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A Resource Requirement Aware Transmit Strategy for Non-Regenerative Multi-Way Relaying

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***Abstract*—Non-regenerative multi-antenna multi-way relaying is considered. The scenario consists of a group of single-antenna nodes that want to communicate using multiple subcarriers. Each node has a message which every other node in the group should receive. The communications between the nodes are performed via a half-duplex multi-antenna relay station. It is assumed that the nodes have individual resource requirements. A new transmit strategy, in which the individual resources requirements of the nodes are considered, is proposed. To ensure that the relay station has enough spatial dimensions to separate the incoming signals, it is proposed that the number of transmitting nodes per subcarrier is equal to the number of antennas at the relay station. Moreover, it is proposed that the required numbers of subcarriers are calculated according to the buffer level of the nodes, reflecting the amount of data a node has to transmit. To allocate the required number of subcarriers to each node, the proposed transmit strategy performs an efficient subcarrier allocation. Numerical results show that the proposed strategy outperforms existing transmit strategies especially when the number of antennas at the relay station is smaller than the number of nodes.**

I. INTRODUCTION

In recent years, relaying has gained a lot of attention since it is a cost effective solution for increasing the coverage, throughput and robustness in wireless networks [1]–[5]. As stated in [5]–[7], applications like video conferences or multi-player gaming require the exchange of messages among a group of nodes, i.e., each node has to transmit its own message and has to receive the messages from the other nodes in the group. This exchange of messages can be performed via multi-way relaying [5]. In multi-way relaying, the nodes, of typically one group, exchange their messages via an intermediate relay station in one multiple access (MAC) phase and several broadcast (BC) phases. In the MAC phase, the nodes transmit to the relay station. Afterwards, in each BC phase, the relay station broadcasts processed versions of the messages back to the nodes.

Recent work on non-regenerative multi-way relaying has focused on designing transceive filters at the relay station to handle the interferences and to increase the sum rate [8]–[11]. In [8], [9], low complexity transceive filters at the relay station, such as zero forcing (ZF) and minimum mean squared error (MMSE) are presented. Pseudo random precoding at the relay station with an MMSE receiver with successive interference cancellation (SIC) at the nodes is introduced in [10]. Moreover, in [11], the sum rate is increased by efficiently combining spatial transceive processing at the relay station with joint receive processing at the nodes. However, when the number of antennas at the relay station is smaller than the number of nodes, the sum rate of these approaches is interference limited. This limitation is due to the fact that the relay station cannot fully separate the signals received from all the nodes.

In several applications, the resource requirements of the nodes are not equal. For example, in file sharing, a group of nodes is interested in a particular file. Each node in the group has part of the file and wants to exchange it with the other nodes. Hence, the required resources depend on the amount of data each node has to transmit. The aforementioned transmit strategies do not take into account the requirements of the nodes. In this paper, we propose a transmit strategy to consider the resource requirements of the nodes and to increase the sum rate when the number of antennas at the relay station is smaller than the total number of nodes in the system.

In contrast to the conventional multi-way strategies, where all the nodes transmit simultaneously, we propose that only part of the nodes transmit on each subcarrier. Moreover, to ensure that the same number of BC phases are required per subcarrier, the number of nodes which transmit on each subcarrier is kept equal. We propose that the number of nodes which transmit per subcarrier is equal to the number of antennas at the relay station to ensure that all the simultaneously received signals can be spatially separated. For the subcarrier allocation, we propose a sub-optimal low-complexity algorithm which considers the resource requirements of the nodes. For this algorithm, the resource requirements of the nodes are considered as subcarrier requirements. Considering [12], [13], the required number of subcarriers is determined according to the buffer level of each node. The proposed algorithm allocates the subcarriers such that the individual requirements are fulfilled and the overall sum rate is increased compared to the case when a random allocation is performed.

The paper is organized as follows. In Section II, the system model is explained. The proposed resource requirement aware transmit strategy, is introduced in Section III. In Section IV, the transceiver filter at the relay station and the receive filters at the nodes are described. The filters are based on the work of [11] but modified for the proposed transmit strategy. Numerical performance results of the proposed transmit strategy are presented in Section V and Section VI concludes the paper. [1]

[1] Throughout the paper, bold lowercase and uppercase letters denote vectors and matrices, respectively. Normal letters are used for scalar values. Matrix or vector transpose, complex conjugate and complex conjugate transpose are denoted by $(\cdot)^{\mathrm{T}}$, $(\cdot)^{*}$ and $(\cdot)^{\mathrm{H}}$, respectively. The Kronecker product is denoted by $\otimes$, and the Frobenius norm is denoted by $\|\cdot\|_2$. The operator $\mathrm{vec}(\cdot)$, stacks the columns of a matrix into a vector. The operator $\mathrm{vec}^{-1}_{M,N}(\cdot)$, divides an $MN \times 1$ vector into N vectors of length M and combines them into a $M \times N$ matrix. The operator $\mathrm{tr}(\cdot)$ denotes the sum of the elements in the main diagonal and $\mathbf{I}_M$ is the $M \times M$ identity matrix.

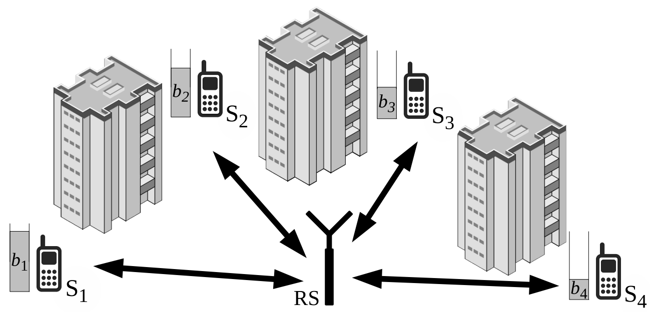

Fig. 1. Multi-way relaying scenario consisting of $K = 4$ single-antenna nodes with different buffer levels and a multi-antenna relay station, termed RS.

II. System Model

In this paper, single-group multi-way relaying is considered. As shown in Fig.1, the scenario consists of $K \geq 2$ single-antenna nodes that want to communicate over $C \geq 1$ orthogonal subcarriers. As mentioned before, each node has a message that all the others nodes have to receive. This type of scenario can be found in video conferences or multi-player gaming applications. The communications are performed via a half-duplex relay station, termed RS, which is equipped with $L \geq 2$ antennas. The term S_k, $k = 1, 2, ..., K$, is used to label the nodes. Additionally, the buffer level of node S_k is termed b_k, with b_k measured in bits and $b_1 \geq b_2 \geq ... \geq b_K$. It is assumed that the buffer level depends on the amount of data each node has to transmit and its value is updated after each transmission cycle of the multi-way scheme.

The maximum transmit power per subcarrier at the RS and at the nodes is P_{RS} and P_{MS}, respectively. The noise at the RS and at the nodes is assumed to be independent and identically distributed (i.i.d.) zero mean additive white Gaussian noise (AWGN) with variances σ^2_{RS} and σ^2_{n}, respectively. Perfect channel state information (CSI) is assumed at the RS and at the nodes. The required CSI can be obtained through channel training and estimation [11]. It is assumed that the nodes know the overall channel coefficients and can perform self-interference cancellation as well as SIC. Moreover, the RS is assumed to have perfect information about the buffer level of each node.

We propose a resource requirement aware (RRA) transmit strategy, in which the number of transmitting nodes on all the subcarriers is fixed and equal to $L \leq K$. Having the number of transmitting nodes equal to L ensures that the received signals at the RS can be spatially separated. The binary variable $\alpha_{k,c} \in \{0, 1\}$ is used to indicate if S_k is transmitting to RS on subcarrier c, $c = 1, 2, ..., C$, such that $\sum_{k=1}^{K} \alpha_{k,c} = L$. On each subcarrier, L nodes transmit to RS during the MAC phase. Afterwards, RS retransmits the received signals during L BC phases. In each BC phase, RS broadcasts one of the L received signals to all the K nodes. In total, $L + 1$ time slots are required for the communication on each subcarrier.

According to our proposal, that only L nodes transmit on each subcarrier, we assume that L spatial resources are available per subcarrier. Moreover, only one of these spatial resources can be allocated to one node because a node can only transmit once per subcarrier. Therefore, the total number of resources available in the system is given by the product CL. We propose to calculate the subcarrier requirement of each node, $C_{\mathrm{req},k}$, based on the buffer level of the nodes as

$$C_{\mathrm{req},k} = \begin{cases} \tilde{C}_{\mathrm{req},k} & \text{for } \tilde{C}_{\mathrm{req},k} < C \\ C & \text{for } \tilde{C}_{\mathrm{req},k} \geq C \end{cases}, \tag{1}$$

where $\tilde{C}_{\mathrm{req},k}$ is given by

$$\tilde{C}_{\mathrm{req},k} = \left[\frac{b_k}{\sum_{j=k}^{K} b_j} \left(CL - \sum_{j=1}^{k-1} C_{\mathrm{req},j} \right) \right], \tag{2}$$

and $[x]$ represents the nearest integer of x. By this approach, more subcarriers are allocated to the nodes which have a higher buffer level than to the nodes with a low buffer level. As $b_k \geq b_{k+1}$, the nodes with higher buffer levels are considered first, such that all the available resources can be distributed among the users. It has to be noticed that each $C_{\mathrm{req},k}$ depends on the required number of subcarriers of the nodes whose index is smaller than k, i.e. $C_{\mathrm{req},j}$, $j = 1, 2, ..., k-1$. For node S_1, $C_{\mathrm{req},1}$ only depends on the number of available resources since there is no other node with a smaller index. For the particular case where $b_k = b \; \forall k$ and $C = mK$ with $m \in \mathbb{N}$, Eq. (1) reduces to $C_{\mathrm{req},k} = \frac{CL}{K}$.

In the following, the system equations for the transmissions on subcarrier c are presented in the equivalent baseband. The channel $\mathbf{h}_{k,c} \in \mathbb{C}^{L\times 1}$, from node S_k to RS, is assumed to be constant during one transmission cycle of the multi-way scheme and channel reciprocity is assumed. During the MAC phase, if $\alpha_{k,c} = 1$, the signal transmitted by S_k on subcarrier c is given by $s_{k,c} \in \mathbb{C}^{1\times 1}$ with $\mathrm{E}[s_{k,c} s^{\mathrm{H}}_{k,c}] = P_{\mathrm{MS}}$. At RS, the received signal on subcarrier c is written as

$$\mathbf{y}_{\mathrm{RS},c} = \sum_{k=1}^{K} \alpha_{k,c} \mathbf{h}_{k,c} s_{k,c} + \mathbf{n}_{\mathrm{RS},c}, \tag{3}$$

where $\mathbf{n}_{\mathrm{RS},c} \in \mathbb{C}^{L\times 1}$ is the complex white Gaussian noise vector at the RS. In the subsequent L BC phases, RS broadcasts linearly processed versions of the received signals. The relay processing matrix on subcarrier c in BC phase t, $t = 1, ..., L$, is termed $\mathbf{G}_{c,t} \in \mathbb{C}^{L\times L}$, and it is given by

$$\mathbf{G}_{c,t} = \gamma_{c,t} \tilde{\mathbf{G}}_{c,t}, \tag{4}$$

where $\tilde{\mathbf{G}}_{c,t}$ is the relay processing matrix without fulfilling the power constraint at the RS and $\gamma_{c,t}$ is a scalar value used to satisfy the relay power constraint. $\gamma_{c,t}$ is given by

$$\gamma_{c,t} = \sqrt{\frac{P_{\mathrm{RS}}}{\mathrm{tr}\left[\tilde{\mathbf{G}}_{c,t} \left(\sum_{k=1}^{K} \alpha_{k,c} P_{\mathrm{MS}} \mathbf{h}_{k,c} \mathbf{h}^{\mathrm{H}}_{k,c} + \sigma^2_{\mathrm{RS}} \mathbf{I}_L \right) \tilde{\mathbf{G}}^{\mathrm{H}}_{c,t} \right]}}. \tag{5}$$

The received signal at node S_k on subcarrier c in BC phase t, is given by

$$y_{\mathrm{S}_{k,c,t}} = d_{k,c,t} (\mathbf{h}^{\mathrm{T}}_{k,c} \mathbf{G}_{c,t} \mathbf{y}_{\mathrm{RS},c} + n_{k,c,t}), \tag{6}$$

where $d_{k,c,t}$ is the receive filter coefficient at node S_k, and $n_{k,c,t} \in \mathbb{C}^{1\times 1}$ is the complex white Gaussian noise at S_k.

In order to consider SIC, let $\mathcal{N}_{k,c,t}$ be a set that contains the indices of the nodes whose signals are already decoded at S_k in BC phase t, i.e., the known interference. The index of the receive node S_k is also included in $\mathcal{N}_{k,c,t}$ to consider perfect self-interference cancellation. Additionally, let S_l be the node whose signal is broadcast by RS in BC phase t on subcarrier c. The power of the desired signal, interference and noise for the transmission of the signal $s_{l,c}$ from S_l to S_k in BC phase t on subcarrier c can be written as

$$P_{\mathrm{S},k,l,c} = \alpha_{l,c} P_{\mathrm{MS}} |d_{k,c,t} \mathbf{h}_{k,c}^{\mathrm{T}} \mathbf{G}_{c,t} \mathbf{h}_{l,c}|^2, \quad (7)$$

$$P_{\mathrm{I},k,l,c} = P_{\mathrm{MS}} \sum_{\substack{j=1 \\ j \notin \mathcal{N}_{k,c,t}}}^{K} \alpha_{j,c} |d_{k,c,t} \mathbf{h}_{k,c}^{\mathrm{T}} \mathbf{G}_{c,t} \mathbf{h}_{j,c}|^2, \quad (8)$$

$$P_{\mathrm{N},k,l,c} = \sigma_{\mathrm{RS}}^2 \| d_{k,c,t} \mathbf{h}_{k,c}^{\mathrm{T}} \mathbf{G}_{c,t} \|_2^2 + |d_{k,c,t}|^2 \sigma_{\mathrm{n}}^2, \quad (9)$$

respectively. With the definitions presented above, and assuming that Gaussian codebooks are used, the rate for the transmission of $s_{l,c}$ from S_l to S_k on subcarrier c is calculated as

$$R_{k,l,c} = \frac{1}{L+1} \log_2 \left(1 + \frac{P_{\mathrm{S},k,l,c}}{P_{\mathrm{I},k,l,c} + P_{\mathrm{N},k,l,c}} \right), \quad (10)$$

where $L+1$ is the number of time slots required for the overall exchange of messages. As all K nodes are receiving messages from the L transmitting nodes, the maximum rate for the transmission of one signal on one subcarrier is limited by the rate achieved by the weakest node. This is, the minimum $R_{k,l,c}$ among all nodes. Thus, the rate on subcarrier c is given by

$$R_c = \sum_{l=1}^{K} (K-1) \min_{\forall k, k \neq l} R_{k,l,c}, \quad (11)$$

where the factor $K-1$ accounts for the number of nodes receiving the message from S_l. The sum rate is then calculated as

$$R_{\mathrm{sum}} = \sum_{c=1}^{C} R_c. \quad (12)$$

III. Resource Requirement Aware (RRA) Transmit Strategy

In this section, the proposed transmit strategy is introduced. As mentioned before, in RRA, only L nodes transmit on each subcarrier during the MAC phase to ensure that the number of BC phases is the same on all the subcarriers. Furthermore, having L transmitting nodes per subcarrier ensures that there are enough dimensions to spatially separate the received signals at the RS. To simplify the description of the transmit strategy, let us consider the transmission on one subcarrier. In the first time slot, L nodes transmit to RS. In the remaining L time slots, RS retransmits linearly processed versions of the received signals back to the nodes. In each BC phase, one signal is considered as the desired signal and it is broadcast to all nodes. Consequently, all the L transmitted signals are considered as the desired signal in one of the BC phases. To simplify the notation, the order in which the desired signals are broadcast is determined according to the index of the nodes. This means, the transmitting node with the lowest index is considered first and the transmitting node with highest index is considered last.

TABLE I
Desired Signals and Interferences for RRA

		$t=1$	$t=2$	$t=3$
S_1	desired signal	-	S_2	S_4
	$\mathcal{N}_{1,1,t}$	S_1	S_1	S_1,S_2
S_2	desired signal	S_1	-	S_4
	$\mathcal{N}_{2,1,t}$	S_2	S_1,S_2	S_1,S_2
S_3	desired signal	S_1	S_2	S_4
	$\mathcal{N}_{3,1,t}$	S_3	S_1, S_3	S_1,S_2,S_3
S_4	desired signal	S_1	S_2	-
	$\mathcal{N}_{4,1,t}$	S_4	S_1,S_4	S_1,S_2,S_4

As SIC and self-interference cancellation are performed at the nodes, RS does not need to suppress signals that can be canceled at the nodes. Consequently, in each subsequent BC phase, the number of suppressed signals at the RS is reduced and the relay processing matrix is recalculated. In the first BC phase, $t=1$, the nodes only know the self-interference because no signals have been decoded. Therefore, the set $\mathcal{N}_{k,c,t}$ of Eq. (8), that contains the indices of the nodes that are the self- and known-interference of S_k on subcarrier c in BC phase t, contains only its own index k. In the subsequent BC phases, the nodes can use the already decoded signals to perform SIC. In each of these BC phases, $\mathcal{N}_{k,c,t}$ additionally includes the indices of the nodes decoded in the previous BC phases.

To illustrate the described strategy, let us consider a scenario with $K=4$ single-antenna nodes and RS equipped with $L=3$ antennas. Three nodes are transmitting to RS and four time slots are necessary for the communication. Table I shows a summary of the desired signals and known interferences in each BC phase. It is assumed that nodes S_1, S_2 and S_4 have been selected for transmission. In the MAC phase, S_1, S_2 and S_4 transmit to RS. Afterwards, in the first BC phase, $t=1$, RS broadcasts S_1 as the desired signal and suppress all the interferences given by the signals from S_2 and S_4. In $t=2$, the signal from S_2 is broadcast and the signal from S_4 is suppressed by RS. The signal from S_1 is not suppressed because the nodes have decoded it and can subtract it from the received signal. In the last BC phase, $t=3$, the signal from S_4 is broadcast. RS does not suppress any signal because all the interferences can be canceled at the nodes.

The transmit strategy explained so far does not take into account the resource requirements of the nodes. Therefore, if a random selection of nodes is performed, a node can get more resources than required and leave other nodes without resources for transmission. Given the subcarrier requirement of the nodes, we propose a low complexity sub-optimal resource allocation algorithm to select the subcarriers that will be

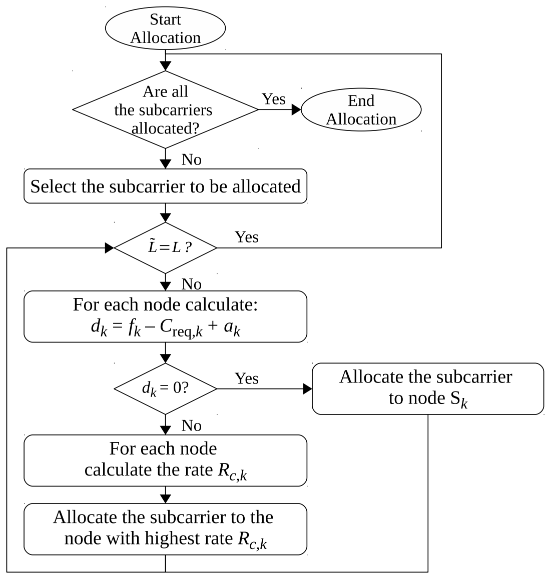

Fig. 2. Flow diagram of the resource allocation algorithm

allocated to each node. Two constraints have to be fulfilled while doing the allocation. This is, $C_{\mathrm{req},k}$ subcarriers should be allocated to each node and additionally, only L nodes should transmit on each subcarrier.

We propose to allocate the subcarriers in an iterative way. For each subcarrier, L nodes are selected based on the rate they can achieve. Let a_k be defined as the number of subcarriers already allocated to node S_k. Moreover, let f_k be the number of subcarriers available per node. In this context, a subcarrier is said to be "available for S_k" if the subcarrier has not been allocated to S_k and if it has been allocated to less than L nodes. Fig. 2 shows the flow diagram of the proposed algorithm. In the first step, subcarrier c is selected for allocation. Initially, $\alpha_{k,c} = 0 \ \forall k$. Without loss of generality, we propose to select the subcarriers according to the corresponding indices in increasing order. The subcarrier with index $c = 1$ is selected first and the subcarrier with index $c = C$ is selected last.

In the second step, the difference d_k between the number f_k of available subcarriers and the number $C_{\mathrm{req},k} - a_k$ of required subcarriers, is calculated for each node S_k. Given that $C_{\mathrm{req},k} > a_k$, d_k is calculated as

$$d_k = f_k - C_{\mathrm{req},k} + a_k. \tag{13}$$

In the third step, d_k is evaluated. The value d_k is used to prioritize the nodes that have a limited number of alternatives. If $d_k = 0$, the number of required subcarriers of node S_k is equal to the number of subcarriers that can be allocated to it. Therefore, in order to fulfill the requirements, subcarrier c has to be allocated to S_k, i.e., $\alpha_{k,c} = 1$. On the contrary, if $d_k > 0$, it is not mandatory to allocate subcarrier c to node S_k because there is at least one other possible subcarrier that can be allocated to it.

In the fourth step, given that $d_k > 0 \ \forall k$, the subcarrier allocation is performed based on the rate $R_{c,k}$ of each node. This is the rate that would be achieved on subcarrier c if it is allocated to S_k. In other words, the rate achieved if $\alpha_{k,c}$ would be set to one. Let $\tilde{L} < L$ be the number of nodes to which subcarrier c has been already allocated, i.e., $\sum_{l=1}^{K} \alpha_{l,c} = \tilde{L}$. $R_{c,k}$ is calculated for the $K - \tilde{L}$ remaining nodes using Eq. (11) considering the $\tilde{L}$ nodes to which c has been already allocated. For the calculation of each $R_{c,k}$, it is assumed that $\tilde{L}+1$ nodes are transmitting. The index k_{alloc} of the node with the highest $R_{c,k}$ is calculated as

$$k_{\mathrm{alloc}} = \underset{k}{\operatorname{argmax}} \ R_{c,k}. \tag{14}$$

Subcarrier c is allocated to the node with the highest $R_{c,k}$, i.e., $\mathrm{S}_{k_{\mathrm{alloc}}}$ and the corresponding $\alpha_{k_{\mathrm{alloc}},c}$ is set to one. The procedure described above is performed on all the subcarriers until all the nodes have obtained their respective number of subcarriers, $C_{\mathrm{req},k}$.

IV. Filters at the Relay Station and at the Nodes

In this section, the filters used at the RS and at the nodes are described. For the receive filters at the nodes, matched filters are considered. For RS, the processing matrix presented in [7] is used as a baseline and it is modified to consider that only L nodes transmit in the MAC phase.

A. Filters at the nodes

At the nodes, spatial receive filters are used to weigh and rotate the received signals and to reverse the channel rotations. The design of the relay processing matrix and the receive filter at the nodes is a joint optimization problem. To decouple the design, we assume, as in [11], that for the calculation of the spatial filters, $\mathbf{G}_{c,t}$ is an identity matrix. Consequently, the matched filter of node S_k for the reception of the desired signal on subcarrier c in BC phase t, with $\mathbf{G}_{c,t} = \mathbf{I}_L$, is given by

$$d_{k,c,t} = \frac{(\mathbf{h}_{k,c}^{\mathrm{T}} \mathbf{h}_{l,c})^{\mathrm{H}}}{|\mathbf{h}_{k,c}^{\mathrm{T}} \mathbf{h}_{l,c}|}, \tag{15}$$

where $\mathbf{h}_{l,c}$ is the channel vector of the node whose signal is being broadcast in BC phase t, i.e., the desired signal.

B. Transceiver Filter at the Relay Station

The relay transceiver filter of [7] minimizes the mean squared error in each BC phase. Let the signal $s_{l,c}$ from S_l be broadcast in BC phase t on subcarrier c. The estimate of $s_{l,c}$ on the receiving node S_k, denoted by $\hat{s}_{k,l,c}$, is calculated as

$$\hat{s}_{k,l,c} = \alpha_{l,c} d_{k,c,t} \mathbf{h}_{k,c}^{\mathrm{T}} \mathbf{G}_{c,t} \sum_{\substack{j=1, \\ j \notin \mathcal{N}_{k,c,t}}}^{K} \mathbf{h}_{j,c} s_{j,c} + n_{k,l,c}, \tag{16}$$

where $n_{k,l,c} = d_{k,c,t}(\mathbf{h}_{k,c}^{\mathrm{T}} \mathbf{G}_{c,t} \mathbf{n}_{\mathrm{RS},c} + n_{k,c,t})$ is the noise component of the received signal. $\hat{s}_{k,l,c}$ does not include the signals that are considered self- and known-interference since it is assumed that they can be canceled at the nodes.

Considering that only L nodes transmit on each subcarrier, the optimization problem of [7], for the calculation of $\mathbf{G}_{c,t}$, is rewritten as

$$\mathbf{G}_{c,t} = \underset{\mathbf{G}_{c,t}}{\arg\min}\, \mathbf{E}\left\{\sum_{k=1}^{K} |s_{l,c} - \hat{s}_{k,l,c}|^2\right\} \tag{17}$$

$$\text{s.t.} \sum_{l=1}^{K} \alpha_{l,c} P_{\text{MS}} \|\mathbf{G}_{c,t}\mathbf{h}_{l,c}\|_2^2 + \|\mathbf{G}_{c,t}\|_2^2 \sigma_{\text{RS}}^2 \leq P_{\text{RS}}. \tag{18}$$

The calculation of $\mathbf{G}_{c,t}$ follows the procedure described in [7]. The detailed derivation is omitted here and only the final results are presented. Let the matrix $\mathbf{\Upsilon}^{k,c}$ be given by [7]

$$\mathbf{\Upsilon}^{k,c} \;\; = \;\; \alpha_{k,c} P_{\text{MS}} \mathbf{h}_{k,c} \mathbf{h}_{k,c}^{\text{H}}. \tag{19}$$

Let also matrices $\mathbf{K}_{c,t}$ and $\mathbf{J}_{c,t}$ be defined as [7]

$$\begin{aligned} \mathbf{K}_{c,t} \;\; = \;\; & \sum_{k=1}^{K} \sum_{\substack{j=1, \\ j \notin \mathcal{N}_{k,c,t}}}^{K} \mathbf{\Upsilon}^{(j,c)^{\text{T}}} \otimes \left(\mathbf{h}_{k,c}^{*} \mathbf{h}_{k,c}^{\text{T}}\right) \\ & + \sum_{k=1}^{K} \left[\sigma_{\text{n,RS}}^2 \mathbf{I}_L \otimes \left(\mathbf{h}_{k,c}^{*} \mathbf{h}_{k,c}^{\text{T}}\right)\right] \\ & + \left(\sum_{k=1}^{K} \mathbf{\Upsilon}^{k,c^{\text{T}}} + \sigma_{\text{RS}}^2 \mathbf{I}_L\right) \otimes \frac{K\sigma_{\text{n}}^2}{P_{\text{RS}}} \mathbf{I}_L, \end{aligned} \tag{20}$$

$$\mathbf{J}_{c,t} \;\; = \;\; \sum_{k=1}^{K} \alpha_{l,c} P_{\text{MS}} \mathbf{h}_{k,c}^{*} d_{k,c,t}^{\text{H}} \mathbf{h}_{l,c}^{\text{H}}, \tag{21}$$

where k is the index of the receiving node and $\mathcal{N}_{k,c,t}$ contains the self- and known-interference of S_k in BC phase t. With the definitions above, the relay processing matrix, $\mathbf{G}_{c,t}$, is calculated as [7]

$$\mathbf{G}_{c,t} = \gamma_{c,t} \left[\text{vec}_{L,L}^{-1} \left(\mathbf{K}_{c,t}^{-1} \text{vec}\left(\mathbf{J}_{c,t}\right)\right)\right], \tag{22}$$

where $\gamma_{c,t}$ is given by Eq. (5).

V. Performance results

In this section, numerical results for the evaluation of the proposed transmit strategy are presented. It is assumed that $P_{\text{RS}} = P_{\text{MS}}$ and $\sigma_{\text{RS}}^2 = \sigma_{\text{n}}^2$. Moreover, it is assumed that the path-losses on the i.i.d. Rayleigh fading channels result in an average receive SNR at the RS of 15dB. For comparison, the following approaches are considered

- RRA:MMSE: Proposed RRA transmit strategy with the filters of Section IV at the RS and at the nodes.
- RRA:MMSE Random: Proposed RRA transmit strategy with the filters of Section IV at the RS and at the nodes and random subcarrier allocation, i.e., in the fourth step of the resource allocation algorithm of RRA, the selection based on the rate achieved by each node is replaced by a random selection.
- S-UCMC: Superimposed Unicast-Multicast (S-UCMC) transmit strategy with joint temporal processing at the nodes [11].
- Joint-Proc.: Random processing matrix at the RS and joint temporal processing at the nodes [10].

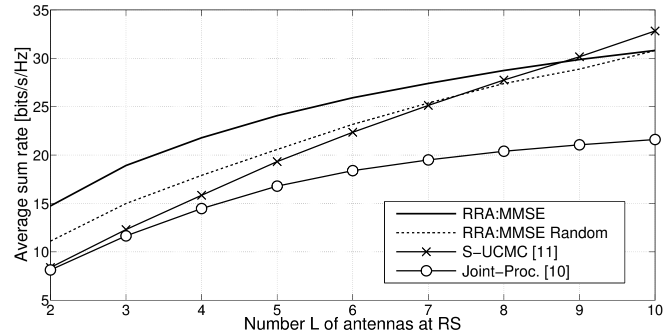

Fig. 3. Average sum rates versus different number of antennas at the RS. Scenario with $K = 10$ nodes, $C = 10$ subcarriers and average SNR = 15dB.

Fig. 3 shows the average sum rate versus the number L of antennas at the RS. The scenario consists of $K = 10$ single-antenna nodes and $C = 10$ subcarriers. The reference approaches, S-UCMC and Joint-Proc., do not consider individual resource requirements for the nodes. Therefore, for S-UCMC and Joint-Proc., all nodes transmit on all subcarriers simultaneously, i.e. the same number C of subcarriers is allocated to each node. To be able to compare the reference approaches with the proposed RRA strategy, the buffer level of all the nodes is assumed to be equal, i.e., $b_k = b \; \forall k$. Thus, according to Eq. (1), $C_{\text{req},k} = L$ for all nodes. This means, L subcarriers are allocated to each node. Assuming that the average channel conditions are equal for all the nodes, long-time fairness can be achieved among the nodes by allocating the same number of subcarriers to each node.

For the simulations, the overhead caused by the report of the buffer level status from the nodes to RS is assumed to be much smaller than the message size, and thus, is neglected. Moreover, all the considered strategies assume perfect CSI at the RS and nodes. Hence, the overhead caused by the transmission of the CSI is assumed to be equal for all the schemes and it is not considered for the calculation of the sum rate. A detailed evaluation of the impact of overhead on the different transmit strategies is beyond the scope of this paper and can be considered in a future work.

Results show that the sum rate is increased when RRA is used. The gain increases for decreasing number L of antennas at the RS. The reason is that for small L, S-UCMC and Joint-Proc. are interference limited. However, since in RRA:MMSE only L nodes are transmitting per subcarrier, the spatial dimensions available at the RS are used more efficiently and the received signal-to-interference-plus-noise ratio (SINR) at the nodes is higher than in S-UCMC or Joint-Proc. For example, for $L = 3$, the rate achieved by RRA:MMSE is approximately 54% higher than the rate achieved by S-UCMC and 62% higher than Joint-Proc. As the number of antennas at the RS increases, the gain of RRA:MMSE compared to S-UCMC is reduced. For $L = 8$ the gain is approximately 4% and for $L = 10$, S-UCMC achieves a higher rate. This is because for $L \geq K$ the number of transmitting nodes is equal to K for both approaches. However, the number of time

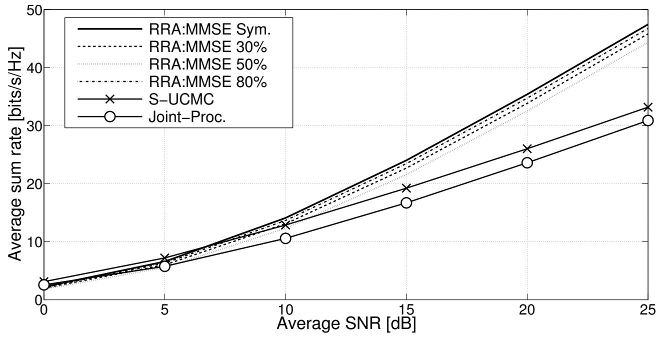

Fig. 4. Average sum rates versus average SNR at the RS. Scenario with $K = 10$ nodes, $C = 10$ subcarriers and $L = 5$ antennas at the RS.

slots required for the transmission is higher in RRA:MMSE compared to S-UCMC. The gain of RRA:MMSE compared to Joint-Proc. is maintained because the random relay processing matrix does not fully exploit the spatial processing capabilities at the RS.

Furthermore, Fig. 3 shows that with the proposed resource allocation algorithm a higher sum rate can be achieved compared to the random selection. For $L = 3$, the rate achieved by RRA:MMSE is approximately 26% higher than the rate of RRA:MMSE Random. In the proposed resource allocation algorithm, the nodes are selected based on the rate they can achieve on each subcarrier. In general, for the subcarrier allocation there is a trade-off between computational effort and sum rate. The minimum computational effort is achieved by the random selection, where the selection of the node to whom a given subcarrier is to be allocated, is performed in only one step, i.e., a node is selected randomly regardless of the rate it achieves. On the contrary, for RRA:MMSE, $C \sum_{l=0}^{L-1} (K - l)$ combinations have to be evaluated for the selection of one node. This is due to the fact that for RRA:MMSE the rate of each node is the selection criteria.

Fig. 4 compares the average sum rate versus the average SNR at the RS for different buffer levels at the nodes. The scenario consists of $K = 10$ nodes, $C = 10$ subcarriers and $L = 5$ antennas at the RS. To consider different buffer levels, it is assumed that some of the nodes have a full buffer while the rest of the nodes have an average buffer level equal to 10% of the buffer size. In Fig. 4, three different cases are considered, i.e. when 30%, 50% and 80% of the nodes have a full buffer. The symmetric case corresponds to equal buffer levels for all the nodes. Additionaly, the reference schemes S-UCMC and Joint-Proc. are included in the comparison. Results show that the proposed RRA strategy can achieve a higher sum rate compared to the reference schemes even when different buffer levels for the nodes are considered. The highest sum rate is achieved by the symmetric case. For non-equal buffer levels, the rate is reduced compared to the symmetric case. This is because for different buffer levels, the number of subcarriers allocated to each node differs from node to node. Therefore, the decision for allocating the subcarriers is not based solely on the rate each node is achieving on each subcarrier but it is constrained by the individual subcarrier requirements of each node.

VI. Conclusions

We have proposed a transmit strategy for non-regenerative multi-way relaying in a multi-carrier scenario. The strategy considers the resources requirements of the nodes as subcarrier requirements. The subcarrier requirements are determined according to the buffer level of each node. In the proposed strategy, only part of the nodes transmit on each subcarrier and for the allocation of the subcarriers, a low-complexity resource allocation algorithm is proposed. In the proposed strategy, the subcarriers are allocated based on the rate of each node. Results show that with the proposed transmit strategy, the sum rate is increased compared to existing approaches, especially when the number of antennas at the RS is smaller than the number of nodes.

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