Parallel Retransmissions in Orthogonal Multiple Access Multiple Relay Networks

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***Abstract*—In this paper, we propose a novel selection strategy for the orthogonal Multiple Access Multiple Relay Networks (MAMRN). Rather than selecting a single relaying node to help one source node at a given retransmission time slot, we propose allocating one source to be helped by multiple relaying nodes. The idea is to exploit the multipath diversity of the different relaying nodes in order to optimize the spectral efficiency. We present the control exchange process in the novel selection strategy and we compare it to that of the prior art. In addition, we investigate the effect of equal gain combining on the performance, as well as the effect of the rates and the channel configuration. The numerical results show that the proposed strategy outperforms the prior art by exploiting the power budget available at each relaying node included in the system.**

***Index Terms*—MAMRN, Scheduling, Selection strategies, Spectral efficiency.**

I. Introduction

Cooperative communications are known for their significant role in providing the spectral efficiency requirements for wireless channels. A cooperative communications system generally consists of three kinds of nodes: source, relay, and destination nodes. Depending on the number of nodes in each category, different classes of relay channels have been defined. Although the research concerning cooperative communications started 50 years ago [1], it is still a hot topic till today [2]. In this work, we consider an orthogonal Multiple Access Multiple Relay Network (MAMRN) with multiple sources, multiple relays, and a single destination. Such a system is seen in nowadays applications. For example, the considered structure is the main topology structure for Unmanned Aerial Vehicle (UAV) cooperative surveillance networks [3]. In addition, it is more general from the typical three-terminal communication network [1] and the multiple relay network [4].

The nodes cooperate to send messages and redundancies to the destination. The destination, on the other hand, plays the role of a centralized scheduler which allocates the transmission and retransmission resources for the users. The relaying nodes apply the Selective Decode-and-Forward (SDF) relaying protocol [5], which means that they can forward only a signal representative of successfully decoded source messages. The SDF relaying protocol is an advanced version of the famous Decode-and-Forward (DF) relaying protocol where the relays are not obliged to wait until they decode all the source nodes' messages before starting the retransmissions.

The selection strategy is an important aspect in cooperative systems. In literature, several works tackled this issue. For example, two relay selection strategies are proposed in [6], but limited to the case of two-user with no direct link scenario. In [7], the notion of multiple relay selection is presented but to a different network model (single source multiple relay channel). Considering a single source simplifies the problem as all the relays will be willing to help the single source included. In [8], the communication of multiple source to their multiple destinations is done via relay nodes, where each source-destination pair is matched to a relay node. Following the considered system (i.e., the MAMRN), few works tackled the problem of relaying node selection strategy. The closest work to what we are presenting is [5], were the selection strategy used was based on choosing the relay node with the highest mutual information with the destination. Although this selection approaches the upper bound (exhaustive search approach), it was limited to selecting a single relay at a time.

Recently, the publication [5] proposed a simplified orthogonal MAMRN protocol based on existing LDPC and Turbo codes which are used in the 3GPP LTE and NR standards. The protocol allows a retransmission of the Incremental Redundancy per source, that is, transmitting bits of different parities on the basis of a single coding with a very low rate. In this work, we build on this protocol and we propose exploiting the diversity of activating several relays at a given retransmission to help a selected source node.

We have investigated earlier different problems of link adaptation [9] for the MAMRN system described above. In this work, we propose an improved node selection strategy which takes advantage of the multipath diversity of the relaying nodes. The idea is based on the fact that each relaying node has

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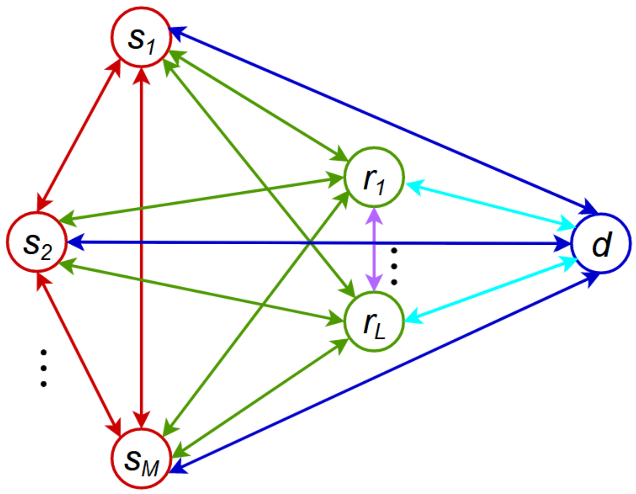

Fig. 1. The Multiple Access Multiple Relay Network (MAMRN) consists of a wireless network with multiple sources, multiple relays, and a single destination.

its own power budget, and accordingly, several relaying nodes can be activated at the same time. Thus, the main contributions of this work can be summarized as:

- We propose a novel scheme of sending redundancies called parallel retransmission where rather than selecting a single relaying node to help one source node at a given retransmission time slot, several relay nodes are activated to help a selected source node.
- We present the control exchange process needed in the novel selection strategy and we compare it with that of the prior art.
- The numerical results validate the gain of using parallel retransmission scheme in both symmetric and asymmetric rate and channel configurations.

Next, we present the system model, followed by the problem formulation and the proposed solution. We then summarize the numerical results before concluding this work.

II. System Model

We consider an $(M, L, 1)$ MAMRN protocol configuration with M sources, L dedicated relays and one destination as shown in Fig. 1. The sources have mutually independent messages and occasionally act as relays for other source messages, while the relay nodes do not have messages to send and are solely present for relaying purposes. Each source $i \in \{1, ..., M\}$ has a message $\mathbf{u}_i \in \mathbb{F}_2^{K_i}$ that consists of K_i information bits, where $\mathbb{F}_2$ is the Binary Galois field, and K_i depends on the Modulation and Coding Scheme (MCS).

For a given transmitting node a from the set of sources and relays and a receiving node b from the set of all nodes (sources, relays, and the destination), and at a given channel use m, the received signal $y_{a,b,m}$ can be written as:

$$y_{a,b,m} = h_{a,b}x_{a,m} + n_{a,b,m}, \quad (1)$$

where $x_{a,m} \in \mathbb{C}$ is the coded modulated symbol whose power is normalized to unity, $h_{a,b}$ is an instance of the channel fading gains which are independent and follow a zero-mean circularly symmetric complex Gaussian distribution with variance $\gamma_{a,b}$, and $n_{a,b,m}$ is an instance of the independent and identically distributed AWGN samples, which follow a zero-mean circularly-symmetric complex Gaussian distribution with unit variance.

The transmissions and retransmissions of source messages occur in time frames structured as shown in Fig. 2. Following an initial link adaptation phase, where a rate allocation process is performed (the rates of the sources are allocated), a time frame is divided into two phases. The first phase is the transmission phase during which the sources transmit their messages in turn over U channel uses. The second phase, called retransmission, is composed of $T_{\text{used}} \in \{0, ..., T_{\text{max}}\}$ retransmissions scheduled by the destination using Q channel uses. T_{max} represents the maximum number of possible retransmissions before declaring an outage event (event of not decoding messages of some source nodes). Thus, the whole frame size is $M + T_{\text{used}}$ which is limited to $M + T_{\text{max}}$ where T_{max} is a fixed system parameter. We note that K is assumed large enough to neglect the effect of control channels on the transmission rate (that is why we see no time slot reserved for the control exchange process). In other words, we assume the presence of "limited control channels" with a large enough packet length. For short packet lengths, however, the control channel overhead cannot be neglected. Nevertheless, this will not change the contribution of the paper, which focuses on the gain of using parallel retransmission.

A retransmission helps in the decoding of a single source message (Single User (SU) encoding), and it can be done by any source node or relay because at each transmission/retransmission, t, all the nodes listen and try to decode a maximum number of source messages. We define here the set of sources $\{1, ..., M\}$ and the set of relaying nodes $\{1, ..., M + L\}$. Note that the first M relaying nodes are the sources that perform user cooperation (sources which act as relays when they have no messages of their own to send), and the remaining L relaying nodes are the dedicated relays. Finally, we define the decoding set of a relaying node j at a retransmission time slot t as $S_{j,t-1}$, where $S_{j,t-1}$ contains the source nodes which the relaying node j was able to decode before the retransmission time slot t. Similarly, the decoding set of the destination d at a retransmission time slot t is written as: $S_{d,t-1}$. By convention, $S_{d,0}$ and $S_{j,0}$ represent the decoding sets of the destination d and the relaying node j at the end of the transmission phase.

In the prior art [5], for each retransmission, the destination chooses the unique active node which has the best connection to the destination and which can assist the destination. We say that a node can assist when its decoding set includes some source nodes which are not decoded at the destination yet. The scheduling decisions are based on the Channel State Information (CSI) of the direct links which is assumed to be available at the destination. The direct links are the source-

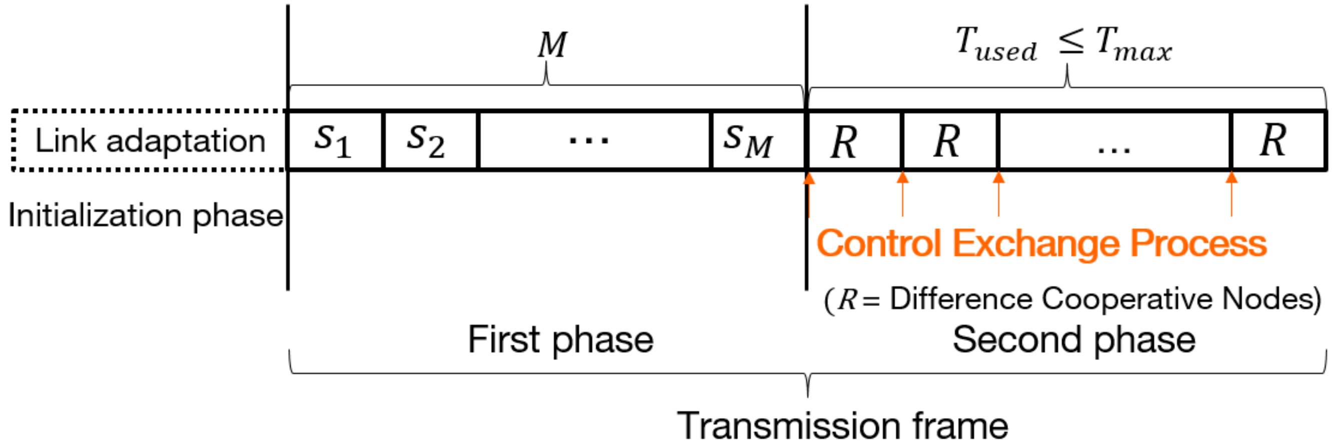

Fig. 2. Transmission of a frame: initialization, first and second phases. A control exchange process is performed before each retransmission time slot.

to-destination links, S-D, and the relay-to-destination links, R-D. The CSI of the indirect links is assumed not available at the destination due to the costly acquisition process needed and the overhead included in this process. The indirect links are the links of source-to-source S-S, source-to-relay S-R, and relay-to-relay R-R. Finally, we assume a slow fading scenario where the radio links between the nodes do not change within a frame transmission. Additionally, the channel realization is assumed independent from frame to frame, which simplifies the analysis and is sufficient to capture the performance of practical systems assuming ergodicity of the underlying random processes.

Here, we describe the information exchange between the nodes and the destination as seen in the prior art selection strategies. Let the retransmissions time slot $t \in \{1, ..., T_{\max}\}$ with the end of the first transmission phase corresponding to $t = 0$. Before each retransmission t, the destination broadcasts a message indicating all the sources $S_{d,t-1}$ that it was able to decode without errors at the end of the retransmission $t-1$ using a Cyclic Redundancy Check (CRC). Relaying nodes $j \in \{1, ..., M+L\}$ that can help the destination (i.e., $S_{j,t-1} \bigcap \overline{S}_{d,t-1} \neq \phi$ where $\overline{S}_{d,t-1}$ represents the messages that are still not decoded by the destination at the end of the retransmission $t-1$) send a signaling bit to the destination. For the retransmission t, the destination chooses the active node $\widehat{a}_t$ that has the best link (highest mutual information with the destination). The node retransmits a redundancy version of a source $\widehat{b}_t$ such that: $\widehat{b}_t \in S_{\widehat{a}_t,t-1} \bigcap \overline{S}_{d,t-1}$. Based on this retransmission, the destination attempts to decode the retransmitted source at the end of the retransmission t and so on until $T_{\max}$ or until the destination decodes all the source messages without errors. A comparison between the control exchange of the prior art's selection strategy and the proposed selection strategy (to be described in the next section) is seen in Fig. 3 (prior art in blue). In this paper, we propose a novel selection strategy, where rather than choosing a relaying node $\widehat{a}_t$ to send redundancies for a random node $\widehat{b}_t$ included in its decoding set, the destination chooses a source node to be helped, by all the relaying nodes which were able to decode its message.

As each node has its independent power budget, the decoding performance of a source could be improved if, during a retransmission t, several relaying nodes transmit, at the same time, the same redundancy version of this source. The equivalent transmitted power will thus be multiplied by the number of active nodes. Therefore, the objective of this work is to exploit multipath diversity to optimize the spectral efficiency which is based on the spectral efficiency per frame as the equation below:

$$\begin{aligned} \eta^{\text{frame}}(\mathbf{H}, \mathbf{P}) &= \frac{\text{nb bits successfully received}}{\text{nb channel uses}} \\ &= \frac{\sum_{i=1}^{M} K_i(1 - \mathrm{O}_{i,T_{\text{used}}})}{MU + QT_{\text{used}}} \\ &= \frac{\sum_{i=1}^{M} R_i(1 - \mathrm{O}_{i,T_{\text{used}}})}{M + \alpha T_{\text{used}}} \end{aligned} \tag{2}$$

where

- $\mathbf{H}$ is the channel realization which contains the channel gains of all the links $h_{a,b}$ previously defined.
- $\mathbf{P}$ is the selection strategy used.
- $R_i = K_i/U$ is the rate of a source $i \in \{1, ..., M\}$, which is fixed in the initialization phase.
- $\mathrm{O}_{i,T_{\text{used}}}$ is a binary Bernoulli random variable as defined above, i.e., $\mathrm{O}_{i,T_{\text{used}}} = 1$ means that source i is not decoded correctly during a frame.
- $T_{\text{used}} \in \{0, \ldots, T_{\max}\}$ is the number of retransmission time slots activated in a frame.
- $\alpha = Q/U$ is the ratio of number of channel uses in a retransmission time slot by that in a transmission slot.

For brevity, we omit including the individual outage event mathematical equation. We just mention that it depends on the mutual information (following the Multiple Access Capacity (MAC) region) between the relaying nodes (based on the channel inputs) which in turn depends on the Signal to Noise

Ratio (SNR). Thus, in order to optimize the spectral efficiency, the scheduler (the destination) needs to know the full CSI of the network. Such an assumption is not practical due to the overhead included in the CSI acquisition of the indirect links, and makes the selection problem challenging. This explains why the prior art's [5], [9] selection strategies were based on selecting the relaying node with the highest mutual information with the destination.

III. Proposed Solution

First, and after the transmission of $S_{d,t-1}$ by the destination, each relaying node $j \in \{1, ..., M+L\}$ transmits the subset of sources that it can help and which are not yet decoded by the destination $S'_{j,t-1} = S_{j,t-1} \bigcap \overline{S}_{d,t-1}$. The destination calculates for each source $i \in \{1, ..., M\}$ the SNR_i associated with the transmission of the redundancy version X_i of the source i. This is calculated on the basis of the number of relaying nodes that were able to decode this source, as well as their channel with the destination (check the three cases described below). The channel from each relaying node $j \in \{1, ..., M+L\}$ to the destination is denoted $h_{j,d}$ and the set of relaying nodes j which can help the source i is denoted $\boldsymbol{H}_i$. Accordingly, the destination selects the source $\widehat{s}_t$ with the best equivalent channel (highest equivalent SNR), and then, all the relaying nodes which decoded the chosen source $\widehat{s}_t$ retransmit redundancies. We consider three cases for estimating the SNR_i:

- **Case 1:** each relaying node $j \in \{1, ..., M+L\}$ does not know the channel $h_{j,d}$

$$\mathrm{SNR}_i = P \left| \sum_{j \in \boldsymbol{H}_i} h_{j,d} \right|^2 / N_0, \tag{3}$$

where P is the transmission power of each node, N_0 is the noise spectral density, and $h_{j,d}$ is the channel whose power is normalized to 1.

- **Case 2 "Equal Gain Combining (EGC)":** each node $j \in \{1, ..., M+L\}$ knows the phase Φ_j of its channel toward the destination $e^{-\mathrm{i}\Phi_j} = h^*_{j,d}/|h_{j,d}|$ with $\mathrm{i}^2 = -1$

$$\mathrm{SNR}_i = P \left(\sum_{j \in \boldsymbol{H}_i} |h_{j,d}| \right)^2 / N_0. \tag{4}$$

- **Case 3:** Assuming that the subset $\boldsymbol{H}_i = \boldsymbol{B}_i \bigcup \boldsymbol{C}_i$ breaks down into a subset $\boldsymbol{B}_i$ of nodes knowing their phase with the destination (sent by the destination) and $\boldsymbol{C}_i$ not knowing it, in this case, SNR_i for $i \in \{1, ..., M\}$ is written as:

$$\mathrm{SNR}_i = P \left| \sum_{j \in \boldsymbol{B}_i} |h_{j,d}| + \sum_{j \in \boldsymbol{C}_i} h_{j,d} \right|^2 / N_0. \tag{5}$$

If the node i is selected, the transmission of each node belonging to $\boldsymbol{B}_i$ will be multiplied by $e^{-\mathrm{i}\Phi_j}$ (coherent reception for the nodes belonging to $\boldsymbol{B}_i$).

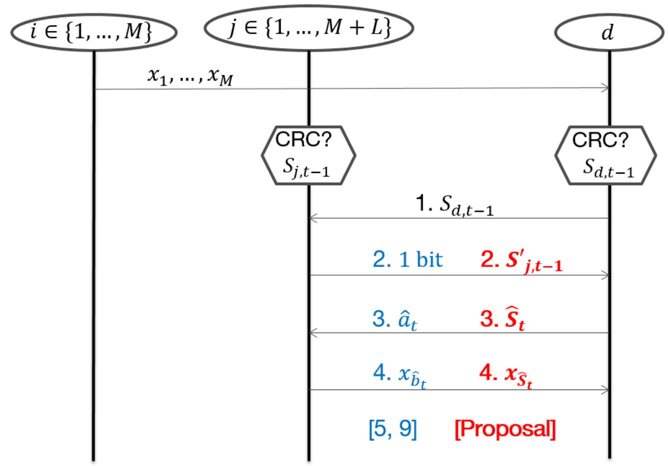

Fig. 3. Information exchange process corresponding to: the prior art (in blue) and the current proposal (in bold red)

Algorithm 1 Parallel retransmissions selection strategy

MAX = 0 ▷ Initialize MAX to zero
for all i in $\overline{S}_{d,t-1}$ **do** ▷ For every non-decoded source node
  $\boldsymbol{H}_i \leftarrow \phi$ ▷ Initialize $\boldsymbol{H}_i$ to empty set
  for all j in $\{1, ..., M+L\}$ **do** ▷ for all relaying nodes
    if $\overline{S}_{d,t-1} \cap S_{j,t-1} \neq \emptyset$ **then** ▷ If node j can help source i
      $\boldsymbol{H}_i \leftarrow \boldsymbol{H}_i \cup \{j\}$ ▷ get the set of helping relaying nodes for source i
    end if
  end for
  Calculate SNR_i ▷ using one of the three equations above
  if $\mathrm{SNR}_i >$ MAX **then**
    MAX $\leftarrow \mathrm{SNR}_i$ ▷ Update the value of MAX
    $\widehat{s}_t \leftarrow i$ ▷ Update the selected source
  end if
end for

In Fig. 3, we present the control exchange process in each of the prior art (in blue) and the proposed (in bold red) selection strategies. In our proposal, the destination returns the source index $\widehat{s}_t$ which has the best SNR. Following the receipt of the source index $\widehat{s}_t$ broadcast by the destination, the nodes having decoded $\widehat{s}_t$ simultaneously transmit the same version of the modulated message of source $\widehat{s}_t$, i.e., $x_{\widehat{s}_t}$ (Fig. 3). In the case where each node $j \in \boldsymbol{H}_{\widehat{s}_t}$ knows the phase Φ_j of its channel towards the destination, the modulated transmission of $x_{\widehat{s}_t}$ is multiplied by $e^{-\mathrm{i}\Phi_j}$ (the conjugate of the channel divided by its norm) to obtain a coherent combination at the destination (case 2). The phase Φ_j is quantized in practice (e.g., 2 bits are sufficient), and the quantized phase relating to each node can be sent from the destination to the nodes during the initialization phase or just after the first transmission phase. Finally, algorithm 1 presents the pseudo-code of the proposed selection strategy using parallel retransmissions at a given retransmission time slot t.

IV. Numerical Results

In this section, we validate the proposed selection strategy using Monte-Carlo simulations. We consider a (3,6,1)-MAMRN scenario, and we set α to 0.25 and $T_{\max}$ to 4. The channel inputs are assumed independent and Gaussian distributed with zero mean and unit variance. Note that other channel inputs might be considered without changing the conclusions of this work. We further assume that the rate of each source is allocated using the best response dynamic algorithm presented in [9]. We consider two link configuration scenarios: symmetric and asymmetric. In the symmetric link configuration (Fig. 4), all the links are considered the same (the average SNR of each link is set to γ). On the other hand, in the asymmetric link configuration (Fig. 5), we design a scenario where the direct links between the source nodes and the destination are bad. Such a scenario helps in showing the importance of the relaying nodes and the gain of the proposed retransmission strategy. Particularly, the links are set as follows: first, the average SNR of each link is set to γ; second, the average SNR of each direct link between the source nodes and the destination is set to $\gamma - 100$dB. In both scenarios, each source is given a rate using the slow link adaptation algorithm presented in [9] from the set of possible rates $\{0.75, 1, 1.25, 1.5\}$ bits/channel use, and thus, rates are optimized based on γ.

Three different curves are seen in the two figures 4 and 5. The first curve corresponds to the proposed selection strategy with parallel retransmissions in the case of EGC. The second curve corresponds to the same strategy, assuming no available information concerning the phase shift at the relaying nodes (no EGC). Finally, a third curve of simple retransmissions, as proposed in the prior art. In Fig. 4, we see that for the symmetric scenario, and for the considered SNR range (-5dB to 15dB), the proposed strategy outperforms the prior art in both cases, with EGC ($\sim$ 1.5dB) or without EGC ($\sim$ 1dB). In Fig. 5, we encounter a significantly higher gain in the asymmetric scenario over the same SNR range, where the proposed strategy outperforms the prior art in both scenarios: with EGC (up to 7dB) or without EGC (up to 4dB).

Finally, in Fig. 6, we investigate the effect of the size of the system on the gain of the proposed strategy. Specifically, we fix γ to 0, and we vary the number of relays available in the system from 2 relays to 10 relays. The other parameters are the same as those of Fig. 5 (i.e., the asymmetric link configuration, the number of sources $M = 3$, the set of possible rates, $\alpha = 0.25$, and $T_{\max} = 3$). We present in Fig. 6 the gain ratio of the proposal with and without EGC. In other words, we present the ratio: (the average spectral efficiency of parallel retransmission) / (the average spectral efficiency of single retransmission). The figure validates that as the number of relays increases, the gain of parallel retransmission compared to single retransmission increases. This can be justified by the fact that when extra relays are available, the gain of exploiting the multipath diversity would be more significant.

We summarize our findings below:

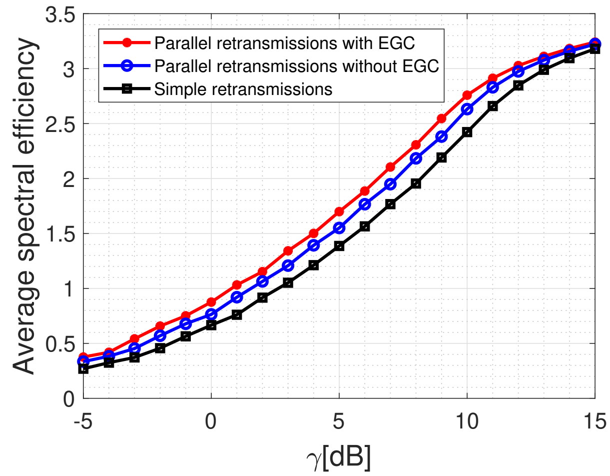

Fig. 4. Average spectral efficiency with symmetric configuration

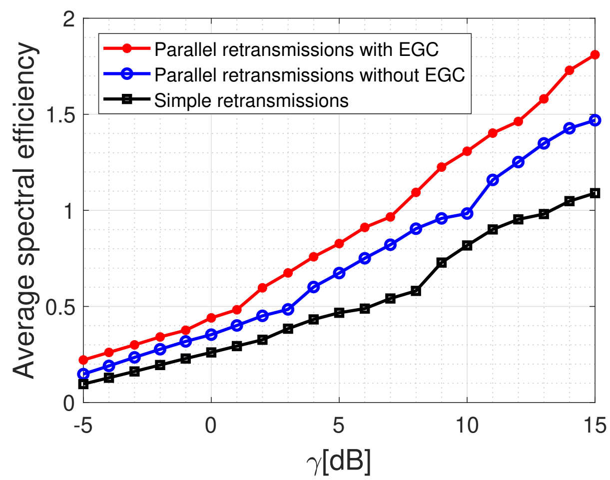

Fig. 5. Average spectral efficiency with asymmetric configuration

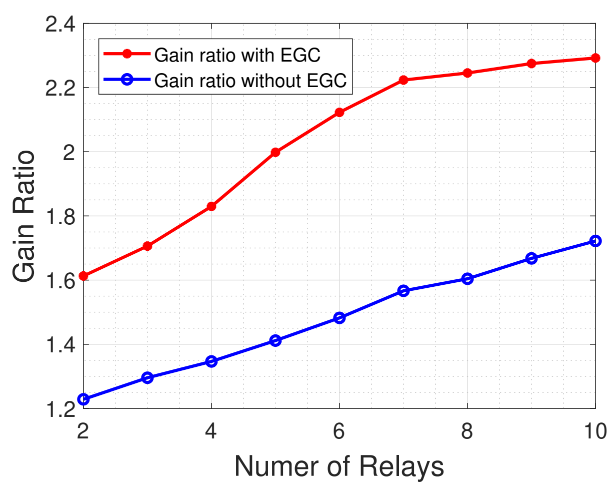

Fig. 6. Gain ratio with asymmetric configuration with respect to the number of relays in the network

1) The gain of the proposed selection strategy is significant in scenarios where direct links are not available.
2) The gain is seen for different values of γ, even for high values (this can be explained by the fact that even if we are in a high SNR regime, the rate allocation will allocate higher rates corresponding to γ leading to better performance).
3) as the number of relays L increase, the gain of the proposed strategy. increases.

V. Conclusion

In this paper, we proposed a novel selection strategy for orthogonal MAMRN. Rather than selecting a single relaying node to send redundancies at a given retransmission time slot, the parallel retransmission strategy allows several relaying nodes to send redundancies for a common source node selected to be helped. The proposed strategy outperforms the prior art (single retransmission) by making use of the power budget available at each relaying node included in the system. The numerical results show that the gain is seen with and without EGC, where in the case of EGC, the system encounters a higher gain. Also, the gain is seen with symmetric and asymmetric scenarios, where in the latter, the gain is higher.

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