Symbol Request Sharing Scheme for Mobile Cooperative Receivers in OFDM Systems

Yasser Samayoa, Jörn Ostermann
Institut für Informationsverarbeitung
Gottfried Wilhelm Leibniz Universität Hannover
30167 Hannover, Germany
Email: {samayoa, office}@tnt.uni-hannover.de

***Abstract*—In this paper, we introduce the symbol request sharing (SRS) cooperative scheme. Assuming a system with one source and several receivers, spatial diversity can be achieved by performing maximum ratio combining (MRC) on selected subcarriers of a coded OFDM-based system. The receivers are physically separated from each other and not restricted to be static. Furthermore, any receiver can be configured as a destination or as a relay. Systems with multiple receivers present some advantages compared to the traditional point-to-point communication. Additional degrees of freedom are available for improving the system performance by means of exploiting the spatial diversity inherent in any wireless communication. Nevertheless, traditional cooperation schemes designed for static relays may not be viable for mobile receivers. These may necessitate a higher cooperation overhead. SRS is a request-answer scheme, in which the destination requests symbols in specific subcarriers from the remaining receivers. It is shown that the proposed scheme can double the diversity gain given by other partial cooperation schemes and reaches the highest throughput by means of sharing a small percentage of received symbols.**

I. Introduction

Good performance at a high data rate has become a constant prerequisite for designing wireless communication networks. Such systems are always suffering from low throughput at boundaries where signal and interference levels are comparable. These aforementioned requirements call for additional efforts in the case where mobile receivers are considered. Cooperative communication is one of the promising topics to address these challenges.

The basic concept of cooperative diversity is to efficiently use a wireless communication system's available degrees of freedom provided by multiple receivers. Many copies of the same message on the destination side can be combined to improve the reliability of the system, i.e., exploiting space diversity by allowing some type of cooperation between the receivers. Research in cooperation in wireless communication has given clear results of enhanced coverage and reliability of the channel, e.g., the inclusion of relays for exploiting space diversity [1], [2], [3], [4]. However, many of these theoretical approaches for cooperation are still nonviable for practical systems. Among other issues and in most of the cases, the required additional time and synchronization make cooperation unattractive in real implementations. To address this, research into decreasing the cooperation time and reducing the overall complexity has been ongoing. In [5], [6], [7], [8] and [9], among others, relaying schemes have been investigated with the aim of reducing the cooperation time.

Some of the literature discusses cooperation protocols exploiting spatial diversity by implementing a maximum ratio combining (MRC) scheme. MRC increases the reliability of the communication, but it requires the exchange of all symbols and channel state information (CSI) for all nodes. For physically separated receivers, the cooperation overhead may increase dramatically. Strategies to reduce this overhead for inter-relaying cooperation protocols are the main focus of [7] and [9] but assuming static relays (source-to-relay channel does not change rapidly). They investigate partial MRC for static relays where the CSI is not frequently required. Nevertheless, the derived solutions of those works will not perform efficiently in scenarios with mobile receivers, which may necessitate a higher cooperation overhead to share CSI for every symbol. Therefore further investigation in this area is required.

In this paper, we propose the symbol request sharing (SRS) scheme for mobile cooperative receivers. The scheme is presented for systems with a distant source and several receivers near to each other but geographically separated. Consider as an example a cellular network in which a base station is communicating with a user equipment (UE) in a wagon of a moving train where other US's are prepared to assist the communication. The target of the communication is only one receiver, however, the remaining receivers may serve as relays. Moreover, the receivers are not restricted to be static. The main goal is to exploit the spatial diversity as much as possible by means of full MRC but with a reduced cooperation overhead. Further analysis and numerical simulations demonstrate the advantages of the proposed scheme.

The paper is structured as follows. In Section II, the system is described. Sections III summarizes previous work relevant to our investigation. Afterwards, Section IV and V are dedicated to the proposed cooperation schemes. Numerical results and performance comparisons for illustration are presented in Section VI, followed by a conclusion in Section VII.

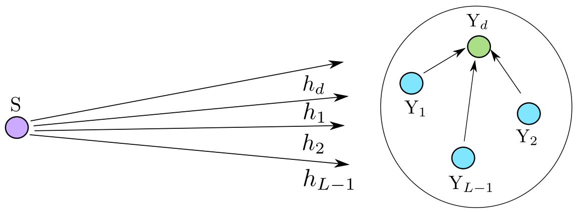

Fig. 1. System model, one source S and L receivers close to each other. S communicates a message to a destination node Y_d, all remaining receivers may serve as relays in order to assist Y_d in decoding the message. Independent channels $h_d, h_1, ..., h_{L-1}$ are assumed.

II. System Description

We consider a half-duplex wireless communication system with one source node S and a group of L receiver nodes Y_i, $i \in \mathbb{Y} = \{1, \ldots, L\}$. We are interested in increasing the reliability of the data transmission from S to any node $\{\mathrm{Y}_i\}$ configured as a destination by means of allowing a cooperation strategy between receivers. To this end, every receiver can be configured as a relay Y_r, where also $r \in \mathbb{Y}$. Referring to the Figure 1, S desires to transmit a message but only to a single receiver node denoted by $\mathrm{Y}_d, d \in \mathbb{Y}$. If Y_d cannot correctly decode the received message, the remaining nodes $\{\mathrm{Y}_r\}$, for all $r \in \mathbb{Y}_d = \mathbb{Y} \setminus \{d\}$ can serve to Y_d as relays in order to fix some transmission errors. Note that $|\mathbb{Y}_d| = L - 1$, i.e., it indexes all other receivers in the group except d.

We consider that S and every receiver node are equipped with a single antenna. Furthermore, the links from S to Y_i node and from the receiver node Y_a to the receiver node Y_b are denoted by Γ_i and Γ_{ab} respectively, where $i, a, b \in \{1, ..., L\}$ with $a \neq b$. The distances for these links are denoted by d_i and d_{ab} respectively, with

$$d_{ab} \ll d_i, \ \forall i, a, b. \tag{1}$$

Moreover, we assume that distances d_{ab} are short enough to consider a perfect wireless channel for Γ_{ab} links, i.e., no fading and a very high signal to noise ratio (SNR). On the other hand, the channels for the links Γ_i are assumed to be independent and identically distributed (i.i.d.), time-varying, frequency-selective multipath Rayleigh fading, with the same time and bandwidth coherence for all i.

In order to overcome the intersymbol interference (ISI) due to the frequency selectivity of the channels, we assume for Γ_i a coded Orthogonal Frequency Division Multiplexing (OFDM) communication scheme. An ideal synchronization in both frequency and time is assumed by using special training symbols in the preamble. The length for the cyclic prefix is configured to be equal or longer than the overall channel impulse response. At S, the information bit vector $\mathbf{b} \in \{0, 1\}^{1 \times k}$ is encoded and interleaved by a random interleaver, resulting in the codeword $\mathbf{c} \in \{0, 1\}^{1 \times n}$. We consider a rate-compatible punctured convolutional (RCPC) code, with a mother code rate $R_{\mathrm{c,m}} = k/m$, the effective code rate $R_{\mathrm{c}} = k/n$, and a total of n_{p} punctured bits. Finally, $\mathbf{c}$ is mapped into $\mathbf{x} \in \mathbb{M}^{1 \times N_{\mathrm{c}}}$, where $\mathbb{M} \subset \mathbb{C}$ is the constellation set of M-QAM symbols and N_{c} the total number of OFDM subcarriers. Subsequently, the vector $\mathbf{x}$ is transmitted by S to Y_i over the channel. Thus, the received signal $y_{i,k}$ at Y_i on the k-th subcarrier in the discrete frequency domain can be expressed as

$$y_{i,k} = h_{i,k} \cdot x_k + n_{i,k}, \text{ with } k \in \mathbb{K}, \tag{2}$$

where $h_{i,k} \sim \mathcal{CN}(0, \nu)$ denotes the Rayleigh distributed fading coefficient, $\nu = \mathrm{E}\{|h_{i,k}|^2\} = 1$ is the variance, $\mathbb{K} = \{1, \ldots, N_{\mathrm{c}}\}$ the set of subcarrier indexes, and $n_{i,k}$ denotes the additive complex Gaussian noise term satisfying $n_{i,k} \sim \mathcal{CN}(0, \sigma_{\mathrm{n}}^2)$ with zero mean and variance σ_{n}^2.

We assume a perfect knowledge of the channel state information (CSI), $\mathbf{h}_i = [h_{i,k}]_{k=1}^{N_{\mathrm{c}}}$, of Γ_i link at receiver Y_i but not at S. Therefore, the total transmit power at the source is denoted by $\mathcal{P}_{\mathrm{S}} = N_{\mathrm{c}} \cdot \mathcal{P}_{\mathrm{S},k}$, where $\mathcal{P}_{\mathrm{S},k} = \mathrm{E}\{|x_k|^2\}$ is the average transmit power on the subcarirer k. Using CSI, each receiver estimates its symbol vector $\tilde{\mathbf{x}}_i = [\tilde{x}_{i,k}]_{k=1}^{N_{\mathrm{c}}}$ on the k-th subcarrier by means of equalizing the vector $\mathbf{y}_i = [y_{i,k}]_{k=1}^{N_{\mathrm{c}}}$. The vector $\tilde{\mathbf{x}}_i$ is demapped, decoded and de-interleaved resulting in the vector of information bits $\tilde{\mathbf{b}}_i$.

III. Previous Work

A brief introduction to maximum ratio combining (MRC) is given and afterwards, the generalized selection combining (GSC) scheme is presented. These two schemes give full and partial cooperation between all receivers in $\mathbb{Y}$, respectively. We consider the special case introduced in Figure 1.

A. Maximum Ratio Combining

It is well known, that with MRC $\forall i, [y_{i,k}]$ can be combined in such a manner that the SNR is maximized on a particular subcarrier k. In the case of OFDM systems as the one described in (2), the combination can be performed in the frequency domain on the k-th subcarrier as follows:

$$\begin{aligned} y_{\mathrm{MRC},k} &= \sum_{i=1}^{L_{\mathrm{MRC}}} h_{i,k}^* \cdot y_{i,k} \\ &= \sum_{i=1}^{L_{\mathrm{MRC}}} |h_{i,k}|^2 \cdot x_k + \sum_{i=1}^{L_{\mathrm{MRC}}} h_{i,k}^* \cdot n_{i,k}, \end{aligned} \tag{3}$$

where L_{MRC} is the number of signals to be combined. If the signals of all available receivers are combined, i.e., $L_{\mathrm{MRC}} = L$, full MRC is achieved and the system can be considered as a virtual single-input multiple-output (SIMO) system. If $1 < L_{\mathrm{MRC}} < L$ only a subset of $\mathbb{Y}$ is taken into account and a partial MRC is achieved. With $L_{\mathrm{MRC}} = 1$, no diversity is gained and the system turns to a single-input single-output (SISO) system. Moreover, in (3) the modification of the noise power in the k-th subcarrier by the influence of the L_{MRC} channel coefficients can be noticed. This noise power must be compensated by

$$\sigma_{\mathrm{MRC},k}^2 = \sigma_n^2 \sum_{i=1}^{L_{\mathrm{MRC}}} |h_{i,k}|^2. \tag{4}$$

In order to fully exploit spatial diversity on an OFDM symbol, all $k \in \mathbb{K}$ and $L_{\text{MRC}} = L$ must be considered in (3), i.e., the total number of combined symbols would be $L \cdot N_\text{c}$. This gives the highest diversity in an OFDM symbol but at the cost of increasing the cooperation overhead, as well as the time and the transmit power at each relay. Considering the case in Figure 1, the total time for MRC consists in the time required for communicating the symbols and the CSI of every relay in $\mathbb{Y}_d$ to the destination node Y_d. Thus, let T_s and M_co denote the time and the M-QAM modulation order for the symbol transmission in any Γ_ab link respectively. The total time of the cooperation overhead can be computed by

$$t_{\text{MRC}} = \frac{T_\text{s}}{\log_2(M_\text{co})} \cdot 2 \cdot N_\text{c} \cdot (L-1) \cdot (Q + Q_\alpha) \,. \tag{5}$$

Since symbols and channel coefficients are complex numbers, both the real and imaginary parts are quantized. This is considered with the factor 2 in (5). Moreover, a quantizer with Q bits of resolution is assumed for the $N_\text{c} \times (L-1)$ channel coefficients, and a $Q_\alpha = \log_2(M_\text{co}) \cdot Q$ bits resolution quantizer is assumed for the $N_\text{c} \times (L-1)$ symbols, where the factor $\log_2(M_\text{co})$ compensates any modulation order. Note that the channel coefficients and the symbols of the destination node Y_d must not be relayed.

The time given in (5) is constant and dependent on the parameters of the system. In order to reduce this time, an appropriate trade-off between spatial diversity degree and extra cooperation overhead must be investigated. This is the topic of the next section, where a scheme will be presented in order to reduce the cooperation overhead by efficiently selecting the receivers and the subcarriers where MRC should be performed.

B. Generalized Selection Combining Scheme

The generalized selection combining (GSC) scheme was introduced in [7] and an application for an inter-relay cooperation system was investigated in [9]. Its aim is to reduce the cooperation overhead by selecting only α of $L \cdot N_\text{c}$ symbols to be possibly shared among the receivers. The number of receivers serving as relays on each subcarrier is limited to 1, and the active relays are set to $0 \leqslant \alpha \leqslant N_\text{c}$. The first limit ensures that only one symbol on the k-th subcarrier can be relayed, and the second limit ensures a reduction from N_c potential symbols to only α. The goal from the GSC scheme is to share the "best" α symbols. With "best" symbols is understood that under the limits stated before, only the symbols conveyed trough the channels with the highest $|h_{i,k}|^2$ are selected. Thus, let $y_{r,k}$ be the symbol relayed from Y_r on the k-th subcarrier, $r \in \mathbb{Y}$. This symbol is selected due to the fact that $|h_{r,k}|^2 > |h_{i,k}|^2$, for all $i \in \mathbb{Y} \setminus \{r\}$. Consequently, the symbol vector $\mathbf{y}_{\text{GSC},d} = [y_{\text{GSC},d,k}]_{k=1}^{N_\text{c}}$ at the receiver Y_d after cooperation, is

$$y_{\text{GSC},d,k} = \begin{cases} h^*_{d,k} \cdot y_{d,k} + h^*_{r,k} \cdot y_{r,k} & \text{if } g_k = 1 \\ y_{d,k} & \text{else} \end{cases} \,, \tag{6}$$

and the noise power regarding (4) is computed by

$$\sigma^2_{\text{GSC},d,k} = \begin{cases} \sigma^2_n \cdot (|h_{d,k}|^2 + |h_{r,k}|^2) & \text{if } g_k = 1 \\ \sigma^2_n & \text{else} \end{cases} \,, \tag{7}$$

where the flag $g_k \in \{1, 0\}$, for all $k \in \mathbb{K}$ simply denotes whether a relay is active or not, i.e., $g_k = 1$ if $h_{r,k}$ belongs to the set of the α largest $|h_{r,k}|^2$.

An important fact of the GSC scheme to note is that the selection of the symbols is done by means of comparing the CSI of all receivers on each subcarrier. Thus, for the selection procedure each receiver first broadcasts its $\mathbf{h}_i$ vector. Therefore, all receivers must have the $L \times N_\text{c}$ CSI matrix

$$\mathbf{H}_{i,k} = \begin{bmatrix} h_{1,1} & h_{1,2} & \cdots & h_{1,N_\text{c}} \\ h_{2,1} & h_{2,2} & \cdots & h_{2,N_\text{c}} \\ \vdots & \vdots & \ddots & \vdots \\ h_{L,1} & h_{L,2} & \cdots & h_{L,N_\text{c}} \end{bmatrix} , \tag{8}$$

before proceeding with the symbol exchange. It is important to stress here, the time required for the communication of $\mathbf{H}$ impacts the total cooperation time independently of α.

The total time for the GSC cooperation scheme can be divided in two, the time required for communicating the CSI matrix given in (8) and the time required for the symbol sharing. The total time of the cooperation overhead can be computed in analogy to (5), i.e.,

$$t_{\text{GSC}} = \frac{T_\text{s}}{\log_2(M_\text{co})} \cdot 2 \cdot (N\text{c} \cdot L \cdot Q + \alpha \cdot Q_\alpha) \,. \tag{9}$$

In (9), it is clear that the time required for communicating the CSI matrix $\mathbf{H}^{N_\text{c} \times L}$ is constant and it is the cost of selecting α of $N_\text{c} \cdot L$ symbols for the cooperation strategy. However, due to the fact that we are considering the case where only one receiver is configured as the destination Y_d, the cooperation overhead can be slightly reduced. The matrix in (8) can be reduced to a $(L-1) \times N_\text{c}$ matrix. This is the small variant that we introduce in the next section.

IV. Modified Generalized Selection Combining Scheme

To achieve a further reduction of the cooperation overhead we slightly adapt the GSC scheme. We denote this variation by modified-GSC (mGSC). We consider $d \in \mathbb{Y}$ and $r \in \mathbb{Y}_d$. Any receiver can be configured as Y_d but automatically the remaining receivers serve as relays. If only one receiver is configured as the destination Y_d, which is the case investigated in this paper, the transmission of $\mathbf{h}_d$ is avoided. Since $\mathbf{h}_d$ is not included in the matrix, α symbols will be chosen taking into account only the relays indicated in $\mathbb{Y}_d$. This case saves some cooperation overhead, but with a small risk that occasionally Y_d receives a symbol in the k-th subcarrier even if it is not necessary, i.e., if $|h_{d,k}|^2 > |h_{r,k}|^2$. Consequently, the symbol vector $\mathbf{y}_{\text{mGSC},d} = [y_{\text{mGSC},d,k}]_{k=1}^{N_\text{c}}$ at the receiver Y_d after cooperation, is calculated as in (6). The only difference here is, thus, that the CSI matrix given in (8) reduces to a $N_\text{c} \times (L-1)$

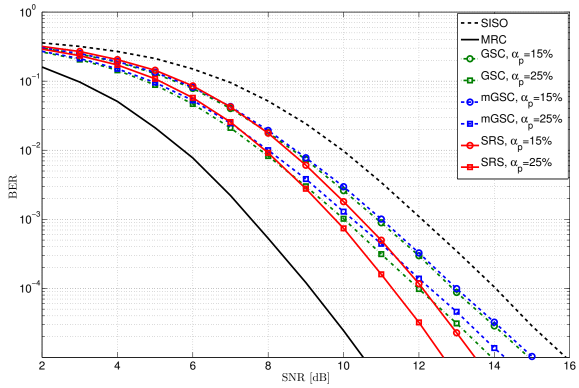

Fig. 2. The resulting BER comparison after cooperation. GSC, mGSC and SRS are considered with $L = 2$ receivers, $\alpha_{\text{p}} = \alpha/N_{\text{c}} = \{15, 25\}$ %, an OFDM symbol with $N_{\text{c}} = 1024$ subcarriers with $16-$QAM modulation.

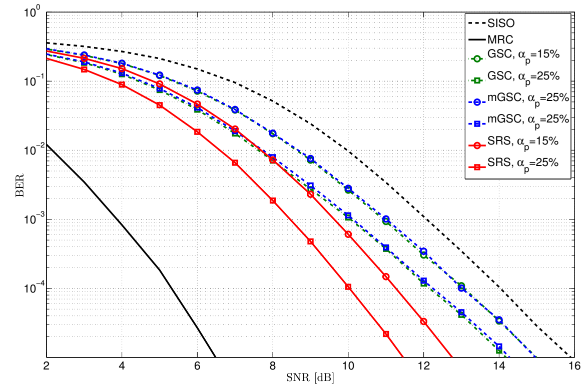

Fig. 3. The resulting BER comparison after cooperation. GSC, mGSC and SRS are considered with $L = 4$ receivers, $\alpha_{\text{p}} = \alpha/N_{\text{c}} = \{15, 25\}$ %, an OFDM symbol with $N_{\text{c}} = 1024$ subcarriers with $16-$QAM modulation.

matrix. Therefore, the total time for the mGSC cooperation scheme can be derived in analogy to (9) but considering a $N_{\text{c}} \times (L-1)$ CSI matrix

$$t_{\text{mGSC}} = \frac{T_{\text{s}}}{\log_2(M_{\text{co}})} \cdot 2 \cdot (N\text{c} \cdot (L-1) \cdot Q + \alpha \cdot Q_\alpha) . \quad (10)$$

In the next section, we introduce a new scheme which provides a different strategy for a cooperative communication and a symbol sharing on the receiver side.

V. Symbol Request Sharing

The goal of the symbol request sharing (SRS) scheme is to share a "better" symbol $y_{r,k}$, which is requested by the receiver Y_d from the relay Y_r, where $d \in \mathbb{Y}$ and $r \in \mathbb{Y}_d$, with $\mathbb{Y}_d = \mathbb{Y} \setminus \{d\}$. We define "better" symbol in the sense that the probability that $|h_{r,k}|^2 > |h_{d,k}|^2$ is greater than the opposite case. Thus, the SRS scheme exploits the fact that

$$(P_{\text{fad}})^L << P_{\text{fad}} , \quad (11)$$

where P_{fad} is the probability that a symbol is deteriorated by a channel in deep fade. In other words, given a k-th subcarrier, the probability of finding L independent channels in deep fade is much lower than the probability of finding one channel in deep fade. The SRS scheme selects the symbols to request as follows. The destination Y_d compares and identifies $0 \le \alpha \le N_{\text{c}}$ coefficients in $\mathbf{h}_d$ with the lowest power among the N_{c} coefficients and stores their indexes in $\mathbb{K}_d = \{v_{d,j}\}_{j=1}^{\alpha} \subseteq \mathbb{K}$. Y_d requests from all $L-1$ relays their respective symbols in the $(v_{d,j})$-th subcarrier, i.e., $y_{r,k}$ for all $k \in \mathbb{K}_d$ and for all $r \in \mathbb{Y}_d$. For each symbol request, there are $L-1$ replies. Consequently, the symbol vector $\mathbf{y}_{\text{SRC},d} = [y_{\text{SRC},d,k}]_{k=1}^{N_{\text{c}}}$ at the receiver Y_d after cooperation by means of (3), is

$$y_{\text{SRS},d,k} = \begin{cases} h^*_{d,k} \cdot y_{d,k} + \sum\limits_{r=1}^{L-1} h^*_{r,k} \cdot y_{r,k} & \text{if } k \in \mathbb{K}_d \\ y_{d,k} & \text{else} \end{cases} , \quad (12)$$

and the noise power regarding (4) is computed by

$$\sigma^2_{\text{SRS},d,k} = \begin{cases} \sigma_n^2 \cdot \left(|h_{d,k}|^2 + \sum\limits_{r=1}^{L-1} |h_{r,k}|^2 \right) & \text{if } k \in \mathbb{K}_d \\ \sigma_n^2 & \text{else} \end{cases} . \quad (13)$$

It follows from (12) that all receivers can serve as relays for each of the α selected subcarriers. Therefore, full MRC is accomplished on the subcarriers in $\mathbb{K}_d$, in contrast to the GSC in which only partial MRC on the α selected subcarriers is achieved. Another important difference is that in mGSC the best symbol is shared while in SRS the better symbol is shared. In SRS, symbols are selected to maximize the SNR on subcarriers with the lowest power. Nevertheless, as for mGSC, these advantages come at the cost of a cooperation overhead. Note also that for SRS in (12) not only the requested symbols but also the channel coefficients are relayed. Therefore, the cooperation time is directly proportional to the parameter α.

In analogy to GSC, the total time for the SRS cooperation scheme can be divided in the time required to send all the indexes in $\mathbb{K}_d$ (request) and the time for the symbol and CSI sharing (answer). T_{s} and M_{co} denote the time and the M-QAM modulation order for the symbol transmission in any Γ_{ab} link respectively. Thus, the total time of the SRS cooperation overhead is then

$$t_{\text{GSC}} = \frac{T_{\text{s}} \cdot (N_{\text{c}} + \alpha \cdot 2 \cdot (L-1) \cdot (Q + Q_\alpha))}{\log_2(M_{\text{co}})} , \quad (14)$$

where Q bits of resolution are assumed for the channel coefficients, and a $Q_\alpha = \log_2(M_{\text{co}}) \cdot Q$ bits resolution quantizer is assumed for every symbol, with the factor $\log_2(M_{\text{co}})$ to compensate any modulation order. Moreover, the method used to communicate the indexes can be selected depending on α. Two methods can be identified for this purpose. The first is to assign $\log_2(N_{\text{c}})$ bits to address each index if the condition $(\alpha) \cdot \log_2(N_{\text{c}}) < 1$ is fulfilled. If it is not the case, the second

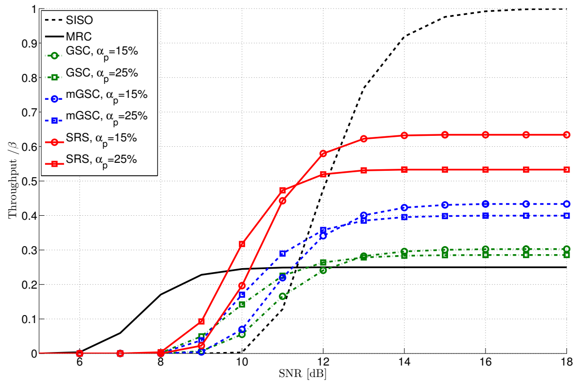

Fig. 4. Normalized throughput comparison between GSC, mGSC and SRS, with $L = 2$ receivers, $\alpha_\text{p} = \alpha/N_\text{c} = \{15, 25\}$ %, an OFDM symbol with $N_\text{c} = 1024$ subcarriers with 16−QAM modulation, and bandwidth β.

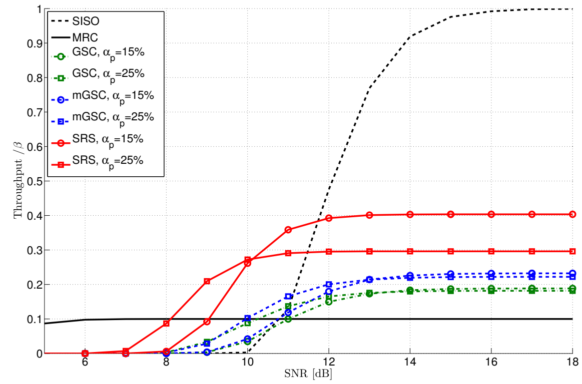

Fig. 5. Normalized throughput comparison between GSC, mGSC and SRS, with $L = 4$ receivers, $\alpha_\text{p} = \alpha/N_\text{c} = \{15, 25\}$ %, an OFDM symbol with $N_\text{c} = 1024$ subcarriers with 16−QAM modulation, and bandwidth β.

method consist in utilizing only one bit for each subcarrier for communicating the indexes in $\mathbb{K}_d$, i.e., with a 1 if the subcarrier is selected and with a 0 otherwise. The second method is considered in (14). Therefore, only N_c bits are required for the index request which is the cost of just selecting α subcarriers for the cooperation strategy. Further, for every index requested, $(L-1)$ symbols and channel coefficients are relayed and thus obtaining full MRC in Y_d for every subcarrier in $\mathbb{K}_d$.

VI. Performance Analysys

In this section, the performance of the proposed scheme SRS is evaluated. The performance of mGSC is also analyzed and used as a benchmark.

A. Throughput

In order to measure not only the diversity gain but also the extra time required for the cooperative scheme, throughput analysis is introduced. This gives the ratio between the amount of information bits correctly received and the time required to its communication. Thus, the throughput is defined as

$$\xi = \frac{N_\text{c} \cdot \log M \cdot R_\text{c}}{t_\text{SY} + t_\text{co}} \cdot (1 - \text{FER}_d) \ , \tag{15}$$

where t_SY is the time incurred in the transmission of a OFDM symbol from S to Y_i, $t_\text{co} \in \{t_\text{MRC}, t_\text{GSC}, t_\text{mGSC}, t_\text{SRS}\}$ the cooperation time given in (5), (9), (10) and (14) respectively, and FER_d the frame error rate at Y_d. FER_d is estimated by simulation.

B. Parameter Settings

The proposed cooperation scheme is evaluated using the Monte-Carlo simulation method. We assume an OFDM system with $N_\text{c} = 1024$ subcarriers with β/N_c inter-carrier spacing, where β is the bandwidth assumed for the links Γ_i and Γ_ab. We consider M-QAM modulation for the Γ_i link, where $M = \{16\}$. A convolutional encoder with a non-systematic codeword and a constraint length set to 4 is used at the source. The mother codeword rate is set to $R_\text{c,m} = 1/3$, with punctured bits $n_\text{p} = m/3$, therefore the effective codeword is $R_\text{c} = 1/2$. A BJCR convolutional decoder with a generator polynomial $[13,15,11]_8$ is employed at Y_d. We consider a system with $L = \{2, 4\}$ receivers. By taking (1) into account, a perfect channel (error-free) is assumed for the Γ_ab links, with a modulation scheme set to 256-QAM, i.e. $M_\text{co} = 256$. For clarity, we denote $\alpha_\text{p} = \alpha/N_\text{c}$ and set it to 15 % and 25 %. At the destination node Y_d, the bit error rate (BER) and frame error rate (FER) are measured.

C. Simulation Results

Several plots of the bit error rate (BER) are depicted in Figures 2 and 3. The SISO plot shows a single-input single-output system, and it denotes the case where no cooperation is performed. MRC is the plot referring to full cooperation given in (3), which is the case when all $N_\text{c} \cdot L$ symbols and channel coefficients are combined. It can be noticed that GSC and mGSC have a similar performance, although GSC performs slightly better. The reason for this similarity lies in the selection criteria. Contrary to mGSC, GSC takes the CSI of Y_d into account for selecting the symbols among the relay nodes. Therefore, GSC ensures a higher diversity gain on each selected subcarrier. In the mGSC scheme, Y_d may unnecessarily receive a symbol on subcarriers even if it has the best channel conditions. This case occurs with a probability of $1/L$. Consequently, this fact is less remarkable when L increases which can be corroborated in Figure 3. Furthermore, the SRS scheme outperforms the mGSC and GSC for higher SNR's. With just sharing 25% of $N_\text{c} \cdot L$ symbols at a BER of 10^{-5} and with $L = 2$, it is shown that SRS gives more than 3 dB of gain with respect to the SISO plot, and a little less than 5 dB for a system with $L = 4$. In comparison to GSC and mGSC, SRS provides approximately 1 and 3 dB of extra gain for $L = 2$ and $L = 4$, respectively. Thus, it doubles the gain given by GSC and mGSC. This behavior can be explained by the fact that SRS is based on relaying the "better" symbol as explained in Section V. The improvement over the other methods is that the shared symbols selected by SRS enhance SNR specifically on subcarriers with low channel gain.

For a fair comparison between schemes, the cooperation time muss be included. In Figures 4 and 5, the throughput given by (15) is illustrated for each cooperation strategy. At very high SNR there is no need of cooperation, for this reason SISO performs better than any other scheme. For lower SNR's, however, the advantages of cooperation schemes are noteworthy. The mGSC scheme performs better than GSC, which demonstrates the advantage of avoiding the communication of the CSI of Y_d. Nevertheless, SRS outperforms mGSC and MRC. For instance, at an SNR of 12 dB and $\alpha_\mathrm{p} = 25\%$, SRS outperforms mGSC and MRC with factors of 1.45 and 2.1 respectively. For $L = 4$ and at an SNR of 11 dB, SRS performs 1.8 times better than mGSC and 3 times better than MRC. This proportion is more notable for $\alpha_\mathrm{p} = 15\%$, for which SRS offers an even better performance. This makes SRS viable as a cooperation scheme.

VII. Conclusion

In this paper, we presented the symbol request sharing (SRS) scheme for mobile cooperative receivers in OFDM systems. Based on MRC, it is shown that SRS reduces the amount of relayed symbols and achieves full gain diversity on selected subcarriers. A question-answer protocol is followed. The destination receiver requests from the remaining receivers the symbols on a certain percentage of subcarriers with the worst SNR. Thus, it achieves only a partial MRC on the OFDM symbol but full MRC for each subcarrier selected. Furthermore, we have presented a modified general selection combining (mGSC) scheme, which necessitates less cooperation overhead in comparison to the general selection combining (GSC) scheme. The performance of SRS has been measured and compared with other cooperation strategies in terms of the BER and throughput. It is shown that SRS doubles the diversity gain given by other partial cooperation schemes and reaches the highest throughput by means of sharing a small percentage of the available symbols. For instance, by sharing symbols for just 15% of the subcarriers in an OFDM symbol at the destination node, SRS gives approximately 3 dB of diversity gain at a BER of 10^{-5} while other schemes reach only 1 dB. Therefore SRS realizes an appropriate trade-off between spatial diversity gain and extra cooperation overhead, which makes it a viable option for a cooperation scheme.

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