Relay Type 1a in LTE-Advanced: Can It Increase Energy Efficiency? (Invited paper)

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Abstract

A comparison of energy efficiency of two-hop transmission via Type 1a relay node (RN) and the direct link in LTE-Advanced, between the same base station (BS) and user terminal (UE), is presented. We build upon an existing energy consumption model, which links the total transceiver power consumption as a function of transmitted power, channel loss along each of the three links, and PHY and protocol parameters. In the space of channel losses, we show equipotential planes of the energy consumption ratio in the transceivers' operating region. In the equivalent space of transmit powers, we show required power levels to enable certain constellation and coding rate pairs. Overlapping the two spaces quantifies the energy efficiency increase. The increase in energy efficiency by a single-digit multiplying factor is possible. It is achieved by maximizing transmit power along both relaying hops, and selecting the constellation size and code rate pair which maximizes data rate, subject to the reliability constraint.

1. Introduction

Relay, a cooperative communication scheme, has been included in the 3GPP LTE standard [1]. It is one of the approaches to improve area coverage and data rates. There are Type 1 relay node (RN) and Type 1a RN. Type 1 RN uses the same channel for communication with the base station (BS), and the user terminal (UE). Type 1a RN uses one channel for communication with the BS, and another channel for communication with the UE [2]. This avoids possibility of self-interference and eliminates overhearing at the BS during transmission to UE and vice versa.

Many novel approaches are targeting increased energy efficiency (EE) (www.greentouch.org). We consider the EE as the number of bits transmitted per unit of energy [bits/J]. A holistic approach to energy efficient mobile radio networks is presented in [3]. Significant energy savings can be achieved by, turning off the equipment when it is not in use.

We focus on energy efficiency during downlink data transmission via Type 1a RN, when the equipment cannot be turned off. The basis for this work is [4], which has derived energy consumption ratio between transmission via relay and transmission via direct link, for heterogeneous transceivers and the same data rates in relay scheme and direct link. However, there is a possibility that data rate can be increased when using relay, which can lead to increased EE.

In Section 2, we briefly review a wireless transceiver power consumption model, and energy consumption comparison of two-hop relay and single-hop transmission with the same data rates, in flat, slow fading (quasi-static) wireless channels. In Section 3, we apply the analysis to downlink in LTE-Advanced networks, with Type 1a RN in a cell, to quantify energy efficiency change in the space of transmit powers. Section 4 concludes the paper.

2. Transceiver Power Model and Energy Consumption Ratio

Consider a total power consumption model of a transceiver described in [4]. This is a raised-fractional-power transmitter power consumption model, with limited transmit power $p_t \in [p_{t,min}, p_{t,max}]$ and the corresponding total transmitter power consumption $p_{TX} \in [p_{TX,min}, p_{TX,max}]$. It generalizes an affine function by introducing a curvature exponent $v \in [0,1]$.

A simplified link budget, where p_r is the received signal power, g_t and g_r are antenna gains at the transmitter and receiver, respectively, and L is the total channel loss, yields

$$p_r = g_t g_r p_t / L. \tag{1}$$

Let P_{th} denote the minimum p_r, for successful reception,

$$P_{th} = s_m \max\left\{S_{RX}, SINR_{th}(N+I)\right\}, \tag{2}$$

where s_m is the required received signal power margin ($s_m \geq 1$), S_{RX} is the receiver sensitivity, SINR$_{th}$ is the minimum SINR for desired probability of successful reception (SINR threshold), I is the interference power, and N is the noise power. Given $p_t \in [p_{t,min}, p_{t,max}]$ and P_{th}, there is the largest channel loss, L_{max}, for which a successful transmission is possible. It is achieved for $p_r = P_{th}$, when $p_t = p_{t,max}$. Similarly, there is the smallest channel loss, L_{min}, such that it is not possible to save power if $L < L_{min}$. L_{min} is achieved for $p_r = P_{th}$, when $p_t = p_{t,min}$.

$$L_{max} = g_t g_r p_{t,max} / P_{th}, L_{min} = g_t g_r p_{t,min} / P_{th}. \tag{3}$$

Table 1: Transmit power bounds

	Macro [dBm]		RRH [dBm]		Micro [dBm]		Pico [dBm]	
	peak	rms	peak	rms	peak	rms	peak	rms
$p_{t,max}$	54	46	51	43	46	38	33	21
$p_{t,min}$	37		34		29		16	

Table 2: Values of $q, w_{q,SD}$ and α_{LB}

	$p_{TX,max,S}$ [W]	$p_{TX,min,S}$ [W]	$p_{RX,S}$ [W]	$p_{TX,max,R}$ [W]	$p_{TX,min,R}$ [W]	$p_{RX,R}$ [W]	$p_{RX,D}$ [W]	q	$w_{q,SD}$	α_{LB}
S: Micro, R: Pico	47	36	28	4.5	4.1	4	2	0.74	3.45	0.94
S: Macro, R: Pico	160	90	50					0.12	1.31	0.62

If a reliable estimate of the channel loss, L, is available, the perfect power control enables adjusting p_t to yield $p_r = P_{th}$. A total transmitter (TX) power consumption model as a function of transmit power, $p_{TX}(p_t)$, with power control at the TX with known channel loss, for $L \in (0, L_{max})$, is given in [4]. The receiver (RX) power consumption, p_{RX}, is constant for any p_r. The energy consumption at TX and RX, during an interval T, is $E_{TX} = p_{TX}T$ and $E_{RX} = p_{RX}T$, respectively.

Consider a two-hop regenerative relay in the cellular scenario, where there are: the source (S) - a base station (BS), the destination (D) - a user terminal (UE), and the relay (R) - a Type 1a RN. Let us consider a file download use case - a downlink transmission from S to D [1, 5]. The first hop, from S to R, is link 1; the second hop, from R to D, is link 2. The single-hop link, from S to D, remains unnumbered. Let p_t, p_{t1}, and p_{t2} denote transmit power for the SD link, link 1 (SR), and link 2 (RD), respectively. Let L, L_1, and L_2 denote channel losses of the same links, respectively.

The energy consumption ratio α, between the two-hop and single-hop transmissions is [4]

$$(E_{TX,1} + E_{RX,1}) + (E_{TX,2} + E_{RX,2}) \quad = \quad \alpha (E_{TX} + E_{RX}), \tag{4}$$

where $E_{TX,j}$ denotes transmitter energy consumption in hop $j = 1,2$ (left-hand side, LHS) or in direct link (right-hand side, RHS); $E_{RX,j}$ denotes receiver energy consumption in hop $j = 1,2$ (LHS) or in direct link (RHS). From (3), it follows

$$\begin{array}{c} L_{max} = g_S g_D p_{t,max}/P_{th},\ L_{min} = g_S g_D p_{t,min}/P_{th}, \\ L_{1,max} = g_S g_R p_{t1,max}/P_{th},\ L_{1,min} = g_S g_R p_{t1,min}/P_{th}, \\ L_{2,max} = g_R g_D p_{t2,max}/P_{th},\ L_{2,min} = g_R g_D p_{t2,min}/P_{th}. \end{array} \tag{5}$$

where $L \leq L_{max}, L_1 \leq L_{max,1}, L_2 \leq L_{max,2}$. The key part of the model is repeated here, for convenience, while parameters c_{RS} and $q(\alpha)$ are defined in [4]

$$z_{SR}(L_1) + c_{RS} z_{RD}(L_2) = \alpha z_{SD}(L) - q(\alpha), \tag{6}$$

$$z_{SR}(L_1) = \left[\max\left(\frac{L_1 - L_{1,min}}{L_{1,max} - L_{1,min}}, 0\right)\right]^{v_S}, \quad z_{RD}(L_2) = \left[\max\left(\frac{L_2 - L_{2,min}}{L_{2,max} - L_{2,min}}, 0\right)\right]^{v_R}, \quad z_{SD}(L) = \left[\max\left(\frac{L - L_{min}}{L_{max} - L_{min}}, 0\right)\right]^{v_S}.$$

3. Energy Efficiency Using Type 1a Relay Node

Using the above model, we quantify the energy efficiency ratio between two-hop regenerative relay and direct link in the downlink. We assume an urban environment in which S is a Micro BS, and Type 1a RN has characteristics of a Pico BS. Note that a RN is not connected to the backhaul network, whereas a Pico BS is. We assume the antenna gains at the BS, RN and UE, respectively, are $g_S = 15dB$, $g_R = 5dBi$ and $g_D = 0dBi$. Antenna(s) at the RN typically have larger antenna gain than antenna at the UE, in the range of 2 - 5 dB, because of the larger form factor and less constraints on the cost.

The assumed values of $p_{t,min}$ and $p_{t,max}$ of four BS types are provided in the Table 1 based on 3GPP requirements [6] (RRH stands for Remote Radio Head). The minimum power is evaluated using the peak maximum power, and the minimum requirements for Total power dynamic range ([6], e.g. for 10MHz bandwith, this range is 16.9dB).

The energy saving, using the same data rate transmission over direct link and both relay links, is achieved when p_{t1} and p_{t2} are minimized subject to guaranteeing that the received signal power is above the threshold P_{th}. The largest energy saving corresponds to the lowest energy consumption ratio, α_{LB} [4]. Table 2 shows α_{LB} in this scenario. The total power consumption values in Table 2 (p_{TX}'s and p_{RX}'s) are based on [5] for 2012 State-of-the-Art. The BS values are for Macro and Micro, whereas the RN has Pico BS characteristics.

Higher energy efficiency is achieved if the data rate over each of the two relay links is increased w.r.t. the direct link data rate, by the same multiplicative factor and as much as possible subject to required power levels.

To see this, let us first consider channel losses along each link. The channel losses for the links BS-UE, BS-RN and RN-UE, following the model of [7] are shown in Fig. 1. The total channel loss is equal to the sum of pathloss and shadowing. We set the shadowing margin at three standard deviations provided in [7].

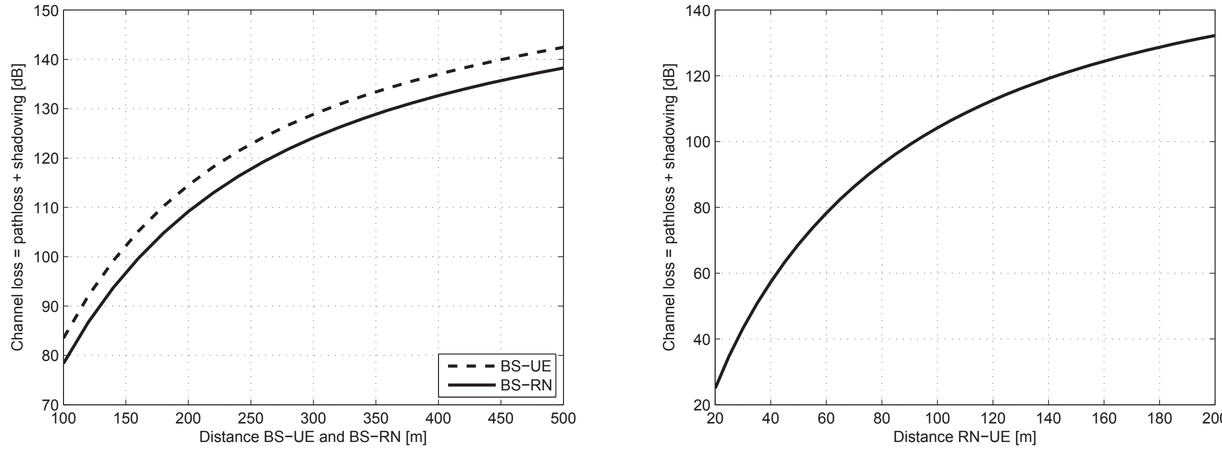

Figure 1: Channel losses as functions of source-destination distance - Left: BS-UE (dashed line) and BS-RN (solid line); Right: RN-UE. Distance is in meters. Channel loss model of [7].

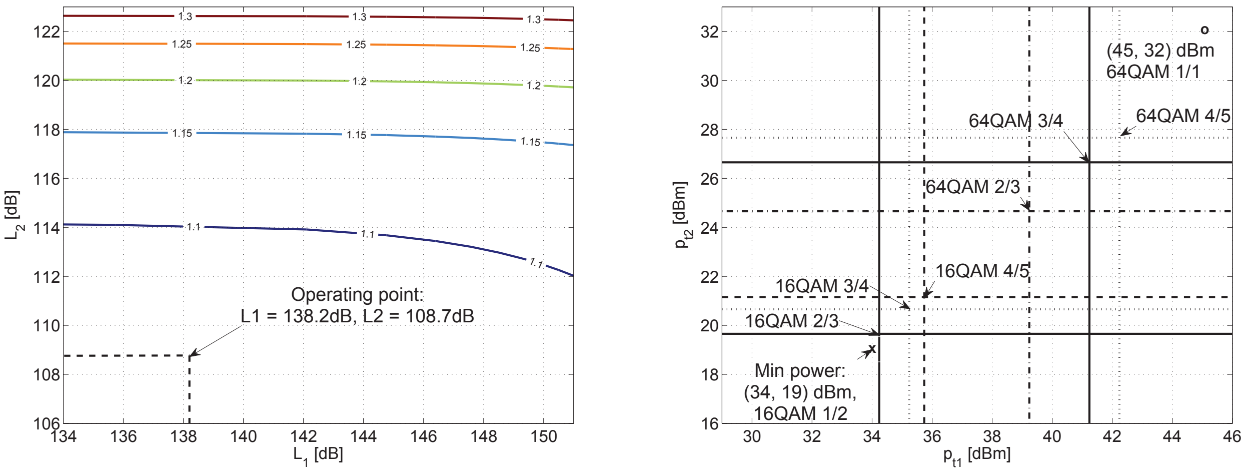

Figure 2: Left: Energy consumption ratio α-levels for $L = 142.4$ dB, and the operating point in $(L_1\,[dB], L_2\,[dB])$ space. Right: Equivalent corresponding space $(p_{t1}\,[dBm], p_{t2}\,[dBm])$, with required power levels for some constellation and code rate pairs. Minimum integer dBm transmit powers $(p_{t1}, p_{t2}) = (34, 19)\,dBm$ enable 16QAM 1/2 transmission along both hops, for $(L_1, L_2) = (138.2, 108.7)\,dB$ operating point.

The BS-RN link typically has smaller channel loss than the BS-UE link, over the same distance (Fig. 1, left), because the RN antenna hight is greater than the UE antenna height, which reduces the number and relative height of obstacles and scatterers. In addition, the antenna gain at RN is higher than at the UE. These two terms improve the BS-RN link w.r.t. the BS-UE link, often sufficiently to enable increased data rate, by appropriate change in the constellation size and code rate. We assume the same BS-UE and BS-RN distances of 500m, so that $L = 142.4$ dB and $L_1 = 138.2$ dB (Fig. 1, left).

It is required that the data rate over the RN-UE link matches the BS-RN link. In our example, the RN-UE channel loss corresponds to the distance of 110m (Fig. 1, right), $L_2 = 108.7$ dB.

To see whether this is possible, we apply the analysis from [4]. We assume $P_{th} = -85$ dBm at both RN and UE, $v_S = 0.9$, and $v_R = 1$. Figure 2, left frame, shows various α-levels in $(L_1\,[dB], L_2\,[dB])$ for $L = 142.4$ dB. The shown α-levels range from 1.1 to 1.3 in 0.05 increments, from bottom to top. The values along x- and y-axis are limited by $L_{1,min}$ and $L_{1,max}$, and $L_{2,min}$ and $L_{2,max}$, respectively (5). The operating point is defined by the values of L, L_1 and L_2 given above.

Fig. 2 right frame, shows an equivalent space $(p_{t1}\,[dBm], p_{t2}\,[dBm])$ to the $(L_1\,[dB], L_2\,[dB])$ space in the left frame (c.f. (1) and (5)). The marked straight lines show the required power levels for constellation and coding rate pairs at 10MHz bandwidth [8] (note: $P_{th} = -85$dBm corresponds to the operating point in the left frame and $(p_{t1}, p_{t2}) = (33.2, 18.7)\,dBm$ in the right frame). The integer transmit powers $p_t = 43dBm$, and $(p_{t1}, p_{t2}) = (34, 19)\,dBm$ enable 16QAM 1/2 transmission along the direct link and both relay hops as $p_r, p_{r1}, p_{r2} \geq P_{th}$.

Let r and r_R denote the data rate achievable over the direct link and relay hops, respectively, such that both relay hops

Table 3: Data rates for various costellations and code rates in LTE downlink, 10MHz bandwidth, approximation from [8]

Constellation and code rate	16QAM 1/2	16QAM 3/4	64QAM 3/4	64QAM 1/1
p_t increment [dB]		3	5.5	2
r_R [Mbps]	14.4	21.6	32.4	43.2
$r_R/\max r$	0.67	1	1.5	2

have the same rate. Let the maximum data rate ratio be

$$\beta = \frac{\max\limits_{p_{t1},p_{t2}} r_R}{\max\limits_{p_t} r}.$$

To determine β, we maximize data rates along relay hops and the direct link. Table 3 gives an example of constellations and code rates, required transmit power increments to switch constellation and code rate, and corresponding downlink data rates, inter-/extrapolated from [8]. From p_t increment row, it follows that setting $\left(p_{t1}^*, p_{t2}^*\right) = (45, 32)\, dBm$ enables 64QAM 1/1 [8], whereas setting $p_t^* = p_{t,max} = 46 dBm$ enables 16QAM 3/4. Finally, $\beta = r_R\,(64QAM\,1/1)\,/\,r\,(16QAM\,3/4) = 2$.

The energy efficiency ratio between the two-hop regenerative transmission and the direct link is

$$\eta = \frac{\beta\left(p_t^*, p_{t1}^*, p_{t2}^*\right)}{\alpha\left(p_t^*, p_{t1}^*, p_{t2}^*\right)} = \frac{r_R\left(p_{t1}^*, p_{t2}^*\right)}{r\left(p_t^*\right)} \cdot \frac{\left(E_{TX}\left(p_t^*\right) + E_{RX}\right)}{\left(E_{TX,1}\left(p_{t1}^*\right) + E_{RX,1}\right) + \left(E_{TX,2}\left(p_{t2}^*\right) + E_{RX,2}\right)},$$

where α is evaluated for the same $\left(p_t^*, p_{t1}^*, p_{t2}^*\right)$ which maximize r and r_R. This yields $\eta \geq \frac{2}{1.12} = 1.79$.

4. Conclusion

This work has developed a model for EE ratio of the two-hop regenerative relay and direct link, applied to LTE-A with Type 1a RN. The EE model is obtained by overlaping the state of channel losses with the state of transmit powers, which are linked by the link budget equation. The former provides information about energy consumption ratio depending on the channel losses of each link. The latter provides regions in which transmit powers at the BS and RN enable certain constellation size and coding rate pair. The provided simplified example is based on realistic parameters of LTE-compliant equipment, and a channel loss model evaluated specifically for regenerative relay transmissions. The EE ratio increase by a low single-digit multiplying factor is achievable. The key is to increase the transmit power over both hops to increase data rate, by selecting appropriate constellation and code rate. This is facilitated by reduced channel losses of relay hops w.r.t. the direct link, due to: increased RN antenna height and gain w.r.t. UE; small RN-UE distance w.r.t. BS-UE distance.

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