Energy Analysis in Cooperative Machine-Type Communications with Reconfigurable RF Transceivers

Edson Leonardo dos Santos, André Augusto Mariano, Glauber Brante and Richard Demo Souza

***Abstract*— In this paper, we consider reconfigurable RF transceivers in cooperative communications towards improving the energy efficiency. More specifically, we combine different operating modes of the power amplifier (PA) and the low noise amplifier (LNA). Our results show that the proper optimization of these modes combined with cooperative relaying may be considerably more energy efficient than non-cooperative schemes with multiple antennas over moderate and long distances. Results also show that most reconfigurability depends on the relay node, since it only acts when necessary.**

***Keywords*— Energy efficiency, cooperative communications, reconfigurable RF transceivers.**

I. Introduction

The fifth-generation (5G) technologies allow the development of new solutions for wireless communications, enabling the transformation of industry and society. With connectivity at the center of this technological revolution, 5G communication systems have a significant role to play [1]. As a result, 5G use cases can grow significantly in several key sectors, thereby unleashing the potential of Industry 4.0 and the Internet of Things (IoT) [2].

Also known as massive IoT, the massive machine-type communication (mMTC) is one of the most important use cases of 5G communication systems. In particular, mMTC networks are designed to provide wide area coverage and the minimum requirement for connection density is 1 million devices per km^2 [3]. Therefore, devices with low cost/complexity solutions are essential to make a business economically feasible. Moreover, wireless nodes will mostly be battery powered and the cost of replacing batteries in the field is often not viable. Thus, a node is expected to be capable of long-term operations (energy-efficient) without constant battery replacement.

With limited power sources, the energy efficiency has become one of the most widely adopted design metric for mMTC networks. Thus, many research efforts are aimed at improving the energy efficiency, such as power-saving mechanism with sleep mode [4], [5], radio resource management [6]–[8], transmission schemes with random access [9]–[11], and cooperative device-to-device communication [12]–[14]. However, these works do not address reconfigurable RF transceivers, which contributes to saving energy and extending battery lifetime.

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In this paper, unlike the works available in the literature, we analyze the energy efficiency in cooperative relaying with reconfigurable RF transceivers. In addition, non-cooperative schemes with multiple antennas are also considered for comparison. Our goal is to maximize the energy efficiency by jointly selecting the best operating modes of the reconfigurable circuits. In particular, we consider the following circuits with reconfigurable operating modes: the power amplifier (PA) at the transmitter (TX) and the low noise amplifier (LNA) at the receiver (RX), which are responsible for the RF signal amplification and the most power-hungry blocks in transceivers. Besides, we consider that the other circuits in the RF chain have a single operating point with fixed power consumption. Results show that significant energy savings can be achieved by performing a joint reconfiguration of the multimode RF amplifiers at source (S), relay (R) and destination (D). In addition, as the relay node operates only if necessary, most of the reconfigurability charge ends up at the relay, whereas the PA and LNA operating modes tend to be reasonably fixed at the source and destination nodes. Results also show that the relay position between the source and destination nodes contributes differently to improve the energy efficiency. Furthermore, it is worth noting that this paper is an extension of our work presented in [15], which addresses reconfigurable RF transceivers for non-cooperative multiple antenna nodes.

II. System Model

In this work, we consider either a three-node cooperative scenario with single antenna, and a non-cooperative scenario with multiple antenna nodes. Thus, in a general form the transmission from a node $i \in \{\mathrm{S}, \mathrm{R}\}$ to a node $j \in \{\mathrm{R}, \mathrm{D}\}$ can be represented by

$$\mathbf{y}_{ij} = \sqrt{\kappa_{ij}\, P_{i,\mathrm{mode}}}\, \mathbf{h}_{ij}\, \mathbf{x} + \mathbf{w}_{ij}, \tag{1}$$

where $P_{i,\mathrm{mode}}$ is the transmission power used by node i, which depends on the operating mode of the PA, $\mathbf{h}_{ij}$ represents the channel fading vector, modeled following a quasi-static Rayleigh fading, $\mathbf{x}$ is the source message and $\mathbf{w}_{ij}$ is the additive white Gaussian noise (AWGN) vector, with variance $N_0/2$ per dimension, where N_0 is the unilateral thermal noise power spectral density. In addition, κ_{ij} is the link budget relationship, which is assumed to be [16]

$$\kappa_{ij} = \frac{G_\mathrm{A}\, \lambda^2}{(4\pi)^2\, d_{ij}^{\alpha}\, M_\mathrm{L}\, F_{j,\mathrm{mode}}}, \tag{2}$$

where G_A is the total antenna gains, $\lambda = \frac{3.10^8}{f_\mathrm{c}}$ is the wavelength, f_c is the carrier frequency, d_{ij} is the communication distance, α is the path loss exponent, M_L is the link margin and $F_{j,\mathrm{mode}}$ is the noise factor at the node j. According to the Friis formula [17], the total noise factor at the receiver depends mainly on the first RF block. Hence, the receiver noise factor can be well approximated by the noise factor of the LNA, *i.e.*, $F_{j,\mathrm{mode}} \approx F_{\mathrm{LNA,mode}}$.

Furthermore, the instantaneous signal-to-noise ratio (SNR) in the i-j link is defined as

$$\gamma_{ij} = |\mathbf{h}_{ij}|^2 \cdot \bar{\gamma}_{ij}, \tag{3}$$

where $\bar{\gamma}_{ij} = \frac{\kappa_{ij} P_{i,\mathrm{mode}}}{N_0 B}$ is the average received SNR and B is the system bandwidth. Notice that the operating modes of the PA and the LNA impact the average SNR at the receiver. Therefore, the joint adaptation of these modes impacts the energy efficiency of the communication system.

In this work, we employ state-of-the-art multimode RF amplifiers, using real data from the PA proposed by [18] and the LNA in [19]. The main characteristics of these reconfigurable circuits are shown in Table I, following [15]. Let us remark that the PA admits 7 operating modes, whereas the LNA features 3 operating modes. On the one hand, the PA is responsible for amplifying the signal to be emitted by the antenna. We can notice that the reconfigurable PA allows to reach greater communication distances as the transmission power increases, at the cost of an increased energy consumption. On the other hand, the LNA is responsible for amplifying the signal received by the antenna with minimal distortion. The receiver sensitivity impacts the link budget relationship in (2) and, therefore, properly adjusting the noise figure through the reconfigurable LNA may help the PA to operate in a lower energy consumption mode.

TABLE I: Characteristics of the reconfigurable PA and LNA circuits for each operating mode at 2.4 GHz.

PA Operating Mode	Transmission Power ($P_{i,\mathrm{mode}}$) [dBm]	Power Consumption ($P_{\mathrm{PA},i,\mathrm{mode}}$) [mW]
1	9.6	153
2	13.6	214
3	14.5	236
4	14.7	245
5	16.5	297
6	17.2	324
7	18.4	394
LNA Operating Mode	Noise Figure[1] ($\mathrm{NF}_{\mathrm{LNA,mode}}$) [dB]	Power Consumption ($P_{\mathrm{LNA},j,\mathrm{mode}}$) [mW]
1	7.3	0.3
2	6.7	0.6
3	6.3	0.9

III. Transmission Schemes

In this section, we present two performance metrics considering different transmission schemes, the energy efficiency and the outage probability. In a cooperative transmission as illustrated in Fig. 1(a), one or two time slots can be used for the communication process. In the first time slot, the source

[1]Let us remark that the noise factor (F) is linear and the noise figure (NF) is expressed in decibels (dB).

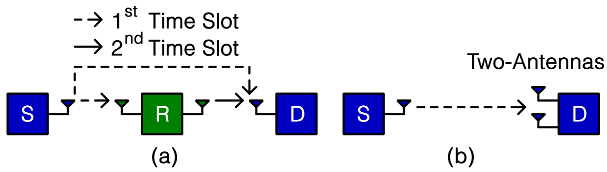

Fig. 1: Wireless transmission schemes: (a) cooperative relaying; (b) multiple receive antennas.

broadcasts its message, which is received by the destination and overheard by the relay node. If the destination fails to decode the message from the source in the broadcast phase, then it replies with a NACK signal asking for a retransmission from the relay. Then, in the second time slot, the relay retransmits the message from the source, only if it has been successfully decoded in the broadcast phase. Finally, the destination combines the signals received from the source and relay nodes using a maximal ratio combining scheme [16].

Moreover, for comparison purposes, we take into account non-cooperative multiple antenna schemes with the same diversity order as the cooperative scheme, as shown in Fig. 1(b). Therefore, throughout this work we consider only a single relay or two receiving antennas. Nevertheless, the analysis can be easily extended to higher diversity orders.

A. Incremental Decode and Forward (IDF) Relaying

We consider that the relay operates under the IDF protocol [20], exploiting a feedback channel from the destination so that the relay retransmits only if required by the destination, which saves energy. As aforementioned, two time slots are considered: broadcast and retransmission. However, the second time slot will be necessary only if the destination is not able to correctly decode data from the source. Thus, the power consumption in the broadcast phase is $P_\mathrm{broad} = P_{\mathrm{PA,S,mode}} + P_{\mathrm{TX,S}} + P_{\mathrm{LNA,R,mode}} + P_{\mathrm{RX,R}} + P_{\mathrm{LNA,D,mode}} + P_{\mathrm{RX,D}}$, whereas in the retransmission phase the power consumption is $P_\mathrm{retr} = P_{\mathrm{PA,R,mode}} + P_{\mathrm{TX,R}} + P_{\mathrm{LNA,D,mode}} + P_{\mathrm{RX,D}}$, then the overall cooperative power consumption is $P_\mathrm{coop} = P_\mathrm{broad} + P_\mathrm{retr}$. Note that $P_{\mathrm{PA},i,\mathrm{mode}}$ and $P_{\mathrm{LNA},j,\mathrm{mode}}$ are the energy consumed by the reconfigurable PA and LNA circuits, according to the Table I; whereas $P_{\mathrm{TX},i}$ and $P_{\mathrm{RX},j}$ represent the power consumption of the other non-reconfigurable RF circuits with fixed operating points in the transmitter and receiver chain, respectively.

Next, the energy efficiency in terms of bits/J/Hz is [21]

$$\begin{aligned}\eta_\mathrm{E}^{(\mathrm{IDF})} = \xi \cdot \frac{\left(1 - \mathcal{O}_\mathrm{SD}^{(\mathrm{IDF})}\right)}{P_\mathrm{broad}} \\ + \frac{\xi}{2} \cdot \frac{\left(1 - \mathcal{O}_\mathrm{SR}^{(\mathrm{IDF})}\right)\left(\mathcal{O}_\mathrm{SD}^{(\mathrm{IDF})} - \mathcal{O}_\mathrm{SRD}^{(\mathrm{IDF})}\right)}{P_\mathrm{coop}},\end{aligned} \tag{4}$$

where the destination receives ξ bps/Hz if the source transmission is successful or receives $\xi/2$ bps/Hz if retransmission from the relay is successful. It is important to note that instantaneous energy efficiency will be considered zero if the source packet cannot be received correctly at the destination during the broadcast or retransmission time slots, thus this packet is discarded. Furthermore, an outage event occurs when the SNR at the node j falls below a threshold of $2^{\xi} - 1$, so that the outage probability expressions are given by [21]

$$\mathcal{O}_{ij}^{(\mathrm{IDF})} = 1 - \exp\left(-\frac{2^{\xi}-1}{\bar{\gamma}_{ij}}\right), \quad (5)$$

$$\mathcal{O}_{\mathrm{SRD}}^{(\mathrm{IDF})} = \frac{\bar{\gamma}_{\mathrm{RD}}\mathcal{O}_{\mathrm{RD}}^{(\mathrm{IDF})} - \bar{\gamma}_{\mathrm{SD}}\mathcal{O}_{\mathrm{SD}}^{(\mathrm{IDF})}}{\bar{\gamma}_{\mathrm{RD}} - \bar{\gamma}_{\mathrm{SD}}}, \quad (6)$$

where (6) assumes that $\bar{\gamma}_{\mathrm{RD}} \neq \bar{\gamma}_{\mathrm{SD}}$.

B. Benchmark Schemes

In this work, we compare cooperative relaying with non-cooperative schemes with two antennas at the receiver, denoted by ($n_{\mathrm{D}} = 2$), which is the same diversity order as the cooperative scheme with a single relay. In the following, we present two diversity combining techniques: 1) selection combining (SC) and 2) maximal ratio combining (MRC).

1) Selection Combining (SC): At the receiver, SC selects only one antenna in each transmission to remain active, which reduces the energy consumption. The antenna at the destination is selected based on the highest received SNR. Then, the total power consumption is $P_{\mathrm{total}}^{(\mathrm{SC})} = P_{\mathrm{PA,S,mode}} + P_{\mathrm{TX,S}} + P_{\mathrm{LNA,D,mode}} + P_{\mathrm{RX,D}}$ and the energy efficiency is

$$\eta_{\mathrm{E}}^{(\mathrm{SC})} = \xi \cdot \frac{\left(1 - \mathcal{O}_{\mathrm{SD}}^{(\mathrm{SC})}\right)}{P_{\mathrm{total}}^{(\mathrm{SC})}}, \quad (7)$$

where the corresponding outage probability follows [21]

$$\mathcal{O}_{\mathrm{SD}}^{(\mathrm{SC})} = \left[1 - \exp\left(-\frac{2^{\xi}-1}{\bar{\gamma}_{\mathrm{SD}}}\right)\right]^{n_{\mathrm{D}}}. \quad (8)$$

2) Maximal Ratio Combining (MRC): In the case of MRC, the signals received at each antenna are weighted and combined at the receiver, so as to yield a higher instantaneous SNR. Since the MRC technique exploits all the receiving antennas, a higher energy consumption is observed at the circuit level. Therefore, the total power consumption of MRC is $P_{\mathrm{total}}^{(\mathrm{MRC})} = P_{\mathrm{PA,S,mode}} + P_{\mathrm{TX,S}} + n_{\mathrm{D}}\left(P_{\mathrm{LNA,D,mode}} + P_{\mathrm{RX,D}}\right)$ and the energy efficiency is represented by

$$\eta_{\mathrm{E}}^{(\mathrm{MRC})} = \xi \cdot \frac{\left(1 - \mathcal{O}_{\mathrm{SD}}^{(\mathrm{MRC})}\right)}{P_{\mathrm{total}}^{(\mathrm{MRC})}}, \quad (9)$$

with the MRC outage probability given by [21]

$$\mathcal{O}_{\mathrm{SD}}^{(\mathrm{MRC})} = 1 - \exp\left(-\frac{2^{\xi}-1}{\bar{\gamma}_{\mathrm{SD}}}\right)\sum_{m=0}^{n_{\mathrm{D}}-1}\frac{1}{m!}\left(\frac{2^{\xi}-1}{\bar{\gamma}_{\mathrm{SD}}}\right)^{m}. \quad (10)$$

C. Optimization Problem

In order to maximize the energy efficiency in the considered transmission schemes, we aim at a joint selection of the best operating modes between the reconfigurable PA and LNA circuits. Let us remember that the PA controls the transmission power, whereas the LNA modifies the sensitivity of the receiver. Thus, our optimization problem becomes

$$\begin{aligned} \max_{P_{i,\mathrm{mode}}, F_{j,\mathrm{mode}}} \quad & \eta_{\mathrm{E}}^{(\mathrm{sch})}, \mathrm{sch} \in \{\mathrm{IDF}, \mathrm{SC}, \mathrm{MRC}\}, \\ \text{s.t.} \quad & P_{i,\mathrm{mode}} \in \mathcal{S}_{\mathrm{PA}}, \\ & F_{j,\mathrm{mode}} \in \mathcal{S}_{\mathrm{LNA}}, \\ & \mathcal{O}^{(\mathrm{sch})} \leq \mathcal{O}^{\star}, \end{aligned} \quad (11)$$

where $\mathcal{S}_{\mathrm{PA}}$ is the set of transmission powers provided by the 7 operating modes of the PA, $\mathcal{S}_{\mathrm{LNA}}$ is the set of noise figures yielded by the 3 operating modes of the LNA, both according to the Table I, and $\mathcal{O}^{\star}$ represents a target outage probability at the receiver.

It is important to note that the complexity of the proposed solution is small, since the variables $P_{i,\mathrm{mode}}$ and $F_{j,\mathrm{mode}}$ belong to discrete sets. Therefore, a look-up table (LUT) can be easily implemented in practice, with the size of the LUT being $|\mathcal{S}_{\mathrm{PA}}| \times |\mathcal{S}_{\mathrm{LNA}}|$. Furthermore, we also assume that the adaptation of the PA and LNA operating modes is done during the transmission of pilot symbols prior to each frame.

IV. Numerical Results

This section demonstrates the energy analysis of our proposed optimization approach. Following the system parameters used in [15], we consider $B = 10$ kHz, $M_{\mathrm{L}} = 30$ dB, $f_{\mathrm{c}} = 2.4$ GHz, $G_{\mathrm{A}} = 5$ dBi, $\alpha = 2.5$, $\mathcal{O}^{\star} = 10^{-3}$, $N_0 = -174$ dBm/Hz and $\xi = 2$ bps/Hz. Moreover, 97.9 mW and 92.2 mW are the power consumption of non-reconfigurable RF circuits in the transmitter and receiver chain, respectively.

Fig. 2 shows the energy efficiency comparison for cooperative relaying and non-cooperative schemes with multiple antennas. From the figure, we can notice that the power consumption of RF circuits is more relevant for shorter distances, in which SC achieves the best performance, outperforming the other schemes in transmissions up to 100 meters, whereas the energy efficiency of MRC is very similar to that of IDF in this communication range. On the other hand, for long-range communications, the transmission power dominates the total power consumption, and cooperative relaying becomes more energy efficient than multiple antennas.

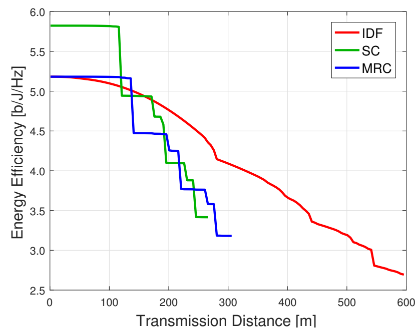

Fig. 2: Energy efficiency of IDF, SC and MRC transmission schemes, with the relay positioned at $d_{\mathrm{SR}} = 0.5\, d_{\mathrm{SD}}$, where it maximizes the energy efficiency of IDF.

Fig. 3 depicts how the reconfigurable PA and LNA circuits operate on multiple antenna transmissions. On the left side of the figure, the total power consumption is represented by the black dashed lines. On the right side of the figure, the operating modes of the PA and LNA circuits are represented by the colored bars. Let us note that the SC and MRC schemes have a similar operation. That is, as the communication distance increases, first the LNA changes its operating mode improving the noise figure to adjust the receiver sensitivity; however, in a certain distance the PA increases the transmission power, so that the link continues active and, consequently, the LNA decreases to a lower consumption mode. We also note that the consumption of MRC is higher than the SC, since this scheme uses all available antennas at the receiver.

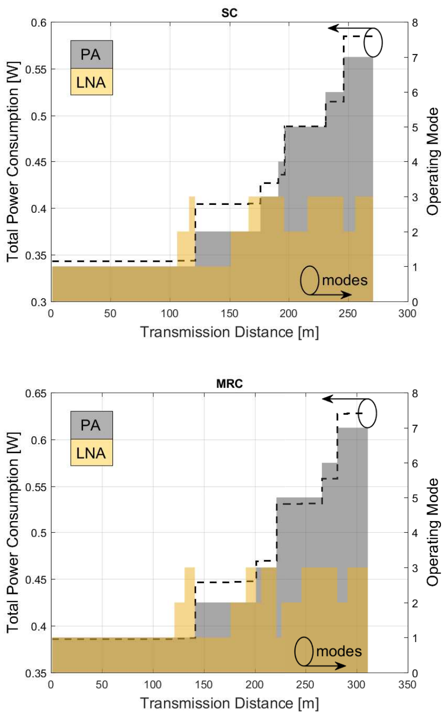

Fig. 3: Total power consumption and best operating mode for the PA and LNA circuits, of SC and MRC schemes.

In Figs. 4-6, we show how the reconfigurable PA and LNA circuits operate for the cooperative relaying scheme, with the relay positioned at different distances between the source and the destination, that is, $d_{\mathrm{SR}} = 0.2\, d_{\mathrm{SD}}$, $d_{\mathrm{SR}} = 0.5\, d_{\mathrm{SD}}$ and $d_{\mathrm{SR}} = 0.8\, d_{\mathrm{SD}}$, respectively. Moreover, note that the figure on the left represents the S-D link, the one in the middle is the S-R link, while the one in the right is the R-D link. First, analyzing the broadcast phase, it is worth noting that at a specific distance the PA transmits the same amount of power to the destination and relay nodes, then the PA switches to a higher transmission power mode only when the distance increases. Besides that, only during transmission between the S-R nodes, we notice that the LNA presents different results in switching operating modes, which is justified with the relay located at different distances.

Furthermore, analyzing the retransmission phase, we observe that an efficient adaptation protocol is required. This can be achieved during the handshake phase in order to obtain the channel estimates and reconfigure the TX and RX circuits as needed. Moreover, since the relay operates only if necessary, results show that the relay is responsible for most of the reconfigurability, then the LNA and PA circuits tend to switch their operating modes more frequently. As we can see in Fig. 4, the relay being closer to the source presents a more significant interaction, which in this case means that the relay cooperates more in the retransmission. Whereas Fig. 6 shows the relay close to the destination, that is, we can observe low activity in the PA and LNA operation modes. Finally, another important observation is that there is an optimal position for the relay node, in our examples a greater communication distance together with the energy efficiency is maximized with the relay positioned in the middle between the source and destination nodes, as shown in Fig. 5.

V. Conclusion

In this paper, we have considered a joint reconfiguration of multimode RF amplifiers in order to improve the energy efficiency in a cooperative scenario. In our framework, reconfigurable PA and LNA circuits were considered at the transmitter and receiver chain, respectively. Comparing different transmission schemes, we concluded that cooperative relaying with single antenna nodes is more energy efficient than non-cooperative schemes with multiple antennas only in distances over 180 meters, whereas the SC scheme is the most efficient option for short-range transmissions. Our results pointed out that most of the reconfigurability ends up being at the relay, since it only acts if necessary in the considered IDF protocol, whereas the switching of the PA and LNA operating modes tends to be more stable at the source and destination nodes.

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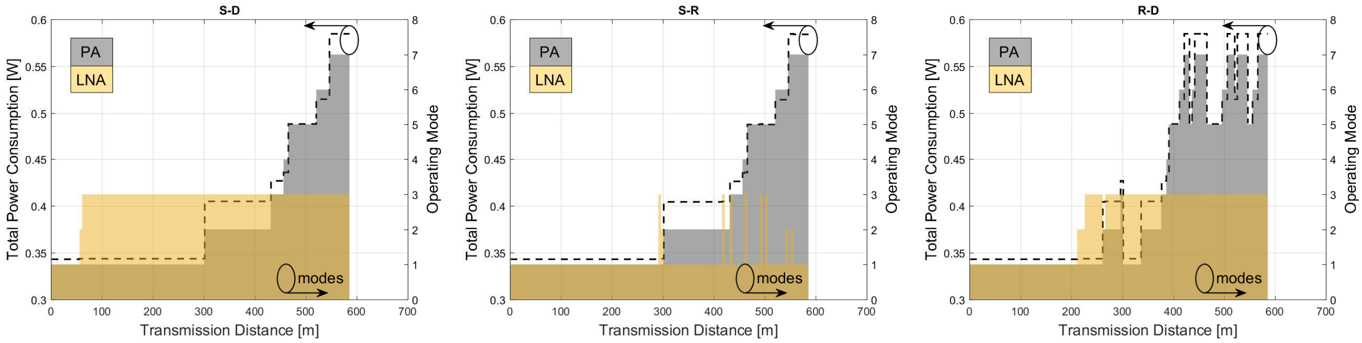

Fig. 4: Total power consumption in each point-to-point transmission and best operating mode for the PA and LNA circuits, with the relay positioned at $d_{\mathrm{SR}} = 0.2\, d_{\mathrm{SD}}$.

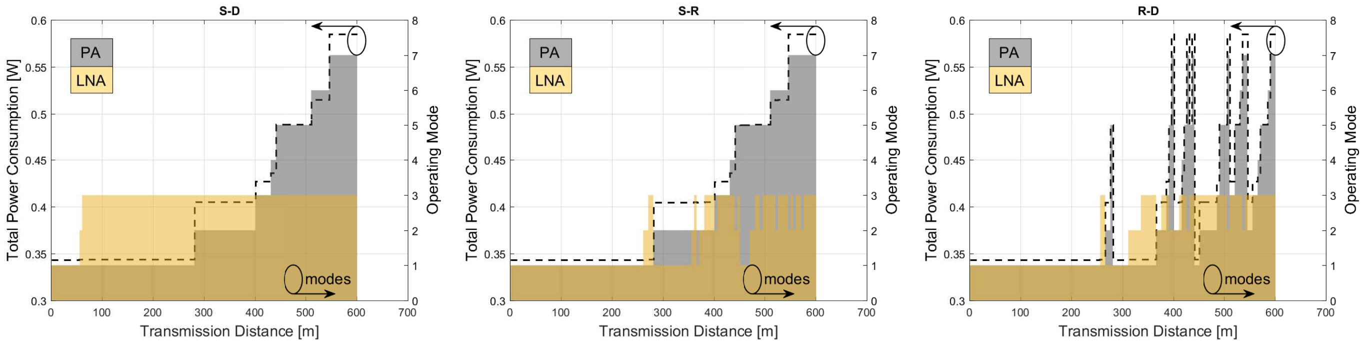

Fig. 5: Total power consumption in each point-to-point transmission and best operating mode for the PA and LNA circuits, with the relay positioned at $d_{\mathrm{SR}} = 0.5\, d_{\mathrm{SD}}$.

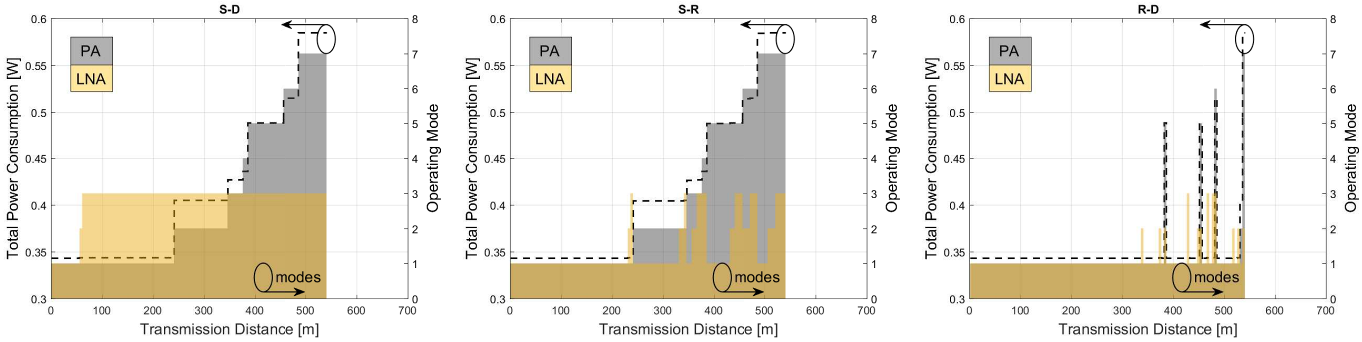

Fig. 6: Total power consumption in each point-to-point transmission and best operating mode for the PA and LNA circuits, with the relay positioned at $d_{\mathrm{SR}} = 0.8\, d_{\mathrm{SD}}$.

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