TTCM-Aided SDMA-Based Two-Way Relaying

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***Abstract*— A novel power- and bandwidth-efficient Turbo Trellis Coded Modulation (TTCM) assisted Space Division Multiple Access (SDMA) based two-way relaying scheme is proposed. The scheme advocated was designed for enhancing the throughput, reliability and coverage area in a cooperative communication system. A twin-antenna Relay Node (RN) is employed for assisting a pair of users, where each user is equipped with a single-antenna mobile unit. During the first transmission period, both users transmit their TTCM-encoded signals to the RN. The twin-antenna RN then detects these signals using various SDMA-based detection algorithms. Iterative SDMA and TTCM detection is invoked at the RN, which then broadcasts the re-encoded TTCM signals to both users during the second transmission period. Finally, each user retrieves the opposite user's signals received from the RN. Our proposed scheme outperforms the non-cooperative TTCM scheme by approximately 4.7 dBs at a BER of 10^{-6}, when communicating over uncorrelated Rayleigh fading channels.**

***Index Terms*— Turbo Trellis Coded Modulation (TTCM), Space Division Multiple Access (SDMA), two-way relaying, Multi-User Detector (MUD), power sharing.**

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 aid 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) design philosophy. Explicitly, the transmitted signal of L simultaneous up-link (UL) Mobile Stations (MS) is received within the same frequency band and differentiated purely by their Channel Impulse Response (CIR). Each MS is equipped with a single transmitter antenna and their signals are received by the P different receiver antennas of the Base Station (BS) [8]. Again, at the BS the 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.

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II. SYSTEM MODEL

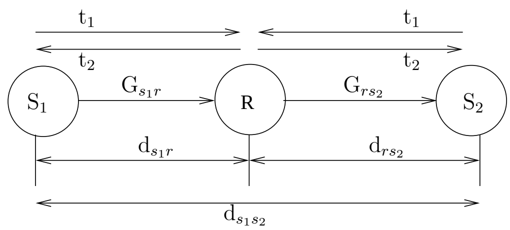

Fig. 1. Schematic of a two-way relay aided system, where t_1 is the first transmission period and t_2 is the second transmission period, d_{ab} is the geographical distance between node a and node b. G_{ab} is the geometrical-gain between node a and node b.

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

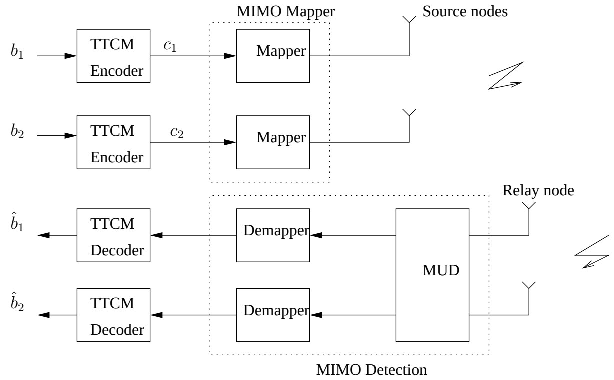

Fig. 2. The schematic of the Source Node (SN) to RN model.

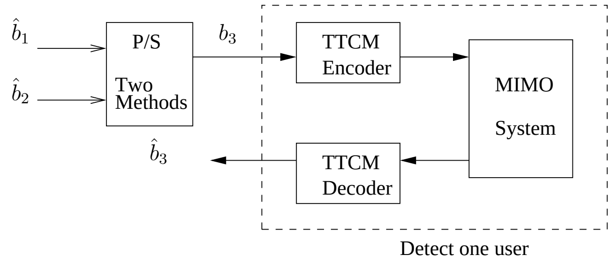

Fig. 3. The schematic of the RN to Destination Node (DN) model.The block P/S denotes the parallel to serial converter.

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 $\hat{b}_1$ and $\hat{b}_2$ are obtained by the TTCM decoders.

As shown in Fig. 3, we consider two methods for combining the estimated information sequences $\hat{b}_1$ and $\hat{b}_2$ into b_3. The RN can concatenate the two decoded N-bit sequences into a $2N$-bit sequence, i.e. we have $b_3 = [\hat{b}_1\ \hat{b}_2]$. Alternatively, the RN may combine the two sequences into another N-bit sequence using modulo-two addition, i.e. we have $b_3 = \hat{b}_1 \oplus \hat{b}_2$, 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 $\hat{b}_3$. For example, at the receiver of MS_2, the information sequence of MS_1, b_1, can be retrieved from the first part of $\hat{b}_3$, if the concatenation method is used. Alternatively, it can be retrieved from $\hat{b}_1 = b_2 \oplus \hat{b}_3$ if the modulo-two addition method is employed, where b_2 is known at the receiver of MS_2.

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 by [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:

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

where the subscript r_i denotes the ith receive antenna of the RN and the subscript s_j 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 $P_{T,a}$ represents the power transmitted from antenna a and h_{ab} represents the CIR coefficient between 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 :

$$W_{\text{zf}} = H(HH^H)^{-1} \ , \tag{2}$$

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

$$\begin{aligned} Z_{\text{zf}} &= W_{\text{zf}}^H Y \\ &= W_{\text{zf}}^H (HX + n) \\ &= (H^H H)^{-1} H^H H X + (H^H H)^{-1} H^H n \\ &= X + (H^H H)^{-1} H^H n \ . \end{aligned} \tag{3}$$

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

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

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:

$$\begin{aligned} Z_{\text{mmse}} &= W_{\text{mmse}}^H Y \\ &= (H^H H + N_0 I_P)^{-1} H^H H X \\ &\quad + (H^H H + N_0 I_P)^{-1} H^H n \ . \end{aligned} \tag{5}$$

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 ith symbol in the 4PSK constellation and $P_r(x^{(i)})$ is the probability of $x^{(i)}$. More specifically, from Eq. (5) the MMSE-detected signal can be written in a matrix format as:

$$\begin{bmatrix} z_1 \\ z_2 \end{bmatrix} = \begin{bmatrix} \sigma & \varsigma \\ \iota & \kappa \end{bmatrix} \times \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} \omega & \varrho \\ \varpi & \psi \end{bmatrix} \times \begin{bmatrix} n_1 \\ n_2 \end{bmatrix} , \quad (7)$$

where $\begin{bmatrix} \sigma & \varsigma \\ \iota & \kappa \end{bmatrix}$ is the $W_{\text{mmse}}^H H$ term and $\begin{bmatrix} \omega & \varrho \\ \varpi & \psi \end{bmatrix}$ is the W_{mmse}^H term. The resultant noise variance in z_1 is given by:

$$\begin{aligned} var(\omega n_1 + \varrho n_2) &= |\omega|^2 N_0 + |\varrho|^2 N_0 \\ &= (|\omega|^2 + |\varrho|^2) N_0, \end{aligned} \quad (8)$$

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:

$$\begin{aligned} \tilde{z}_1 &= z_1 - \varsigma x_2 \\ &= \sigma x_1 + \omega n_1 + \varrho n_2 \ . \end{aligned} \quad (9)$$

Similarly, the signal received from MS_2 can be detected as:

$$\begin{aligned} \tilde{z}_2 &= z_2 - \iota x_1 \\ &= \kappa x_2 + \varpi n_1 + \psi n_2 \ . \end{aligned} \quad (10)$$

Then, $\tilde{z}_1$ and $\tilde{z}_2$ 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 SR 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 (2×2)-element MIMO scheme, which requires a lower SNR, i.e. a lower transmit power than the (2×1)-element RD link. Hence appropriately sharing the total transmit power between them allows us to reduce the overall power required. Naturally, in a practical system an appropriately designed agile SR power-control scheme is required for maintaining the optimum sharing of the transmit power between the SN and RN. We consider a free-space path-loss model. 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:

$$G_{s_1r} = \left(\frac{d_{s_1s_2}}{d_{s_1r}}\right)^2 , \quad (11)$$

and

$$G_{rs_2} = \left(\frac{d_{s_1s_2}}{d_{rs_2}}\right)^2 , \quad (12)$$

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 $G_{s_1r} = G_{rs_2} = 4$.

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:

$$\begin{aligned} \gamma_R &= \frac{P_{t,a} E\{|G_{ab}|\}}{N_0} \cdot \frac{\sum_{b_i=1}^{N_b} \sum_{a_j=1}^{N_a} E\{|h_{b_i a_j}|^2\} E\{|x_{a_j}|^2\}}{N_b \ N_a} \\ &= \frac{P_{t,a} G_{ab}}{N_0} , \end{aligned} \quad (13)$$

where N_b and N_a are the number of antennas at node b and node a, respectively. Furthermore, x_{a_j} is the symbol transmitted from the jth antenna of node a, $h_{b_i a_j}$ is the channel coefficient from antenna a_j to antenna b_i, $P_{t,a}$ is the power transmitted from node a and the expected values are given by $\text{E}\{|h_{b_i a_j}|^2\} = 1$ and $\text{E}\{|x_{a_j}|^2\} = 1$. 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:

$$\gamma_T = \frac{P_{t,a}}{N_0} \ . \quad (14)$$

Hence, the relationship between γ_T and γ_R can be shown to be:

$$\gamma_R = \gamma_T \ G_{ab} \ , \quad (15)$$

which is also given by

$$\Upsilon_R = \Upsilon_T + 10 \log_{10}(G_{ab}) \ \text{[dB]}, \quad (16)$$

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 γ_{T,s_1}, γ_{T,s_2} and $\gamma_{T,r}$, 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. $\gamma_{T,s} = \gamma_{T,s_1} = \gamma_{T,s_2}$. The average transmit SNR of the system can be computed as:

$$\begin{aligned} \bar{\gamma}_T &= \frac{\gamma_{T,s} + \gamma_{T,r}}{2} , & (17) \\ &= \frac{10^{\frac{\Upsilon_{T,s}}{10}} + 10^{\frac{\Upsilon_{T,r}}{10}}}{2} , & (18) \end{aligned}$$

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 SR 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:

$$\Upsilon_{R,\Delta} = \Upsilon_{R,r} - \Upsilon_{R,s} \ \text{[dB]}, \quad (19)$$

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

$$\gamma_{T,s} = \frac{2\bar{\gamma}_T}{1 + \gamma_{R,\Delta}} \ . \quad (20)$$

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

$$\gamma_{T,r} = \frac{2\bar{\gamma}_T \gamma_{R,\Delta}}{1 + \gamma_{R,\Delta}} \ . \quad (21)$$

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

$$\xi_s = \frac{L I_b}{N_1 + N_2}, \quad (22)$$

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] We introduced the terminology of per-user, per-receive antenna SNR for the sake of a fair comparison of the different scenarios considered and to emphasize the fact that these results may be applicable to other relaying scenarios.

[2] 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

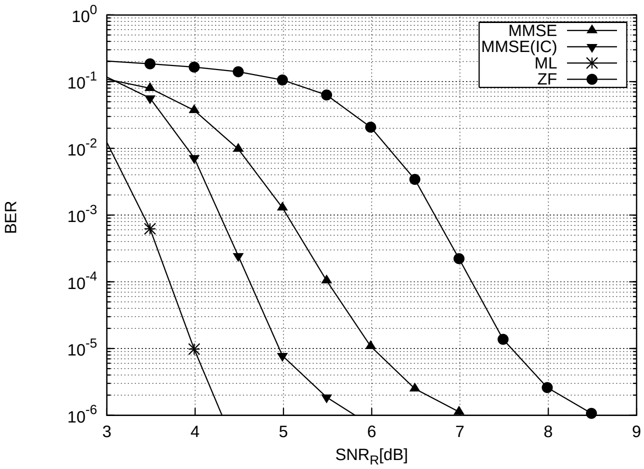

Fig. 4. BER versus received SNR per-user per-receiver antenna performance of various 4PSK-TTCM-aided SDMA schemes employing ML, MMSE, IC and ZF MUDs in the SR link. The TTCM decoder employs 4 inner iterations and 4 outer iterations for exchanging extrinsic information with the SDMA detector. The frame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

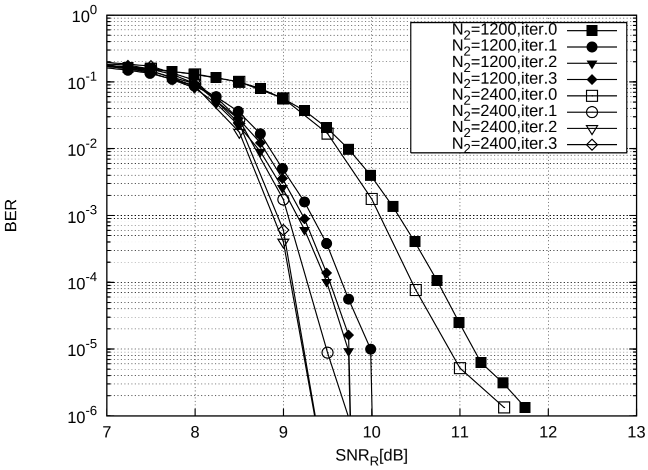

Fig. 5. BER versus received SNR per-user per-receiver antenna performance of various 4PSK-TTCM-aided SDMA schemes employing ML MUD in the RD link. The TTCM decoder employs 4 inner iterations and 4 outer iterations for exchanging extrinsic information with the SDMA detector. The frame lengths considered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

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 $\xi_s = 1$ bit-per-second (bps). By contrast, that of the scheme using the modulo-two addition method is given by $\xi_s = 1.33$ 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

Method	Outer iteration	ML	MMSE	IC	ZF
Concatenation	0	7.38	4.50	5.89	3.10
	1	5.45	2.66	3.85	1.25
	2	5.03	3.33	3.52	1.12
	3	5.03	3.33	3.52	1.12
Modulo-two addition	0	7.62	4.92	6.12	3.54
	1	5.78	3.12	4.14	1.53
	2	3.35	2.69	3.70	1.19
	3	3.35	2.69	3.70	1.19

TABLE I

TABLE OF RECEIVE SNR DIFFERENCES $\Upsilon_{R,\Delta}$ IN DECIBEL.

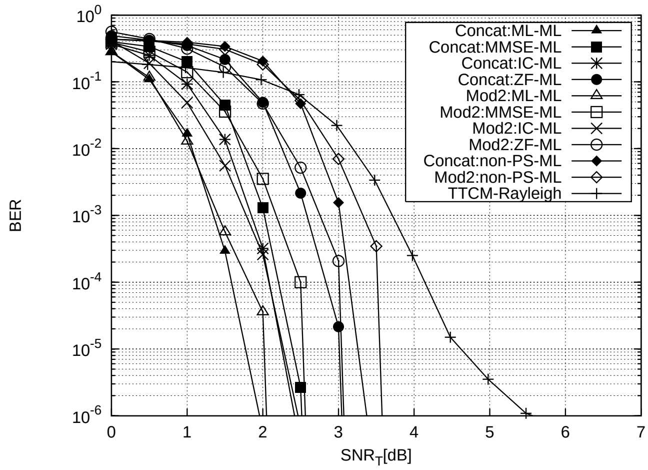

Fig. 6. BER versus transmitted SNR per user performance of various 4PSK-TTCM-aided SDMA-based two-way relay schemes. The notation 'MMSE-ML' is used to refer to a scheme employing MMSE MUD at the SR and then the ML MUD at the RD link. Similar meaning applies to the notations 'ML-ML', 'IC-ML' and 'ZF-ML'. The modulo-two addition method is represented by 'mod2' and the concatenation method is represented by 'concat'. Furthermore, all schemes employ the power sharing mechanism except those with the notation 'Non-PS'. The TTCM decoder employs 4 inner iterations and 4 outer iterations with the SDMA detector. The 'TTCM-Rayleigh' scheme is our single-user benchmarker which communicates over a single transmitter and a single receiver link.

per user performance of various TTCM-aided SDMA-based two-way relaying schemes. We have also considered a single-user non-cooperative benchmark scheme denoted as 'TTCM-Rayleigh', where a single transmitter and a single receiver are employed. Its throughput is 1 bps. At the same throughput, the two-way relaying scheme employing the concatenation method, but operating without the power sharing mechanism, denoted as 'Concat:non-PS-ML', outperforms the 'TTCM-Rayleigh' benchmarker by approximately 2 dBs at a BER of 10^{-6}. When the power sharing mechanism is activated, a further

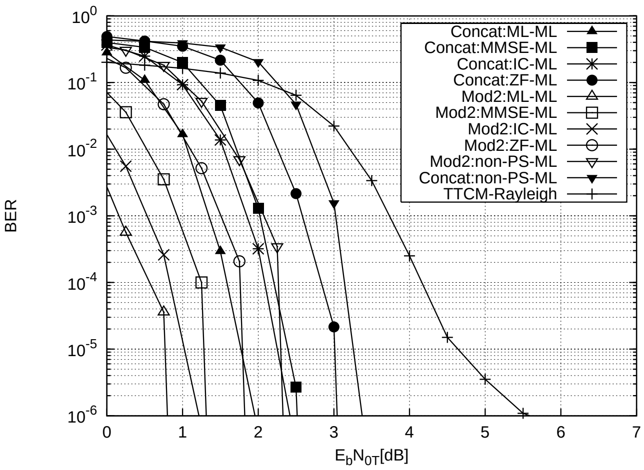

Fig. 7. BER versus transmitted E_b/N_0 per user performance of various 4PSK-TTCM-aided SDMA-based two-way relay schemes. The notation 'MMSE-ML' is used to refer to a scheme employing MMSE MUD at the SR and then the ML MUD at the RD link. Similar meaning applies to the notations 'ML-ML', 'IC-ML' and 'ZF-ML'. The modulo-two addition method is represented by 'mod2' and the concatenation method is represented by 'concat'. Furthermore, all schemes employ the power sharing mechanism except those with the notation 'Non-PS'. The TTCM decoder employs 4 inner iterations and 4 outer iterations with the SDMA detector. The 'TTCM-Rayleigh' scheme is our single-user benchmarker which communicates over a single transmitter and a single receiver link.

1.5 dBs SNR gain can be attained by the 'Concate: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 $E_b/N_0[\text{dB}] = \text{SNR}[\text{dB}] - 10\log_{10}(\xi_s)$. 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 schemes employing 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 'Concate: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.

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