An E³F based assessment of energy efficiency of Relay Nodes in LTE-Advanced networks

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Abstract— this document analyses the energy efficiency of two possible schemes that have been discussed as a possible way to deploy a relay enhanced network. In the first part the main results obtained in a previous work [1] are summarized, showing the energy efficiency of a relay enhanced network obtained considering small scale simulations, in a full load scenario and measuring only the radiated power. These results provided a first indication of the potentiality of relay nodes as a tool to reduce energy consumption. In the second part a deeper analysis is provided, showing how the energy efficiency of the network can be obtained also considering the whole power consumed by all the components of the transmitting nodes, and considering scenarios where the network is not fully loaded. This kind of result has been used as input to the E³F framework proposed by the EARTH project, that allows to take into account long-term traffic variations and the mix of deployments that are typical of a modern telecommunication network, providing in that way a global assessment of energy efficiency in relay enhanced network.

Keywords—component; relay node; energy efficiency; type 1 relay; type 2 relay; 2 hop relay; multicast cooperative relay; relay power models; EARTH, E³F

I. INTRODUCTION

Relays are a quite recent architectural concept for infrastructure networks. Relays pick up signals transmitted from a base station to a mobile device and resend an amplified signal to the mobile device: thus a relay does not have a wired backhaul connection. Relaying is being studied as part of the LTE-Advanced study item as a technology that offers the possibility to extend coverage and increase capacity, allowing more flexible and cost-effective deployment options [2]. Relay nodes (RNs) cover much smaller areas than macro cells, so they have significantly lower transmit power compared to the macro eNB and are expected to have more in general a power consumption model more efficient. As a consequence Relay Nodes can be considered as a promising solution to increase the energy efficiency of a mobile network.

Different approaches are under investigation in 3GPP in order to assess the advantages of relaying in terms of capacity and coverage. So far two relay strategies are defined in 3GPP, depending on whether the relay node is part of the donor cell or not: Type 1 and Type 2 relays. A Type 1 relay controls cells of its own, each one with a unique physical-layer cell identity, and

it provides all the RRM mechanisms usually offered by a LTE Rel-8 eNodeB, so that it appears to LTE Rel-8 UEs as a normal eNodeB. Type 2 relays are part of the donor cell: they do not create cells of their own, nor they transmit PDCCH and CRS. They are transparent to LTE Rel-8 UEs, and their main purpose is to increase network capacity rather than coverage. At least Type 1 relay nodes will be part of LTE-Advanced. A number of contributions exist in 3GPP that provide Shannon Capacity evaluation [3]–[7], considering both a two hop half-duplex scenario, which can be seen as a Type 1 relay node in 3GPP nomenclature, or advanced schemes like the Multicast cooperative scheme, which can be a possible implementation of a Type 2 relay node (see Fig. 1).

This paper will go further in examining the potential of relay enhanced network, measuring the potential increase in power efficiency that the deploying of a certain number of low powered relay nodes can provide.

Figure 1. Two hop and multicast cooperative relay schemes

While section II analyzes the Energy efficiency of a relay enhanced network in full load condition and taking into account just the emitted Radio Frequency (RF), section III provides a deeper level of detail, considering the whole amount of power consumed by the nodes in the network, and variable load conditions, in order to align the evaluations here reported to the energy efficiency evaluation framework (E³F) provided in the EARTH project [8].

II. ENERGY EFFICIENCY BASED ON RADIATED POWER

Network performance is analyzed by means of static evaluations, taking into account average behaviours of the system and assuming that a single user is present in the cell. The simulated network is represented by a regular hexagonal cellular grid with 19 tri-sectorized sites, with inter-site distance (ISD) of 1732 m, corresponding to Case 3 in 3GPP scenarios

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[2]. Different deployments can be considered, with a variable number of relays and different possible positions in the cell. In the following two Relay Nodes are considered placed near the cell edge. Simulation parameters follow in general the settings in [2], although a static channel is assumed. The main parameters considered are summarized in TABLE I.

TABLE I. SIMULATION PARAMETERS

Parameter	Value
Reference System	LTE FDD (10 MHz+10 MHz), 2.1 GHz
Deployment	Hexagonal layout with 3 sector per site.
ISD (inter-site distance)	1732 m (rural)
Relay positions	(4/9 ISD, $\sqrt{3}/9$ ISD) (4/9 ISD, $-\sqrt{3}/9$ ISD)
Antenna System	SISO
TX power	eNB = 46 dBm (40 W) Relay node = 37 dBm (5 W)
Propagation model	According to [2], case 3 rural, outdoor relays. No fast fading
User distribution	Single user, random with uniform probability
Traffic model	Full buffer when scheduled

As summarized in [1] the Shannon Capacity available in the direct link (eNB to UE) and that offered considering the Relay Enhancement can be evaluated, following an approach provided in different 3GPP contributions. In particular, for the two hop half-duplex scheme the effective rate is given by:

$$R_{eff}|_{2-hop} = \frac{R_{eNB-RN} \cdot R_{RN-UE}}{R_{eNB-RN} + R_{RN-UE}}, \quad (1)$$

while for the multicast cooperative scheme it is given by [4]:

$$R_{eff}|_{m-coop} = \frac{R_{eNB-RN} \cdot (R_{eNB-UE,T2} + R_{RN-UE})}{(R_{eNB-UE,T2} + R_{RN-UE}) + (R_{eNB-RN} - R_{eNB-UE,T1})}, \quad (2)$$

where the rate between node x and y , R_{x-y} , can be evaluated knowing the signal to interference ratio of the link ($SINR_{x-y}$) and the available bandwidth B with:

$$R_{x-y} = B \cdot \log(1 + SINR_{x-y}). \quad (3)$$

As shown in [1] the energy efficiency of these schemes can be evaluated through the Energy Consumption Index (ECI), defined in EARTH [8]. In the two hop half-duplex scheme the eNB will send data to the RN in time T_1 , and the same amount of data will then be delivered from the relay node to the UE in time T_2 , so that the effective amount of power that will be needed to deliver the data is:

$$P_{eff}|_{2-hop} = \frac{T_1}{T_1 + T_2} \cdot P_{eNB} + \frac{T_2}{T_1 + T_2} \cdot P_{RN}, \quad (4)$$

where P_{eNB} and P_{RN} are respectively the eNB and the RN transmitted powers. Using these relations it is possible to derive the Energy Consumption Index as:

$$\eta|_{2-hop} = \frac{P_{eff}}{R_{eff}}|_{2-hop} = \frac{R_{RN-UE} \cdot P_{eNB} + R_{eNB-RN} \cdot P_{RN}}{R_{eNB-RN} \cdot R_{RN-UE}}. \quad (5)$$

The same approach can be followed for the multicast cooperative scheme, even if in this case at time T_2 both the eNB and one of the RN are transmitting, therefore:

$$P_{eff}|_{m-coop} = \frac{T_1}{T_1 + T_2} \cdot P_{eNB} + \frac{T_2}{T_1 + T_2} \cdot (P_{RN} + P_{eNB}), \quad (6)$$

and the energy consumption index for the multicast cooperative scheme can be derived as:

$$\eta|_{m-coop} = \frac{P_{eff}}{R_{eff}}|_{m-coop} = \frac{R_1 \cdot P_{NB} + R_2 \cdot P_{RN}}{R_{eNB-RN} \cdot (R_{RN-UE} + R_{eNB-UE,T2})}$$

$$R_1 = R_{RN-UE} + R_{eNB-RN} + R_{eNB-UE,T2} - R_{eNB-UE,T1}$$

$$R_2 = R_{eNB-RN} - R_{eNB-UE,T1} \quad (7)$$

With previous formulas and 3GPP scenarios, it is possible to build maps showing in each point of the cell the available SINR, capacity and expected energy efficiency (see [1]). These results can be compared with similar results obtained with a classical deployment without relays.

With this approach, it was shown that even if the multicast cooperative scheme can provide slightly better improvement in capacity, the two hop scheme is more energy efficient, as highlighted also in Fig 2. In particular, from the distributions in Fig 2 it can be found that the 2 hop scheme in the simulated scenario has on average an energy saving of 15.6% respect to the case without relays, while in the multicast cooperative scheme the energy saving is 8.5%.

The improvement in energy efficiency is first of all due to the improvement in capacity offered by both schemes. However this improvement is obtained through additional power transmitted by the RN, so the actual energy per bit will depend also on how this power is used in these two schemes. In the two hop scheme the transmission is completed in two steps: during the first step from the BS to the RN only the high power emitted by the BS is used, but the link is usually in good radio condition so that high capacity can be exploited, while during the second step from the RN to the UE only the low power emitted by the RN is used, thus reducing the overall energy consumption.

Figure 2. Energy Consumption Index cumulative distribution

In the multicast cooperative case the energy consumption improvement is mainly due to the higher capacity that can be offered by this scheme, since in this case the BS is transmitting all of the time, and for a certain period an additional power is consumed by the relay. For this reason the overall energy efficiency is lower if compared to the 2 hop scheme, even if from a capacity point of view the former was better.

III. ENERGY EFFICIENCY IN THE E³F FRAMEWORK

Results summarized in section II provide a first positive indication for the possibility to use relays as a tool to increase the energy efficiency in a communication network. However these results suffer for two limitations that make a deeper analysis necessary. First of all they are obtained considering only the consumption due to the radiated RF power of the transmitting nodes, and secondly they are relative to the specific case of full load, assuming therefore that all the radio frequency resources (in power and bandwidth) are always used.

However, the EARTH project has provided power models [8] for different kind of base station (macro, micro, pico and femto), showing how the total consumed power is linked to the RF power, but is usually much higher. In general the relations between relative RF output power P_{out} and BS power consumption P_{in} of these configurations are nearly linear. Hence, for studies not dealing specifically with component improvements, a linear approximation of the power model is justified:

$$P_{in} = P_0 + \Delta_P \cdot P_{out}, \quad 0 \leq P_{out} \leq P_{max}, \quad (8)$$

where P_{max} denotes the maximum RF output power at maximum load, P_0 is the power consumption calculated at the minimum possible output power, assumed to be 1% of the maximum, and Δ_P express the dependency from the radiated power. The parameters for a macro BS based on the 2010 State-of-the-Art estimation are summarized in TABLE II.

TABLE II. EARTH PARAMETERS FOR DIFFERENT BASE STATIONS (2010 – STATE OF THE ART ESTIMATION)

LTE BS type	P_{max} [W]	P_0 [W]	Δ_P
Macro	40	712	14.5
Micro	6.3	106	6.35
Pico	0.25	14.9	8.4
Femto	0.1	10.1	15

From the values reported in TABLE II, it is clear that the radiated power is only a small fraction of the total amount of consumed power. Therefore in order to assess correctly the energy efficiency of a relay enhanced network it is necessary to include in the simulation framework a power model that captures the whole power consumed by the transmitting nodes.

Starting from the EARTH power models, the overall power consumed in the two hop scheme can be written as:

$$P_{eff}|_{2-hop} = \frac{T_1}{T_1 + T_2} \cdot P_{T1} + \frac{T_2}{T_1 + T_2} \cdot P_{T2}, \quad (9)$$

where

$$\begin{aligned} P_{T1} &= (P_{0,BS} + \Delta_{P,BS} \cdot P_{out,BS}) + 2 \cdot P_{0,RN} \\ P_{T2} &= P_{0,BS} + (P_{0,RN} + \Delta_{P,RN} \cdot P_{out,RN}) + P_{0,RN}. \end{aligned} \quad (10)$$

The variables $P_{0,BS}$, $\Delta_{P,BS}$ and $P_{0,RN}$, $\Delta_{P,RN}$ depend on the power models used for the base station and relays. Note that in T_1 only the base station is transmitting, but relays are still giving a contribute to the overall energy consumption with their minimum consumed power term $P_{0,RN}$. In the time interval T_2 one of the two relay nodes will be transmitting, while the other transmitting nodes will contribute with their minimum power consumption.

Note that in the previous equations, it is possible to scale the amount of used RF power P_{out} in order to take into account those conditions where the traffic load can be satisfied without using the whole cell resources. In that sense, assuming that for a given traffic condition it is sufficient to use n of the physical resources available in a OFDM sub-frame (i.e. only n Resource Blocks, RB , are used), it is possible to express the RF power of the transmitting node x as:

$$P_{out,x} = P_{cc} + n \cdot P_{RB}, \quad (11)$$

where P_{cc} represents the amount of power used for common and broadcast channels, while P_{RB} is the amount of power necessary to transmit a single Resource Block.

Comparing (9) with (4) it can be seen that the expression to evaluate the Energy Consumption Index is unchanged, by substituting $P_{BS}=P_{T1}$ and $P_{RN}=P_{T2}$:

$$\eta|_{2-hop} = \frac{P_{eff}}{R_{eff}} \Big|_{2-hop} = \frac{R_{RN-UE} \cdot P_{T1} + R_{BS-RN} \cdot P_{T2}}{R_{BS-RN} \cdot R_{RN-UE}} \quad (12)$$

In the same way it is possible to evaluate the expression for the multicast scheme, where in this case:

$$\begin{aligned} P_{T1} &= (P_{0,BS} + \Delta_{P,BS} \cdot P_{out,BS}) + 2 \cdot P_{0,RN} \\ P_{T2} &= (P_{0,BS} + \Delta_{P,BS} \cdot P_{out,BS}) + (P_{0,RN} + \Delta_{P,RN} \cdot P_{out,RN}) + P_{0,RN}, \end{aligned} \quad (13)$$

since in time interval T_1 only the base station is transmitting, while in T_2 one of the two relay nodes becomes active in order to cooperate with the base station.

Also in this case it is possible to keep the expression given in (7) with the substitution:

$$\begin{aligned} P_{BS} &= P_{T1} \\ P_{RN} &= (P_{0,RN} + \Delta_{P,RN} \cdot P_{out,RN}) - P_{0,RN}, \end{aligned} \quad (14)$$

which leads to:

$$\begin{aligned} \eta|_{m-coop} &= \frac{P_{eff}}{R_{eff}} \Big|_{m-coop} = \frac{R_1 \cdot P_{T1} + R_2 \cdot [(P_{0,RN} + \Delta_{P,RN} \cdot P_{out,RN}) - P_{0,RN}]}{R_{BS-RN} \cdot (R_{RN-UE} + R_{BS-UE,T2})} \\ R_1 &= (R_{RN-UE} + R_{BS-RN} + R_{BS-UE,T2} - R_{BS-UE,T1}) \\ R_2 &= (R_{BS-RN} - R_{BS-UE,T1}) \end{aligned} \quad (15)$$

Having introduced in that way the EARTH power models in the simulator, it is possible to obtain an Energy Consumption Index more realistic, that takes into account all

the consumed power. However the expressions here obtained also underline another important aspect: energy consumption is strongly linked with the traffic load in the cell. For this reason any analysis that only considers full load scenario may lead to results that do not capture properly the actual energy consumption of a certain network solution.

In order to provide a more complete analysis of the energy consumption of relay enhanced network, the static simulator introduced in section II has been improved with the possibility to evaluate capacity and energy efficiency for variable traffic load. In every point of the cell, the signal to interference ratio has been evaluated assuming that the serving eNB is using only a subset n of the available N Resource Block, while the interfering nodes use k of them. In that case the useful power is lower, but also the interference decreases since it is lower the amount of interfering power emitted and it is lower the probability that this power is used in the same Resource Blocks used by the serving node. It can be shown that in that case the interference is given by;

$$\hat{I} = \sum_{m=\max(0, n+k-N)}^{\min(n, k)} \left\{ m \cdot \frac{I_{\max}}{N} \cdot \frac{\binom{n}{m} \cdot \binom{N-n}{k-m}}{\binom{N}{k}} \right\}, \quad (16)$$

where $I_{\max}$ express the whole interference power when all the N RB are used.

Computing the signal to interference ratio taking into account the number of used RB it is possible to evaluate the theoretical capacity available in that point using Shannon law, as reported in (3).

However since relay nodes will be a part of LTE-Advanced networks it is reasonable to assume that in that case a MIMO technique will be implemented, therefore in order to capture the higher capacity offered by this transmission technique, the capacity expression given in (3) has been aligned to the MIMO case following the approach reported in [9], obtaining:

$$R_{x-y} = B \cdot \log \det \left[I_{=n_R} + (SINR_{x-y}/n_T) \cdot \underline{H} \underline{H}^H \right], \quad (17)$$

(a)

(b)

Figure 3. ECI with variable traffic condition, in a rural scenario (a) and overall ECI with different power models and deployments (High Traffic Profile).

where I is the identity matrix, n_R and n_T are respectively the number of receiving and transmitting antennas and $\underline{H}$ is the channel matrix.

The simulator has been then aligned to the various propagation scenarios (urban, sub-urban, rural) presented in 3GPP [2] and in the EARTH project [10], and it has been used to calculate in each point of the cell, given a certain amount of traffic to serve, the amount of RF resources necessary to reach the desired rate, and consequently, using a defined power model, the correspondent ECI. The map of ECI so obtained for each point of the cell has been averaged to provide the average ECI necessary to satisfy a certain traffic request in the cell.

At present realistic power models for relay nodes cannot be provided, since no commercial solution is available. For this study network performance from an energy consumption point of view has been evaluated deriving two different power models for this kind of node (see TABLE III).

TABLE III. EARTH PARAMETERS FOR DIFFERENT BASE STATIONS (2010 – STATE OF THE ART ESTIMATION)

LTE BS type	$P_{\max}$ [W]	P_0 [W]	Δ_P
Relay SOTA	5 or 1	84.13	6.35
Macro Advanced	40	156.38	28.4
Relay Advanced	5 or 1	13.91	20.4

In particular the State Of The Art (SOTA) model “Relay SOTA” has been derived scaling a micro base station model (see TABLE II) proportionally considering the different peak RF powers. The “Relay Advanced” model, and a similar model for the macro base station (“Macro Advanced”) has been also introduced, starting from a model presented in [11] for an advanced node that strongly scales the consumed power with the actual traffic load.

Fig. 3(a) reports an example of the results obtained for a rural scenario, considering advanced power models.

As one may expect, in particular when the amount of traffic to serve is high, it is possible that in certain point of the cell the desired traffic cannot be reached, even using all the RF resources. In that case the energy consumption index saturates to its limit value.

These evaluations have been conducted for all scenarios (urban, suburban and rural) and for a representative set of traffic loads, which captures the range between the minimum and the maximum load observed for a certain deployment.

These system level evaluations provide energy consumption and throughput performance assessment for each small-scale deployment as a function of the traffic load. This small-scale, short-term evaluation however still fails to capture the energy efficiency of the entire network which typically includes rural areas and densely populated areas, with different small-scale deployments for each of these areas. Moreover the load situation of a network varies radically over the time of a day and a week. As shown in EARTH [8], for a global assessment of network energy efficiency, these aspects need to be included by weighted summing of all the small-scale energy consumption evaluations.

Using long-term traffic variations provided in EARTH, that specify the traffic load over time for a given scenario and traffic profile (high, mid or low), and the mix of deployment scenarios that quantify the area covered by cities, suburbs, highways and villages, as depicted in [8], yield the global set of the large-scale system energy consumption evaluations. Using these inputs from the E³F, the overall energy consumption index can be computed.

In particular, long-term traffic variations for the high traffic profile defined in [8] have been considered for this study, that correspond to 120 Mbps/km² peaks in dense urban areas and approximately 68 GB/month/subscriber (which is enough to provide HDTV simultaneously for all active users). Results for this kind of evaluation are collected in Fig 3(b), considering different solutions: a network without relay nodes and eNBs with SOTA power models, a network with SOTA eNB enhanced with SOTA relay nodes, a network with SOTA eNB enhanced with advanced power model relay nodes, a network with only eNBs having advanced power models and finally a network with advanced eNBs and advanced Relay Nodes.

From Fig. 3(b) it is clear how the power models play a very important role in the overall energy consumption of the system. Note that this wouldn't be observable in a full load scenario, where always the peak power is consumed.

In general results also show that the 2 hop scheme is more energy efficient than the multicast scheme, and that a gain up to 13.2% can be reached with the high traffic profile, and assuming advanced power models for both relays and eNBs. It should be noted that this value is the result of a gain up to 68% in energy consumption in the area covered by relays. For the multicast scheme on the other hand no gain is visible, and in general from an energy consumption point of view this solution

is less efficient, even if from a capacity point of view is the one that provides the greater gains.

IV. CONCLUSIONS

This work analyses the energy efficiency of two possible schemes that have been discussed as a possible way to deploy a relay enhanced network. Results were obtained first of all considering small scale simulations, in full load scenario and measuring only the radiated power. These results provided a first indication of the potentiality of relay nodes as a tool to reduce energy consumption in a network. In the second part of this study a deeper analysis is provided, where results are obtained following the E³F framework proposed in EARTH, that allows to take into account long-term traffic variations and the mix of deployments that are typical of a modern telecommunication network, together with power models that capture all the power that is consumed by a transmitting node, which is usually largely greater than that emitted at radio frequency.

Using this framework it has been possible to underline that only two hop scheme has the potentiality to save some energy, and that in order to reach this aim relay nodes (and possibly also eNB) must be implemented with a power models that can efficiently scale the consumed power depending on the experienced traffic load.

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REFERENCES

- [1] R. Fantini, D. Sabella, M. Caretti, "Energy efficiency in LTE-Advanced networks with relay nodes," 2011 IEEE 73rd Vehicular Technology Conference, Budapest, May 2011.
- [2] 3GPP TR 36.814 v1.5.1 (2009-12), Further Advancements for E-UTRA, Physical Layer Aspects.
- [3] R1-083205 Application of L2 Relay in an Interference Limited Environment for LTE-A.
- [4] R1-091423 Comparison of Type 1 Relay and L2 Cooperative Relay.
- [5] R1-090073 A system simulation study of downlink L2 relay network.
- [6] R1-100353 Comparing In-band vs. Out-band Relays in coverage limited scenario.
- [7] R1-084354 Considerations on the Relay Maximum Transmit Power.
- [8] EARTH project, "D2.3 - Energy efficiency analysis of the reference systems, areas of improvements and target breakdown," <https://www.ict-earth.eu/publications/publications.html>
- [9] G.J. Foschini and M.J. Gans, "On Limits of Wireless Communications in a Fading Environment when Using Multiple Antennas", *Wireless Personal Communications* 6: 311-335, 1998
- [10] EARTH project, "D2.2 - Definition and Parameterization of Reference Systems and Scenarios," <https://www.ict-earth.eu/>
- [11] O. Arnold, F. Richter, G. Fettweis, and O. Blume, "Power consumption modeling of different base station types in heterogeneous cellular networks," in *Proc. of 19th Future Network & Mobile Summit* 2010, Florence, Italy, June 2010