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Interference Relay Channel with precoded Dynamic Decode and Forward protocols

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***Abstract*—In this paper, a full duplex relay using a Dynamic Decode and Forward (DDF) protocol is considered for improving the performance of multiple source-destination pairs interfering one on each other. A relay precoder is optimized as a function of the symbols correctly decoded by the relay in order to improve the channel capacity. Furthermore, a DDF-Patching technique allows for increasing the number of precoded symbols by the relay and providing highly improved performance in interference-limited scenarios.**

I. Introduction

When interference occurs during concurrent communications, the performance can be improved by the help of a relay. For example, [1] considers the combination of dirty paper coding and beamforming under the assumption of non causal knowledge of the messages at the relay. In [2], interference forwarding is proposed in order to improve the successive interference cancellation at the receiver. Interference neutralization is mentioned by S.Mohajer et al. [3], [4], where the signals sent by the relay cancel the interference over the air. The aim of this work is first to improve the achievable capacity on each source-destination link by the combination of a relay precoder optimization and an in-band reception/transmission [5] DDF protocol [6]. The performance is further improved by a Patching technique originally proposed to maximize the achievable macro and micro diversity orders for the relay channel [7]. The paper is organized as follows: the system model is presented in Section II. In Section III, we describe the precoder optimization. The DDF protocol and Patching technique are presented in Section IV. Simulations results are presented in Section V.

II. System Model and Parameters

We consider n sources transmitting data on the same physical resource to n destinations carrying N_r reception antennas, and a full-duplex relay with N_t antennas shared by all the sources. The Interference Relay Channel (IRC) is presented in Fig.1. The full-duplex relay can stay in reception mode of the DDF protocol for a subset of source-to-destination links while being in transmission mode for the others. We also consider the half-duplex as an adaptation of the full-duplex case. Sources are relay-unaware, i.e., they do not know the relay's presence in the system [8], [9], [10] and no control signal is needed between the sources and the relay. We assume that the relay has a perfect channel state information (CSI) knowledge of all transmission links. Each source information word is built from the concatenation of a message and Cyclic Redundancy Check (CRC) bits. The information bits are then encoded and sent to the input of a Quadrature Amplitude Modulation (QAM). The resulting codeword is transmitted during T symbol times, or time-slots. The relay jointly decodes the received messages. After the correct decoding of one of the messages, which is detected thanks to the embedded CRC bits, the relay perfectly knows the information bits. The relay can perfectly re-build the codeword sent by this source and deduce its past and future symbols. By definition, the k-th correct decoding at the relay occurs after having correctly decoded the message sent by the k-th source S_k to the destination D_k. Phase k ends after the k-th correct decoding. Thus, there might be at most $n+1$ phases. During the $k+1$-th phase, the relay can generate the symbols sent by sources 1 to k. A vector of k non-null symbols and $n-k$ null symbols is then precoded by $\mathbf{P}_{k+1}$ of size $N_t \times n$, and sent by the relay on the same resource as the sources. The precoder at the relay is optimized so as to achieve a trade-off between boosting the destination useful signal and reducing the interference as proposed in Section III. The k-th destination tries to decode S_k's message with a low complexity reception scheme, i.e., does not perform a joint decoding of the sources messages. If a Patching technique is used, the according low-complexity reception scheme must be used at the destination [7].

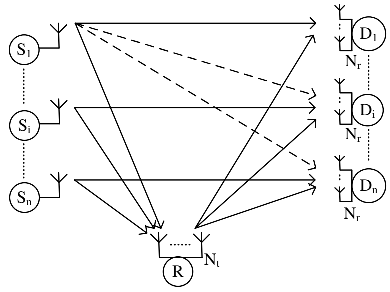

Fig. 1. Interference Relay Channel with n pairs. Only the interference from S_1 are illustrated (dashed lines).

We consider quasi static flat-fading channels remaining constant during the transmission of one codeword, and independent from one transmission to another. We denote $\mathbf{H}_m$ the matrix of fading coefficients between all the sources and the m-th destination, and $\mathbf{F}_m$ the matrix of fading coefficients between the relay and the m-th destination. The destinations estimate the channel coefficients and forward it to the relay. Each fading coefficient is composed of the transmit power

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affected by the path gain between the transmitter and the receiver, and a complex Gaussian distributed random variable of variance 1. Thus, each fading coefficient appears to be a complex Gaussian variable whose variance is equal to the average receive power on the considered link. At each receive antenna, the additive complex white Gaussian noise has zero mean and variance $2N_0$. The Signal to Noise Ratio (SNR) and Signal to Interference plus Noise Ratio (SINR) are defined by taking into account the path gain between the transmitter and the receiver, interferers and noise power. We denote $s_{m,k,i}$ the symbol sent by the source S_m and $\mathbf{y}_{m,k,i}$ the signal received by the destination D_m during the i-th time-slot of the Phase k. Bold upper case letters denote matrices, bold lower case letters denote vectors,$[.]^t$ is the transpose operator, $[.]^\dagger$ is the transpose conjugate operator and $[.]^*$ is the conjugate operator. The trace and determinant of the matrix $\mathbf{M}$ are noted $\mathrm{Tr}(\mathbf{M})$ and $|\mathbf{M}|$, respectively. The expectation operation is denoted by E.

III. Precoder Optimization at the Relay

During Phase k, a linear precoder $\mathbf{P}_k$ of size $N_t \times n$ is applied at the relay in order to improve the capacity obtained at each destination. The precoder $\mathbf{P}_k$ is recomputed as soon as the relay has correctly decoded S_k's message. For instance, during Phase 1, full interference is experienced at the destinations, and during Phase k, the symbols $s_{1,k,i}$ to $s_{k-1,k,i}$ are precoded altogether by $\mathbf{P}_k$ at the relay. The m-th destination receives the vector $\mathbf{y}_{m,k,i}$ during the i-th time-slot of Phase k

$$\mathbf{y}_{m,k,i} = \mathbf{M}_m(\mathbf{P}_k)\mathbf{s}_{k,i} + \mathbf{n}_{m,k,i} \tag{1}$$

where

$$\mathbf{M}_m(\mathbf{P}_k) = \mathbf{H}_m + \mathbf{F}_m\mathbf{P}_k\boldsymbol{\Delta}_k \tag{2}$$

and $\mathbf{s}_{k,i} = [s_{1,k,i}, \cdots, s_{n,k,i}]^t$ and $\mathbf{n}_{m,k,i}$ is the noise vector. We note $\boldsymbol{\Delta}_k$ as a $n \times n$ matrix whom non-null entries are the first $k-1$ diagonal coefficients, equal to one. As a result, the $N_t \times n$ precoder matrix $\mathbf{P}_k$ is only applied to the $k-1$ first symbols.

This channel model is specific to IRC channels with DDF. Thus, the following precoder optimization is different from existing precoders mostly derived for AF channels [11][12] or for a joint-source/relay precoding (e.g., [13]), as we assume relay-unaware sources.

The precoder matrix $\mathbf{P}_k$ is computed according to channel capacity metrics [14]. We define the capacity at the m-th destination during Phase k as

$$\begin{aligned} C_{m,k}(\mathbf{P}_k) = &\log_2 \left|\mathbf{M}_m(\mathbf{P}_k)\mathbf{M}_m(\mathbf{P}_k)^\dagger + 2N_0\mathbf{I}\right| \\ &- \log_2 \left|\mathbf{M}_m(\mathbf{P}_k)\bar{\mathbf{D}}_m\mathbf{M}_m(\mathbf{P}_k)^\dagger + 2N_0\mathbf{I}\right| \end{aligned} \tag{3}$$

where $\mathbf{D}_m$ is a $n \times n$ matrix with a single non-null entry at the m-th position on the diagonal, and $\bar{\mathbf{D}}_m = \mathbf{I} - \mathbf{D}_m$. The derivation of $C_{m,k}(\mathbf{P}_k)$ leads to (3), which could be seen as the difference between the capacity of the MIMO scheme formed by all sources and the relay transmitting to the $m-th$ destination and the capacity of the MIMO scheme formed by all interferers (all sources except S_m) and the relay transmitting to the $m-th$ destination. We define $C_k(\mathbf{P}_k)$ as the generalized mean of the capacities $C_{m,k}(\mathbf{P}_k)$

$$C_k(\mathbf{P}_k) = \left(\frac{1}{n}\sum_{m=1}^{n} C_{m,k}(\mathbf{P}_k)^p\right)^{1/p} \tag{4}$$

where p is the parameter of the generalized mean.

For $p = 1$, $C_k(\mathbf{P}_k)$ corresponds to the sum capacity which is relevant for the Multiple Access Channel. As our work deals with the interference channel, fairness is needed between users. Thus, we maximize the minimal capacity by considering $p \to -\infty$, or p negative and sufficiently low.

One can optimize $C_k(\mathbf{P}_k)$ under a total maximal power constraint at the relay $h(\mathbf{P}_k) = \mathrm{Tr}\left(\mathbf{P}_k\Delta_k\mathbf{P}_k^\dagger\right) - 1 \leq 0$, which leads to the following Lagrange multipliers system

$$\frac{\partial C_k(\mathbf{P}_k)}{\partial \mathbf{P}_k^*} = \lambda\frac{\partial h(\mathbf{P}_k)}{\partial \mathbf{P}_k^*} \quad \text{and} \quad h(\mathbf{P}_k) \leq 0 \tag{5}$$

where

$$\frac{\partial C_k(\mathbf{P}_k)}{\partial \mathbf{P}_k^*} = \frac{C_k(\mathbf{P}_k)^{1-p}}{n}\sum_{m=1}^{n} C_{m,k}(\mathbf{P}_k)^{p-1}\frac{\partial C_{m,k}(\mathbf{P}_k)}{\partial \mathbf{P}_k^*} \tag{6}$$

and which leads, after derivation using the matrix differentiation tools [15] not described here for space limitation, to

$$\begin{aligned} &\frac{\partial C_{m,k}(\mathbf{P}_k)}{\partial \mathbf{P}_k^*} = \\ &\frac{1}{\ln(2)}\mathbf{F}_k^\dagger\Big[\left(\mathbf{M}_m(\mathbf{P}_k)\mathbf{M}_m(\mathbf{P}_k)^\dagger + 2N_0\mathbf{I}\right)^{-1}\mathbf{M}_m(\mathbf{P}_k) \\ &- \left(\mathbf{M}_m(\mathbf{P}_k)\bar{\mathbf{D}}_m\mathbf{M}_m(\mathbf{P}_k)^\dagger + 2N_0\mathbf{I}\right)^{-1}\mathbf{M}_m(\mathbf{P}_k)\bar{\mathbf{D}}_m\Big]\boldsymbol{\Delta}_k \end{aligned} \tag{7}$$

No closed form expression can be derived from (5), a gradient descent iteratively optimizes the precoder $\mathbf{P}_k$ instead:

$$\mathbf{P}_k \leftarrow \left(\mathbf{P}_k + \mu\frac{\partial C_k(\mathbf{P}_k)}{\partial \mathbf{P}_k^*}\right) / \min\left(\mathrm{Tr}\left(\Delta_k^\dagger\mathbf{P}_k^\dagger\mathbf{P}_k\Delta_k\right), 1\right) \tag{8}$$

where μ is the gradient descent parameter, and the denominator allows for projecting the estimated precoder matrix on the set of solutions satisfying the constraint $h(\mathbf{P}_k)$. It is preferable to choose a moderately high value for the generalized mean parameter such as $p = -5$ in order to find a good trade-off between the approximation of the min function and the good convergence of the system.

We have presented in this section an optimization of the precoder applied at the shared relay in order to reach fairness between the destinations. The relay transmit power is shared between useful signal boosting and interference reduction. The proposed optimization can be applied for any number of sources, transmit antennas at the relay and receive antennas at the destination. In the following, we illustrate how to combine the precoder optimization at the relay with a DDF relaying protocol. Remark that the precoder could be optimized using a metric based on mutual information with discrete symbol

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alphabet as presented in [14], but it would not modify the use of the precoder at the relay presented hereafter.

IV. A DDF protocol design for IRCs

A. Implementation of the DDF protocol for IRCs

The precoder is optimized at each phase end, according to $\mathbf{\Delta}_k$ which characterizes the set of symbols correctly decoded at the relay. The precoder optimization requires full CSI knowledge at the relay, which is forwarded by the destinations or obtained from channel reciprocity when possible, allowing the sources to be relay-unaware.

An early decoding of a symbol at the relay will drastically improve the destination's performance if the transmission link does not suffer from a high interference level. Equivalently, if a source whom message has been decoded by the relay generates a high interference level on an another transmission link, the later will highly take benefit from interference reduction from the relay precoder. Unfortunately, for late correct decoding events, the relay does not bring much gain on the system. In the next section, we use a Patching technique similar to the one presented in [7] for a different target: the Patching technique is used in order to virtually apply the precoding matrix on symbols sent in previous phases of the DDF protocol, i.e. symbols transmitted before the correct decoding of the related messages by the relay.

B. Patching principle

A Patching technique aims at increasing the number of source symbols taking benefit from the relay-destination link and from the relay precoder, while keeping a low complexity decoding at the destination side. A Patching technique is composed of two steps. The first one is done at the relay which, after having correctly decoded a message, transmits a linear combination of symbols previously sent by the source and of symbols the source is going to send. The combination must be chosen so as to allow a low-complexity decoding at the destination. For instance, one can build a 4^q-QAM symbol by combining q QPSK symbols s_i using the expression:

$$s = a(q) \sum_{i=1}^{q} 2^{i-1} s_i \quad \text{with } a(q) = \sqrt{\frac{3}{4^q - 1}} \tag{9}$$

where the weighting coefficients are chosen in order to keep the unity energy property of the constellation, and the Patching order is by definition equal to q. The second step is performed by the destination which combines the received signals according to the combination at the relay. After this combination, the combined symbols appear to be transmitted through both the source-destination and the relay-destination links. A coding gain loss is observed due to the constellation expansion and the attenuation of the relay received power.

C. Patching for n-pair IRC

The Patching technique combines symbols of different phases in order to increase the number of symbols virtually sent through the precoder.

For the sake of clarity, we present the simplest version of the Patching algorithm, where Patching is only applied on the symbols of Phase 1, experiencing and generating interference. We denote L_1 the number of time-slots in the first phase of the DDF protocol. At the beginning of a new transmission, a variable v storing the index of the last patched symbol of Phase 1 is initialized to zero. Then, the relay executes Algorithm 1 for each time slot i of each Phase k ($2 \leq k \leq n+1$), for each source $m \leq k-1$ and for a Patching order q.

Algorithm 1 Generation of m-th symbols $\tilde{s}_{m,k,i}$ to be precoded by the relay for the i-th time slot of Phase k.

$\tilde{s}_{m,k,i} \leftarrow 0$
$j_{k,i} \leftarrow 1$
while $v + j_{k,i} \leq L_1$ **and** $j_{k,i} < q$ **do**
  $\tilde{s}_{m,k,i} \leftarrow \tilde{s}_{m,k,i} + 2^{j_{k,i}-1} s_{m,1,v+j_{k,i}}$
  $j_{k,i} \leftarrow j_{k,i} + 1$
end while
$\tilde{s}_{m,k,i} \leftarrow a(j_{k,i})(\tilde{s}_{m,k,i} + 2^{j_{k,i}-1} s_{m,k,i})$
$v \leftarrow v + j_{k,i}$

As a remark, as soon as all symbols from Phase 1 have been precoded, the system behaves as the DDF protocol for IRC. The m-th destination receives

$$\begin{aligned}\mathbf{y}_{m,k,i} = \mathbf{H}_m \mathbf{s}_{k,i} + \mathbf{F}_m \mathbf{P}_k \mathbf{\Delta}_k \\ \times (\tilde{s}_{1,k,i}, \cdots, \tilde{s}_{k-1,k,i}, 0, \cdots, 0)^t + \mathbf{n}_{k,i}\end{aligned} \tag{10}$$

By knowing the instant of correct decoding at the relay, each destination m applies Algorithm 1 for combining the received vectors $\mathbf{y}_{m,k,i}$ instead of the symbols $s_{m,k,i}$, which leads to the following equivalent channel model:

$$\tilde{\mathbf{y}}_{m,k,i} = (\mathbf{H}_m + \mathbf{F}_m \mathbf{P}_k \mathbf{\Delta}_k a(j_{k,i}) 2^{j_{k,i}-1}) \tilde{\mathbf{s}}_{k,i} + \mathbf{n}'_{k,i} \tag{11}$$

where $\tilde{\mathbf{s}}_{k,i} = (\tilde{s}_{1,k,i}, \cdots, \tilde{s}_{n,k,i})^t$, i.e. the symbol combination described by the Algorithm 1 is realized for all sources symbols, and $\mathbf{n}'_{k,i}$ is the resulting complex gaussian noise. During the i-th time slot of Phase k, the symbols after patching are $4^{j_{k,i}}$-QAM symbols sent on the equivalent channel with power boosting and interference reduction thanks to the precoding of the symbols decoded at the relay, i.e. from sources 1 to $k-1$. If Phase 1 is longer than the cumulated length of the other phases, unprecoded symbols remain. When all sources are decoded at the same time, if Phase 1 is shorter than the last Phase, all symbols are precoded, some of them being patched, the other being transmitted through the relay-destination link using the DDF protocol. An adaptation of this protocol to half-duplex relays implies that the relay waits for all messages to be correctly decoded before switching into the transmission mode.

D. Patching example for the 2-pair IRC

Let's consider a 2-pair IRC, where the frames transmitted by both sources are composed of 5 QPSK symbols. We assume that the relay correctly decodes the message of S_1 after receiving the second symbol, and that it correctly decodes the message of S_2 after receiving the third symbol. This means that the first phase contains 2 time-slots, the second phase contains one time-slot and the last phase contains 2 time-slots.

The relay transmits using a DDF protocol with precoder optimization and Patching. We define the Patching order $q = 2$, which means that the relay generates 16-QAM symbols. The variable v (see Algorithm 1) is setted to zero at the beginning of the transmission.

During the second phase of the DDF protocol with Patching, the relay generates the symbol $\tilde{s}_{1,2,1} = a(2)(2s_{1,2,1} + s_{1,1,1})$ which is precoded by $\mathbf{P}_2$. The variable v is now equal to 2. Both destinations realize the combination of received signals:

$$\begin{aligned}\tilde{\mathbf{y}}_{m,2,1} &= a(2)(2\mathbf{y}_{m,2,1} + \mathbf{y}_{m,1,1}) \\ &= \mathbf{H}_m \begin{bmatrix} a(2)(2s_{1,2,1} + s_{1,1,1}) \\ a(2)(2s_{2,2,1} + s_{2,1,1}) \end{bmatrix} \\ &\quad +2a(2)\mathbf{F}_m\mathbf{P}_2 \begin{bmatrix} \tilde{s}_{1,2,1} \\ 0 \end{bmatrix} + n \\ &= \mathbf{H}_m \begin{bmatrix} \tilde{s}_{1,2,1} \\ \tilde{s}_{2,2,1} \end{bmatrix} + 2a(2)\mathbf{F}_m\mathbf{P}_2 \begin{bmatrix} \tilde{s}_{1,2,1} \\ 0 \end{bmatrix} + \mathbf{n}\end{aligned}$$

with $m = 1, 2$, and where the resulting noise $\mathbf{n}$ is a complex white gaussian noise of zero mean and unit variance. Consequently, during this time slot, thanks to the Patching technique, a 16-QAM symbol is precoded by $\mathbf{P}_2$ with a SNR loss coming from the $2a(2)$ coefficient, whereas without Patching, only a QPSK symbol would have been precoded by $\mathbf{P}_2$.

During the first time-slot of the third phase of the DDF protocol with Patching, as the condition $v \leq L_1 = 2$ is satisfied, the relay generates the symbols $\tilde{s}_{m,3,1} = a(2)(2s_{m,3,1} + s_{m,1,2})$, with $m = 1$ and $m = 2$. These symbols are then precoded by $\mathbf{P}_3$, and the variable v is now equal to 4. Both destinations realize the combination of received signals:

$$\begin{aligned}\tilde{\mathbf{y}}_{m,3,1} &= a(2)(2\mathbf{y}_{m,3,1} + \mathbf{y}_{m,1,2}) \\ &= \mathbf{H}_m \begin{bmatrix} \tilde{s}_{1,3,1} \\ \tilde{s}_{2,3,1} \end{bmatrix} + 2a(2)\mathbf{F}_m\mathbf{P}_2 \begin{bmatrix} \tilde{s}_{1,3,1} \\ \tilde{s}_{2,3,1} \end{bmatrix} + \mathbf{n}\end{aligned}$$

with $m = 1, 2$, and where the resulting noise $\mathbf{n}$ is a complex white gaussian noise of zero mean and unit variance. Consequently, during this time slot, thanks to the Patching technique, two 16-QAM symbols are precoded by $\mathbf{P}_3$ with a SNR loss coming from the $2a(2)$ coefficient, whereas without Patching, only two QPSK symbols would have been precoded by $\mathbf{P}_3$.

During the second time slot of the third phase, the condition $v \leq L_1$ is not satisfied, the relay does not use Patching and transmits the precoded versions of $s_{1,3,2}$ and $s_{2,3,2}$ by $\mathbf{P}_3$.

V. Simulation results

In this Section, we consider a two sources case ($n = 2$) where the wireless links are symmetric, i.e., the long term SNRs and SINRs of the two pairs without relay are equal. By assuming that the m-th destination estimates $\mathbf{M}_m(\mathbf{P}_k)$ (full CSI at the receiver) and does not jointly decode the other source symbols for complexity reasons, the mutual information $\chi_{m,k}$ during Phase k with a Gaussian approximation of the interference plus noise signal is

$$\chi_{m,k} = E_{s_{m,k},\mathbf{n}_k}\left[\log_2\left(\frac{E_{s_{\forall m' \neq m,k}}\left[p(\mathbf{y}_{m,k}|\mathbf{s}_k)\right]}{E_{\mathbf{s}'_k}\left[p(\mathbf{y}_{m,k}|\mathbf{s}'_k)\right]}\right)\right] \quad (12)$$

where $p(\mathbf{y}_{m,k}|\mathbf{s}_k) \propto e^{-\|\mathbf{\Lambda}^{-1}(\mathbf{y}_{m,k} - \mathbf{M}_m(\mathbf{P}_k)\mathbf{D}_m\mathbf{s}_k)\|^2}$ and $\mathbf{\Lambda}\mathbf{\Lambda}^\dagger = \mathbf{M}_m(\mathbf{P}_k)\bar{\mathbf{D}}_m\mathbf{M}_m(\mathbf{P}_k)^\dagger + 2N_0\mathbf{I}$.

We focus on the mutual information achieved by one of the two pairs in the system. The transmitting node of this pair is called source S, and the other transmitter is called interferer I. The nodes transmit QPSK symbols. We define as P_R/P_S the ratio of the average power received by the destination from the relay and from the source. We consider that the destination has a single receive antenna $N_r = 1$ and that the relay has two antennas $N_t = 2$.

Fig. 2 illustrates the gain brought by the precoder optimization based on the capacity metric as presented in Section III. It can be shown that this precoder optimization provides almost equal performance as a precoder specifically optimized for maximizing the discrete input mutual information, with a lower computational complexity. We consider that the relay knows the symbols sent from the source and interferer, and we focus on the improvement of the average QPSK discrete input mutual information observed during the phase in which the relay transmits signal from both sources. When no precoder is used, the relay transmits each symbol of each source from its two transmit antennas. We can observe that for high SINR values, when the interference becomes negligible with respect to the noise level, the relay without precoder introduces interference in the system which drastically degrades the discrete input mutual information. By using the full CSI knowledge at the relay in order to optimize the precoder, we see that the relay transmit power is efficiently used to remove the interference and boost the useful signal. It has to be noted that, since the precoder is not distributed among the sources and relay, the transmit beamforming or zero forcing approach do not show such high performance. When the SINR is close to zero, we see how the relay improves the performance by a factor up to 200%. The performance can be further improved by increasing the number of transmit antennas at the relay N_t.

In the following, we assume that the power received from the relay is 6dB higher than the power received from the source. We consider a particular codeword segmentation, such as for HARQ with Incremental Redundancy (IR) OFDM systems, which restricts the possible instants of correct decoding to the set $\{\frac{3T}{7}, \frac{4T}{7}, \frac{5T}{7}, \frac{6T}{7}, T\}$, where T is the total number of time slots for a given codeword transmission. We denote M_S and M_I the index of the segment after which the relay correctly decodes the source message and the interferer message, respectively. Note that the case with no relay activation corresponds to $M_S = M_I = 5$. All the results are presented according to the SINR observed at D for a SNR between the source and destination of 30dB.

In Fig.3 and Fig.4, the first $\frac{3T}{7}$ time-slots only carry information bits. We consider an open loop transmission, in which the source transmits the whole codeword, whose figure

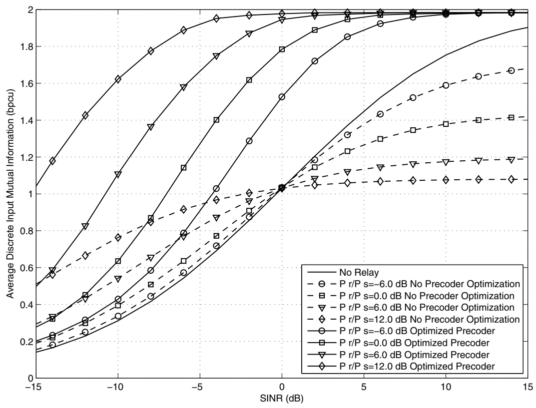

Fig. 2. Impact of the precoder optimization on the average QSPK input mutual information between the source and destination according to the SINR observed at D, P_R/P_S, for $n=2$, $N_r=1$ and N_t=2.

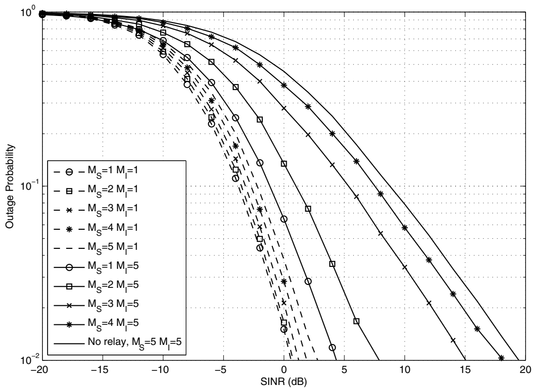

Fig. 3. Average outage probability at D according to the SINR, $P_R/P_S = 6dB$, $N_r=1$. The relay uses DDF protocol with optimized precoder.

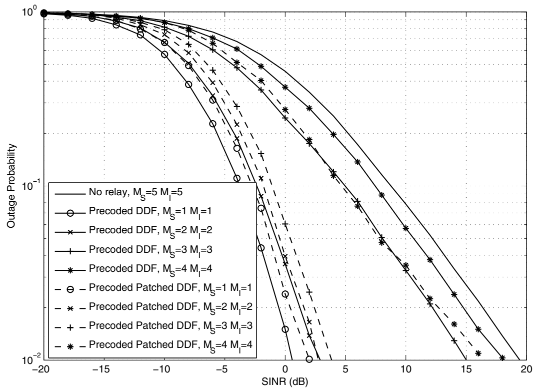

Fig. 4. Average outage probability at D according to the SINR, $P_R/P_S = 6dB$, $N_r=1$ for $M_S = M_I \in \{1,2,3,4\}$. The relay uses the optimized precoder for the DDF protocol or the Patched DDF protocol.

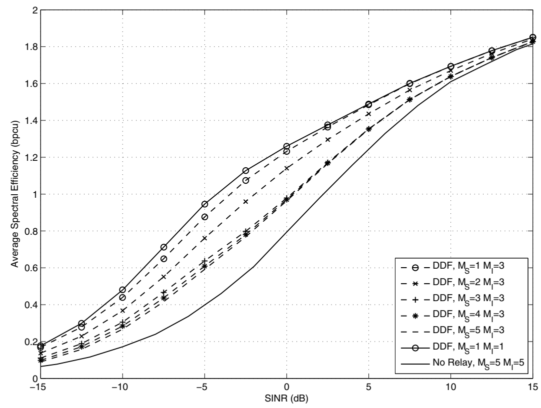

Fig. 5. Average spectral efficiency at D maximized over the available coding rates, according to the SINR, $P_R/P_S = 6dB$, $N_r=1$ for $(M_S, M_I) \in \{(1,1),(5,5)\}$ and all possible M_S for $M_I=3$. The relay uses the DDF protocol with an optimized precoder.

of merit is the outage probability.

In Fig.3, the averaged outage probability achieved for $M_I \in \{1,5\}$ and $M_S \in \{1,2,3,4,5\}$ are presented. The relay uses the DDF protocol with the optimized precoder presented in Section III. The performance obtained when the relay uses the DDF protocol outperforms the case without relay whatever the considered couples (M_S, M_I). The sooner the relay correctly decodes the source message, the higher the performance, which is due to the power boosting by the relay. Furthermore, the sooner the instant of correct decoding of the interferer, the higher the performance, which is due to the interference reduction by the relay.

In Fig.4, the averaged outage probability obtained using the DDF protocol or the Patched DDF protocol, is presented for $M_S = M_I$, which is also the performance obtained for a half duplex relay (beginning to transmit after the correct decoding of both messages). Using the Patched DDF protocol enables to improve the performance for late decoding at the relay (M_S = M_I = 3 or 4), whereas for the other cases, performance are lightly decreased due to the coding gain loss resulting from the generation of hyper-symbols.

In Fig.5 and Fig.6, we consider a closed loop transmission in which the destination tries to decode the message after each frame segment, and transmits acknowledgement message when it correctly decodes the message. The figure of merit is the spectral efficiency in bit per channel use (bpcu). It is classically computed for the HARQ-IR systems by taking into account the events of correct decoding after each codeword segment. Moreover, the available coding rates at the end of the first $\frac{3T}{7}$ can vary from 0 to 1. Thus, slow link adaptation is realized, i.e. the coding rate is adapted according to the SINR to maximize the averaged spectral efficiency.

In Fig.5, the cases $M_S = M_I = 1$ and $M_S = M_I = 5$ illustrate the best and worst achievable spectral efficiency for the DDF protocol. The case $M_I = 3$ presents the fact that when $M_S > M_I$ performance are quite similar. Indeed as the relay has already removed the suffered interference, it results that the destination correctly decodes the message very quickly. For SINR lower than 0dB, because of its power constraint, the relay cannot totaly remove the interference, thus M_S influences the performance.

In Fig.6, spectral efficiency performance, achievable with the DDF protocol or the Patched DDF protocol, are presented for $M_S = M_I$. The Patched DDF protocol enables to improve the performance achieved with the DDF protocol for SINR

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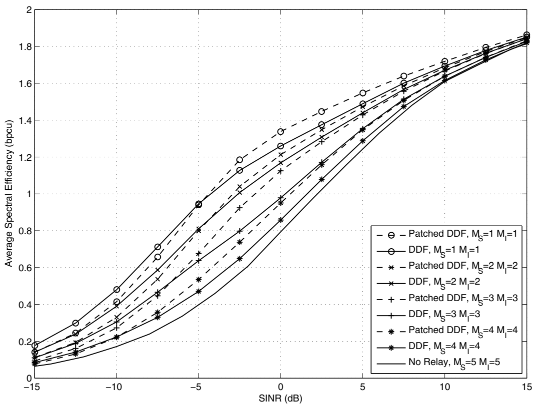

Fig. 6. Average spectral efficency maximized over the coding rates, according to the SINR observed at D, $P_R/P_S = 6dB$, $N_r = 1$ for $M_S = M_I \in \{1, 2, 3, 4, 5\}$. The relay uses the optimized precoder for the DDF protocol or the Patched DDF protocol.

above a threshold depending on the number of patched symbols. The higher the number of patched symbols by the relay, the higher the threshold. Indeed, when $M_S = 1$ and $M_S = 2$, $\frac{3T}{7}$ symbols are patched which leads to the same threshold of -5dB. For higher values of M_S, less symbols are patched resulting in a lower threshold.

VI. Conclusion

We have studied an interference channel with a relay using the DDF protocol. The channel capacity is maximized as the relay transmits a precoded version of the symbols sent by the different sources. This precoding step and the choice of the precoding matrix are optimized under a power constraint at the relay which leads to a practical scheme. The precoded DDF technique brings performance improvement to the IRC channel, which can be further increased by using Patching technique. The precoder optimization allows for obtaining good performance even when the destination only has $N_r = 1$ receive antenna.

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