Energy-Efficiency of Selective Relaying in a MIMO Network-Coded Cooperative System

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This work was partially supported by the National Council for Scientific and Technological Development (CNPq), under Grants 305052/2017-9 and 405115/2016-4, and by the Coordination of Superior Level Staff Improvement (CAPES), Brazil.

ABSTRACT We evaluate the outage probability and the energy efficiency (EE) of a network composed of multiple sources, multiple relays and a single common destination, all of them provided with multiple antennas. More specifically, we resort to the network-coded cooperative (NCC) technique with multiple relay selection (MRS) and compare the EE of the network when operating under two combining techniques at the receiver, namely selection combining (SC) and maximum ratio combining (MRC). Our analysis, which adopts a realistic energy consumption model that encompasses the circuitry consumption, shows that MRC, which is optimal from the reliability perspective, may be outperformed by SC in terms of EE. Moreover, we also provide some insights about the number of relays that must be selected to maximize the EE. Finally, numerical results are presented and confirm the mathematical analysis.

INDEX TERMS Cooperative communications, energy efficiency, mimo, network coding.

I. INTRODUCTION

With the advent of the Internet-of-Things (IoT), there has been an increasing interest in Wireless Sensor Networks (WSNs) [1]. In these networks, a set of spatially distributed end-devices (EDs) are usually responsible for gathering some information and transmitting to a common sink. However, such EDs have typically limited power supply, compromising their communication range [2].

Multiple-Input Multiple-Output (MIMO) is a well established multi-antenna technique capable of achieving spatial diversity and consequently combat the harmful effects of fading, which is inherent to the wireless channel [3]. In devices with size and/or cost restrictions, the effect of multiple antennas can be emulated or even boosted through the concept of cooperative communications [4], where the nodes take advantage of the broadcast nature of the wireless channel and help each other by relaying the messages from their partners. In a cooperative network, spatial diversity is then achieved in a distributed way across the network [5].

More recently, it was shown that network coding, a technique initially proposed to increase throughput [6], is also capable of boosting the reliability of cooperative networks [7]–[11]. In a network-coded cooperative (NCC) scenario, instead of just relaying individual frames, the nodes can transmit linear combinations of more than one frame, which are potentially performed over a non-binary finite field GF\( (q) \), where \( q \) is the field size. A NCC scheme is proposed in [7], where the sources themselves act as relays, showing that diversity order is increased over traditional cooperation not based on network coding, such as [4], [5], and that non-binary NCC may be more advantageous than binary field-based (XOR) NCC.

Since cooperation usually relies on multiple orthogonal channels, relay selection protocols have been proposed to improve spectral efficiency [12], [13], being recently considered also in the scope of internet-of-things (IoT) [14], [15] and 5G [16], [17]. From a reliability perspective, it is shown in [8] that multiple relay selection (MRS) improves the diversity order of a NCC network. The authors in [9], [10] then extend the results from [8] by considering that the relays and the destination have multiple antennas. When the transmitters and receivers operate, respectively,
under the transmit antenna selection (TAS) and maximum ratio combining (MRC) protocols, reliability can be improved even further by combining the benefits from MRS and MIMO [9], [10]. However, the schemes in [9], [10] assume that the destination possesses global channel state information (CSI) of the entire network, including the channels between sources and relays, which might be very hard to obtain in practice. Later, the authors extend in [11] the results from [9], [10], but now without the assumption of global CSI. Their results indicate that a similar performance can be obtained, regardless the global CSI assumption or not.

Nevertheless, in many situations reliability is not the only performance metric of interest. In some scenarios, such as wireless sensor networks (WSNs), the nodes are powered by batteries. Thus, it is always desirable to prolong their lifetime as long as possible. Usually, for improving the energy-efficiency (EE) of a communication scheme, the focus is to minimize the transmit power, which is valid when the energy consumed by the circuitry is of little relevance in the total consumption. However, in short-range communications, the circuitry energy consumption becomes relevant [2], [18].

Recently, several works analyzed the EE improvement provided by NCC schemes, as is the case of [19], where the EE of the NCC method from [7] is evaluated, showing that there is an optimal number of cooperative nodes that maximizes the EE.

In this work, we evaluate the EE of the NCC scheme with MRS from [11], when operating not only under the MRC technique at the receivers as in [11], but also with the less complex SC technique. This is aligned with low-complexity hardware networks where the devices are provided with just one radio frequency (RF) chain such as IEEE 802.15.4 based networks [20]. Moreover, we also adopt a realistic power model to evaluate the network consumption, which encompasses the circuitry consumption of all the transmitting/receiving nodes of the network [2], [18]. Our main contributions can be summarized as follows:

- We obtain the outage probability of the NCC scheme from [11] when operating under the SC technique at the receiver side, and considering that the source nodes are also provided with multiple antennas;
- We show that it may be more advantageous from an EE perspective to adopt the SC scheme at the receiver rather than MRC, although the latter is known to be the optimal solution in terms of reliability;
- We provide some insights on how the EE varies with the number of selected relays and the number of antennas per node.

The rest of this paper is as follows. Section II presents the system model along with some preliminaries. The outage probability and the EE of the proposed NCC scheme with MRS when operating under both TAS/MRC and TAS/SC are evaluated respectively in Section III and Section IV. Numerical results are presented in Section V, while Section VI concludes the paper.

**Notation:** The symbols and acronyms adopted in this work are summarized in Table 1 and Table 2, respectively.

### II. SYSTEM MODEL

We consider the multiple access part of a network composed of $N_s$ sources (denoted by $S_n$, with $n \in \{1, \ldots, N_s\}$), $M_r$ relays (denoted by $R_m$, with $m \in \{1, \ldots, M_r\}$) and a common destination ($D$), as illustrated in Fig. 1. All nodes are assumed to be equipped with multiple antennas, being $n_s \geq 1$, $n_r \geq 1$ and $n_D \geq 1$ the number of antennas at sources, relays and the destination respectively.

![System model](image)

Thus, omitting the time index and considering for the moment an individual link $A \rightarrow B$ being $A \in \{S_n, R_m\}$ and $B \in \{R_m, D\}$ with $A \neq B$, we can write the point-to-point signal transmitted by the $i$-th antenna of a node $A$ and received by the $j$-th antenna of $B$ as

$$y_{B,j}^{i} = \sqrt{\kappa P_t} h_{B,j}^A x_A + n_{B,j},$$

where $P_t$ is the transmit power of the selected antenna, $x_A$ the transmitted signal, $n_{B,j} \sim \mathcal{CN}(0, N_0)$ the zero mean additive white Gaussian noise and $h_{B,j}^A \sim \mathcal{CN}(0, 1)$ the fading coefficient, whose envelop follows a Rayleigh distribution, being independent and identically distributed in time and space. Moreover,

$$\kappa = \frac{G_t G_r \lambda^2}{M_r N_f d^4 (4\pi)^2},$$

is the path-loss [3], where $G_t$ and $G_r$ are the transmit and receive antenna gains, respectively, $M_t$ the link margin, $N_f$ the receiver noise figure, $d$ is the distance between transmitter and receiver, $\alpha$ the path-loss exponent and $\lambda$ the carrier wavelength. Finally, $x_A$ is assumed to have unity average energy. Thus, the instantaneous signal-to-noise ratio (SNR) is then defined as $\gamma_{B,j} = \frac{y^2}{\| n_{B,j} \|^2}$, being $\gamma = \kappa P_t / (B N_0)$ the average SNR, where $B$ is the bandwidth (in Hz). In order to gain analytical tractability, we assume that all links in the...
TABLE 1. Nomenclature adopted in this work.

| Symbol | Description                  |
|--------|------------------------------|
| $N_s$  | Number of source nodes       |
| $S_n$  | n-th source                  |
| $D$    | Common Destination           |
| $n_r$  | Number of antennas at relay nodes |
| $\kappa$ | Path-loss                   |
| $h$    | Fading coefficient           |
| $x$    | Transmitted signal           |
| $G_t$  | Transmit antennas gain       |
| $M_l$  | Link margin                  |
| $d$    | Distance                     |
| $\lambda$ | The carrier wavelength     |
| $N_0$  | Noise power spectral density |
| $\tau$ | Average SNR                  |
| $l_{eff}$ | Effective number of relays  |
| $l$    | Number of relays in set $\mathcal{R}_l$ |
| $O$    | Outage probability           |
| $\mathcal{R}_0$ | Attempt transmission rate   |
| $\binom{\tau}{l}$ | Binomial coefficient        |
| $R_b$  | Transmission rate            |
| $P_{tx}$ | Power of transmitter         |
| $P_{ctx}$ | Transmitter circuitry consumption |
| $P_{mix}$ | Mixer consumption            |
| $P_{syn}$ | Frequency synthesizer consumption |
| $P_{LNA}$ | LNA consumption              |
| $P_{f_{ir}}$ | Active filter (RX) consumption |
| $\eta$ | RF power amplifier drain efficiency |
| $\mathcal{L}^*$ | $\mathcal{L}$ that minimizes $EE$ |

TABLE 2. Acronyms adopted in this work.

| Acronym | Description                  |
|---------|------------------------------|
| AWG     | Additive White Gaussian      |
| ADC     | Analog-to-Digital Converter  |
| LNA     | Low Noise Amplifier          |
| BP      | Broadcasting Phase           |
| GF      | Galois Field                 |
| SNR     | Signal-to-Noise Ratio        |
| DAC     | Digital-to-Analog Converter  |
| IFA     | Intermediate Frequency Amplifier |
| RP      | Relaying Phase               |
| MDS     | Maximum Distance Separable   |

Moreover, we also consider that the receivers are provided with channel state information (CSI), while the transmitters, following the low-complexity requirement of a WSN and despite the antenna index required by TAS, do not have any CSI. Thus, advanced transmission techniques such as beamforming [21] cannot be implemented.

III. MRS - TRANSMISSION PROTOCOL

Following [11], we consider that the communication process occurs in two phases, namely the broadcasting phase (BP) and the relaying phase (RP). In the BP, the $N_s$ sources broadcast their own messages (one per source) through orthogonal time slots and adopting their best antenna as from the destination perspective, following a TAS approach [3]. That is, the messages broadcasted by the sources are potentially decoded by the destination (we assume the existence of a direct link S-D) and the relays. Let us define $\mathcal{R}_l$ as the set of relays that correctly recovered all the $N_s$ messages broadcasted in the BP, with $|\mathcal{R}_l| = l$.

The maximum number of relays allowed to transmit in the RP is a design parameter of the system, which we represent by $L \leq M_r$. Depending on the instantaneous relay decoding set $\mathcal{R}_l$ and the pre-defined value of $\mathcal{L}$, two different outcomes are possible when performing MRS: If $l \geq \mathcal{L}$, then only the relays that experience the best $\mathcal{L}$ instantaneous SNR values in the links $R_m \rightarrow D$ are selected to transmit. Otherwise, when $l < \mathcal{L}$, all the $l$ relays from $\mathcal{R}_l$ transmit their messages to $D$ without any kind of selection. In short, the effective number

\[ l_\text{eff} = \min\{l, \mathcal{L}\} \]
of relays that transmit in the RP is a random variable given by \( l_{\text{eff}} = \min(l, \mathcal{L}) \).

The packet transmitted by each relay is a linear combination, performed over a finite field GF(\( q \)), of all the packets received during the BP. In practice, the coefficients of such combinations could be chosen, for example, from a generator matrix of a maximum distance separable (MDS) linear block code, in order to guarantee that the parities received by the destination are linearly independent and consequently achieve the maximum diversity order [7]. Thus, under the consideration that a proper network code is being adopted, in our analysis we just assume that all the packets received by the destination are linearly independent.

### A. OUTAGE PROBABILITY OF THE MRS PROTOCOL

Let \( \gamma_{B}^{A} \) represent the instantaneous SNR at the output of the combiner in receiver \( B \) considering a signal transmitted by \( A \). Depending on the combining scheme adopted in the receiver, and having in mind that transmission is performed under TAS, \( \gamma_{B}^{A} \) is obtained as [3]

\[
\gamma_{B}^{A} = \begin{cases} 
\max_{i \in [1,n_{A}]} \| h_{B,j}^{A} \|^2 & \text{TAS/SC} \\
\max_{i \in [1,n_{A}]} \sum_{j=1}^{n_{B}} |h_{B,j}^{A}|^2 & \text{TAS/MRC} 
\end{cases}
\]

where \( n_{A} \in \{ n_{s}, n_{r} \} \) for a source or a relay, respectively and \( n_{B} \in \{ n_{s}, n_{r} \} \) for a relay or the destination, respectively.

Regardless of the combining scheme at the receiver, \( D \) can potentially receive \( N_{s} + \mathcal{L} \) packets \((N_{s} \text{ during the BP and } \mathcal{L} \text{ in the RP)}\), among which it needs to correctly recover at least \( N_{s} \) packets. In other words, an outage occurs if less than \( N_{s} \) packets are not recovered at \( D \).

Let \( O_{S}^{D} \), \( O_{S}^{R} \) and \( O_{R}^{D} \) represent respectively the outage probabilities in \( S_{n} \to D \), \( D_{n} \to R_{m} \) and \( R_{m} \to D_{l} \) links, which, due to the average SNR assumption and for the sake of readability, the indexes \( m \) and \( m \) dropped. We also define as \( n_{\text{tot}} \) and \( l_{\text{eff}} \) the number of packets correctly decoded by \( D \) during the BP (sources transmitting) and RP (relays transmitting), respectively, such that \( n_{\text{tot}} \leq N_{s} \) and \( l_{\text{eff}} \leq l_{\text{eff}} \).

Having in mind that the destination is capable of recovering the packets from the sources upon correctly recovering at least \( N_{s} \) packets out of the overall amount of \( N_{s} + l_{\text{eff}} \) transmitted packets, an outage does not happen in the three cases listed below [11]:

**Case 1.** All the packets transmitted in BP are correctly decoded by \( D \), i.e., \( n_{\text{tot}} = N_{s} \);

**Case 2.** \( n_{\text{tot}} < N_{s} \) and \( l < \mathcal{L} \), but \( n_{\text{tot}} + l_{\text{eff}} \geq N_{s} \);

**Case 3.** \( n_{\text{tot}} < N_{s} \) and \( l \geq \mathcal{L} \), but \( n_{\text{tot}} + l_{\text{eff}} \geq N_{s} \).

The outage probability is then obtained from the complementary probability as

\[
O_{\text{sch}} = 1 - \left( \Pr \{ \text{Case 1} \} + \Pr \{ \text{Case 2} \} + \Pr \{ \text{Case 3} \} \right),
\]

where \( \text{sch} \in \{ \text{MRC, SC} \} \).

**Theorem 1:** The outage probabilities of the TAS-aided NCC-MRS scheme, when operating under both MRC and SC at the receiver side is given by (4) at the bottom of the next page (depending on whether \( N_{s} \leq \mathcal{L} \) or not).

The individual outage probabilities \( O_{S}^{D} \), \( O_{S}^{R} \) and \( O_{R}^{D} \) from (4) depend on the combination scheme adopted at the destination, which, for Rayleigh fading, are obtained as:

\[
O_{S}^{D} = \left\{ \begin{array}{ll}
(1 - e^{-\Lambda})^{n_{rd}} \approx \Lambda^{n_{rd}} & \text{TAS/SC} \\
\left[ 1 - \frac{\Gamma(A, n_{d})}{\Gamma(n_{d})} \right]^{n_{rd}} \approx \Lambda^{n_{rd}} & \text{TAS/MRC}
\end{array} \right.
\]

\[
O_{S}^{R} = \left\{ \begin{array}{ll}
(1 - e^{-\Lambda})^{n_{rd}} \approx \Lambda^{n_{rd}} & \text{TAS/SC} \\
\left[ 1 - \frac{\Gamma(A, n_{r})}{\Gamma(n_{r})} \right]^{n_{rd}} \approx \Lambda^{n_{rd}} & \text{TAS/MRC}
\end{array} \right.
\]

and

\[
O_{R}^{D} = \left\{ \begin{array}{ll}
(1 - e^{-\Lambda})^{n_{rd}} \approx \Lambda^{n_{rd}} & \text{TAS/SC} \\
\left[ 1 - \frac{\Gamma(A, n_{d})}{\Gamma(n_{d})} \right]^{n_{rd}} \approx \Lambda^{n_{rd}} & \text{TAS/MRC}
\end{array} \right.
\]

where the approximations hold in the high-SNR regime and \( \Gamma(A, n) = \Gamma(n) e^{-\Lambda} \sum_{k=0}^{n} \frac{\Lambda^{k}}{k!} \) is the upper incomplete gamma function for positive integer values of \( n \) [22, Eq. (8.352.4)], \( \Gamma(n) \) the complete gamma function, \( \Lambda \triangleq \left( 2^{2R_{0} - 1} / \gamma \right) \), being \( R_{0} \) the attempted transmission rate (in bits per channel use), and \( \binom{n}{m} \approx \frac{n^{m}}{m!} \) the binomial coefficient.

Proof: Please refer to Appendix A.

It is worthy mentioning that, as can be seen from (6), the relays do not experience TAS diversity since the best transmit antenna is chosen from the destination perspective.

In what follows we present an asymptotic approximation (for high-SNR regime) to (4), which is valid for \( n_{rd} > 1 \) and \( n_{s} = n_{r} \), (number of antennas at the sources is equal to the number of antennas at relays). Since all the outage probabilities presented in this work refer to a NCC-MRS scheme operating under TAS, we opt for omitting this information from the equation indices for the sake of readability.

**Corollary 1:** The outage probabilities of the TAS-aided NCC-MRS scheme when operating respectively at the MRC and SC schemes at the receiver side, in a scenario where \( n_{sd} > 1 \) and \( n_{sd} = n_{rd} \), can be approximated in the high-SNR regime as

\[
O_{\text{MRC}}^{\text{SC}} = \left\{ \begin{array}{ll}
\frac{N_{s}^{M_{r} + 1}}{(n!)^{M_{r}} (n_{rd}!)^{n}} \Lambda^{n(M_{r} + 1)} & N_{s} > \mathcal{L} \\
+ N_{s}^{M_{r} + 1} \Lambda^{n(M_{r} + 1)} & N_{s} \leq \mathcal{L}
\end{array} \right.
\]

and

\[
O_{\text{SC}}^{\text{MRC}} = \left\{ \begin{array}{ll}
\frac{N_{s}^{M_{r} + 1}}{(n!)^{M_{r}} (n_{rd}!)^{n}} \Lambda^{n(M_{r} + 1)} & N_{s} > \mathcal{L} \\
+ N_{s}^{M_{r} + 1} \Lambda^{n(M_{r} + 1)} & N_{s} \leq \mathcal{L}
\end{array} \right.
\]
Proof: The proof follows by approximating \( \gamma_{\text{SNR}}^D \approx \gamma_{\text{SNR}}^{\text{DAC}} \), which depends on the modulation technique \([2], [23]\). The term \( P_{\text{rx}} \) in \((10)\) depends on the number of RF chains simultaneously in use in the receivers, being \([18]\)

\[
P_{\text{rx}}(n_{\text{rx}}) = n_{\text{rx}}P_{\text{rx}} + P_{\text{syn}},
\]

where \( P_{\text{rx}} = P_{\text{DAC}} + P_{\text{mix}} + P_{\text{filt}} \) is the transmitter circuitry power, with \( P_{\text{DAC}}, P_{\text{mix}}, P_{\text{filt}} \) and \( P_{\text{syn}} \) being respectively the consumptions of the digital- to- analog converter (DAC), mixer, active filter and the frequency synthesizer, respectively. If the transmitters adopt a transmission rate (in bits/s) equal to \( R_b = 1/T_b \) (\( T_b \) is the bit period), the EE is formulated as \([2]\)

\[
EE = T_b (P_{\text{tx}} + P_{\text{rx}}) \quad \text{[Joules/bit]},
\]

where \( P_{\text{tx}} \) and \( P_{\text{rx}} \) represent the power consumed by the transmitter and receiver, respectively. In \((10)\), \( P_{\text{tx}} \) can be modelled as \([18]\)

\[
P_{\text{tx}} = P_{\text{PA}} + P_{\text{ctx}} + P_{\text{syn}},
\]

where \( P_{\text{tx}} = P_{\text{DAC}} + P_{\text{mix}} + P_{\text{filt}} \) is the transmitter circuitry power, with \( P_{\text{DAC}}, P_{\text{mix}}, P_{\text{filt}} \) and \( P_{\text{syn}} \) being respectively the consumptions of the digital- to- analog converter (DAC), mixer, active filter and the frequency synthesizer, while \( P_{\text{PA}} = (\xi/\eta)P_I \) is the amplifier power consumption, where \( \eta \) is the RF power amplifier drain efficiency and \( \xi \) is the peak-to-average ratio (PAR), which depends on the modulation technique \([2], [23]\). The term \( P_{\text{rx}} \) in \((10)\) depends on the number of RF chains simultaneously in use in the receivers, being \([18]\)

\[
P_{\text{rx}}(n_{\text{rx}}) = n_{\text{rx}}P_{\text{rx}} + P_{\text{syn}},
\]

where \( P_{\text{rx}} = P_{\text{DAC}} + P_{\text{mix}} + P_{\text{filt}} + P_{\text{ADC}} \) with \( P_{\text{DAC}}, P_{\text{mix}}, P_{\text{filt}} \) and \( P_{\text{ADC}} \) being the power of the low noise amplifier, intermediate frequency amplifier, active filter and analog-to- digital converter (ADC), respectively, and \( n_{\text{rx}} \in \{1, n_r, n_d\} \) is the number RF chains used at the receiver (equal to 1 when adopting SC).

Thus, one can estimate the overall EE of the network by accounting for the total number of transmissions and receptions performed by the protocol, and summing the individual consumption of each transmission/reception. In our cooperative scenario, there are \( n_s \) transmissions, \( n_r M_r \) receptions at the relays and \( n_s \) receptions at \( D \) during the BP. In the RP, there are \( l_{\text{eff}} \) transmissions and also \( l_{\text{eff}} \) receptions, since all the transmissions are uniquely addressed to the destination. This is summarized in Table 3.

However, due to the randomness of the relay decoding set \( \mathcal{R}_l \), the number of effective transmissions/receptions in the RP, \( l_{\text{eff}} = \min(l, L) \), is also a random variable. Moreover, when operating under the SC scheme, the receivers adopt only a single antenna (i.e., a single RF chain), while in the MRC mode the relays and the destination employ respectively all their \( n_r \) and \( n_d \) antennas to receive the \( N_s M_r \) and

\[
\mathcal{O} = \left\{ \sum_{n_{\text{sop}}=0}^{N_l-1} \binom{N_s}{n_{\text{sop}}} \left( 1 - \frac{\mathcal{O}_D^S}{\mathcal{O}_D^S - N_l} \right)^{n_{\text{sop}} - N_l} \sum_{l=0}^{N_l-1} \binom{M}{l} \left( \frac{1 - \mathcal{O}_D^R}{1 - \mathcal{O}_D^R/N_l} \right)^{l - M_r} \sum_{l_{\text{op}}=0}^{N_r} \binom{M_r}{l_{\text{op}}} \left( \frac{1 - \mathcal{O}_D^R}{1 - \mathcal{O}_D^R/N_r} \right)^{l_{\text{op}} - 1}, \right. \\
\left. \sum_{N_l > L}^{N_l} \sum_{n_{\text{sop}}=0}^{N_l-1} \binom{N_s}{n_{\text{sop}}} \left( 1 - \frac{\mathcal{O}_D^S}{\mathcal{O}_D^S - N_l} \right)^{n_{\text{sop}} - N_l} \sum_{l=0}^{N_l-1} \binom{M}{l} \left( \frac{1 - \mathcal{O}_D^R}{1 - \mathcal{O}_D^R/N_l} \right)^{l - M_r} \sum_{l_{\text{op}}=0}^{N_r} \binom{M_r}{l_{\text{op}}} \left( \frac{1 - \mathcal{O}_D^R}{1 - \mathcal{O}_D^R/N_r} \right)^{l_{\text{op}} - 1}, \right. \\
\left. \sum_{l=0}^{M_r} \binom{M}{l} \left( \frac{1 - \mathcal{O}_D^R}{1 - \mathcal{O}_D^R/N_r} \right)^{l - M_r} \sum_{l_{\text{op}}=0}^{N_r} \binom{M_r}{l_{\text{op}}} \left( \frac{1 - \mathcal{O}_D^R}{1 - \mathcal{O}_D^R/N_r} \right)^{l_{\text{op}} - 1}, \right.
\]

(4a)
(\(N_s + l_{eff}\)) packets. Thus, the average EE when adopting the MRC and SC scheme can be written with the aid of Table 3 respectively as

\[
EE^{\text{MRC}} = T_h \left[ (N_s + E[l_{eff}]) (P_{tx} + P_{rx}(n_d)) \right]
\]

and

\[
EE^{\text{SC}} = T_h \left[ (N_s + E[l_{eff}]) (P_{tx} + P_{rx}(1)) \right]
\]

where \(E[\cdot]\) corresponds to the expected value operator. Even though \(l_{eff}\) ranges from \(l\) (when \(l < L\)) to \(L\) (when \(l \geq L\)), it can be shown that, in the high-SNR regime, \(E[l_{eff}] \rightarrow L\). Please refer to Appendix B for more details.

Thus, note that, more than just considering the circuitry consumption of both transmitter and receivers and the power amplifier of transmitters [2], the consumption model adopted in this work also encompasses the overall number of transmissions and receptions performed by the protocol.

Since the circuitry consumption is usually fixed (hardware dependent), the transmit power \(P_t\) adopted in (13) is usually set as to achieve a given target outage probability \(O^*\), i.e., for a given \(O^*\), the value of \(P_t\) is isolated from (8) and (9) for the MRC and SC techniques, respectively. Since SC requires more \(P_t\) than MRC to achieve a given required \(O^*\), but on the other hand adopts only a single RF chain at the receiver (reducing the energy consumption), a practical approach would be to choose the combining scheme that, for a given reliability requirement, leads to the lowest energy consumption.

Although increasing \(n_{rx}\) leads to a higher reliability in (8), it also increases \(EE^{\text{SC}}\) in (13a). On the other hand, \(EE^{\text{SC}}\) from (13b) does not increase with \(n_{rx}\), since a single receive antenna is used at a time. One can also see from (13) that the EE increases when \(l_{eff}\) (or even \(L\)) is increased. However, the reliability is also increased as presented in (8) and (9), such that the required transmit power to achieve a target outage probability is reduced. Thus, one could expect that there is an optimal maximum number of selected relays \(L\) that minimizes (13), as discussed in what follows.

### A. OPTIMAL MAXIMUM NUMBER OF SELECTED RELAYS

In the MRC scheme, the EE depends on both the number of receive antennas as well as the number of selected relays, while in SC only the latter influences the EE. Since jointly optimizing \(n_{rx}\) and \(L\) for MRC is a hard (if possible) task. In what follows we obtain an approximation to the optimal \(L\), for a fixed \(n_{rx}\).

**Theorem 2**: The optimal value of \(L\) that minimizes the EE can be approximated as

\[
L^* = \left[ \frac{\log \left( \frac{\zeta}{\Theta(n_{rx})} \right)}{n_{rx} \cdot W \left( \frac{\Theta(n_{rx})}{\delta} \right)} \right] - 1,
\]

where \(\Theta^*\) is a predefined target outage probability, \([\cdot]\) the nearest integer rounding function, \(W(\cdot)\) the Lambert-W function [24], while the parameters \(\delta, \zeta\) and \(\Theta(n_{rx})\) are defined as

In (15b), \(\sum_{i=1}^{n_{rx}} N_s m_i - m_i - 1\) for SC and \(\sum_{i=1}^{n_{rx}} N_s m_i - m_i - 1\) for MRC.

**Proof**: Please refer to Appendix C.

Note that the influence of the combining scheme on the optimal number of relays from (14) comes from parameter \(\Theta(n_{rx})\) in (15c).

### TABLE 4. System parameters.

| Parameter | Value | Parameter | Value |
|-----------|-------|-----------|-------|
| \(f_c\)   | 2.5 GHz | \(\eta\) | 0.35 |
| \(G_t G_r\) | 5 dB | \(\xi\) | 1 |
| \(B\)     | 10 kHz | \(P_{\text{syn}}\) | 50 mW |
| \(O^*\)   | \(10^{-3}\) | \(P_{\text{LNA}}\) | 20 mW |
| \(P_{\text{RF}} = P_{\text{Blk}}\) | 2.5 mW | \(M_t\) | 40 dB |
| \(N_0\)   | -171 dBm | \(R_0\) | 1 bpcu |
| \(d\)     | 40 m | \(\alpha\) | 4 |
| \(N_f\)   | 10 dB | \(\delta\) | |
Outage probability versus SNR for $n_d = 2$ and $n = 1$. The numbers between parentheses represent $(N_s, M_r, \mathcal{L})$.

FIGURE 3. EE as function of $\mathcal{L}$, for $N_s = 8$, $M_r = 10$, $n_d = 2$ and $n = 2$.

The overall EE as a function of $\mathcal{L}$, for both MRC from (13a) and SC from (13b), is evaluated in Fig. 3. In this figure, “Simulation” is the result obtained by means of Monte Carlos simulations, “Exact” is the EE obtained from (13) by means of the exact outage probability from (4), while “Approximation” refers to the EE obtained also from (13) but adopting the high-SNR approximation from Corollary 1. Even though MRC needs less transmit power to achieve the predefined target outage probability, the consumption of the receiver circuitry compromises its EE when compared to SC. Moreover, note that the EE obtained from the exact outage probability from Theorem 1 precisely matches the simulations. Finally, although the EE obtained from the approximated outage probability presented in Corollary 1 does not match the simulation results in this particular configuration, it is still very precise in finding $\mathcal{L}^*$, the value of $\mathcal{L}$ that minimizes the consumption. Besides that, note that Fig. 3 presents a EE ceil when $\mathcal{L}$ increases, which happens when the transmit power adopted to achieve a given outage probability is not enough to increase the number of relays in the set $\mathcal{R}$, thus limiting the consumption.

FIGURE 4. EE versus $n_d$, with $N_s = 8$, $M_r = 6$, $n \in \{1, 2\}$ and adopting the exact $\mathcal{L}^*$ and the approximated $\mathcal{L}^*$ from (14).

FIGURE 5. EE versus $M_r$, with $N_s = 5$, $n_d = 2$, $n \in \{1, 2\}$ and adopting the exact $\mathcal{L}^*$ and the approximated $\mathcal{L}^*$ from (14).

In Fig. 4 and Fig. 5 we evaluate the EE as a function of $n_d$ and $M_r$, respectively, when considering the approximate values of the optimal $\mathcal{L}^*$ obtained analytically from Theorem 2 (“$\mathcal{L}^*$ from (14)”) and the exact values obtained by means of numerical simulations (“Exact $\mathcal{L}^*$”). Thus, as long as the result from (14) in Theorem 2 provides the same optimal value of $\mathcal{L}$ as the exact one obtained numerically, there should be a perfect match between the curves.

It can be clearly seen from Fig. 4 that, for a given value of $\mathcal{L}$, there exists an optimal $n_d$ that minimizes the EE in the MRC scheme. However, in the SC scheme the EE is a decreasing function of $n_d$. As a result, even though MRC may represent the most efficient scheme for small number of antennas (as is the case for $n = 1$ and $n_d < 6$), the SC scheme tends to be more energy efficient when the number of antennas increases.

The influence of the number of relays in the overall EE is evaluated in Fig. 5, when adopting the optimal number of selected relays $\mathcal{L}^*$. For $n = 1$, SC is slightly worse than MRC, since the reliability gain provided by MRC, in this scenario, compensates the increased consumption imposed.
by the concurrent use of \( n_f \) RF chains at the destination. Note that in this scenario, the energy consumption of both schemes varies in a similar fashion when increasing \( M_r \), since a single antenna is adopted at the relays. However, for \( n_f = 2 \), it can be noticed that there is a crossing point between the curves, so that SC becomes the most energy efficient scheme. Here, it is clear that the improved reliability gain obtained from MRC is not worth due to the larger energy consumption required by \( M_r \) relays using all RF chains simultaneously. It is worthy mentioning that the slight difference between the curves for small values of \( M_r \) is due to the fact that the approximated \( \mathcal{L}^* \) obtained analytically from Theorem 2 is not equal to the exact value in such cases, although it still gives a reasonable approximation to the final EE result.

VI. FINAL COMMENTS

In this work we evaluated the EE of a NCC scheme with MRS, in a scenario with multiple sources, multiple relays and a single common destination, all of them provided with multiple antennas. The EE of the network is evaluated under two different combining techniques at the receiver side, namely MRC and SC. Our mathematical and simulation results, which also encompasses the circuitry consumption of all nodes, showed that MRC, which is optimal from a reliability perspective, may be outperformed by SC in terms of EE. Moreover, we also obtain the number of relays that must be used to optimize the EE. As future work, one can evaluate the influence of beamforming and line-of-sight (LOS) among the nodes in the network by assuming that the fading follows, for example, a Nakagami-\( m \) distribution [19].

APPENDIX A

PROOF OF THEOREM 1

First, we obtain the probability of the three cases mentioned in (3), following a similar approach as the one used to obtain the outage probability of the “strategy \( B_2 \)” in [11, Eqs. (69)-(74)].

1) PROBABILITY OF CASE 1

The probability that all the \( N_s \) packets broadcasted in the BP are correctly decoded by the destination is

\[
\text{Pr} \{ \text{Case 1} \} = \Pr \left\{ n_{\text{sop}} = N_s \right\} = \left(1 - O^D_S \right)^{N_s}, \tag{16}
\]

where \( O^D \) corresponds to the outage probability in the link between sources and \( D \), which, for Rayleigh fading along with TAS/sch is given by (5).

2) PROBABILITY OF CASE 2

In this case, the system will not be in outage if the number of packets successfully received at the destination during the BP, \( n_{\text{sop}} \), is smaller than \( N_s \) but the destination still received a sufficient number of packets from the relays in the RP, i.e.

\[
\text{Pr} \{ \text{Case 2} \} = \sum_{n_{\text{sop}}=0}^{N_s-1} \Pr \left\{ \mathcal{E}_{n_{\text{sop}}} \right\} \sum_{l=0}^{\mathcal{L}-1} \Pr \left\{ \mathcal{E}_{l} \right\} \times \sum_{l_{\text{op}}=N_i-n_{\text{sop}}}^{l} \Pr \left\{ \mathcal{E}_{l_{\text{op}}} \right\}, \tag{17}
\]

where \( \mathcal{E}_{n_{\text{sop}}} \) is the event that \( n_{\text{sop}} \) packets are correctly recovered by the destination after the BP, whose probability of occurrence is given by

\[
\Pr \left\{ \mathcal{E}_{n_{\text{sop}}} \right\} = \left( \frac{N_s}{n_{\text{sop}}} \right) \left(1 - O^D_S \right)^{n_{\text{sop}}} \left( O^D_S \right)^{N_i-n_{\text{sop}}}, \tag{18}
\]

while \( \mathcal{E}_{l} \) and \( \mathcal{E}_{l_{\text{op}}} \) correspond respectively to the events \( |\mathcal{R}_l| = l \) and number of packets recovered by the destination in the RP equals \( l_{\text{op}} \), whose probabilities are obtained as

\[
\Pr \left\{ \mathcal{E}_{l} \right\} = \binom{M_r}{l} \left(1 - O^R_S \right)^l \left(1 - O^R_S \right)^{N_i-l}, \tag{19}
\]

\[
\Pr \left\{ \mathcal{E}_{l_{\text{op}}} \right\} = \binom{l}{l_{\text{op}}} \left(1 - O^D_R \right)^{l_{\text{op}}} \left( O^D_R \right)^{l-l_{\text{op}}}, \tag{20}
\]

where \( O^R_S \) and \( O^D_R \) are obtained respectively from (6) and (7). Again, note that the relays do not experience TAS diversity since the best transmit antenna is chosen from the destination perspective.

3) PROBABILITY OF CASE 3

Here, the system is not be in outage if \( n_{\text{sop}} < N_s \) and \( l_{\text{op}} < N_i - n_{\text{sop}} \) with \( l < \mathcal{L} \). For convenience, this case can be split in two sub-cases, for \( N_s > \mathcal{L} \) and \( N_s \leq \mathcal{L} \):

\[
\text{Pr} \{ \text{Case 3} \} = \begin{cases} \sum_{n_{\text{sop}}=0}^{N_s-1} \Pr \left\{ \mathcal{E}_{n_{\text{sop}}} \right\} \sum_{l=0}^{\mathcal{L}-1} \Pr \left\{ \mathcal{E}_{l} \right\} \times \sum_{l_{\text{op}}=N_i-n_{\text{sop}}}^{l} \Pr \left\{ \mathcal{E}_{l_{\text{op}}} \right\} ; & N_s > \mathcal{L} \\ \sum_{n_{\text{sop}}=0}^{N_s-1} \Pr \left\{ \mathcal{E}_{n_{\text{sop}}} \right\} \sum_{l=0}^{\mathcal{L}-1} \Pr \left\{ \mathcal{E}_{l} \right\} \times \sum_{l_{\text{op}}=N_i-n_{\text{sop}}}^{l} \Pr \left\{ \mathcal{E}_{l_{\text{op}}} \right\} ; & N_s \leq \mathcal{L} \end{cases} \tag{21}
\]

Thus, the complete outage probability equation from (4) is obtained by replacing (16), (17) and (21) in (3), concluding the proof.

APPENDIX B

PROOF THAT \( \mathbb{E} \{ l_{\text{eff}} \} = \mathcal{L} \) FOR HIGH-SNR REGIME

The expected number of relays that transmit in RP can be obtained by averaging (19), as

\[
\mathbb{E} \{ l_{\text{eff}} \} = \sum_{l=0}^{\mathcal{L}-1} l \Pr \{|\mathcal{R}_l| = l\} + \mathcal{L} \sum_{l=\mathcal{L}}^{l_{\text{op}}} \Pr \{|\mathcal{R}_l| = l\}, \tag{22}
\]
where

$$\Pr (|R_1| = l) = \left( \frac{M_r}{l} \right) (1 - \mathcal{O}_S)^{N_s, l} \left[ 1 - (1 - \mathcal{O}_S)^{N_s} \right]^{M_r - l}$$  \hspace{1cm} (23)$$

is the probability that the number of relays belongs to set $R_1$ (have decoded all the $N_s$ packets broadcasted in the BP) is equal to $l$. After expanding (23), it can be shown that $\Pr (|R_1| = l) \approx \left( \frac{M_r}{l} \right) (N_s \mathcal{O}_S)^{M_r - l}$ in the high-SNR regime, which, after being placed in (22), reveals that the most relevant term of (22) is $l = M_r$, leading to $\Pr (\{l = \text{eff} = L\}) = 1$ and concluding the proof that $E [\{\text{eff}\}] \approx L$.

**APPENDIX C**

**PROOF OF THEOREM 2**

The derivatives of the EE with respect to $L$ for both MRC and SC schemes are

$$\frac{\partial EE}{\partial L} \bigg|_{\text{MRC}} \approx \frac{\Delta N_0 B_5 (2^{R_0} - 1)}{\Delta L} \left( \frac{n_d}{R_0} \right)^{1/n_d} \eta \frac{P_{\text{syn}} + P_{\text{ctx}} + n_d P_{\text{ctx}}}{R_0}$$ \hspace{1cm} (24a)$$

and

$$\frac{\partial EE}{\partial L} \bigg|_{\text{SC}} \approx \frac{\Delta N_0 B_5 (2^{R_0} - 1)}{\Delta L} \left( \frac{n_d}{R_0} \right)^{1/n_d} \eta \frac{P_{\text{syn}} + P_{\text{ctx}} + n_d P_{\text{ctx}}}{R_0}$$ \hspace{1cm} (24b)$$

where $\Delta = \left[ \frac{1}{\sigma^2} \left( \frac{N_s}{N_s - L - 1} \right) \frac{1}{n_d} \right]^{1/(n_d + 1)}$. Thus, we can write $\frac{\partial EE}{\partial L} = 0$ in order to find the $L^*$ that minimizes (24a) and (24b). In order to simplify the solution, we approximate $L$ to a constant using least squares as

$$\frac{\Delta}{L + 1} \left[ \frac{1}{n_d} - \log |\Delta| \right] \approx -\Delta \frac{\delta}{L} \log |\Delta|$$  \hspace{1cm} (25)$$

such that the mean square error is minimized in the interval $L \in [1, N_s - 1]$ when $N_s < M_r$ or $L \in [1, M_r]$ when $N_s > M_r$, since outage probability only depends on $L$ in this interval.

After solving (25) and approximating $\left( \frac{N_s}{N_s - L - 1} \right)^{1/(n_d + 1)}$ to a constant with the same process used to obtain (25), we can find the optimal $L$ as in (14), concluding the proof.

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