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# MIMO Systems for Turbo Coded Cooperation over Orthogonal and Non-Orthogonal Channels

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**Abstract**—Multiple-input multiple-output (MIMO) systems can be adopted in cooperative wireless networks to bring further space diversity or/and to improve the throughput of the system. In this paper, we evaluate the performance of MIMO applied to a turbo coded cooperation system. The considered system is studied under two scenarios where the sources transmit over either orthogonal channels or non-orthogonal channels. For the latter, interleave-division multiple-access (IDMA) is used for multi-source detection. We evaluate the performance improvement in terms of reliability (frame error rate) and efficiency (throughput efficiency), and determine the channel conditions where adopting MIMO in addition to cooperation is beneficial.

## I. INTRODUCTION

The interest in cooperative communications for wireless networks has been rising sharply in the recent years. The major benefit of cooperative communication is that, exploiting the intrinsic broadcast nature of the wireless channel, several nodes help each other by sharing their own antennas in order to transmit information to the destination. This is an efficient way to introduce space diversity. In [1], it was shown that cooperation between sources brings higher data rates as well as higher reliability. A practical cooperation scheme, known as *coded cooperation* (CCoop), was proposed in [2, 3], where channel coding and cooperation were combined. In particular, distributed turbo coding and cyclic redundancy code (CRC) at the partner node was proposed in [3] as an efficient coding scheme for cooperation, called *turbo coded cooperation* (TC-Coop). The partner decodes, interleaves and re-encodes the message prior to forwarding (decode-and-forward protocol). This approach benefits from cooperative diversity, coding and turbo processing gain.

On the other hand, it is known that the capacity of wireless communications increases when multiple transmitter and receiver antennas are used. Therefore, we still witness an increasing interest in the research community on multiple-input multiple-output (MIMO) systems.

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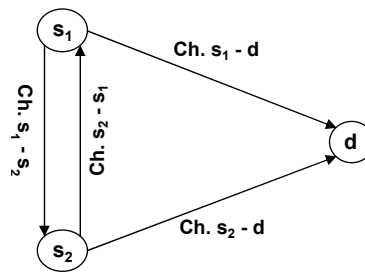


Fig. 1. A three-node cooperative wireless network: Each source acts as a relay for its partner

In this paper, we study the turbo coded cooperation scheme using multiple antennas in the operating nodes. This study is important in order to check if MIMO techniques still bring further gains besides the distributed space diversity offered by the cooperative system.

Furthermore, compared to the non-cooperative scheme, it is well-known that the coded cooperation may suffer from a throughput degradation, since two phases are always occupied for a single frame. The second phase brings degradation in throughput if the frames from both sources are correctly decoded in the first phase. Therefore, in order to improve the throughput efficiency of such cooperative systems, we consider a more general multi-source cooperative network based on the turbo coded cooperation scheme where both sources transmit to a destination over a non-orthogonal multiple-access channel. Several transmitting techniques can be used to deal with this multiple-access interference at the destination. Among them, we consider the use of interleave-division multiple-access (IDMA) for multi-source detection. This choice is dictated by the low complexity of the IDMA receiver. Separation between sources is obtained by the use of a different interleaver for each source. The complexity of the IDMA receiver increases linearly with the number of the sources [4].

The remainder of this paper is organized as follows. The general system model with multiple antennas at the operating nodes is defined in Section II. In Section III, we describe the original turbo coded cooperation scheme, over the orthogonal channels scenario. We further present the more general scheme, where non-orthogonal channels are assumed for the

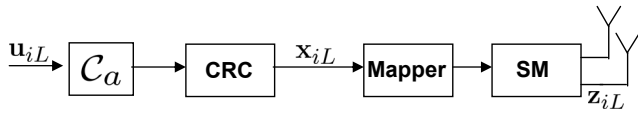


Fig. 2. Local information transmission during the broadcast phase.

second binding cooperation phase. The IDMA technique used for multi-source detection is explained for this particular context. Finally, numerical results are given in Section V and some conclusions are drawn in Section VI.

## II. SYSTEM MODEL

We consider the wireless relay network depicted in Fig. 1. Two sources  $s_1$  and  $s_2$  cooperate to transmit statistically independent data to a single destination  $d$ . Both sources operate in the half-duplex setup. Source  $s_i$  ( $i = 1, 2$ ) can either transmit its own local information (*transmission mode*) or help the partner node by relaying its information (*relaying mode*). We denote by  $\mathbf{u}_{iL}$  the local data at source  $s_i$ . Both sources are equipped with two encoders  $\mathcal{C}_a$  and  $\mathcal{C}_b$  of rates  $R_a = 1/2$  and  $R_b = 1$ , respectively. Multiple-antenna may be employed on the operating nodes (sources and destination). In this case, a space multiplexing (SM) operation is performed during the broadcast phase and the cooperation phase. This operation allows to achieve more diversity as well as higher data rates. On the other hand, in order to perform MIMO detection at the receiver side, a maximum likelihood (ML) algorithm is used that delivers soft information to the channel decoder.

Thereafter, we describe the considered MIMO channel with  $N_t$  transmit antennas,  $N_r$  receive antennas and perfect channel state information (CSI) at the receiver but not at the transmitter. All channels are modeled as Rayleigh block fading with additive white Gaussian noise. We denote by  $\gamma_{s_i d}$  and  $\gamma_{s_i s_j}$  the signal-to-noise ratio (SNR) of the  $s_i$ -to- $d$  channel and of the  $s_i$ -to- $s_j$  channel, respectively.

The coded cooperation is performed within two transmission phases: a *broadcast phase*, where both sources transmit their local information, and a *cooperation phase*, where a source may act as a relay helping the partner by forwarding its information. Therefore, to still operate in the half-duplex setup, the sources have to transmit in an orthogonal way for the first transmission phase (broadcast phase). After the broadcast phase, the received observations from  $s_i$  at  $s_j$  ( $i, j = 1, 2$  with  $i \neq j$ ) and at the destination  $d$ , can be written, respectively as

$$\mathbf{y}_{s_i s_j}^{(1)} = \mathbf{H}_{s_i s_j} \mathbf{z}_{iL} + \mathbf{n}_{s_i s_j} \quad (1)$$

$$\mathbf{y}_{s_i d}^{(1)} = \mathbf{H}_{s_i d} \mathbf{z}_{iL} + \mathbf{n}_{s_i d} \quad (2)$$

where  $\mathbf{z}_{iL}$  is a transmitted signal vector with  $N_t$  Gray-mapped complex elements. The channel matrices  $\mathbf{H}_{s_i s_j}$  and  $\mathbf{H}_{s_i d}$  of dimensions  $(N_t, N_r)$  are assumed to be constant over the transmission of a source frame, i.e., over all transmission phases. This channel model is considered in order to investigate the ability of the distributed spatial diversity to enhance

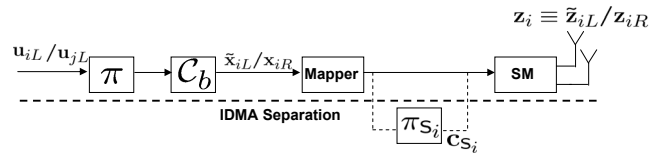


Fig. 3. Relayed information transmission during the cooperation phase.

link level performance in scenarios where temporal diversity is limited or unavailable. These channel matrices turn into scalar coefficients when single-input single-output (SISO) systems are considered ( $N_t = N_r = 1$ ).

The orthogonal and non-orthogonal channels differ only in the cooperation phase, where signals from both sources are separated (orthogonal channel) or superposed (non-orthogonal channel).

### A. Orthogonal channels

The sources transmit on orthogonal channels, e.g., time division multiple access (TDMA), which allows the destination to detect each source separately. After the cooperation phase, the received observations from partner nodes at the destination  $d$  are disjoint and, for one channel use, can be written as

$$\mathbf{y}_{s_1 d}^{(2)} = \mathbf{H}_{s_1 d} \mathbf{z}_1 + \mathbf{n}_{s_1 d}^{(2)} \quad (3)$$

$$\mathbf{y}_{s_2 d}^{(2)} = \mathbf{H}_{s_2 d} \mathbf{z}_2 + \mathbf{n}_{s_2 d}^{(2)} \quad (4)$$

where  $\mathbf{z}_i$  is a transmitted signal vector with  $N_t$  Gray-mapped complex elements. From equations (3) and (4), we note that  $s_i$  transmits over its own uplink channel the relayed information  $\mathbf{z}_i$ ,  $i = 1, 2$ . According to the transmission mode,  $\mathbf{z}_i$  can convey two different pieces of information:  $\mathbf{z}_{iR}$ , the relayed information of  $s_j$  (*relaying mode*), and  $\tilde{\mathbf{z}}_{iL}$ , another version of the local information of  $s_i$  (*transmission mode*). The protocol for turbo-coded cooperation is detailed in section III.

### B. Non-Orthogonal channels

Both sources transmit simultaneously during the cooperation phase. The received signal at the destination, being the superposition of the transmitted vectors  $\mathbf{z}_i$  (weighted by the channel coefficients) from the different sources, can be written as

$$\mathbf{y}_{s_d}^{(2)} = \mathbf{H}_{s_1 d} \mathbf{z}_1 + \mathbf{H}_{s_2 d} \mathbf{z}_2 + \mathbf{n}_{s_d}^{(2)} \quad (5)$$

Like for orthogonal channels,  $\mathbf{z}_i$  conveys  $\mathbf{z}_{iR}$ , the relayed information of  $s_j$  or  $\tilde{\mathbf{z}}_{iL}$ , another version of its local information according to the protocol described in section III.

## III. ORTHOGONAL TURBO CODED COOPERATION

In the following, we briefly describe the coded cooperation scheme of Fig. 1. Since we assume TDMA, all channels are orthogonal. Without loss of generality, we focus on the information generated at source  $s_1$ . The transmission of user data  $\mathbf{u}_{1L}$ , of length  $K$  bits, is performed over two phases. In the first phase, referred to as the broadcast phase, source  $s_1$  encodes  $\mathbf{u}_{1L}$  by  $\mathcal{C}_a$  into codeword  $\mathbf{x}_{1L}$ , of length  $N_a = K/R_a = 2K$

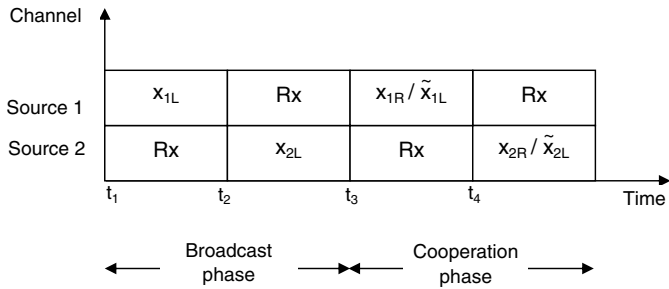


Fig. 4. The transmission time of the coded cooperation scheme is divided into two totally orthogonal phases: broadcast phase and cooperation phase.

bits.  $\mathbf{x}_{1L}$  is augmented with a CRC in order to facilitate error detection and transmitted over the wireless channel. For simplicity, in the remainder of the paper, when referring to a codeword  $\mathbf{x}$ , we shall assume that it includes a CRC. The broadcast phase for source  $s_i$  is described in Fig. 2. Thereafter, generated codewords at both sources are Gray-mapped into complex symbols before passing the SM block. Due to the broadcast nature of the wireless channel both the destination and the partner node  $s_2$  receive a noisy observation of  $\mathbf{x}_{1L}$ . If decoding is successful at node  $s_2$  (i.e.,  $s_2$  is able to regenerate  $\mathbf{u}_{1L}$ ), it switches to the relaying mode; at the cooperation phase,  $\mathbf{u}_{1L}$  is then interleaved through an interleaver  $\pi$  into  $\mathbf{u}_{2R} = \pi(\mathbf{u}_{1L})$ , encoded by  $\mathcal{C}_b$  into  $\mathbf{x}_{2R}$  and forwarded to the destination after being modulated and restructured into a space block vector. On the other hand, if decoding is not successful,  $s_2$  operates in the transmission mode (non-cooperative); at the second phase  $\mathbf{u}_{2L}$  is then interleaved by  $\pi$  into  $\tilde{\mathbf{u}}_{2L}$ , encoded by encoder  $\mathcal{C}_b$  into  $\tilde{\mathbf{x}}_{2L}$ , modulated and space multiplexed before being forwarded to the destination. A similar operation is performed at node  $s_1$  during the second phase.

Notice that with some abuse of language we call the second phase the *cooperation* phase. However, in this phase source  $s_i$  may work either in the transmission mode or in the relaying mode, depending on the CRC check. The cooperation phase for source  $s_i$  is described in Fig. 3. The figure illustrates both cases: the typical cooperation phase over orthogonal channels and the cooperation phase over non-orthogonal channels, where a specific random interleaver is used to ensure IDMA separation between superposed sources.

With reference to source  $s_1$  four cases are possible at the destination:

- 1) decoding at nodes  $s_1$  and  $s_2$  is successful: the destination receives two noisy observations of  $\mathbf{x}_{1L}$  from  $s_1$  and  $s_2$ . Notice that  $\mathbf{x}_{1L}$  and  $\mathbf{x}_{2R}$  form a codeword of a (distributed) turbo code, where the first component codeword is generated at  $s_1$  and the second component codeword is generated at  $s_2$ . Therefore, the relay network of Fig. 1 behaves as a distributed (over space) turbo code, and the destination can estimate  $\mathbf{u}_{1L}$  in an iterative fashion.
- 2) decoding at node  $s_1$  is successful, decoding at node  $s_2$  fails: the destination attempts to estimate  $\mathbf{u}_{1L}$  by

decoding only codeword transmitted during the first phase.

- 3) decoding at node  $s_1$  fails, decoding at node  $s_2$  is successful: the destination receives three noisy observations of  $\mathbf{x}_{1L}$ , two from  $s_1$  and one from  $s_2$ , which are decoded in a turbo fashion.
- 4) decoding at nodes  $s_1$  and  $s_2$  fails: the destination receives two noisy observations of  $\mathbf{x}_{1L}$ , both from  $s_1$ . Therefore, a distributed (over time) turbo code is obtained and the destination can estimate  $\mathbf{u}_{1L}$  in an iterative fashion.

The four cases are summarized in Fig. 4. With multiple antennas at the source nodes, spatial multiplexing is used for both phases. At the receiver side, prior to the turbo-decoding, the ML detector is applied to the received vector  $\mathbf{y}_{s_i,d}^{(k)}$ ,  $k = \{1, 2\}$ ,  $i = \{\emptyset, 1, 2\}$ .

#### IV. NON-ORTHOGONAL TURBO CODED COOPERATION

A throughput degradation characterizes cooperative communications due to a supplementary fixed cooperation phase. This drawback may be circumvented by reducing the transmission time of this critical phase. The most trivial solution is to transmit over non-orthogonal channels. However, we limit the non-orthogonal multi-source transmission to the second phase (*cooperation phase*) since the sources are constrained to operate in a half-duplex setup. The transmission time is illustrated in Fig. 5. During the cooperation phase, the superposition of the source signals leads to multiple access interference that degrades the BER performance if not processed. In this paper, the IDMA technique, presented in [4], is proposed to mitigate the multiple access interference. IDMA is considered as a special case of the CDMA technique, where the different sources are distinguished by means of interleavers (see Fig. 3) and a low-complexity iterative receiver is used to mitigate the multiple access interference. Originally, unlike the CDMA technique, a same spreading code is used for all the sources. Besides, it was proved that this spreading code is not needed if a low-rate channel code is used. However, in our work, no spreading code is employed while a high-rate channel code is used. This is due to the fact that part of the information transmitted during the broadcast phase does not suffer from interference thanks to the half-duplex setup. The key principle of IDMA is the use of interleavers  $\pi_{s_i}$  to distinguish between different sources leading to an iterative multi-source separation at the receiver, described below.

##### A. IDMA receiver structure for SISO systems

For SISO systems, the received vector  $\mathbf{y}_{sd}^{(2)}$ , given by equation (5), turns into a scalar coefficient and the iterative receiver described in [5] is directly applied. Thus, in the receiver, two main blocks are used: an *elementary signal estimator (ESE)* that exchanges extrinsic information with two turbo-decoders, one for each source, in an outer iterative process. Thanks to the use of interleavers  $\pi_{s_i}$ , the ESE operation can be carried out by a low complexity chip-by-chip detection algorithm [5] that manages the multiple access interference. The ESE computes the extrinsic information  $L_{e,ESE}$  for the considered

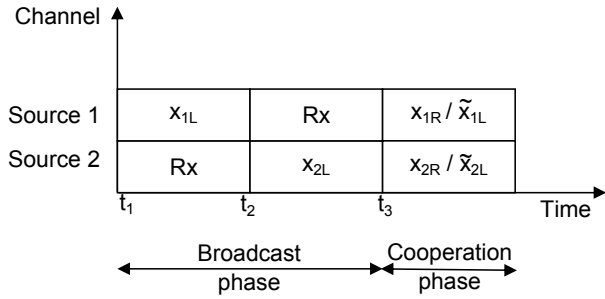


Fig. 5. The transmission time is yet divided into two phases: orthogonal broadcast phase (two time slots) and a non-orthogonal cooperation phase (a unique time slot allocated for both sources).

source  $s_i$  by assuming that the signal of the partner  $s_j$  is a Gaussian noise. The extrinsic information  $L_{e,ESE}$  is then used as input information for the turbo coded cooperation protocol summarized by the four cases in section III. Hence, an inner iterative process is performed to obtain the distributed turbo decoding for each source.

### B. Extended IDMA receiver structure for MIMO systems

For MIMO systems, the maximum ratio combiner (MRC) is first used in order to compute  $\hat{\mathbf{z}}_i$ , an estimation of  $\mathbf{z}_i$ , ( $i = 1, 2$ ) such that

$$\hat{\mathbf{z}}_i = \mathbf{H}_{s_i,d}^H \mathbf{y}_{sd}^{(2)} \quad (6)$$

where  $(\cdot)^H$  denotes the Hermitian function. Then, the ESE is applied to compute the extrinsic information for both sources. Since the MRC does not remove the spatial interference generated by the spatial multiplexing scheme at the source nodes, the ESE cancels multiple access interference plus spatial interference.

## V. PERFORMANCE EVALUATION

In this section, we give frame error rate (FER) results and throughput performance of MIMO systems applied to turbo coded cooperation scheme and compare them with the turbo coded cooperation where SISO nodes are assumed. For the examples here we consider the rate-1/2 convolutional encoder with generator polynomials (1, 15/13) in octal form for  $C_a$  and the rate-1 convolutional encoder with generator polynomial (17/13) in octal form for  $C_b$ . The information block length is  $K = 128$  bits, symmetric  $s_i$ -to- $d$  channel ( $\gamma_{s_1d} = \gamma_{s_2d}$ ) is assumed and a random interleaver is used for  $\pi$ . FER results are given as a function of  $\gamma_{sd}^b$ , where  $\gamma^b = (N_t N_r \gamma) / R$ . The normalization by  $N_t N_r$  compensates for the antenna gain at the transmitter and the receiver so as to highlight the diversity gain.  $R$  is the overall rate of the system given by

$$R = m R_c R_{st} \quad (7)$$

where  $R_c$  is the rate of the distributed channel code over the two transmission phases,  $m$  is the number of bits per modulated symbol and  $R_{st}$  is the rate of the space-time code, equal to  $N_t$  for spatial multiplexing.  $R_c$  depends on the channel code rate and the number of time slots that are needed for the cooperation protocol. For instance, for an orthogonal

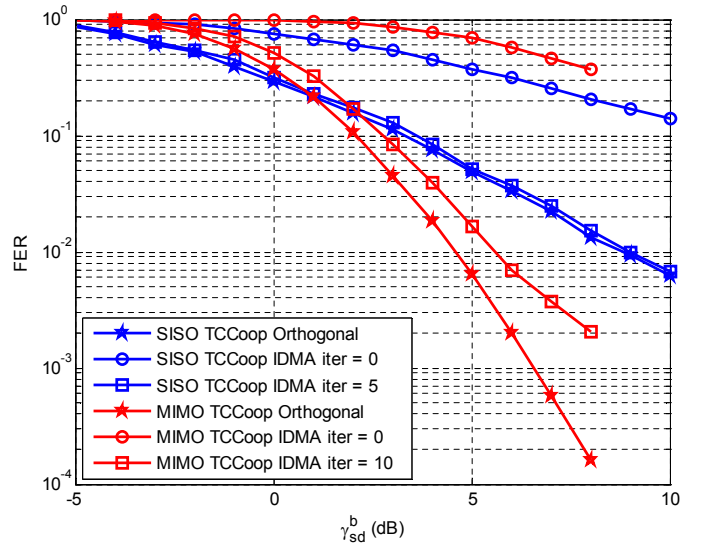


Fig. 6. Frame error rate curves of turbo coded cooperation with SISO and MIMO systems for  $\gamma_{ss}^b = \infty$  dB.

TCCoop,  $R_c$  is equal to 1/3, which corresponds to 6 different time slots allocated to transmit the two source frames (see Fig. 4). On the other hand, for a non-orthogonal TCCoop, both frames of cooperating sources take 5 different time slots to reach the destination (see Fig. 5); then,  $R_c$  is fixed to 2/5.

In order to operate at the same spectral efficiency, for the SISO setup a quadrature phase shift keying (QPSK) modulation is used, while for the MIMO  $2 \times 2$  setup ( $N_t = N_r = 2$ ), a binary phase shift keying (BPSK) modulation is considered. Finally, for both MIMO and SISO nodes,  $R$  is equal to  $2R_c$ .

We consider perfect inter-source channel quality ( $\gamma_{ss}^b = \infty$ ) in order to highlight MIMO contributions over a cooperative system. Thus, in order to perform cooperation continuously, an error-free inter-source channel has to be assumed. Both sources operate all the time under the first cooperative case described in Section III. Since cooperation always occurs, the codewords of both sources are always turbo-decoded (8 inner iterations). For the non-orthogonal channel, IDMA involves an iterative process between the ESE and the turbo-decoders. We assume 5 outer iterations for SISO nodes and 10 outer iterations for MIMO nodes.

In Fig. 6 FER curves are given for SISO and MIMO nodes with orthogonal and non orthogonal channels (IDMA needed). Adding MIMO spatial multiplexing to the SISO TCCoop scheme yields 4.5 dB gain at  $\text{FER}=10^{-2}$ . We note that cooperative systems still benefit from space diversity offered by the multi-antenna network deployment, since the slope of the curve is changed. However, this gain is not exclusively due to space diversity. It is also the result of using BPSK instead of QPSK thanks to spatial multiplexing operation. Furthermore, the FER performance of SISO TCCoop system is slightly affected when operating over non-orthogonal channels. For instance, a very low degradation persists after 5 outer iterations of the IDMA process. This performance degradation in terms of FER is larger for the MIMO TCCoop system after

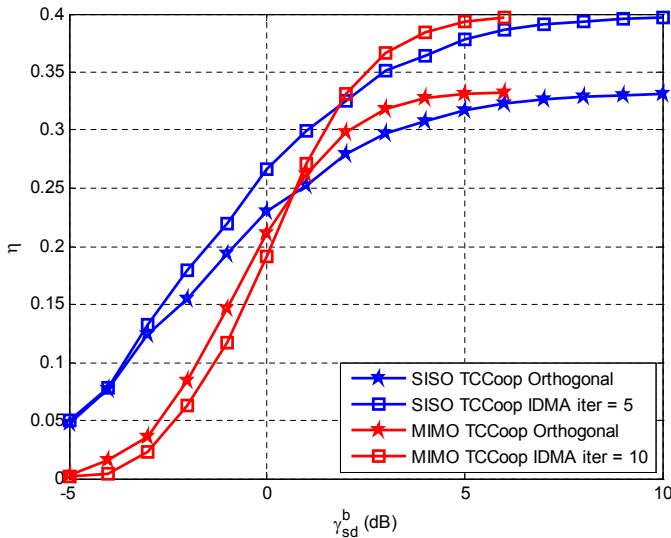


Fig. 7. Throughput efficiency curves of turbo coded cooperation with SISO and MIMO systems for  $\gamma_{ss}^b = \infty$  dB.

10 outer iterations. Therefore, more iterations are needed to better separate both sources. This is particularly due to the suboptimality of the detection (MRC plus ESE) regarding spatial and multiple access interference. Better FER performance (not shown) has been observed with a joint maximum a posteriori turbo-detection.

Throughput performance is reported in Fig. 7. In particular, we plot the *throughput efficiency* ( $\eta$ ), defined as [6]

$$\eta = \rho T \quad (8)$$

where  $\rho$  is the *reliability*, defined as the ratio between the number of accepted bits and the number of received bits, and  $T$  is the *throughput* of the system, defined as the ratio between the average number of accepted bits and the total number of bits sent over the channel per unit time. Therefore, the throughput efficiency is defined as the ratio between the number of information bits correctly transmitted per source and channel time allocation. Note that the throughput efficiency has to be multiplied by 2 to take into account the spectral efficiency of the SISO and MIMO schemes, equal to 2 bits/s/Hz.

The throughput efficiency of the turbo coded cooperation system with orthogonal channels is limited to  $\eta \leq 1/3$ , since two phases are always allocated for the transmission of a frame, hence  $R_c = 1/3$ . A sizable throughput efficiency increase is obtained for the non-orthogonal scenario thanks to the use of the IDMA technique. In this case, the throughput

efficiency is limited to  $R_c = 2/5$  since better transmission delay is obtained when the same time slot is allocated to both sources to perform the cooperation phase. The FER degradation observed with respect to the orthogonal scenario is largely compensated by the throughput gain. Therefore, the throughput efficiency behavior is globally better for the non-orthogonal TCCoOp than for the orthogonal TCCoOp, for both SISO and MIMO setups. This is mainly observed in the high-SNR regime. Asymptotically, the throughput efficiency gain of non-orthogonal TCCoOp systems with respect to the orthogonal one is about 20%. In the low-SNR regime, MIMO TCCoOp behave worse than SISO TCCoOp. This observation is congruent with the results in terms of FER depicted in Fig. 6. For instance, under the orthogonal scenario, the MIMO TCCoOp system outperforms the SISO one for  $\gamma_{sd}^b > 1$  dB. On the other hand, under the non-orthogonal scenario, the MIMO TCCoOp system still performs worse than the SISO TCCoOp system for  $\gamma_{sd}^b \leq 2$  dB.

## VI. CONCLUSIONS

In this paper, we considered turbo coded cooperation with multiple antennas at the operating nodes and we compared it with the original turbo coded cooperation where no multi-antenna nodes are deployed. We studied the considered system over two scenarios: orthogonal (TDMA) and non-orthogonal (IDMA). First, it was shown that turbo coded cooperation still benefits from spatial diversity offered by MIMO systems. Furthermore, it was pointed out that, even if IDMA process requires a higher transmitter/receiver complexity, it offers sizable throughput efficiency improvement.

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