Centralized Scheduling for Frequency Domain Orthogonal Multiple Access Multiple Relay Network

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***Abstract*—In this paper, we consider an orthogonal Multiple Access Multiple Relay Network (MAMRN), where several nodes cooperate to send their messages to a single destination. Frequency Division Multiplexing (FDM) is adopted for the sources and the relays, and the destination acts as the central node responsible for scheduling the cooperative retransmissions. Since FDM is used for orthogonality, different nodes are allocated at each sub-band of the transmission and retransmission phases. In this work, we present the system model of the considered orthogonal MAMRN when the FDM mechanism is adopted, while including the analytical derivations of the utility metrics (spectral efficiency and outage events). Then, two centralized node selection strategies are proposed. Moreover, we present the control information exchange process between the destination and the different nodes. The proposed strategies allocate for each sub-band the node that will transmit (or retransmit) with the goal of maximizing the spectral efficiency. Our numerical analysis considers both symmetric and asymmetric channel and source rate scenarios, and shows that the proposed algorithms outperform the algorithms used in the prior-art, and achieve a spectral efficiency that is close to the upper bound calculated by an exhaustive search approach while reducing the complexity and the overhead.**

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

I. Introduction

In cooperative communication systems, the different communicating nodes cooperate and share resources in order to boost the overall network efficiency. This kind of communication network is seen in different nowadays scenarios [1]. In this work, we consider an orthogonal Multiple Access Multiple Relay Network (MAMRN) which consists of multiple sources and relays and a single destination. In this system, the sources need to transmit messages to a shared destination, and they perform user cooperation where they occasionally act as relays for other source messages. The dedicated relays, on the other hand, are solely present for relaying purposes and do not have messages of their own. Such a system (i.e., the MAMRN system) is seen in nowadays applications. For example, the considered structure is the main topology structure for Unmanned Aerial Vehicle (UAV) cooperative surveillance networks [2].

The destination acts as a centralized scheduler which allocates the rates and channel resources for the different nodes in the network. In [3], the analysis of the Hybrid Automatic Repeat Request (HARQ) mechanism in single relay cooperative networks is presented. In [4], the error rate performance analysis is presented for a multiple relay network. The work in [5], on the other hand, analyzes an orthogonal MAMRN system based on the Incremental Redundancy (IR)-HARQ protocol. User scheduling for cooperative communication systems is studied in [6]. There, a perfect source-to-relay links assumption is adopted which might be unrealistic from a practical point of view. Finally, a relaying node selection strategy is proposed in [7], but it is only applicable for symmetric rate scenarios, i.e., scenarios where the source rates are the same.

Recognizing the limitations in the prior-art, we have investigated the orthogonal MAMRN in our earlier work, where Time Division Multiplexing (TDM) was adopted. We considered different problems for the TDM-based orthogonal MAMRN including rate allocation and relaying node selection strategies (scheduling) [8], and we proposed efficient solutions for solving these problems. However, one drawback of the earlier proposals is that the system model is limited to TDM with no consideration to other forms of orthogonality such as Frequency Division Multiplexing (FDM). Upon adopting the FDM mechanism, we encounter a new Degree of Freedom (DoF) represented by the several sub-bands at each transmission or retransmission time slots. To exploit this DoF, the relaying nodes must be able to transmit on a given sub-band while listening to the others, i.e., the relaying nodes are capable of full duplex communication. Guard bands between sub-bands can be inserted to simplify the implementation of duplexer filters. Accordingly, the relaying node selection problem tackled in [6]–[8] becomes more complex, and the previously proposed strategies become inapplicable. Therefore, we propose here node selection strategies that are suitable to the frequency-based orthogonal MAMRN system. The goal of the proposed selection strategies is to choose the nodes which are active in the transmission and retransmission phases, aiming at maximizing the Average Spectral Efficiency (ASE). The main contributions of this paper are:

- We present the FDM-based orthogonal MAMRN with the derivations of the analytical utility metrics.
- We propose different centralized low-complexity scheduling strategies for node allocation with the control information exchange process between the destination and the relaying nodes.
- The numerical results show the efficiency of the proposed strategies as they outperform the strategies used in the prior-art and approach the exhaustive search performance.

The remaining of this paper is structured as follows. Section II presents the technical context. Section III presents our proposed solution including the system model and selection strategy with the corresponding analytical framework. Section IV presents the numerical results. Finally section V concludes the work.

II. Technical Context

We consider an (M, L, 1) system model, where M sources communicate with a single destination, using the help of $L+M$ relaying nodes. The relaying nodes consist of L dedicated relays and M sources, where the latter sources perform user cooperation (i.e., they occasionally act as relays). In figure 1, we see an illustration of a simple MAMRN. In this figure, we see that all the nodes (sources, relays, and the destination) can listen to each other. Furthermore, we see that there is a link from the destination (the central node) toward the different relaying nodes (sources and relays) representing the feedback information flow. Accordingly, the destination uses these links to share its different decisions and allocations with the different relaying nodes (e.g., allocated rates, selected relaying node, etc.).

Sources and relays are full-duplex nodes; that is, one node can transmit on one sub-band while listening to the other sub-bands. The case of half duplex nodes can be deduced straightforwardly with the constraint that a node cannot transmit and receive at the same time, i.e., within a time slot, only the non-active nodes can listen to the other nodes on all sub-bands. The cooperating nodes apply the Selective Decode and Forward (SDF) relaying protocol [4], [7], which means a relaying node can start relaying before decoding all the source messages. We further assume that Single User (SU) encoding is used. That is, a selected relaying node will only help a random source node chosen from its decoding set (the set containing its correctly decoded source messages). From a practical point of view, and following the state-of-the-art punctured codes, the SU encoding is attractive being compatible with codes such as Low-Density Parity-Check (LDPC) codes or turbo codes.

A time frame is divided into two phases. In the first phase, referred to as the transmission phase, the destination (being the centralized node) schedules the M sources to transmit their signals while using FDM for sharing the channel. Similarly during the second phase, the destination schedules in each retransmission time slot (limited to $T_{\max}$ time slots) the nodes (sources or relays) to transmit redundancies, with the goal to maximize the ASE.

We assume that the Channel Distribution Information (CDI) of all the links (e.g., the average Signal to Noise Ratio (SNR)) is available at the destination. This information is used to allocate the rates of all the sources following a Slow Link Adaptation (SLA) algorithm [8]. Following this model, different selection strategies have been proposed based on the methodology of choosing a single node at each retransmission time slot [7], [8]. The objective of the selection strategy is to maximize the ASE by applying the proper centralized scheduling for the sources and relays. Although the selection strategies used in [8] are promising, the selection is limited to a single sub-band (TDM mechanism). The drawback of the state-of-the-art is that the used time-orthogonality can cost a high latency for the system. Furthermore, the proposed algorithms in the prior-art are not applicable for the FDM mechanism. In [8] for example, the destination simply chooses the relay node having the best channel state with the destination (which gives the highest mutual information). In an FDM regime, such an algorithm does not take into consideration the power cost of allocating multiple sub-bands to a relaying node. The scheduling problem has to be investigated taking into consideration the varying power allocation per sub-band with respect to the number of allocated sub-band(s) per node. Accordingly, and following the Ultra Reliable Low Latency Communication (URLLC) aspect, and aiming at decreasing the transmission (and retransmission) time, FDM-based algorithms are introduced.

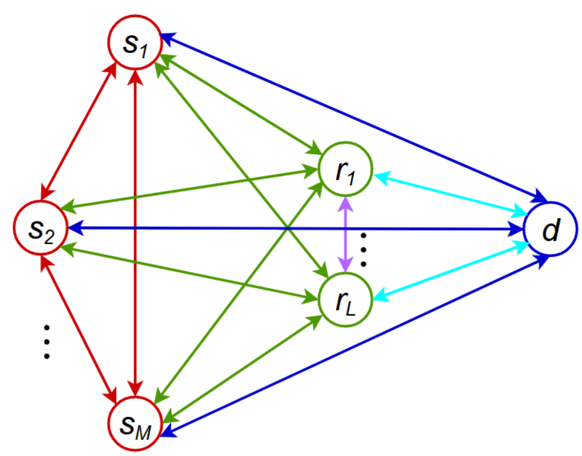

Fig. 1. The Multiple Access Multiple Relay Network (MAMRN) consists of a wireless network with multiple sources, multiple relays, and a single destination.

III. Proposed Selection Strategies

A. Utility Metric

In the proposed FDM-based orthogonal MAMRN, each time slot is composed of several frequency sub-bands, and each sub-band is made of a time-frequency grid corresponding to F resource elements made of consecutive Orthogonal Frequency Division Multiplexing (OFDM) symbols and consecutive sub-carriers set per OFDM symbols. As mentioned earlier, each source from the set of sources $\mathcal{S} = \{s_1, \ldots, s_M\}$ communicates with a common destination d with the help of the other cooperating sources and a set of relays $\mathcal{R} = \{r_1, \ldots, r_L\}$. We denote by $\mathcal{N} = \mathcal{S} \cup \mathcal{R} = \{1, \ldots, M + L\}$ the combined set of sources and relays, where the first M indices correspond to the sources, while the last L indices correspond to the relays; in other words, the source s_i is the i^{th} node in the set $\mathcal{N}$, and the relay r_i is the node $M+i$ in the set $\mathcal{N}$. We fix the number of sub-bands to B, and thus, the first $\lceil M/B \rceil$ time slots are reserved for transmission (first phase), while the other $T_{\max}$ time slots are dedicated for retransmissions (second phase). $\lceil q \rceil$ represents the ceiling function which gives the first integer greater than or equal to q. In each time slot, the number of channel uses is defined as: $N = B \times F$ resource elements. In the first phase, a scheduler at the destination decides which source node will be allocated to each different sub-band, with the constraint that at least one sub-band is allocated for each source. At a given time slot in the second phase, the scheduler decides which subset of relaying nodes will be active in the retransmission phase. The scheduler also allocates the partition of sub-bands given for each element of this active subset of nodes.

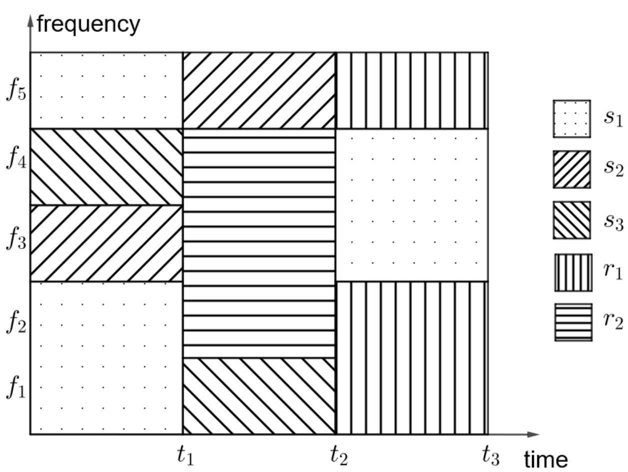

Fig. 2. Allocation of resources between sources and relays in transmission and retransmission phases.

We define the B-dimensional vector of selected nodes in the transmission and retransmission phase at a certain time slot t as $\mathbf{a}_t \in (\mathcal{S} \cup \mathcal{R})^B$. The i^{th} element $a_{t,i}$, of vector $\mathbf{a}_t$ refers to the i^{th} sub-band and the selected node active during this time slot in sub-band i. Similarly, we define the vector of number of allocated sub-bands for each node at a certain time slot t as the (M+L)-dimensional vector $\mathbf{n}_t \in \{0, 1, \ldots, B\}^{M+L}$. The i^{th} element $n_{t,i}$ of vector $\mathbf{n}_t$ refers to the number of sub-bands allocated for the node $i \in \mathcal{N}$ at time slot t. An example is given in fig. 2, where $M = 3$, $L = 2$, and $B = 5$. Following this example, the vector $\mathbf{a}_t$ is written as: $\mathbf{a}_0 = [s_1, s_1, s_2, s_3, s_1]$, $\mathbf{a}_1 = [s_3, r_2, r_2, r_2, s_2]$, and $\mathbf{a}_2 = [r_1, r_1, s_1, s_1, r_1]$; and the vector $\mathbf{n}_t$ is written as: $\mathbf{n}_0 = [3, 1, 1, 0, 0]$, $\mathbf{n}_1 = [0, 1, 1, 0, 3]$, and $\mathbf{n}_2 = [2, 0, 0, 3, 0]$. It can be seen that $\mathbf{n}_t$ can be directly deduced from $\mathbf{a}_t$.

The goal is to maximize the ASE (utility metric) $\eta^{\text{SLA}} = \mathbb{E}\{\eta^{\text{frame}}\}$, which is the expectation of the spectral efficiency per frame η^{frame}. η^{frame} depends on the channel realization $\mathbf{H}$, and the selection strategy used P. $\mathbf{H}$ contains the channel gains per sub-band of all the links $h_{f,a,b}$ where f is the sub-band, a a source or a relay, and b a source or a relay or the destination. The channel gains $h_{f,a,b}$ are independent and follow a zero-mean circularly symmetric complex Gaussian distribution with variance $\gamma_{a,b}$. Also, η^{frame} depends on the relaying protocols used, link adaptation considered (how rates are allocated based on the channel information, e.g., SLA), and the parameters of the system (e.g., $M, L, T_{\max}$). For simplicity, we only include within the following equations the dependency on the channel and the selection strategy. Now, η^{frame} can be defined as:

$$\begin{aligned} \eta^{\text{frame}}(\mathbf{H}, P) &= \frac{\text{nb bits successfully received}}{\text{nb channel uses}} \\ &= \frac{\sum_{i=1}^{M} R_i (1 - \mathrm{O}_{i,T_{\text{used}}})}{\lceil M/B \rceil + T_{\text{used}}} \end{aligned} \quad (1)$$

where

- $R_i = K_i/N$ is the rate of a source i, with K_i being the number of bits that can be transmitted by source i given N channel uses. R_i is allocated based on the SLA process.
- $\mathrm{O}_{i,T_{\text{used}}}$ is a binary Bernoulli random variable which indicates an outage event $\mathcal{O}_{i,t}$. In other words, $\mathrm{O}_{i,t}$ takes the value 1 if the event $\mathcal{O}_{i,t}$ happens, and 0 otherwise.
- $T_{\text{used}} \in \{0, \ldots, T_{\max}\}$ is the number of retransmission time slots activated in a frame.

B. Outage Events

The individual outage event $\mathcal{O}_{s,t}(\mathbf{a}_t, \mathcal{S}_{\mathbf{a}_t,t-1} | \mathbf{h}_{\text{dir}}, \mathcal{P}_{t-1})$, of a source s after time slot t, depends on the selected vector of nodes $\mathbf{a}_t$, the vector of number of allocated sub-bands $\mathbf{n}_t$, and the associated decoding sets $\mathcal{S}_{\mathbf{a}_t,t-1}$ (i.e., the set containing the sets of successfully decoded source messages in the previous time slots at the nodes selected to transmit redundancies at different sub-bands at time slot t). It is conditional on the knowledge of the channel realization of the direct links $\mathbf{h}_{\text{dir}}$ and on $\mathcal{P}_{t-1}$ which denotes the set collecting the vectors $\mathbf{a}_k$ and $\mathbf{n}_k$ that were selected in time slots $k \in \{1, \ldots, t-1\}$ prior to time slot t together with their associated decoding sets $\mathcal{S}_{\mathbf{a}_k,k-1}$, and the decoding set of the destination $\mathcal{S}_{d,t-1}$ ($\mathbf{a}_0$ is the selected vector of source nodes allocated in the transmission phase; $\mathbf{n}_0$ is the selected vector of number of sub-bands allocated for each source node in the transmission phase; and $\mathcal{S}_{d,0}$ is the destination's decoding set after the first phase). In the rest of the paper, and in order to simplify the notation, the dependency on $\mathbf{h}_{\text{dir}}$ and $\mathcal{P}_{t-1}$ is omitted. Analytically, and following the SU encoding case, where a selected relaying node $a_{l,f}$ only helps a random source node chosen from its decoding set which is not decoded yet at the destination (called $b_{l,f}$ such that $b_{l,f} \in \mathcal{S}_{a_{l,f},l-1} \cap \overline{\mathcal{S}}_{d,l-1}$), the individual outage using SU encoding of a source s can be written as:

$$\mathcal{O}^{SU}_{s,t}(\mathbf{a}_t, \mathcal{S}_{\mathbf{a}_t,t-1}) = \left\{ BR_s > \overline{\ell}^{(s)}_0 + \sum_{l=1}^{t-1} \overline{\ell}^{(s)}_l + \overline{\ell}^{(s)}_t \right\}, \quad (2)$$

where

- Index l is for the retransmission time slot with the convention that $l = 0$ corresponds to the end of the transmission phase; $l \in \{1, \ldots, T_{\max}\}$.
- $\overline{\ell}^{(s)}_l$ corresponds to the block fading mutual information from the nodes of $\mathbf{a}_t$ to the destination d allocated at time l over the whole sub-bands:

$$\overline{\ell}^{(s)}_l = \sum_{f=1}^{B} I_{l,f,a_{l,f},d} \left[s = b_{l,f} \right] \quad (3)$$

  where $b_{l,f} \in \mathcal{S}_{a_{l,f},l-1} \cap \overline{\mathcal{S}}_{d,l-1}$ is the selected source among the decoding set of node $a_{l,f}$, and $[q]$ represents the Iverson bracket which gives 1 if the event q is satisfied, and 0 otherwise.

$I_{l,f,a_{l,f},d}$ is the mutual information between node $a_{l,f}$ allocated to sub-band f at time slot l and the destination, and which is defined based on the channel inputs (check section IV for the Gaussian inputs example). The mutual information depends on the transmit power on sub-band f which is $\frac{P_T}{n_{l,a_{l,f}}}$ and the channel between $a_{l,f}$ and d, where P_T is the total power given for each node.

C. Selection Strategies

Here, rather than choosing a unique node to transmit/retransmit, a subset of nodes are chosen simultaneously. Due to the power distribution over the allocated sub-bands of each node, an optimal selection strategy needs to allocate the sub-bands jointly. In fact, in an exhaustive search strategy (optimal strategy), one can simply check all the possible combinations of vector allocations at all time slots. Conditional on the knowledge of the Channel State Information (CSI) of all the links in the network (the matrix $\mathbf{H}$), we can find the optimal activation sequence of vectors with respect to the considered utility metric. Since there are $T_{\max}$ retransmission time slots and $\lceil M/B \rceil$ transmission time slot, the complexity of this strategy is $(M+L)^{B(\lceil M/B \rceil + T_{\max})}$. Clearly, this strategy is computationally very expensive. In addition, we should stress that the knowledge of the CSI of all the links (the matrix $\mathbf{H}$) would cost an extremely large feedback overhead. Thus, this strategy is practically infeasible and is only considered as an upper bound to the proposed algorithms.

As the optimal solution costs a high complexity and heavy overhead, we propose a lower-complexity algorithm which does not need the full CSI of the channel. In strategy 1, we allocate the vector which maximizes the mutual information with the destination at each time slot. The idea of this strategy is to go through all the vector selection alternatives and find the one with the highest mutual information with the destination. In other words, we try all the possible values of the vector $\mathbf{a}_t$, and we select the one with the highest $\overline{\ell}_t$ where $\overline{\ell}_t = \sum_{f=1}^{B} I_{t,f,a_{l,f},d}$. Note that we do not take into consideration the nodes which cannot help any non-decoded source node, i.e., we only consider the nodes i satisfying $\overline{\mathcal{S}}_{d,t-1} \cap \mathcal{S}_{i,t-1} \neq \emptyset$, for $i \in \{1, \ldots, M+L\}$. Finally, the selection criterion at a time t has the following form:

$$\widehat{\mathbf{a}}_t \in \underset{\mathbf{a}_t \in \mathcal{H}^B}{\operatorname{argmax}} \left\{ \sum_{f=1}^{B} I_{t,f,a_{t,f},d} \right\} \quad (4)$$

where $\mathcal{H}$ is the set of nodes that can help at time slot t. Note that for $t = 0$, the only candidate nodes are the source nodes, where their decoding sets are exactly themselves. Other relay nodes have empty decoding sets. Algorithm 1 presents strategy 1, which as we can see faces a complexity issue, as the destination needs to exhaustively search all the allocation vectors belonging to $\mathcal{H}^B$. Since the cardinality of $\mathcal{H}$ is lower or equal to $L + M$, the complexity is upper bounded by $(M + L)^B$ operations, each operation being the sum of B mutual information terms.

Algorithm 1 Selection process of strategy 1: Highest Mutual Information

```
1: H ← ∅                              ▷ Empty set of candidate nodes
2: for all i in (S ∪ R) do            ▷ For every candidate node
3:     if S̄_{d,t−1} ∩ S_{i,t−1} ≠ ∅ then     ▷ If node i can help
4:         H ← H ∪ {i}
5:     end if
6: end for
7: â_t ← argmax_{a_t ∈ H^B} { Σ_{f=1}^{B} I_{t,f,a_{t,f},d} }
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As a lower complexity approach, we propose selection strategy 2. Here, rather than considering exhaustively all possible allocation vectors, we perform a sequential allocation per sub-band conditional on the increasing order of sub-bands. The active node selection for a given sub-band b is based on the computation of the cumulative mutual information up to that sub-band ($f = 1, \cdots, b$). Indeed, the transmit power per sub-band depends on the number of sub-bands each node (source or relay) occupies. As a result, the mutual information of each previously allocated sub-bands needs to be re-evaluated if the power constraint is modified. Then, after each sub-band selection, the number is incremented for the allocated node. Strategy 2 can be implemented at a given time t and sub-band b as:

$$\widehat{a}_{t,b} \in \underset{i \in \mathcal{H}}{\operatorname{argmax}} \left\{ \sum_{f=1}^{b-1} I_{t,f,\widehat{a}_{t,f},d} + I_{t,b,i,d} \right\} \quad (5)$$

where $\mathcal{H}$ is defined above. Strategy 2 is presented in algorithm 2. This algorithm reduces the complexity of algorithm 1 by removing partially the inter-dependency of sub-band allocations. The number of needed operations is upper bounded by $B(M + L)$ where each operation corresponds to an accumulated mutual information computation which has a lower or equal complexity than the sum of B mutual information terms.

Algorithm 2 Selection process of strategy 2: Highest Cumulative Mutual Information per Sub-band

$\mathcal{H} \leftarrow \emptyset$ ▷ Empty set of candidate nodes
for all i in $(\mathcal{S} \cup \mathcal{R})$ **do** ▷ For every candidate node
  if $\overline{\mathcal{S}}_{d,t-1} \cap \mathcal{S}_{i,t-1} \neq \emptyset$ **then** ▷ If node i can help
    $\mathcal{H} \leftarrow \mathcal{H} \cup \{i\}$
  end if
end for
$n_{t,i} = 1$ for all $i \in \mathcal{H}$ ▷ fix n_t to 1 for all candidate nodes
for $b = 1$ to B **do** ▷ At each sub-band
  $\widehat{a}_{t,b} \leftarrow \text{argmax}_{i \in \mathcal{H}} \left\{ \sum_{f=1}^{b-1} I_{t,f,\widehat{a}_{t,f},d} + I_{t,b,i,d} \right\}$
  $n_{t,i} = n_{t,i} + 1$ ▷ Increment the number of allocated sub-bands for the selected node $i = \widehat{a}_{t,b}$
end for

Note that the presented algorithms are applicable in the transmission and the re-transmission time slots. The only difference in the transmission phase is the presence of an additional constraint, that each source will be allocated at least 1 sub-band. Since relays' decoding sets are empty in the transmission phase, we only pass through all possible combinations of source nodes giving the highest mutual information.

D. Control Information Exchange

Fig. 3 describes the control information exchange process between the destination and the relay nodes. During the first phase, each source transmits its message at its dedicated sub-band(s) following the vector $\mathbf{a}_0$. Since the relays and sources are full-duplex, all nodes will be able to listen to the message vector $u_S = \{u_1, \ldots, u_M\}$. During the second phase, at the retransmission time slot t, the following control information exchange procedure occurs:

1) The destination broadcasts its decoding set $\mathcal{S}_{d,t-1}$ after the time slot $t-1$ over the feedback broadcast control channel. M bits are broadcasted in this step. If all the sources are included in the set $\mathcal{S}_{d,t-1}$ (i.e., the Cyclic Redundancy Check (CRC) succeeds), the process terminates, and a new frame transmission is initiated. Otherwise, the procedure continues through steps 2-4.
2) Each node which was able to decode at least one source message that is not included in the decoding set of the destination $\mathcal{S}_{d,t-1}$ sends one bit on a dedicated unicast forward coordination control channel.
3) The destination allocates the node vector $\mathbf{a}_t$ which has the highest mutual information with the destination following the strategy mentioned in the previous subsection. Only the nodes described in step 2 are candidates at this step.
4) Each element $a_{t,f} \in \mathbf{a}_t$ retransmits on its dedicated sub-band f. Each node performs SU encoding and chooses to help one source node from its decoding set.

In the following section, we compare the proposed strategies with three benchmark strategies: the exhaustive search strategy, and the strategies used in [7] and [8]. In [7], the selection strategy is based on minimizing the probability of the common outage event after each retransmission time slot. A common outage event is the event that at least one source node is in outage. Although the individual outage probability is lowered in this strategy (since $\Pr(\mathcal{O}_{s,T_{\max}}) \leq \Pr(\text{common outage})$), it is not minimized. In [8], the selection strategy is based on choosing the relaying node having the best channel with the destination at each time slot. Here (i.e., in the FDM regime), as we have several sub-bands, the selection using the strategy of [8] is repeated at each different sub-band. The drawback of this method is that it ignores the fact that one sub-band allocation may affect other sub-bands allocations.

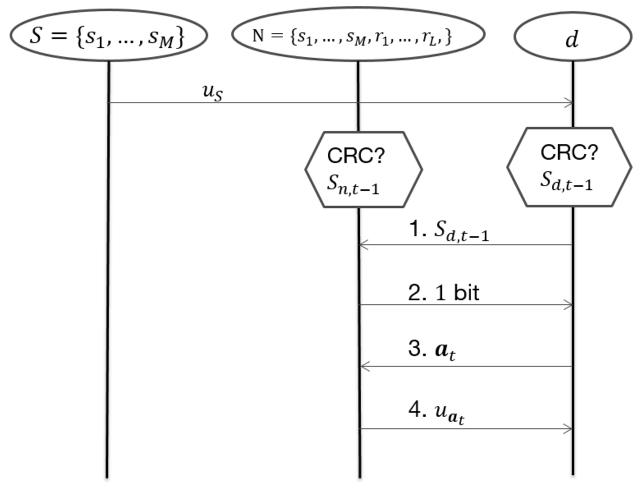

Fig. 3. Control information exchange.

IV. Numerical results

In this section, we validate the proposed selection strategies using Monte-Carlo simulations. We consider a (3,3,1)-MAMRN scenario, with 3 sub-bands per time slot. We set $T_{\max}$ to 1 following the goal of reducing the latency, although the results are similar with higher $T_{\max}$. The channel inputs are assumed independent and Gaussian distributed with zero mean and unit variance with $I_{t,f,a,b} = \log_2(1 + \frac{|h_{f,a,b}|^2}{n_{t,a}})$ being the mutual information between the transmitting node a and the receiving node b at a given sub-band f, where $n_{t,a}$ is the number of allocated sub-bands for the transmitting node a at time slot t. Note that other channel inputs might be considered without changing the conclusions of this work. 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), and all the rates are fixed to 0.5 bits/channel use (b/cu). On the other hand, in the asymmetric link configuration (fig. 5), we design a scenario where source 1 is in the best radio conditions and source 3 is in the worst radio conditions. Particularly, the links are set as follows: first, the average SNR of each link is set to γ; second, the average SNR of each link that includes source 2 is set to $\gamma - 1$dB and which includes source 3 is set to $\gamma - 1.5$dB; lastly, the average SNR of the link between the

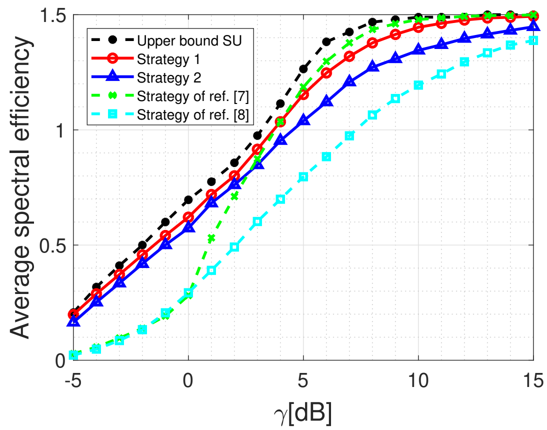

Fig. 4. ASE with symmetric link and rate configuration.

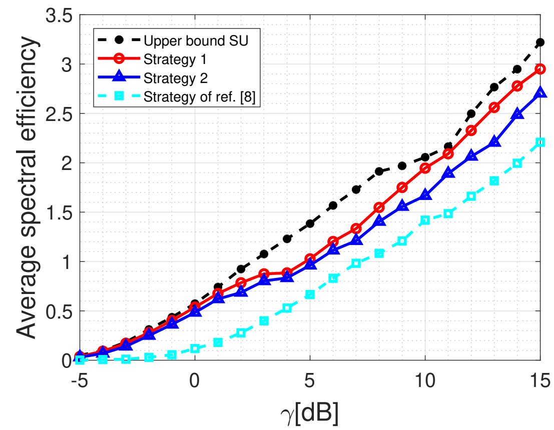

Fig. 5. ASE with asymmetric link and rate configuration.

sources 2 and 3 is set to $\gamma - 2$dB. Here, the rate allocation of each source is given using the SLA algorithm presented in [8] from the set of possible rates $\{0.75, 1, 1.25, 1.5\}$ b/cu, and thus, the rates are optimized based on the value of γ.

In fig. 4, we see the results of the five strategies in the symmetric link and rate scenario. For the considered SNR range (-5dB to 15dB), strategy 1 is approaching the upper bound with a shift less than 2 dB. Similarly, strategy 2 is approaching strategy 1 with approximately the same shift. Both proposed strategies (1 and 2) outperform the strategy used in [8] for all the SNR range with a significant shift. Finally, the strategy of ref. [7] outperforms that of ref. [8], but still faces a significant shift at low SNR values. In fig. 5, a similar performance is seen over the same SNR range (-5dB till 15dB) for the asymmetric link and rate scenario. The strategy of ref. [7] is left out of the simulations as it is only considered for the symmetric scenarios. For other strategies, we encounter a similar performance as in the symmetric scenario, where strategies 1 and 2 approach the upper bound and perform similarly, outperforming the strategy used in [8].

We have also investigated the performance of the proposed strategies while fixing γ and varying the number of relaying nodes (sources and relays). It is seen that as the network grows, the proposed strategies consistently outperform the existing methods. Moreover, it is seen that strategy 2 performs close to strategy 1 which validates the scalability of the low-complexity strategy 2. We omit presenting this figure due to size limitation.

We summarize our findings as follows: 1- The selection strategies used in the prior-art are not effective in the FDM-based orthogonal MAMRN. 2- The proposed strategy 1 achieves a performance that is close to that of the exhaustive search approach, while including no overhead for full CSI acquisition and reducing the complexity. 3- The sub-optimal strategy 2 represents a good trade-off between complexity/optimality, and can be practically used to reduce the complexity included in strategy 1. 4- the previous findings are valid with symmetric/asymmetric channel realizations and with fixed or optimally allocated rates.

V. Conclusion

In this paper, we presented an FDM-based orthogonal MAMRN. Using a two-phase system, we reduce latency trying to reach the requirements of URLLC. We defined the error events and the spectral efficiency utility metric, and proposed two low-complexity low-overhead selection strategies that aim at maximizing this metric. Then, we presented the control information exchange procedure. The proposed algorithms outperform the strategies used in the prior-art and achieve a spectral efficiency that is close to the upper bound while incurring no overhead for the full CSI acquisition and lowering the complexity. In future work, we might investigate the effect of parallel retransmissions of relaying nodes and work on reducing the control exchange process between the destination and the different nodes.

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