}_{Op} and the embodied energy E^{Tot}_{Em} given by:

$$P^{Tot}_{Op} = N_{eNB} \times P^{eNB}_{Op} + M_{RN} \times P^{RN}_{Op}, \quad (6)$$

$$E^{Tot}_{Em} = N_{eNB} \times E^{eNB}_{Em} + M_{RN} \times E^{RN}_{Em}, \quad (7)$$

where N_{eNB} and M_{RN} are the total number of eNBs and RNs in the joint network, P^{eNB}_{Op} and P^{RN}_{Op} are the operational power of the eNB and RN, while E^{eNB}_{Em} and E^{RN}_{Em} are the equivalent embodied energy per second of the eNB and RN computed using the proportions in Table 1.

The energy consumption gain (ECG) metric is defined as the ratio of the operational power or embodied energy for a baseline macro eNB only network and a joint macro eNB-RN network:

$$\mathrm{ECG}_{Op}\% = \left(\left(P^{Tot}_{Op}\right)_{Base} / \left(P^{Tot}_{Op}\right)_{Joint} \right) \times 100\,[\%], \quad (8)$$

$$\mathrm{ECG}_{Em}\% = \left(\left(E^{Tot}_{Em}\right)_{Base} / \left(E^{Tot}_{Em}\right)_{Joint} \right) \times 100\,[\%]. \quad (9)$$

The energy reduction gain (ERG) (expressed in percent) is derived from the ECG metric, defined in (8) and (9), as:

$$\mathrm{ERG}\% = \left(1 - \frac{\left(P^{Tot}_{Op} + E^{Tot}_{Em}\right)_{Joint}}{\left(P^{Tot}_{Op} + E^{Tot}_{Em}\right)_{Base}} \right) \times 100[\%]. \quad (10)$$

IV. NUMERICAL RESULTS AND DISCUSSION

The total energy consumption and cost comparison is presented for four combinations of macro eNB and RN networks with a similar service level (cell-edge throughput). A baseline macro eNB network and three joint macro eNB-RN networks using 29, 12 and 9 RNs per macrocell (see Table 1).

Figure 2 illustrates an operational power comparison, based on the ECG% defined in (8), of the four network types. It is clear that the three joint macro eNB-RN networks consume less operational power compared to the baseline macro eNB network, with ECG% equal to 209, 250 and 136% for eNB to RN exchange ratios equal to 29, 12 and 9 RNs, respectively. Also, the joint macro eNB-RN network deploying RNs of medium transmit power (33 dBm) is more power efficient compared to those using low or high transmit power RNs (24 or 38 dBm).

Figure 3 shows the total energy consumption including both operational and embodied energy, based on ERG% defined in (10), of the three joint macro eNB-RN networks using 29, 12 and 9 RNs (per macrocell). All three networks are more energy efficient with ERG% equal to 52, 58, and 24% for eNB to RN exchange ratios equal to 29, 12, and 9 RNs, respectively. However, similar to Figure 3, the joint macro eNB-RN deployment using 12 RNs per macrocell is the most energy efficient.

[4] We only consider total power consumption in the access network for joint macro basestation-relay networks. This assumes that the power consumption in the core network can be neglected compared to that for the access network.

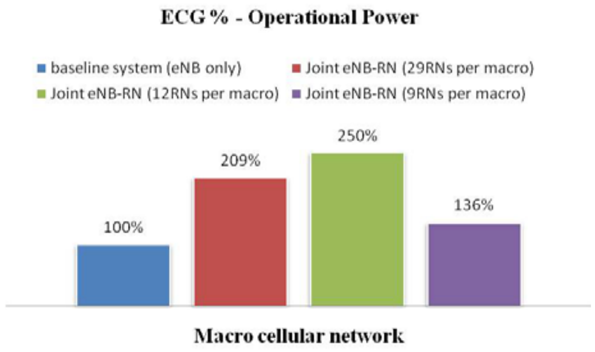

Figure 2: a comparison of operational power based on ECG% for four macro cellular networks: a baseline macro eNB and three joint macro eNB-RN networks. $P_{\mathrm{RFmax,\,eNB}} = 46$ dBm and $P_{\mathrm{RFmax,\,RN}} = 24$, 33, and 38 dBm. The number of RNs deployed per macrocell is equal to 29, 12, and 9 RNs.

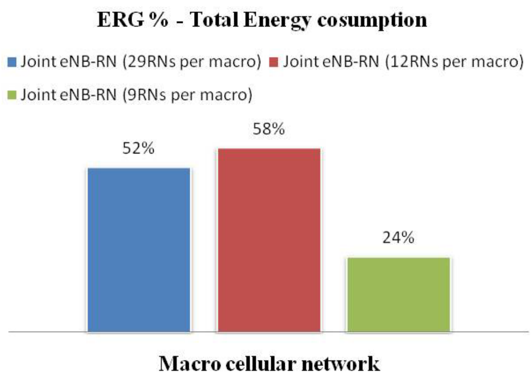

Figure 3: ERG% for three joint macro eNB-RN networks with $P_{\mathrm{RFmax,\,eNB}} = 46$ dBm and $P_{\mathrm{RFmax,\,RN}} = 24$, 33, and 38 dBm. The number of RNs deployed per macrocell is equal to 29, 12, and 9 RNs.

V. Conclusions

The paper investigates the total energy consumption impact of relay deployment in heterogeneous LTE-Advanced networks. The numerical calculations and the results are obtained based on power consumption models for the macro basestation and relay nodes that are introduced in this paper. The results show that a deployment of medium transmission power relay nodes can provide up to 58% energy reduction gain for the joint macro basestation-relay network compared to the traditional macro-centered basestation only network.

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