

# Trade-off Analysis of Energy-Efficiency versus Generated Interference when Using Regenerative Relay

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**Abstract** — When using a regenerative relay, a trade-off between increasing the energy efficiency versus reducing the generated interference arises. In this paper, the generated interference in the direct link from the base station to a user terminal is compared with the generated interference from both the base station and the relay node in regenerative relay transmissions. In the space of channel losses, in the transceivers' operating region, the lines corresponding to the generated interference ratio comparing the relay scheme and the direct link are depicted. It is shown that it is possible to tune the energy-efficiency vs generated interference trade-off, by adjusting the transmit powers, constellation size and code rate. The trade-off depends on the channel losses along the links. A key enabler of the trade-off is the appropriate placement of the relay node.

**Keywords** — energy efficiency, hetnets, interference reduction, power control, regenerative relay, wireless.

## I. INTRODUCTION

THE use of a regenerative relay (RR) may improve several performance metrics in wireless communications [1], and in the LTE-Advanced in particular [2]. A holistic approach to energy efficiency (EE) in mobile radio networks is presented in [3]. We consider improving the EE by using RR, where the metric is the number of bits transmitted per unit of energy [bits/J].

The work [4] focused on EE during the downlink data transmission in the cellular scenario. It shows the EE ratio between the RR and the direct link in the space of channel

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losses of the former and both relay hops. The EE ratio can be greater than one, by increasing the RR data rate as much as possible. This increases the spectral efficiency (SE) of the relay scheme as well, to (partially) compensate for the loss of SE due to doubling of the number of time slots when using RR and possibly due to using 2 channels.

However, this requires increased transmit power, which in turn increases generated interference. Reducing the generated interference is beneficial, because a large number of non-distinguishable interference components can limit the capacity of a wireless system, even if strong interference components are cancelled-out [5]. A careful design is required to achieve desired performance metrics, while limiting the interference, when using the RR [6].

This paper analyzes interference at an unintended receiver A, during the downlink transmission, in cases of the direct link and the two-hop RR, generated by the base station (BS) and the relay node (RN). In particular, the paper analyzes the variations of interference channel losses at the unintended receiver. Then, it combines the EE analysis of the RR, from previous work, with the analysis of the generated interference to formulate their trade-off. It is shown that the trade-off depends on the channel losses along the direct link, both RR links and the interference links. The benefits of the trade-off are enabled by a good BS-RN link, achieved by appropriate RN placement.

The rest of the paper is structured as follows. Section II presents the scenario, the energy consumption model of the RR and the direct link, and the channel loss model. Sec. III considers power consumption characteristics of the BS and the RN, and derives the generated interference ratios. Sec. IV provides an assessment of a key parameter which influences the generated interference ratios. Sec. V provides an example. Sec. VI discusses the results of the assessment. Sec. VII concludes the paper.

## II. SCENARIO, ENERGY CONSUMPTION MODEL AND CHANNEL LOSS MODEL

### A. Scenario

Fig. 1 shows a two-hop RR in the cellular scenario downlink transmission, where the BS is the source (S), a user terminal (UE) is the destination (D), and the RN is a relay (R). The direct link BS-UE is shown as a dashed line with arrow denoting downlink. The two-hop relay, BS-RN and RN-UE, is depicted by two solid lines with arrows denoting downlink. The figure also shows an unintended receiver, A, which is actually a UE in other cell. The

signals it receives from the BS during either the direct link or the first hop of the RR, and the signals that A receives from the RN during the second hop of the RR are interference. The interference links are represented by dash-dotted lines. Throughout the paper, we use notation shown in Fig. 1. The subscripts  $i = \text{void}, 1, 2$ , denote the direct link (BS-UE), the first relay link (BS-RN) and the second relay link (RN-UE), respectively. For each RR link, we use term hop. The subscripts A and A2 denote the interference links BS-A and RN-A, respectively.

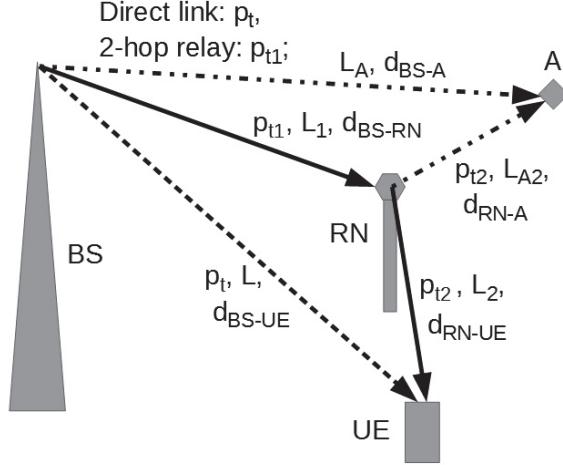


Fig. 1. Scenario of the downlink transmission: the direct link (BS-UE) and the 2-hop RR (BS-RN and RN-UE).

There is an unintended receiver A.

$p_{ti}$  denotes the transmit power at the transmitter (TX) of the link  $i$ .  $p_{TXi}$  denotes the total TX power consumption of the link  $i$  (not shown in Fig. 1).

$L_i$  denotes the channel loss in dB over the link  $i$ .

$d$  denotes the separating distance between a transmitter-receiver (RX) pair, where subscript denotes TX-RX pair.

$p_{ri}$  and  $p_{RXi}$  denote the received signal power and the total RX power consumption, respectively, at the RX of the link  $i$ .  $p_{RXi}$  is assumed constant for each RX  $i$ . Values of  $p_{ti}$ ,  $p_{TXi}$ ,  $p_{ri}$  and  $p_{RXi}$  are obtained from [2], [7].

$P_{th}$  denotes the  $p_r$  threshold for successful reception, which depends on several parameters [8].

$g_t$  and  $g_r$  denote the antenna gains at the TX and RX, respectively.

$r$  and  $r_R$  denote the data rate achievable over the direct link and RR, respectively.

We use the following **assumptions**:

- A deterministic condition for successful reception,  $p_r \geq P_{th}$ .
- The perfect power control to adjust  $p_t$  at all transmitters (BS and RN) to yield  $p_r = P_{th}$  at all the receivers.
- Both relay hops (BS-RN and RN-UE) have the same data rate,  $2r_R$ , i.e.,  $P_{th,1} = P_{th,2}$ .

### B. Energy Consumption and Energy Efficiency Ratios

We use the total TX power consumption model,  $p_{TX} = f(p_t)$ , of [8], with constraints  $p_t \in [p_{t,min}, p_{t,max}]$  and  $p_{TX} \in [p_{TX,min}, p_{TX,max}]$ .

An EE comparison between the RR and the direct link, is based on a simplified link budget

$$p_r = g_t g_r p_t / L, \quad (1)$$

which yields [9]

$$L_{max} = g_t g_r p_{t,max} / P_{th}, \quad L_{min} = g_t g_r p_{t,min} / P_{th}, \quad (2)$$

$$p_t = (P_{th} L) / (g_t g_r). \quad (3)$$

Comparing the two-hop and single-hop transmissions, the energy consumption ratio  $\alpha$  [8], the data rate ratio,  $\beta$ , and the EE ratio,  $\eta$ , [4], are:

$$\begin{aligned} \alpha &= \frac{(E_{TX,1} + E_{RX,1}) + (E_{TX,2} + E_{RX,2})}{(E_{TX} + E_{RX})}, \\ \beta(p_t, p_{t1}, p_{t2}) &= \frac{r_R(p_{t1}, p_{t2})}{r(p_t)}, \\ \eta(p_t, p_{t1}, p_{t2}) &= \frac{\beta(p_t, p_{t1}, p_{t2})}{\alpha(p_t, p_{t1}, p_{t2})}. \end{aligned} \quad (4)$$

Here,  $\alpha$  is evaluated for the same  $(p_t, p_{t1}, p_{t2})$  as  $\beta$  and  $\eta$ . Increased  $\beta$  increases  $\eta$  [4]. Under a typical downlink scenario,  $\alpha$  increases at a smaller rate than  $\beta$ .

It is shown in [4] that it is possible to increase  $r_R$  w.r.t.  $r$  ( $\beta \geq 1$ ), by increasing the constellation and adjusting the code rate along both relay hops. For instance, for QAM constellations used in OFDM, approximately, if  $P_{th,1} \geq P_{th} + 6\text{dB}$ , then  $\beta \geq 1$  [4]. If  $\beta = 1$ , then both the direct link and the RR transmit the same amount of data in two slots: the former half of data in each slot, the latter all data in each hop. We use the assumption  $\beta = 1$  in the rest of the paper.

### C. Channel Loss Model

The trade-off between improving EE and limiting the generated interference using RR, is based on exploiting the differences between channel losses along the direct link and relay hops. To demonstrate this claim, we use a modified Urban channel loss model for relay communications [9], which accounts for the path loss and shadowing, in both line-of-sight (LOS) and non-LOS (NLOS) channel types (log stands for  $\log_{10}$ ):

$$L_i[\text{dB}] = \begin{cases} [b_i + 10n_i \log d_i] + \\ + m_i \sigma_i \left[ 1 - \exp \left( -\frac{d_i - d_0}{D_{S,i}} \right) \right], & \text{NLOS} \\ [-27.6 + 20 \log d_i] + \\ + m_i 2 \left[ 1 - \exp \left( -\frac{d_i}{30} \right) \right], & \text{LOS} \end{cases} \quad (5)$$

where subscript  $i$  denotes the link. The left square brackets in the sum model the path loss and the right additive term models shadowing, with standard deviation  $\sigma_i$ .  $d_i$  denotes the TX-RX distance of the link  $i$ , and is expressed in meters. The parameters are:  $b_i$ , expressed in dB,  $n_i$ , a dimensionless number, and  $d_0$  and  $D_{S,i}$ , expressed in meters. Their values are provided in the model [9] (Table I and II). The LOS case has the same channel loss function (bottom case in (5)) irrespective of the TX-RX pairs [9]. Parameter  $m_i$  is the multiplicative factor of the shadowing standard deviation. It is introduced in this paper to serve as a shadowing margin, which may depend on the shadowing distribution or receiver design requirements. In NLOS case, the shadowing distribution is confirmed to be log-normal, whereas in LOS case it is more similar to a Uniform distribution [9]. Fig. 2 shows the NLOS channel losses of the links, individually, with  $m_i = 1$ ,  $m_i = 3$ , and the LOS curve being equal for all three TX-RX pairs, but

two distinct shadowing variations (2dB, 6dB).

The conditional probability of LOS as a function of the separating distance between the transmitter and receiver is given in [9 (Fig. 4)]. This probability is 1 for the separating distance less than 10, and non-negligible for the separating distance of less than 200 [meters]. The conditional LOS probability of the BS-RN link dominates the BS-UE link, and the BS-UE link dominates the RN-UE link over all separating distances.

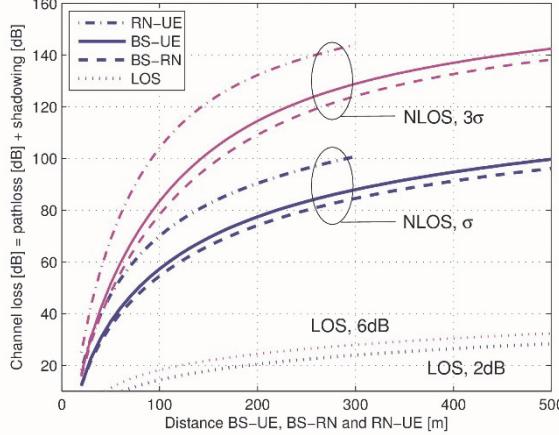


Fig. 2. Channel losses along the links: BS-UE, BS-RN and RN-UE.

### III. GENERATED INTERFERENCE LEVELS IN THE SPACE OF CHANNEL LOSSES

The interference power the BS makes at an *unintended* receiver - a point A, during both slots of the direct link, is

$$I_A = p_{rA}^{BS-UE} = \frac{P_t g_S g_D}{L_A} = P_{th} \frac{L}{L_A}, \quad (6)$$

where  $p_t$  is determined from (3).

The interference power of the BS in slot 1, and the RN in slot 2, at the point A, when RR is used, are

$$I_A^{R1} = p_{rA}^{BS-RN} = \frac{P_{th1} g_S g_D}{L_A} = P_{th1} \frac{g_D L_1}{g_R L_A}, \quad (7)$$

$$I_A^{R2} = p_{rA}^{RN-UE} = \frac{P_{th2} g_R g_D}{L_{A2}} = P_{th2} \frac{L_2}{L_{A2}}, \quad (8)$$

where  $P_{th1}$  and  $P_{th2}$  are determined from (3) for  $L_1$  and  $L_2$ , respectively. Parameters  $g_D$  and  $g_R$  are given and constant;  $P_{th}$  and  $P_{th1,2}$  are given, but may be adjusted.  $L$ ,  $L_1$ ,  $L_2$  are obtained from the model (5) for given positions of the BS, RN and UE (Fig. 2).

Point A being a UE narrows the results of our paper, but keeps the analysis within the Urban channel model (5). If A were another BS or RN, we would need the channel models BS-BS, RN-BS and BS-RN, which are not provided in [9]. Hence, we consider:  $b_A=b$ ,  $b_{A2}=b_2$ ,  $n_A=n$ ,  $n_{A2}=n_2$ ,  $\sigma_A=\sigma$ ,  $\sigma_{A2}=\sigma_2$ ,  $D_{S,A}=D_S$ ,  $D_{S,A2}=D_{S,2}$ .

Variables  $L_A$  and  $L_{A2}$  are unknown, but have the same path loss and shadowing model as  $L$  and  $L_2$ , respectively, c.f. (5). Multipliers  $m_A$  and  $m_{A2}$  may not be equal to  $m$  and  $m_2$ , respectively. There may be correlation between  $L_A$  and  $L$ , and/or between  $L_{A2}$  and  $L_2$ . Consideration of the correlations is beyond the scope of this paper, but by allowing the difference in multipliers we enable the case of uncorrelated channel losses. Let the interference channel

losses ratio at a point A, denoted  $\tau$ , be

$$\tau = \frac{L_{A2}}{L_A}. \quad (9)$$

In logarithmic scale,  $x[\text{dB}] = x^{\text{dB}}$ ,  $\tau^{\text{dB}} = L_{A2}^{\text{dB}} - L_A^{\text{dB}}$ . Let

$$\kappa_1 = \frac{I_A^{R1}}{I_A}, \quad \kappa_2 = \frac{I_A^{R2}}{I_A} \quad (10)$$

for a feasible ratio  $\tau$ . In logarithmic scale, the relationships in the space of channel losses ( $L$ ,  $L_1$ ,  $L_2$ ) , are

$$L_1^{\text{dB}} = L^{\text{dB}} + \Delta P_{th}^{\text{dB}} + \Delta g^{\text{dB}} + \kappa_1^{\text{dB}}, \quad (11)$$

$$L_2^{\text{dB}} = L^{\text{dB}} + \Delta P_{th}^{\text{dB}} + \tau^{\text{dB}} + \kappa_2^{\text{dB}}. \quad (12)$$

Note that  $\kappa_i^{\text{dB}} < 0\text{dB}$  ( $\kappa_i < 1$ ) means that interference is reduced when using the relay link  $i$  w.r.t. the direct link in hop  $i$ , for  $i=1,2$ . Ideally, the values of variables and parameters in (11) and (12) will enable  $\kappa_i^{\text{dB}} < 0\text{dB}$ , but this is not guaranteed.

In (11), the key to lower  $\kappa_1$  is decrease of  $L_1$  w.r.t.  $L$  by appropriate placement of the RN w.r.t. the BS, e.g. by providing LOS. The increase of  $\Delta g$  enables decrease of  $\kappa_1$ , but the change is limited to a few dB.

In (12), a key to lower  $\kappa_2$  is decrease of  $L_2$  w.r.t.  $L$ , but this depends on the terrain and buildings along the RN-UE link, which are not under network designer's control. Another key is attaining a desired value of  $\tau$ , which is also not under network designer's control. However, the region of points A in which desirable values of  $\tau$  are achievable can be determined.

### IV. ANALYSIS OF INTERFERENCE CHANNEL LOSSES RATIO AT A POINT A

Because of the influence of  $\tau$  on  $\kappa_2$  (12), we are interested in the range of values of  $\tau$  for various possible values of path-loss and shadowing parameters (c.f. (5)), and separating distances BS-A and RN-A. We partition the cases based on the LOS/NLOS conditions, in Table 1.

The analytical expression for evaluation of  $\tau$  for the four cases *c1-c4* is (log stands for  $\log_{10}$ ) is:

$$\tau^{\text{dB}} = \begin{cases} 20 \log d_{A2} + 2m_{A2} \left[ 1 - \exp \left( -\frac{d_{A2}}{30} \right) \right] - \\ - 20 \log d_A - 2m_A \left[ 1 - \exp \left( -\frac{d_A}{30} \right) \right], & \text{c1} \\ b_2 + 10n_2 \log d_{A2} + m_{A2} \sigma_2 \left[ 1 - \exp \left( -\frac{d_{A2} - d_0}{D_{S,2}} \right) \right] + \\ + 27.6 - 20 \log d_A - 2m_A \left[ 1 - \exp \left( -\frac{d_A}{30} \right) \right], & \text{c2} \\ - 27.6 + 20 \log d_{A2} + 2m_{A2} \left[ 1 - \exp \left( -\frac{d_{A2}}{30} \right) \right] - \\ - b - 10n \log d_A + m_A \sigma \left[ 1 - \exp \left( -\frac{d_A - d_0}{D_S} \right) \right], & \text{c3} \\ b_2 + 10n_2 \log d_{A2} + m_{A2} \sigma_2 \left[ 1 - \exp \left( -\frac{d_{A2} - d_0}{D_{S,2}} \right) \right] - \\ - b - 10n \log d_A - m_A \sigma \left[ 1 - \exp \left( -\frac{d_A - d_0}{D_S} \right) \right], & \text{c4} \end{cases}$$

A reference value of  $\tau$  corresponds to  $\kappa_2^{\text{dB}}=0\text{dB}$ :

$$\tau_0^{\text{dB}} = L_2^{\text{dB}} - L_A^{\text{dB}} - \Delta P_{th}^{\text{dB}}.$$

Note that  $\tau$  may not be correlated to  $L_2$  and  $L$ , so that  $\tau^{\text{dB}}$

may deviate significantly from  $\tau_0^{\text{dB}}$ . If  $\tau^{\text{dB}} > \tau_0^{\text{dB}}$  then  $\kappa_2^{\text{dB}} < 0 \text{ dB}$ , which favors the use of the RR in the sense that the generated interference is reduced. The opposite favors the direct link BS-UE.

TABLE 1: POSSIBLE LOS/NLOS CONDITIONS OVER RN-A AND BS-A LINKS.

	c1	c2	c3	c4
RN-A	LOS	NLOS	LOS	NLOS
BS-A	LOS	LOS	NLOS	NLOS

The evaluation of  $\tau$  requires known distances BS-A and RN-A, as well as known LOS/NLOS conditions. Alternatively, one can evaluate  $d_{A2}$  for the given LOS/NLOS conditions,  $d_A$  and desired  $\tau^{\text{dB}}$ . This defines the region in which the interference from the RN during the second hop of RR is below the interference from the BS during the second slot.

There is a wide interval of values of  $\tau$ . For instance, for distances greater than 20m from the RN,  $\tau$  ranges from less than -50 dB to more than 50dB. The dependence of  $\tau$  on the independent BS-A and RN-A distances, in NLOS/NLOS case, is shown in Fig. 3. Equipotential lines of  $\tau$  having values of [-50, -20, 0, 20, 50]dB appear in ascending order going counter-clockwise from the x-axis. The solid lines stretching from the lower left corner are  $\tau$  levels. The dashed line and dash-dotted line show the distance between the BS and RN of 400m and 300m, respectively. For a given BS-RN distance, the feasible values of  $\tau$  lie to the right and above the BS-RN distance line, because of the triangle inequality  $d_A + d_{A2} \geq d_{\text{BS-RN}}$ .

#### A. Variations in $\tau$ Ratio

The dependence of  $\tau$  on the variation of channel losses due to change in shadowing deviation/margin along both BS-A and RN-A links can be assessed from

$$\frac{\partial \tau^{\text{dB}}}{\partial m_A} = \begin{cases} -2 \left[ 1 - \exp\left(-\frac{d_A}{30}\right) \right], & c1, c2 \\ -\sigma \left[ 1 - \exp\left(-\frac{d_A - d_0}{D_S}\right) \right], & c3, c4 \end{cases},$$

$$\frac{\partial \tau^{\text{dB}}}{\partial m_{A2}} = \begin{cases} 2 \left[ 1 - \exp\left(-\frac{d_{A2}}{30}\right) \right], & c1, c3 \\ \sigma_2 \left[ 1 - \exp\left(-\frac{d_{A2} - d_0}{D_{S,2}}\right) \right], & c2, c4 \end{cases}.$$

It follows that

$$\frac{\partial \tau^{\text{dB}}}{\partial m_A} < 0 \quad \text{and} \quad \frac{\partial \tau^{\text{dB}}}{\partial m_{A2}} > 0,$$

in all cases, for all separating distances and shadowing deviations. In the case of interest when point A is outside the cell of interest, closer to the RN than the BS,  $d_A > d_{A2}$ ,  $\tau^{\text{dB}}$  is somewhat more sensitive to changes in shadowing deviation/margin along the RN-A link than along the BS-A link. It is shown in Fig. 4. For instance, when the RN-A channel improves relative to the BS-A channel for the given point A (case  $\tau(3\sigma, \sigma_2)$ ),  $\tau$  decreases. While the bending of the  $\tau = 0$  dB line is significant, as the channel losses change, the bending of the  $\tau = -50$  dB and  $\tau = 50$  dB is less pronounced.

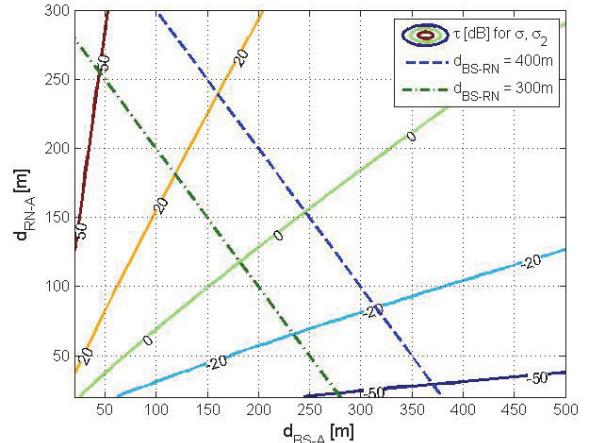


Fig. 3.  $\tau$  [dB] depending on distances BS-A (x-axis) and RN-A (y-axis).

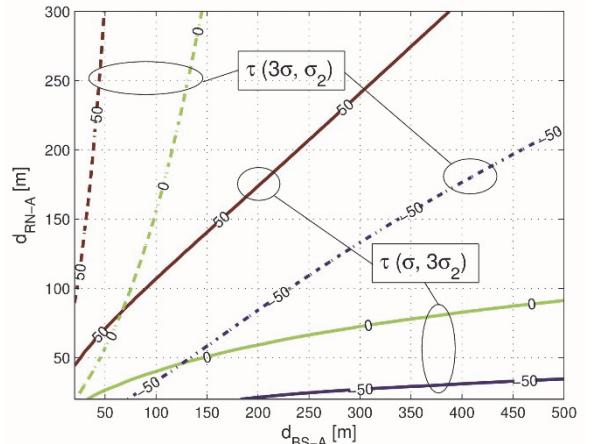


Fig. 4.  $\tau$  [dB] depending on distances BS-A (x-axis) and RN-A (y-axis), NLOS/NLOS.

A different perspective on changes of  $\tau$  is obtained when taking into account change in separating distances BS-A and RN-A.

$$\frac{\partial \tau^{\text{dB}}}{\partial d_A} = \begin{cases} -\frac{20}{d_A \ln 10} - \frac{m_A}{15} \exp\left(-\frac{d_A}{30}\right), & c1, c2 \\ -\frac{10n}{d_A \ln 10} - \frac{m_A \sigma}{D_S} \exp\left(-\frac{d_A - d_0}{D_S}\right), & c3, c4 \end{cases},$$

$$\frac{\partial \tau^{\text{dB}}}{\partial d_{A2}} = \begin{cases} -\frac{20}{d_{A2} \ln 10} - \frac{m_{A2}}{15} \exp\left(-\frac{d_{A2}}{30}\right), & c1, c3 \\ -\frac{10n_2}{d_{A2} \ln 10} - \frac{m_{A2} \sigma_2}{D_{S,2}} \exp\left(-\frac{d_{A2} - d_0}{D_{S,2}}\right), & c2, c4 \end{cases}.$$

It follows that

$$\frac{\partial \tau^{\text{dB}}}{\partial d_A} < 0, \quad \text{and} \quad \frac{\partial \tau^{\text{dB}}}{\partial d_{A2}} > 0$$

in all cases, for all separating distances, shadowing deviations and margins. For distances  $d_A = 400\text{m}$  and  $d_{A2} = 100\text{m}$ ,  $\tau^{\text{dB}}$  is around 4 times more sensitive to the change of  $d_{A2}$  than to the change of  $d_A$ . An example is given in Fig. 5, which shows the values of  $\tau^{\text{dB}}$  around the RN, assuming the Urban model of channel losses (5). The BS-RN distance is 400m, in NLOS/NLOS case, with shadowing deviations ( $\sigma, \sigma_2$ ). The shown values change from -80dB to -5dB as the distance from the RN increases. In Fig. 5, at the distance of approximately 50m from the

RN,  $\tau^{\text{dB}} \in (-40, -50)$  dB. It can be shown that for NLOS/NLOS case with shadowing deviations ( $\sigma, 3\sigma_2$ ), at the distance  $d_{A2} \approx 50$  meters,  $\tau^{\text{dB}} \in (-20, -30)$  dB.

The values of  $\tau^{\text{dB}}$  around the RN change little if the BS-RN distance is changed between 300m and 500m.

We note that  $\tau^{\text{dB}}$  typically changes more due to changes in shadowing deviation/margin than due to changes in separating distances. This is partly because the relative change of shadowing deviation/margin is larger than the relative change in the separating distances ratio,  $d_{A2}/d_A$ .

### B. A Generalized Model of Changes in $\tau$ Ratio

To assess all possible changes of  $\tau$ , including changes in LOS/NLOS conditions, we propose a simple generalized model of changes in channel losses. Let

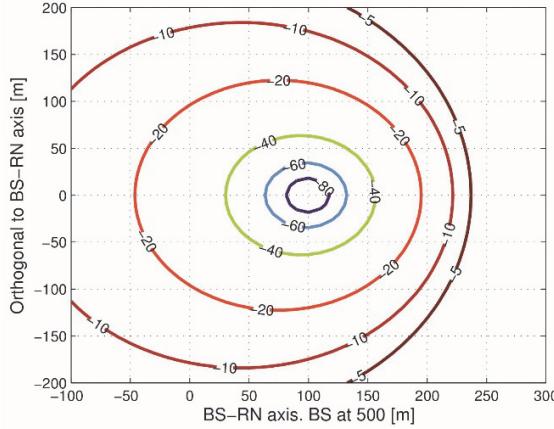


Fig. 5. Equipotential  $\tau$  lines around the RN, against a 2-D “map”: BS is at (500, 0) [m], RN is at (100, 0) [m].

$$\begin{aligned} L_A^{\text{dB}} &= \bar{L}_A^{\text{dB}} + \Delta L_A^{\text{dB}}, \\ L_{A2}^{\text{dB}} &= \bar{L}_{A2}^{\text{dB}} + \Delta L_{A2}^{\text{dB}}. \end{aligned}$$

Then

$$\tau^{\text{dB}} = \bar{\tau}^{\text{dB}} + \Delta \tau^{\text{dB}},$$

where

$$\begin{aligned} \bar{\tau}^{\text{dB}} &= \bar{L}_{A2}^{\text{dB}} - \bar{L}_A^{\text{dB}}, \\ \Delta \tau^{\text{dB}} &= \Delta L_{A2}^{\text{dB}} - \Delta L_A^{\text{dB}}. \end{aligned}$$

For instance, one may set  $\bar{L}_A^{\text{dB}}$  and  $\bar{L}_{A2}^{\text{dB}}$  to correspond to NLOS case with multipliers  $m_A = 1$ ,  $m_{A2} = 1$  and selected shadowing deviation. If the BS-A path has NLOS with stronger shadowing, then its multiplier,  $m_A$ , is increased, so that  $\Delta L_A^{\text{dB}} > 0$ . If the BS-A path has LOS, then its shadowing deviation is significantly reduced:  $\Delta L_A^{\text{dB}} < 0$  (c.f. (5)). The same holds for RN-A path and  $\Delta L_{A2}^{\text{dB}}$ .

As an illustration, the Table 2 shows discrete possibilities for  $\Delta \tau^{\text{dB}}$ , when both RS-A and BS-A links experience NLOS (case c4), with two different shadowing margin values, relative to the  $m_A = 1$ ,  $m_{A2} = 1$ .

Table 3 expands Table 1 to show possibilities for  $\Delta \tau^{\text{dB}}$ , depending on the existence of LOS, relative to case c4.

Existence of LOS along exactly one of the links (in cases c2 and c3), changes path loss parameters in addition to the shadowing margin/deviation relative to the NLOS link. Therefore, relative to the case c4 with changes in shadowing margin (see Table 2), cases c2 and c3 may have a larger absolute value of  $\Delta \tau^{\text{dB}}$ .

TABLE 2: POSSIBLE NLOS/NLOS CONDITIONS OVER RN-A AND BS-A LINKS, WITH VARIATIONS IN MARGIN MULTIPLIERS.

RN-A	$m_{A2} = 1$	$m_{A2} = 3$	$m_{A2} = 1$	$m_{A2} = 3$
BS-A	$m_A = 1$	$m_A = 1$	$m_A = 3$	$m_A = 3$
	/	$\Delta \tau^{\text{dB}} > 0$	$\Delta \tau^{\text{dB}} < 0$	ANY

TABLE 3: CHANGE IN TAU DUE TO VARIOUS LOS/NLOS CONDITIONS OVER RN-A AND BS-A LINKS.

	c1	c2	c3	c4
RN-A	LOS	NLOS	LOS	NLOS
BS-A	LOS	LOS	NLOS	NLOS
$\Delta \tau^{\text{dB}}$	ANY	$\Delta \tau^{\text{dB}} > 0$	$\Delta \tau^{\text{dB}} < 0$	/

### V. AN EXAMPLE

Assume an urban environment with a Micro BS, and Pico-BS-like characteristics of the RN. The total power consumption values are based on [7] for 2012 State-of-the-Art. The values of  $p_{t,\min}$  and  $p_{t,\max}$  of the BS and RN are based on 3GPP requirements [10]. The minimum power is evaluated using the peak maximum power and the minimum requirements for Total power dynamic range (e.g. 16.9dB for 10MHz bandwidth [10]) [4]. An example is shown in Fig. 6, where the x-axis is logarithmic [dBm], and the y-axis is linear [W].  $\beta = 1$ , so that 2 slots are consumed in direct link (dash-dotted vertical lines with arrow on top: SLOT 1, SLOT 2). The difference in the range of  $p_{TX}$ , motivates the use of relay to improve the EE.

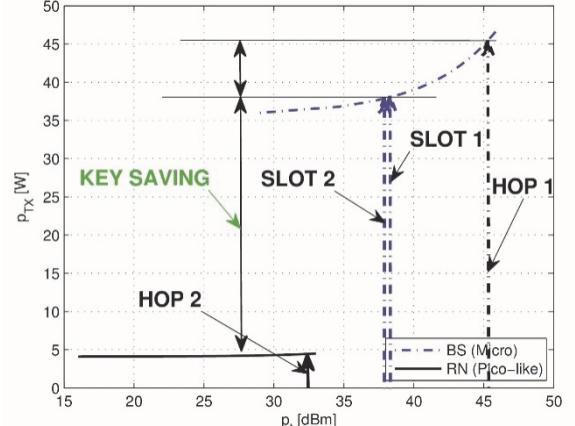


Fig. 6. Power consumption: Micro-BS and Pico-BS-like RN.

The antenna gains at the BS, RN and UE, respectively, are  $g_S = 15$  dB,  $g_R = 5$  dBi and  $g_D = 0$  dB.

We consider point A to be out of the cell of interest, and assume  $\tau^{\text{dB}} \approx -3$  dB at the point A and around it. This value of  $\tau^{\text{dB}}$  appears at some distance from the cell edge, so that with high probability, both BS-A and RN-A links experience NLOS conditions. Larger values of  $\tau^{\text{dB}}$  are possible at larger distances, which favors the RR.

Assume equal BS-UE and BS-RN distances of 500m, so that we assume NLOS along both links (which occur with high probability),  $L = 142.4$  dB and  $L_1 = 138.2$  dB. The RN-UE distance is 100m with assumed NLOS condition, so that  $L_2 = 104.2$  dB (c.f. (1), see Fig. 2). Then, the operating point (OP) in the space of channel losses is  $(L, L_1, L_2) = (142.4, 138.2, 104.2)$ .

Fig. 7 shows achievable  $\kappa_1, \kappa_2$  for  $\tau = -3$  dB at the OP.

The axes limits correspond to  $[L_{1,min}, L_{1,max}]$  and  $[L_{2,min}, L_{2,max}]$ , which are obtained from (2) for  $P_{th} = -85$  dBm. The dotted lines with markers show  $\alpha$ -levels (4). The data rate ratio is leveled,  $\beta = 1$ , due to selection of appropriate  $P_{th,1}$ , constellation and code rate over relay hops. At the OP,  $\kappa_1 \approx -3$  dB,  $\kappa_2 \approx -29$  dB, whereas the EE ratio,  $\eta \approx 1.85$ .

Note that by changing the OP, it is possible to increase  $\eta$  at the expense of increased  $\kappa_1, \kappa_2$  (by increasing the transmit power over relay hops and changing the constellation size and code rate accordingly) or decrease  $\kappa_1, \kappa_2$  at the expense of decreased  $\eta$  (by decreasing the transmit power over the relay hops and adjusting constellation and code rate accordingly). That is the trade-off that has to be made.

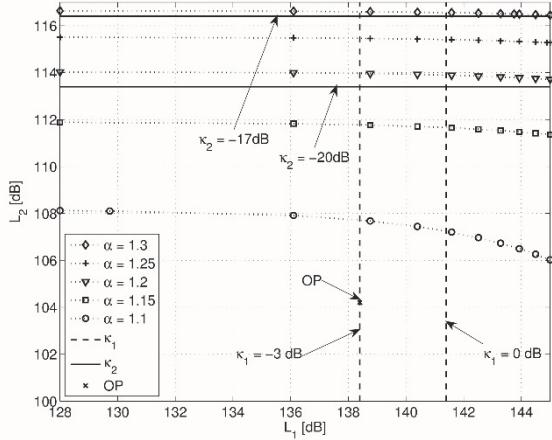


Fig. 7.  $(L_1, L_2)$  space,  $\tau = -3$  dB:  $\alpha$ -levels overlapped with  $\kappa_1, \kappa_2$  lines.

## VI. DISCUSSION

The trade-off between EE and generated interference at an unintended receiver A, using RR, depends on a number of conditions and parameters. If only LOS/NLOS conditions along each of the 5 relevant links (BS-UE, BS-RN, RN-UE, BS-A and RN-A) are considered, there are  $2^5 = 32$  possibilities. For each link, the probability of a certain LOS/NLOS condition depends on the source-destination separating distance [9]. We emphasize the most probable outcomes.

Within the RN pico-cell, e.g. beyond 60% of the radius of the cell of interest (300m for radius of 500m), the BS-UE link is NLOS with high probability [9]. Beyond the cell edge, the BS-A link is NLOS with high probability.

Then, the worst case for EE increase is NLOS/NLOS along both BS-RN and RN-UE. The BS-RN link is subject to network design, so the probability of LOS is not negligible. In case of NLOS BS-RN link, the shadowing effect may be small with non-negligible probability. The RN-UE link also has non-negligible probability of either LOS or NLOS with a small shadowing effect.

The RN-A link beyond the cell edge is NLOS with high probability (case c4), but there may be areas with either LOS or NLOS with low shadowing (case c3). The case c4 is amenable to the EE-SE vs generated interference trade-off because of the large channel loss  $L_{A2}$ , which may yield a sufficiently large  $\tau$ . However, the case c3 is not, because of the large generated interference from the RN, i.e. small

$\tau$ .

If RR increases EE, it is due to:  $L_1 < L$ ,  $\Delta g^{\text{dB}} = g_R^{\text{dB}} - g_D^{\text{dB}} > 0$  dB and adjustment of the constellation size and code rate over both relay hops [4].

However, doubling of the data rate ratio  $\beta$  requires, on average, a 6dB increase in transmit power, whereas the same increase in transmit power quadruples the generated interference. Therefore, it is essential to place the RN in a cell such that the channel losses along BS-RN and RN-UE links (within the RN pico-cell) are minimized, whereas channel losses from the RN to unintended receivers (out of the RN pico-cell) are as large as possible. If this is not possible, then the use of a small BS (with wireline backhaul) instead of a RN is recommended.

## VII. CONCLUSION

When using the RR, a trade-off between increased EE vs the reduced generated interference is possible. It has been quantified and key parameters have been assessed in this paper. The key to achieving a good trade-off is appropriate placement of the RN and exploitation of the differences in channel losses along different links: low losses for desirable links and high losses for undesirable links. A complete assessment requires integration over the areas of interest, which is a goal of the future work.

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