TTCM-Aided SDMA-Based Two-Way Relaying

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individual UL signals are separated with the aid of their unique, user-specific spatial signature constituted by their CIRs, which have to be
accurately estimated [8].

A TTCM-aided SDMA OFDM system was studied in [8], [9]. We have investigated a variety of SDMA-based Multi-User Detectors (MUD) [10], namely the Zero Forcing (ZF), the Minimum Mean-Square Error (MMSE), the Interference Cancellation (IC) and Maximum Likelihood (ML) MUDs. The ML MUD provides the best
performance at the cost of the highest complexity. By contrast, the
ZF and MMSE MUDs have a poorer performance, but impose a lower complexity. Furthermore, the TTCM-assisted IC arrangement
was found to give a better performance than that of the MMSE MUD.

Relay-assisted cooperative communication schemes have been
proposed in [11]. The most popular cooperative communication protocols
are the Decode-and-Forward (DF) and Amplify-and-Forward (AF)
schemes [8], [12]. More explicitly, the attractive two-way relaying
scheme of [11] assists a pair of MSs to exchange their signals with the aid of either a single or several Relay Nodes (RN) using
two transmission periods. The two-way relaying protocol aims for
improving the power efficiency, achievable rate and throughput.

Against this background, in this contribution, we consider a new
TTCM-aided SDMA-based two-way relaying scheme constituted by
a pair of users, as well as a RN. Both users transmit simultaneously
to the RN during the first transmission period. Then, the RN decodes
and forwards the received superposed messages to both MSs during the second transmission period. More specifically, we propose a
TTCM-aided SDMA-based two-way relaying scheme, where each
MS is equipped with a single UL transmit antenna, while the RN is
equipped with two antennas. Two beneficial methods are employed
for creating the bit sequence before TTCM-encoding at the RN.
Finally, a power-sharing technique is employed for approaching
the achievable throughput and for reducing the overall transmit power.

The paper is organized as follows. The system model and our
novel TTCM-aided SDMA-based two-way relaying structure are
described in Section II. The performance of the scheme is evaluated in
Section III. Finally, our conclusions are presented in Section IV.

I. INTRODUCTION

Turbo Trellis Coded Modulation (TTCM) [1] is a joint coding and modulation scheme that has a structure similar to binary turbo
codes [2], [3], where two identical parallel-concatenated Trellis Coded Modulation (TCM) [4] schemes are employed as component
codes. The TTCM schemes in [1] were designed based on the search for
the best component TCM codes using the so-called ’punctured’ minimal distance criterion for communicating over the Additive
White Gaussian Noise (AWGN) channel. Recently, various TTCM
schemes were designed in [5] with the aim of Extrinsic Information
Transfer (EXIT) charts [6], [7] and union bounds for approaching
the capacity of the Rayleigh fading channel.

Space Division Multiple Access (SDMA) is a bandwidth efficient
scheme, which relies on the Multi-Input-Multi-Output (MIMO) de-
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up-link (UL) Mobile Stations (MS) is received within the same
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II. SYSTEM MODEL

Fig. 1. Schematic of a two-way relay aided system, where t1 is the first
transmission period and t2 is the second transmission period. dab is the
geometrical distance between node a and node b. G_{ab} is the geometrical-gain between node a and node b.

The schematic of a two-way relaying scheme is shown in Fig. 1.
During the first time slot, both users transmit their information
simultaneously to a RN. Then the RN decodes and forwards the
received message back to the two users during the second time
slot [13]–[15]. Hence, the overall system throughput is higher than
that of a one-way relaying scheme, which requires two time slots to
transmit one user’s information.

A. System Structure

The general schematic of the TTCM-aided SDMA-based Source-to-Relay (SR) model is shown in Fig. 2. Note that we have opted for
TTCM to assist the SDMA system, since the TTCM-SDMA scheme was found to be the best arrangement from a range of coded modulation
aided SDMA schemes [9].

As shown in Fig. 2, the information bit sequences b_1 and b_2 are
encoded by the TTCM encoders of MS_1 and MS_2, respectively. The
two TTCM codewords c_1 and c_2 are then fed into a virtual MIMO

mapper for transmission to the RN. Again, at the RN we consider four MUDs, namely the ML, MMSE, ZF and IC MUDs. The estimated information sequences \(b_1\) and \(b_2\) are obtained by the TTCM decoders.

As shown in Fig. 3, we consider two methods for combining the estimated information sequences \(b_1\) and \(b_2\) into \(b_3\). The RN can concatenate the two decoded \(N\)-bit sequences into a \(2N\)-bit sequence, i.e. we have \(b_3 = [b_1 \ b_2]\). Alternatively, the RN may combine the two sequences into another \(N\)-bit sequence using modulo-two addition, i.e. we have \(b_3 = b_1 \oplus b_2\), where \(\oplus\) is an element-by-element modulo-two addition operator. However, the overall system throughput of the modulo-two addition aided method is higher than that of the concatenation method. The combined sequence \(b_3\) is TTCM-encoded and broadcast from the RN to the two MSs during the second time slot. This is similar to an SDMA system using two transmit antennas and one receive antenna. Each MS then detects the signal from the opposite MS based on the TTCM-decoded sequence \(b_3\). For example, at the receiver of MS2, the information sequence of MS1, \(b_1\), can be retrieved from the first part of \(b_3\), if the concatenation method is used. Alternatively, it can be retrieved from \(b_1 = b_2 \oplus b_3\) if the modulo-two addition method is employed, where \(b_2\) is known at the receiver of MS2.

**B. SDMA Channel Model**

The received signal of an SDMA system supporting \(L\) users, each is equipped with a single-antenna unit, and a BS receiver equipped with \(P\) antennas can be represented as [8], [9]:

\[
Y = HX + n \tag{1}
\]

where the received signal is a \((P \times 1)\)-dimensional vector \(Y = [y_0, y_1, \cdots, y_{P-1}]^T\). Still referring to Eq. (1), the transmitted signal is an \((L \times 1)\)-dimensional vector \(X = [x_0, x_1, \cdots, x_{L-1}]^T\) and \(n = [n_0, n_1, \cdots, n_{P-1}]^T\) is a \((P \times 1)\)-dimensional Gaussian noise vector, which has a zero mean and a noise variance of \(N_0/2\) per dimension.

We consider a two-user SDMA scheme, where the two MSs are considered to be a two-transmitter virtual SN. We also consider a two-antenna aided RN. Note that we have incorporated the reduced-pathloss-induced geometrical-gain [12], [16], [17] and the transmit power factor in the channel matrix of Eq. (1). Hence, the channel matrix between the two users and the two-antenna aided RN may be written as:

\[
H = \begin{bmatrix} G_{s_1} \sqrt{P_{r_1}} h_{s_1 r_1} & G_{s_2} \sqrt{P_{r_2}} h_{s_2 r_2} \\ G_{s_2} \sqrt{P_{r_1}} h_{s_2 r_1} & G_{s_1} \sqrt{P_{r_2}} h_{s_1 r_2} \end{bmatrix},
\]

where the subscript \(r\) denotes the ith receive antenna of the RN and the subscript \(s\) denotes the jth transmit antenna of the virtual two-antenna-aided SN, namely of the jth user. Furthermore, we denote the geometrical-gain between antenna \(a\) and antenna \(b\) as \(G_{ab}\), while \(P_{r_a}\) represents the power transmitted from antenna \(a\) and antenna \(b\).

**C. Multi-user Detector**

The MMSE, ZF and IC MUD based SDMA schemes require at least the same number of receiver antennas as that of the transmit antennas [18]. We considered the MMSE, ZF, IC and ML MUDs in the SR link. However, only the ML MUD is used in the RD link, because there is only a single receive antenna at each DN. The weight matrix of the ZF MUD is defined as:

\[
W_{zf} = H(HH^H)^{-1},
\]

where \(H^H\) is the Hermitian transpose of the channel matrix. The ZF-detected signal can be expressed as [9]:

\[
Z_{zf} = W_{zf}^H Y = W_{zf}^H (HX + n) = (H^H H)^{-1} H^H H X + (H^H H)^{-1} H^H n = X + (H^H H)^{-1} H^H n. \tag{3}
\]

By contrast, the weight matrix of the MMSE MUD is given by [9]:

\[
W_{mmse} = H(HH^H + N_0 I_P)^{-1}, \tag{4}
\]

where \(I_P\) is a \((P \times P)\)-element matrix having ones on its diagonal. More explicitly, the MMSE-detected signal can be written as:

\[
Z_{mmse} = W_{mmse}^H Y = (H^H H + N_0 I_P)^{-1} H^H H X + (H^H H + N_0 I_P)^{-1} H^H n. \tag{5}
\]

Furthermore, the ML MUD is a non-linear detector, which is optimal in terms of minimizing the symbol error probability, when all possible vectors are equally likely [19]. However, all possible \(M^L\) combinations of the transmitted symbols have to be considered in a ML detector, where \(M\) is the number of constellation points and \(L\) is the number of transmit antennas. By contrast, the ZF, MMSE and IC MUDs only have to consider \(M\) combinations for each. As seen from Eq. (5), the BER performance of the MMSE MUD is influenced by the interference introduced by the matrix \((H^H H + N_0 I_P)^{-1} H^H H\), which is non-diagonal. We advocated a low-complexity MMSE-based IC MUD for improving the system performance by removing the off-diagonal elements in the \((H^H H + N_0 I_P)^{-1} H^H H\) matrix.

It is clear from Eq. (3) that no residual interference persists after ZF MUD. However, some residual interference still contaminates the MMSE detected signal, as shown in Eq. (5). Our IC scheme is described as follows. We assume that 4PSK modulation is employed, where we have \(M = 4\). The soft estimate of a 4PSK symbol was formulated as:

\[
\hat{x} = \sum_{i=1}^{J} P_r(x^{(i)}|x^{(i)}), \tag{6}
\]
where $x^{(i)}$ is the $i$th symbol in the 4PSK constellation and $P_i(x^{(i)})$ is the probability of $x^{(i)}$. More specifically, from Eq. (5) the MMSE-detected signal can be written in a matrix format as:

$$\begin{bmatrix} z_1 \\ z_2 \end{bmatrix} = \begin{bmatrix} \sigma_x & \varsigma \\ \varsigma & \kappa \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} \omega_x & \theta_x \\ \theta_x & \psi_x \end{bmatrix} \begin{bmatrix} n_1 \\ n_2 \end{bmatrix},$$

(7)

where $\begin{bmatrix} \sigma_x & \varsigma \\ \varsigma & \kappa \end{bmatrix}$ is the $W_{\text{mmse}}^H H$ term and $\begin{bmatrix} \omega_x & \theta_x \\ \theta_x & \psi_x \end{bmatrix}$ is the $W_{\text{mmse}}$ term. The resultant noise variance in $z_1$ is given by:

$$\text{var}(\omega n_1 + \theta n_2) = |\omega|^2 N_0 + |\theta|^2 N_0 = (|\omega|^2 + |\theta|^2) N_0,$$

(8)

where $N_0/2$ is the original noise variance per dimension. We can detect the signal received from MS$_1$ by removing the interference from MS$_2$ based on Eq. (7), as follows:

$$\hat{z}_1 = z_1 - \varsigma x_2 = \sigma_x x_1 + \omega n_1 + \theta n_2.$$

(9)

Similarly, the signal received from MS$_2$ can be detected as:

$$\hat{z}_2 = z_2 - \varsigma x_1 = \kappa x_2 + \omega n_1 + \psi n_2.$$

(10)

Then, $\hat{z}_1$ and $\hat{z}_2$ of Eqs. (9) and (10) can be fed into the corresponding TTCM decoder for detecting the corresponding information sequences.

D. Optimum Power Sharing Between the SN and RN

The employment of an appropriate power sharing technique is proposed for apportioning the transmit power between the SN and RN. This will allow us to reduce the overall transmission power required in the two-way cooperative relaying scheme. This is necessary, because the SN and the RD links require different received SNRs for achieving the same BER. The reason behind this is that the two-antenna virtual user at the SN and the RN constitutes a two-antenna virtual user at the SN and the RN of achieving the same BER. The reason behind this is that the two-antenna virtual user at the SN and the RN constitutes a two-antenna virtual user at the SN and the RN.

The corresponding reduced-pathloss-induced geometrical gains [12], [16], [17] between MS$_1$ and the RN as well as between the RN and MS$_2$ are given by:

$$G_{s1,r} = \left( \frac{d_{s1,r}}{d_{s1,r}} \right)^2,$$

(11)

and

$$G_{s2,r} = \left( \frac{d_{s2,r}}{d_{s2,r}} \right)^2,$$

(12)

respectively, where $d_{ab}$ denotes the geometrical distance between node $a$ and node $b$. If the RN is located at the mid-point between MS$_1$ and MS$_2$, then we have $G_{s1,r} = G_{s2,r} = 4$.

The average received Signal to Noise power Ratio (SNR) per-user per-receive antenna 1 at the receiver node $b$ with respect to the transmitter node $a$ can be computed as:

$$\gamma_R = \frac{P_{l,a} E[\{|G_{ab}|^2\}]}{N_b N_a} \sum_{b=1}^{N_b} \sum_{a=1}^{N_a} E[|h_{ba}|^2] E[|x_a|^2],$$

(13)

where $N_b$ and $N_a$ are the number of antennas at node $b$ and node $a$, respectively. Furthermore, $x_a$ is the symbol transmitted from the $j$th antenna of node $a$, $h_{ba}$ is the channel coefficient from antenna $a$ to antenna $b$, $P_{l,a}$ is the power transmitted from node $a$ and the expected values are given by $E[|h_{ba}|^2] = 1$ and $E[|x_a|^2] = 1$. We define the term transmit SNR $2$ as the ratio of the power transmitted from node $a$ to the noise power encountered at the receiver of node $b$ as:

$$\gamma_T = \frac{P_{l,a}}{N_0}.$$  

(14)

Hence, the relationship between $\gamma_T$ and $\gamma_R$ can be shown to be:

$$\gamma_T = \gamma_R G_{ab},$$

(15)

which is also given by

$$\Upsilon_R = \Upsilon_T + 10 \log_{10}(G_{ab}) \text{ [dB]},$$

(16)

where $\Upsilon_R = 10 \log_{10}(\gamma_R)$ and $\Upsilon_T = 10 \log_{10}(\gamma_T)$. Let us denote the transmit SNR of MS$_1$, MS$_2$ and the RN as $\Upsilon_{T,s}$, $\Upsilon_{T,r}$ and $\Upsilon_{T,r}$, respectively. We jointly consider the two users as a single two-transmitter SN during the first time slot and the RN is located at the mid-point between the two users. Hence, the power transmitted from both MSs is considered to be equal, i.e. $\Upsilon_{T,s} = \Upsilon_{T,r} = \Upsilon_{T,r}$. The average transmit SNR of the system can be computed as:

$$\bar{\Upsilon}_T = \frac{\Upsilon_{T,s} + \Upsilon_{T,r}}{2},$$

(17)

$$= \frac{10 \log_{10}(\Upsilon_{T,s}) + 10 \log_{10}(\Upsilon_{T,r})}{2},$$

(18)

where we have $\Upsilon_{T,s} = 10 \log_{10}(\gamma_{T,s})$ and $\Upsilon_{T,r} = 10 \log_{10}(\gamma_{T,r})$. The proposed power sharing method is provided to minimize the overall transmit power, while ensuring that both the RN and the DN simultaneously achieve a bit error ratio (BER) of $10^{-6}$ at the lowest possible transmit SNR. More specifically, we first find the receive SNR required for the RD link, namely $\Upsilon_{R,s} = 10 \log_{10}(\gamma_{R,s})$, and that of the RD link, namely $\Upsilon_{R,r} = 10 \log_{10}(\gamma_{R,r})$, for achieving a BER of $10^{-6}$. The difference between these receive SNRs is given by:

$$\Upsilon_{R,\Delta} = \Upsilon_{R,r} - \Upsilon_{R,s} \text{ [dB]},$$

(19)

where $\Upsilon_{R,\Delta} = 10 \log_{10}(\gamma_{R,\Delta})$. It can be shown that the transmit SNR at the SN is given by:

$$\gamma_{T,s} = \frac{2\gamma_T}{1 + \gamma_{R,\Delta}}.$$  

(20)

Similarly, the transmit SNR at the RN can be formulated as:

$$\gamma_{T,r} = \frac{2\gamma_T}{1 + \gamma_{R,\Delta}}.$$  

(21)

Moreover, the overall system throughput $\xi_s$ of our two-way relaying scheme is given by:

$$\xi_s = \frac{L_{b,s}}{N_1 + N_2},$$

(22)

where $N_1$ denotes the number of symbol periods during the first time slot, $N_2$ is the number of modulated symbols transmitted from the

1. Although the concept of transmit SNR [16] is unconventional, because it relates the transmit power to the noise power at the receiver, which are at physically different locations, it is convenient for our discussions.
RN during the second time slot, $L = 2$ denotes the number of users, while $I_b$ is the number of information bits transmitted per user within a duration of $(N_1 + N_2)$.

### III. Performance Evaluation

![Fig. 4. BER versus received SNR per-user per-receiver antenna performance of various 4PSK-TTCM-aided SDMA schemes employing ML, MMSE, IC and ZF MUDs in the SR link. The TTCM decoder employs 4 inner iterations and 4 outer iterations for exchanging extrinsic information with the SDMA detector. The frame length is $N_1 = 1200$.](image1)

![Fig. 5. BER versus received SNR per-user per-receiver antenna performance of various 4PSK-TTCM-aided SDMA schemes employing ML MUD in the RD link. The TTCM decoder employs 4 inner iterations and 4 outer iterations for exchanging extrinsic information with the SDMA detector. The frame lengths considered are $N_2 = 1200$ and $N_2 = 2400$.](image2)

An uncorrelated Rayleigh fading channel is considered and an outer iteration is defined as that when the SDMA detector and the TTCM decoder are activated once. As seen from Fig. 4, the scheme employing ML MUD that invokes four outer iterations has the best BER performance and the ZF MUD has the worst BER performance in the SR link. There is an approximately 4 dB difference in terms of their received SNRs at a BER of $10^{-6}$. Furthermore, after the fourth iteration the IC scheme outperforms the MMSE MUD. This is because the interfering signal introduced by the MMSE MUD is cancelled by the IC MUD. The performance of the ZF MUD cannot be further improved by having additional outer iterations, because the interfering signal has already been removed. In the first time slot, the transmitted frame length is $N_1 = 1200$ symbols.

The performance of various TTCM-aided SDMA-based schemes employing ML MUD, when communicating over the RD link during the second time slot is shown in Fig. 5. When the concatenation method of Section II-A is employed, the total number of 4PSK modulated symbols transmitted from the RN is 2400. By contrast, when the modulo-two addition method of Section II-A is employed, we have 1200 symbols. However, due to the employment of two transmit antennas at the RN, the total transmission period is given by $N_2 = 1200$ or $N_2 = 600$ symbols, depending on whether the concatenation or the modulo-two addition method is employed, respectively. As shown in Eq. (22), the overall system throughput of the scheme employing the concatenation method is $\xi = 1$ bit-per-second (bps). By contrast, that of the scheme using the modulo-two addition method is given by $\xi = 1.33$ bps, because we have $I_b = 1200$ information bits transmitted per user. Based on Fig. 4 and Fig. 5, the differences between these received SNRs are shown in Table I. Fig. 6 portrays the BER versus transmitted SNR.
1.5 dBs SNR gain can be attained by the ‘Concat:ML-ML’ scheme over the ‘Concat:non-PS-ML’ scheme, as seen in Fig. 6 at a BER of $10^{-6}$. The IC based scheme outperforms the MMSE and ZF based MUDs, while as expected, the ML based scheme gives the best BER performance.

Note that the SNR per bit is defined as $E_b/N_0[\text{dB}] = \text{SNR}[\text{dB}] - 10 \log_{10}(E_b/N_0)$. Fig. 7 shows the BER versus transmit $E_b/N_0$ per user performance of various TTCM-aided SDMA-based two-way relaying schemes, which is useful for comparing the performance of the concatenation and the modulo-two addition methods, because they have different throughputs. The scheme employing modulo-two addition outperforms that employing the concatenation method by approximately 1.2 dBs at a BER of $10^{-6}$, as seen by comparing the ‘Mod2:ML-ML’ and the ‘Concat:ML-ML’ curves in Fig. 7, where both schemes employ the ML MUD and the power sharing mechanism is activated. Similar improvements can be observed in Fig. 7 for the IC, MMSE and ZF based schemes, when the modulo-two addition method is employed instead of the concatenation method. As seen in Fig. 7, the ‘Mod2:ML-ML’ scheme outperforms the ‘TTCM-Rayleigh’ benchmark scheme by approximately 4.7 dBs, which is a benefit of the proposed power- and bandwidth-efficient SDMA-based two-way relaying scheme. The MMSE-detected SDMA-based two-way relay scheme offers a lower complexity at the cost of a modest 0.5 dB SNR loss in comparison to the ML-based scheme, as shown by the ‘Mod2:ML-ML’ and ‘Mod2:MMSE-ML’ curves in Fig. 7 at a BER of $10^{-6}$.

IV. CONCLUSIONS

We have proposed a power- and bandwidth-efficient TTCM-aided SDMA-based two-way relaying scheme. We first quantified the achievable BER performance of the TTCM-aided SDMA schemes, when the ZF, MMSE, IC and ML MUDs are considered in the SR and RD links, respectively. Then, we invoked a power sharing mechanism to minimize the overall transmit power based on these single-link performances. The power sharing mechanism is capable of saving approximately 2 dBs of power. We have also quantified the performance of the TTCM-aided SDMA-based two-way relaying scheme, when the concatenation and modulo-two addition methods are employed at the RN. The modulo-two addition method is capable of providing another dB or so SNR gain.

We found that our proposed ML-detected SDMA-based two-way relaying scheme is capable of outperforming the non-cooperative TTCM benchmark scheme by approximately 4.7 dBs at a BER of $10^{-6}$. The MMSE detected scheme offers the best compromise in terms of the detection complexity imposed and the performance gain attained.

REFERENCES


