Energy and Spectral Efficient Inter Base Station Relaying in Cellular Systems

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Abstract—**This paper considers a classic relay channel which consists of a source, a relay and a destination node and investigates the energy-spectral efficiency tradeoff under three different relay protocols: amplify-and-forward; decode-and-forward; and compress-and-forward. We focus on a cellular scenario where a neighbour base station can potentially act as the relay node to help on the transmissions of the source base station to its assigned mobile device. We employ a realistic power model and introduce a framework to evaluate the performance of different communication schemes for various deployments in a practical macrocell scenario. The results of this paper demonstrate that the proposed framework can be applied flexibly in practical scenarios to identify the pragmatic energy-spectral efficiency tradeoffs and choose the most appropriate scheme optimising the overall performance of inter base station relaying communications.**

I. INTRODUCTION

Energy efficiency (EE) of communication networks and particularly of wireless access networks has attracted growing attention and is becoming a main design criterion for both environmental and economical reasons [1], [2]. However, the ongoing spectral efficiency (SE) race to satisfy the rapid proliferation of high quality applications and services that require broadband wireless access technologies inevitably leads to growing energy demand and increasing energy related expenses in wireless networks. For that reason, the EE-SE tradeoff is considered as an important performance measure in deployment and operation of future wireless access systems [3] and high research effort has been drawn to technologies promising high performance in that respect.

An auspicious technique to deliver high SE-EE performance in future systems is relaying. Relay-assisted communications are introduced as an inexpensive deployment strategy to improve coverage in small areas, provide service to small groups of low mobility UEs where their needs for high quality links would inevitably require extra infrastructure deployment [4]. For that reason, relaying is currently studied in 3GPP as a technology allowing more flexible, low-energy and cost-effective deployment options [5].

The concept behind relaying is simple. Relay nodes exploit the broadcasting nature of wireless transmission and pick up signals transmitted from a source node and re-send it to the desired destination which then combines all the received signal versions. From energy perspective, there are several ways relays can reduce overall system consumption: 1) relays can cover much smaller areas than macro cells, and thus, have significantly lower transmit power compared to widely deployed macro Base Stations (BSs); 2) propagation distance per hop is reduced and therefore the transmission power of the source can be lowered [6]; and 3) minimal non-complicated infrastructure modifications are envisaged since there is no need for a wired back-haul connection [4], [7].

Although relaying is not a newly introduced concept, its realistic performance in terms of both SE and EE has not been fully addressed so far. An initial theoretical study in [8] is addressing the EE of various communication schemes, including that of a present relay node, on a link level analysis. In [9], the EE of single antenna amplify and forward relay channel in the low-power regime has been studied. Furthermore, the authors in [10] examine the uplink MIMO case and the energy consumption gain in a cellular propagation environment. However, the aforementioned studies consider only the nodes' transmit power to facilitate the EE analysis. To this end, the optimal relaying strategy in practical wireless networks has not yet been fully understood in terms of EE.

This paper's main objective is to investigate the pragmatic SE-EE tradeoff under three different relay protocols: amplify-and-forward, decode-and-forward, and compress-and-forward by introducing a realistic power consumption model for the transmitting nodes. Neighbouring BSs are considered to act as source and relay nodes to serve a user device. This *inter-BS relaying* is especially motivated by scenarios where frequent handovers need to be avoided or additional nodes cannot be deployed into the system. We compare different communication schemes with each other for various system deployments to: 1) highlight the importance of including realistic power models for SE-EE tradeoff evaluations; 2) examine the effect of source-relay and source-destination channels' condition on the performance of each scheme; and 3) introduce a general framework for identifying the most appropriate communication scheme in practical energy-aware cellular systems.

The rest of the paper is organised as follows. Section II describes the cooperation scenario to formulate the system model and introduces the various relaying schemes. Section III characterises the EE of the inter BS relaying system by implementing a realistic BS power model. Section IV formulates the EE-SE tradeoff analytical expressions for the various schemes considered. Finally, Section V provides simulation results evaluating a practical macrocell scenario along with insightful observations while Section VI concludes the paper.

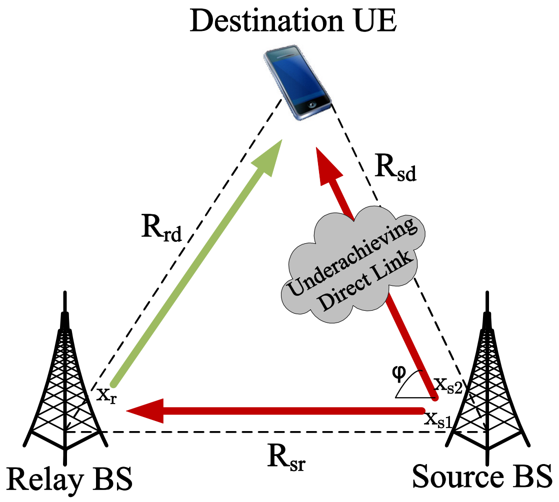

Fig. 1. Cooperation scenario.

II. Cooperation Scenario & Schemes

We consider a three node wireless network comprising a source, a relay and a destination node. Most previous works on cooperative communications have assumed user devices to act as relays (e.g. [11]). In this study, we take a different approach. We investigate the equivalently interesting scenario where, in a cellular system, a neighbouring BS can potentially act as the relay node to help on the transmissions of the source BS to an assigned UE. This scenario is rather fitting when: 1) the relay BS does not (or cannot) sustain a wired backhaul connection with the source BS and/or the core network; 2) frequent handovers are experienced due to e.g. medium-scale fading conditions; or 3) additional low power nodes cannot be deployed to the system due to feasibility or economical reasons. The practical applications of this scenario can be several and include the following cases:

- cover source BS transmission errors due to e.g. low source-destination channel quality. In that case, source spends extra resources to adequately serve the device. By accepting help from another BS having a better channel with the destination at this time, the whole system may use more efficiently its resources to serve that device.
- improve quality of service to high priority users when neighbouring BSs have free resources;
- source BS has full buffer but needs to maintain quality of service to a user device;
- take advantage of cooperative transmission during handover to maintain user quality of service.

The respective three-node system, where a Source BS (SBS) and a Relay BS (RBS) cooperatively serve a user equipment (UE) standing for the destination node, is illustrated at Fig. 1. By including RBS in the direct SBS-UE transmission process, the information recovered from SBS to RBS can be also received by the UE. The RBS processes and forwards this received information so that the UE may receive two independent versions of the desired signal and can make better decisions on the actual transmitted data than what would have been possible by only attaining the direct link. As mentioned above, we consider the case where the RBS-UE channel is better than the SBS-UE channel and we will investigate when the system SE-EE tradeoff can be improved.

In our study, we assume that the RBS cannot transmit and receive data over the same time-frequency band. Therefore, we assume that RBS operates in time division duplexing (TDD) mode, i.e. SBS transmits information to RBS and UE in time slot 1 and RBS transmits information to UE in time slot 2. In particular, assuming that the first time slot contains $M_1 = \alpha M$ symbol periods, SBS transmits a $M_1 \times 1$ block of symbols x_{s1}, with $\mathbb{E}\left[\|x_{\mathrm{s1}}\|^2\right] = \alpha M$, that is received at RBS as

$$y_{\mathrm{r1}} = h_{\mathrm{sr}}\sqrt{\frac{P_{\mathrm{s1}}}{\alpha}}x_{\mathrm{s1}} + n_{\mathrm{r}} \ , \tag{1}$$

and at the destination UE as

$$y_{\mathrm{d1}} = h_{\mathrm{sd}}\sqrt{\frac{P_{\mathrm{s1}}}{\alpha}}x_{\mathrm{s1}} + n_{\mathrm{d1}} \ , \tag{2}$$

where the $M_1 \times 1$ vectors y_{r1} and y_{d1} are the received blocks of symbols at RBS and UE, respectively; h_{sr} and h_{sd} denote the coefficients for SBS-RBS and SBS-UE channels, respectively. Furthermore, at the second time slot comprising $M_2 = (1-\alpha)M$ symbol periods, SBS transmits a $M_2 \times 1$ block of symbols x_{s2} while the relay transmits x_{r}, with $\mathbb{E}\left[\|x_{\mathrm{s2}}\|^2\right] = \mathbb{E}\left[\|x_{\mathrm{r}}\|^2\right] = M - \alpha M$. Thus, the UE destination node will receive

$$y_{\mathrm{d2}} = h_{\mathrm{sd}}\sqrt{\frac{P_{\mathrm{s2}}}{1-\alpha}}x_{\mathrm{s2}} + h_{\mathrm{rd}}\sqrt{\frac{P_{\mathrm{r}}}{1-\alpha}}x_{\mathrm{r}} + n_{\mathrm{d2}} \ , \tag{3}$$

where h_{rd} denotes the coefficient for the RBS-UE channel. Note that $P_{\mathrm{s1}} + P_{\mathrm{s2}} \triangleq P_{\mathrm{s}}$ and P_{r} stand for the SBS and RBS average transmit symbol power, respectively. All channels in the system are assumed to be wireless links with coefficients modeled by $h = gf$, where $g \in \mathbb{R}$ stands for distance-dependent path loss and $f \in \mathbb{C}$ denotes the Rayleigh fast fading fading i.e. the fast fading coefficients are independent and identically distributed (i.i.d.) $\backsim \mathcal{N}(0,1)$. Finally, n_{d1}, n_{d2} and n_{r} are independent zero-mean additive white Gaussian noise terms with power spectral density of N_0.

Based on the different signal processing methods used at the RBS, relay-assisted communication can be performed in various ways. The main relay schemes, being also the focus of this work, are amplify-and-forward (AF), decode-and-forward (DF) and compress-and-forward (CF) [11]. In AF scheme, the destination receives the original signal from the source and its amplified version from the relay. Its main disadvantage is that the amplified signal version includes also an amplified noise term from the source-relay communication. In DF scheme, the relay node decodes the received signal from the source, removing the noise before forwarding the signal to the destination. The study in [9] indicated that DF is better than AF in terms of transmit EE. However, DF scheme has its own limiting issues. Decode failures require signal retransmissions that result in delay. Moreover, in [12], it is proved that if the source-destination channel is better than source-relay channel, DF will not work at all. To this end, in the CF scheme, there is no decoding process but the relay node first quantizes the signal received from the source and then forwards it to the destination. Yet, compared to DF relay scheme, CF scheme introduces quantization noise. In the following we characterise the EE of the inter BS relaying system to construct a comprehensive comparison on the pragmatic EE-SE tradeoff of the various relay schemes.

III. SYSTEM ENERGY CONSUMPTION AND EFFICIENCY

The considered system scenario comprises two transmitting BSs whose energy consumed during the cooperative communication will dominate the overall system energy consumption since BSs are the most energy-intensive components of mobile networks [13]. In order to get a realistic view on the EE of the system, it is imperative that we employ an accurate BS power model. A simplified yet practical linear power model was suggested in [13], [14] for BSs used in real-world deployments. According to this model, the overall BSs power is a linear function of the radiated power from transmissions. Considering that SBS and RBS are of the same type, the total power at any BS, P, can determined by:

$$P = P_0 + \Delta_p P_{\text{Tx}} \ , \tag{4}$$

where $P_{\text{Tx}} \leq P_{\max}$ denotes the RF per-antenna output power of the BS, constrained by a maximum $P_{\max}$ value. P_0 represents the circuit power consumption at zero RF output power and Δ_p is the slope of the load dependent power consumption.

For the EE evaluation it is important to adopt an appropriate metric that follows the generalised definition of *efficiency*, i.e. the quality characterizing the correspondence between *consumed resources* and *attained utility* of interest. In our case, the resource of interest is the total energy consumed by the two BSs during transmission at both time slots of the relayed communication. On the other hand, the desired attained utility is the useful information, RT, obtained at UE in bits, during the same overall transmission period. Thus, by implementing the realistic BS power model, the system average energy performance during relayed communication can be determined in terms of: a) efficiency, i.e. U in bit/Joule; or 2) a consumption indicator, i.e. E_b in Joule/bit, as:

$$U = (E_b)^{-1} = \left(\frac{P_1 T_1 + P_2 T_2}{RT} \right)^{-1} \ , \tag{5}$$

where T_1 stands for duration of time slot 1, T_2 for duration of time slot 2, and $T = T_1 + T_2$. Note that, the chosen energy performance metric is rather appropriate to evaluate EE in capacity limited systems which is the case for future multimedia applications' networks.

IV. ENERGY-SPECTRAL EFFICIENCY TRADEOFF

In this section, we formulate the EE-SE tradeoff expressions for the benchmark *direct link* scheme, i.e. where there is no RBS helping with the SBS-UE transmission, and the various cooperative schemes. We consider that the maximum achievable SE (i.e. capacity) is achieved in each scheme. For that reason, we assume that the transmitted symbols x_{s1}, x_{s2} and x_{r} follow a Gaussian distribution and the UE has perfect channel state information while SBS and RBS have statistical information of the system channels.

A. Direct Link

The direct link channel model can given by (2) with $\alpha = 1$ and $P_{\text{s1}} = P_{\text{s}}$. Thus, the EE-SE tradeoff in that case is:

$$U_{\text{DL}} = \frac{\mathbb{E}_f \left[\log_2 \left(1 + |h_{\text{sd}}|^2 \gamma_{\text{DL}} \right) \right]}{P_0 + \Delta_p P_{\text{s}}} \ , \tag{6}$$

where $\gamma_{\text{DL}} = \frac{P_{\text{s}}}{N_0 W}$ is the channel's Signal-to-Noise Ratio (SNR) for bandwidth W, since there is no relay in that case. Note that the expectation is taken over all fading realisations.

B. Amplify and Forward

In AF scheme, RBS simply amplifies the received signal from SBS in time slot 1 and forwards it to the UE in time slot 2. We assume, without loss of generality, that SBS does not transmit in the second time slot, i.e $P_{\text{s}} = P_{\text{s1}}$ and slots have the same duration, i.e. $\alpha = \frac{1}{2}$. In that case, at the second time slot, the RBS transmits:

$$x_{\text{r}} = \frac{1}{\sqrt{2 |h_{\text{sr}}|^2 P_{\text{s}} + N_0 W}} y_{\text{r1}} \ . \tag{7}$$

The maximum achievable SE, when vector combining method is adopted at destination, has been derived in [9]. Considering that the SNR of the relayed communication is given as $\gamma_{\text{R}} = \frac{P_{\text{s}} + P_{\text{r}}}{N_0 W}$ and the power ratio $\gamma = \frac{P_{\text{s}}}{P_{\text{s}} + P_{\text{r}}}$, the EE-SE tradeoff in that case can be given by:

$$U_{\text{AF}} = \frac{\frac{1}{2} \mathbb{E}_f \left[\log_2 \left(1 + 2\gamma_{\text{R}} \gamma |h_{\text{sd}}|^2 + \frac{4\gamma_{\text{R}} \gamma \acute{\gamma} |h_{\text{sr}}|^2 |h_{\text{rd}}|^2}{1 + 2\gamma_{\text{R}} \left(\acute{\gamma} |h_{\text{rd}}|^2 + \gamma |h_{\text{sr}}|^2 \right)} \right) \right]}{2P_0 + \Delta_p \left(P_{\text{s}} + P_{\text{r}} \right)} \tag{8}$$

where $\acute{\gamma} \triangleq 1 - \gamma$.

C. Decode and Forward

In DF scheme, x_{s1} is decoded by RBS at the first time slot. At the second time slot, RBS, after regenerating the decoded signal, forwards it to the UE. It is assumed again that SBS does not transmit at all during the second time slot and $\alpha = \frac{1}{2}$. It is apparent that for the DF scheme to work, RBS has to fully decode the source information, i.e. no decode failure throughout the overall transmission. The maximum achievable SE for such a repetition-coded-and-forward scheme has been derived in [9] as the minimum between the maximum rate, C_{dec}, at which the UE can decode x_{s1} from y_{d1} and x_{d2}, and the capacity, C_{sr}, of the SBS-RBS channel. Therefore, the EE-SE tradeoff in that case is given by:

$$U_{\text{DF}} = \frac{\min \left\{ C_{\text{dec}}, C_{\text{sr}} \right\}}{2P_0 + \Delta_p \left(P_{\text{s}} + P_{\text{r}} \right)} \ , \tag{9}$$

where

$$C_{\text{dec}} = \frac{1}{2} \mathbb{E}_f \left[\log_2 \left(1 + 2\gamma_{\text{R}} \gamma |h_{\text{sd}}|^2 + 2\gamma_{\text{R}} \acute{\gamma} |h_{\text{rd}}|^2 \right) \right] \tag{10}$$

and

$$C_{\text{sr}} = \frac{1}{2}\mathbb{E}_f\left[\log_2\left(1 + 2\gamma_{\text{R}}\gamma\left|h_{\text{sr}}\right|^2\right)\right] . \tag{11}$$

D. Compress and Forward

In CF scheme, RBS quantizes the received signal in the first time slot and forwards it to the destination in the second time slot. The achievable SE of such a scheme assuming equal ratio combination has been derived in [12]. Considering again $\alpha = \frac{1}{2}$, the EE-SE tradeoff will be given by:

$$U_{\text{CF}} = \frac{\frac{1}{2}\mathbb{E}_f\left[\log_2\left(1 + \gamma_{\text{R}}\left(\left|h_{\text{sd}}\right|^2 + \frac{\left|h_{\text{sr}}\right|^2}{1+\sigma_\omega^2}\right)\right)\right]}{2P_0 + \Delta_p\left(P_{\text{s}} + P_{\text{r}}\right)} , \tag{12}$$

where σ_ω^2 stands for the compression noise given by:

$$\sigma_\omega^2 = \frac{P_{\text{s}}\left(\left|h_{\text{sr}}\right|^2 + \left|h_{\text{sd}}\right|^2\right) + 1}{P_{\text{r}}\left|h_{\text{rd}}\right|^2\left(P_{\text{s}}\left|h_{\text{sd}}\right|^2 + 1\right)} . \tag{13}$$

V. SIMULATION RESULTS & DISCUSSION

This section evaluates the performance of the various communication schemes in the context of a practical system. To this end, an "Urban Macro" (UMa) environment, with propagation parameters suggested by 3GPP in [5], is chosen as an example for establishing the relation of various system modelling parameters with practical ones. Path loss coefficients are fitted to respective empirical scenarios [13], as functions of SBS-RBS and RBS-UE distances, i.e. R_{sr} and R_{rd}, respectively, assuming that the channel between relay and destination is better than the channel between source and relay:

- SBS-RBS path loss model (UMa-LOS with shadowing standard deviation of 4):

$$g_{\text{sr}}^2\left(R_{\text{sr}}\right) = 97.4 + 20\log\left(f_c\right) + 24.2\log\left(R_{\text{sr}}\right) . \tag{14}$$

- RBS-UE path loss model (UMa-NLOS with shadowing standard deviation of 6):

$$g_{\text{sd}}^2\left(R_{\text{sd}}\right) = 125.1 + 20\log\left(f_c\right) + 42.8\log\left(R_{\text{sd}}\right) . \tag{15}$$

A large enough number of iterations for generating fading coefficients ensured the consideration of the fast fading process. Thus, the averaged numerical results on UE SNR were obtained by generating multiple (i.e. 10^4) random *system instances* and constructing the system channels at each instance for a specific deployment. Table I summarises the system parameters considered. In the following evaluation we vary the SBS and RBS transmit power jointly, i.e. $P_{\text{s}} = P_{\text{r}}$ at all times, focusing on the effect of system deployment on the EE-SE tradeoff. Nevertheless, power allocation among source and relay is an interesting topic for future research as it can improve overall performance [9].

First, we quantify the importance of including the realistic power model for accurate EE evaluations. Fig. 2 compares the EE-SE tradeoff obtained by the AF relay scheme and the benchmark direct link case. We consider the SBS, RBS and UE forming a right triangle (i.e. $\phi = 90^o$ in Fig. 1) and two different deployment scenarios for the three node system. We observe that the *conventional approach* of considering only transmit power in EE evaluations (i.e. $P_0 = 0$ and $\Delta_p = 1$ in (4)) overestimates significantly the system's EE and provides inaccurate insights for the EE-SE tradeoff performance. In fact, the conventional approach suggests that the EE-SE tradeoff relationship is always linear. However, applying the realistic power model, we observe a concave EE-SE tradeoff behaviour where an optimal EE point exists. Moreover, for the case of $R_{\text{sr}} = R_{\text{sd}} = 0.5$Km, where both SBS-UE and RBS-UE channels are comparably strong, the conventional approach suggests the existence of a cut-off point between the direct link and AF schemes' EE-SE tradeoff curves. However, employing the realistic power model we observe that the AF scheme is always suboptimal to direct link at this deployment scenario.

TABLE I
SYSTEM MODEL PARAMETERS

Parameter	Symbol	Values & Ranges
Frequency Carrier	f_c	2 GHz
Channel Bandwidth	B	10 MHz
Noise Power Spectral Density	N_0	-174 dBm/Hz
macro-BS Transmit Power	P_{s}, P_{r}	0.1 - 20 W
macro-BS Circuit Power	P_0	130 W
macro-BS Power slope	Δ_p	4.7

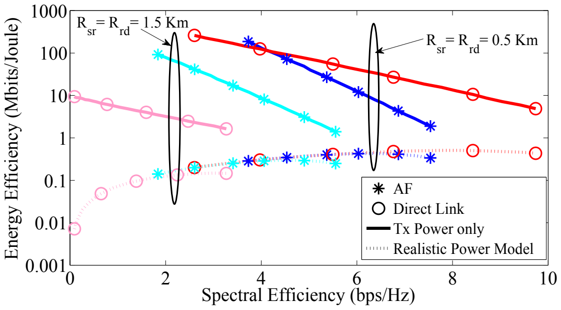

Fig. 2. EE-SE tradeoff with and without the realistic power model. Comparison of direct link and AF schemes for two deployment scenarios: 1) $R_{\text{sr}} = R_{\text{rd}} = 0.5$Km; 2) $R_{\text{sr}} = R_{\text{rd}} = 1.5$Km. $\phi = 90^o$.

At a next step, we compare the EE-SE tradeoff obtained by the three relay schemes for various deployment scenarios to identify the effect of the SBS-RBS and SBS-UE channel condition on each scheme's performance. To this end, the left plot of Fig. 3 depicts the EE-SE tradeoff for a fixed SBS-UE distance of 1Km. It is observed that when RBS is closer to SBS (e.g. $R_{\text{sr}} = 1$Km or 2Km), the CF scheme provides the best overall performance. On the other hand, for larger SBS-RBS distances (e.g. $R_{\text{sr}} = 3$Km or 4Km), the DF scheme outperforms the other relaying schemes while no-cooperation becomes the most viable solution for achieving higher SE. The right plot of Fig. 3 illustrates the EE-SE tradeoff for a fixed SBS-RBS distance of 1Km. In that case, CF is always the optimal scheme. It should also be noted that no-cooperation is always suboptimal to the relaying schemes in that case as we can always benefit from the cooperative transmission due to the advantageous condition of the SRB-RBS link.

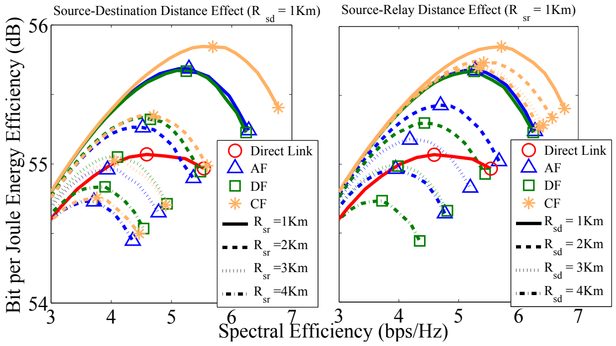

Fig. 3. EE-SE tradeoff of the various schemes for different system deployments. $\phi = 90^o$.

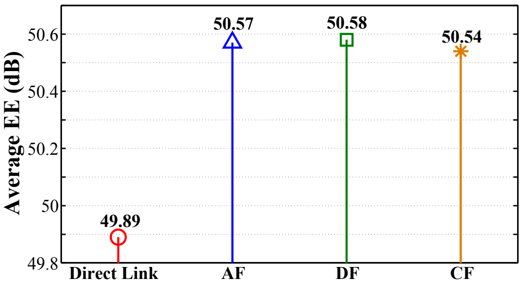

Fig. 4. Average bit-per-Joule EE of the various schemes for a fixed SE target of 1.5 bps/Hz. R_{sr}=4Km.

Finally, we demonstrate how our framework can be used to compare the average EE of the various schemes for a fixed target SE. This evaluation is rather useful for the case where we cannot switch from one scheme to another in short time period and an overall recommendation for the employment of the most EE scheme must be given to the respective BSs. As an example scenario we have considered a fixed SBS-RBS distance of 4Km and a large enough number (i.e. 100) of potential user locations in a uniform grid over SBS's cell area adjacent to RBS's cell. We have set a target SE which all schemes can achieve in any of the potential deployment scenarios (i.e. 1.5 bps/Hz). To this end, Fig. 4 illustrates the comparison results where all relaying schemes perform similarly and better than the benchmark no-cooperation scheme while, without taking any decode failures and extra processing complexity into account, DF stands for the most energy efficient choice.

VI. CONCLUSION

In this work, we have introduced a framework for evaluating the energy-spectral efficiency tradeoff of relay-assisted communications in real-world systems. The study is conducted by considering neighbour BSs acting as the source and relay nodes, cooperatively serving a UE. By introducing a realistic power model we formulated the pragmatic EE-SE tradeoff of AF, DF, and CF relay schemes and provided numerical simulation results evaluating a practical macrocell cooperative scenario. We showed that it is of high importance to include realistic power models in order to obtain accurate insights regarding EE. Specifically, we observed that the conventional approach taking only the transmit power into consideration suggests a linearly increasing EE-SE tradeoff relationship when the actual one is concave. Moreover, we investigated the effect of system deployment on the performance of each scheme. For the examined scenario, we observed that CF scheme can provide higher overall performance when RBS-SBS channel is much better than the SBS-UE channel. On the other hand, when both channels are of the same average quality, DF scheme outperforms the other relaying schemes and no-cooperation becomes the most viable solution for achieving higher SE. The most important contribution of this work is the introduction of a general flexible framework for choosing the appropriate cooperation scheme in practical energy-aware cellular networks. Applying this framework to any given scenarios, operators can find and employ the most EE relaying scheme (if needed) while providing the target quality of service to their subscribers.

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