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Turbo equalization for block fading MIMO channels using random signal mapping

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Abstract

We present a novel turbo equalization scheme for block fading MIMO channels, where diversity is achieved using random signal mapping. We show that the computational complexity of the proposed scheme is not a function of the number of transmit antennas, and compares favorably to the complexity of similar systems based on space–time trellis codes and space–time block codes. Finally, we provide simulation results showing that the proposed scheme achieves full diversity, and investigate its performance in terms of the number of transmit antennas, ISI length and imperfect channel knowledge.

Keywords: Wireless communications; MIMO channels; Random signal mapping; Turbo equalization; Space diversity

1. Introduction

Wireless systems with multiple transmit and/or receive antennas have been the topic of intense research activity lately. The interest in these multiple-input multiple-output (MIMO) systems was spurred by two results. Independently, Telatar [1] and Foschini and Gans [2] showed that a significant increase in capacity can be obtained in wireless systems when multiple antennas are employed at both the transmitter and the receiver. Besides this increased capacity, multiple antennas can also lead to increased robustness against fading, even without channel knowledge at the transmitter. Indeed, in [3], Tarokh et al. proposed a transmission scheme known as space–time coding (STC). In STCs, redundancy is introduced into the transmit streams both in space (across transmit antennas) and in time, leading to diversity and coding gains.

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STC for flat fading channels has been extensively analyzed, and it can essentially be divided into space–time trellis codes (STTC) [3,4] and space–time block codes (STBC) [5,6]. However, for high bit rates, the transmit bandwidth may be larger than the channel coherence bandwidth [7,8]. In this case, the channel becomes frequency selective, leading to intersymbol interference (ISI), and thus equalization becomes necessary. Many equalization schemes for space–time coded data have already been proposed in the literature and can also be divided according to the use of STTC or STBC. In [9], the author draws an extensive comparison of these schemes, concluding that time-reversal space–time block coding (TR-STBC) [10,11] and its generalizations [12] achieve the best complexity-performance trade-off.

Recently, a new transmission strategy that achieves spatial diversity based on a random signal mapper (RSM) was proposed in [13] for the case of flat-fading channels. In RSM, the bit stream is first encoded with a regular error-correcting code. Then, N copies of the encoder output are generated, where N is the number of transmit antennas. Each of these copies goes through a random signal mapper, whose output is then transmitted through one antenna. This simple scheme achieves full diversity. Furthermore, the RSM receiver has much lower complexity than that of STBCs, which is itself less complex than that of STTCs. In addition, transmit and/or receive antennas can be added to an RSM scheme without significant changes to the system, a flexibility not found in STBCs and STTCs. Finally, in most STBCs, adding more transmit antennas incurs in a rate penalty, but this penalty is not observed in RSM.

RSM was originally proposed for flat-fading channels. In this paper, we extend RSM to frequency selective fading MIMO wireless channels. To that end, we propose the use of a parallel-concatenated turbo code [14], and a receiver employing a turbo equalizer [15]. MIMO systems based on turbo equalizers were first proposed in [16], and were based on STTCs. As we will see, such turbo equalizers are much more complex than that of an RSM receiver. We also compare the complexity of the proposed system to that of a system using TR-STBC, and show that the complexity of both systems is similar to that of a single-input multiple-output (SIMO) system. Finally, we provide simulation results showing that the proposed scheme achieves full diversity, and investigate its performance in terms of the number of transmit antennas and ISI length.

This paper is organized as follows. In Section 2, we present the model of the frequency selective wireless channel, the RSM transmission scheme, and the proposed turbo equalizer. In Section 3, we present computer simulations showing that the new scheme achieves full diversity. In Section 4, we compare the proposed system with STTC and STBC based schemes, mostly in terms of computational complexity. Finally, we draw some concluding remarks in Section 5.

2. System model

Consider the transmission of a sequence of equiprobable and independent message bits u_k using N transmit antennas. To that end, we use the RSM transmitter depicted in Fig. 1. The bits first go through a binary parallel-concatenated turbo code, whose internal interleaver has length I. The output of the encoder then goes through another interleaver of length J, and is then mapped into an m-PSK symbol. The interleaver is repre-

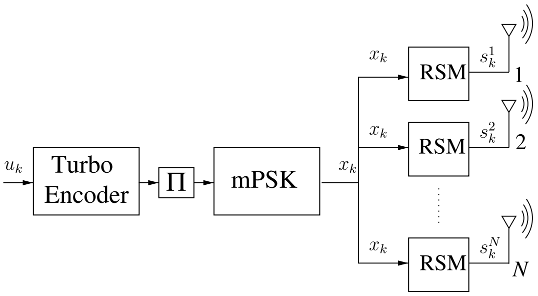

Fig. 1. Block diagram of the proposed transmitter, with N transmit antennas, turbo encoding, interleaving, m-PSK modulation and random signal mapping. Π represents the interleaver.

sented by Π in Fig. 1. The block m-PSK symbols x_k then goes through N random signal mappers, whose outputs are given by

$$s_k^i = e^{j\phi_k^i} x_k, \tag{1}$$

for $i = 1, \ldots, N$, where ϕ_k^i are N independent sequences of random phases known also to the receiver. Finally, the sequence s_k^i is transmitted through the i-th antenna with energy E_S/N.

The receiver may employ M antennas. The signal received by the j-th receive antenna at time instant k, $y^j(k)$, is given by

$$y^j(k) = \sum_{i=1}^{N} \sum_{d=0}^{D-1} \sqrt{E_S/N} s^i(k-d) h_{i,j}(d) + \eta^j(k), \tag{2}$$

where $\eta^j(k)$ is the zero-mean additive white Gaussian noise with variance $N_0/2$ per dimension, and $h_{i,j}(d)$ is the d-th coefficient of the impulse response of the channel between the i-th transmit antenna and the j-th receive antenna, which includes transmit-receive filters and multipath effects. The coefficients $h_{i,j}(d)$ are assumed to be zero-mean independent and identically distributed complex Gaussian random variables with variance σ_{d}^2, where $\sum_{d=0}^{D-1} \sigma_{\mathrm{d}}^2 = 1$. We further assume that the channel coefficients are spatially uncorrelated and remain constant during the transmission of one block, i.e., one codeword of the turbo code.

Note that (2) can be rewritten as

$$y^j(k) = \sum_{d=0}^{D-1} \sqrt{E_S} f_k^j(d) x(k-d) + \eta^j(k), \tag{3}$$

where

$$f_k^j(d) = \sqrt{1/N} \sum_{i=1}^{N} h_{i,j}(d) e^{j\phi_k^i}. \tag{4}$$

Thus, using RSM, the received signal at the j-th antenna can be written as the output of a single-input single-output (SISO) channel with time-varying taps $f_k^j(d)$. In other words, given that there are M receive antennas, using RSM at the transmitter reduces the quasi-static MIMO channel to a time-varying SIMO channel. As we will see, this reduction has no negative impact on the diversity gain of the system.

However, reducing the MIMO channel to an equivalent SIMO channel does have a beneficial impact on the receiver complexity. Indeed, we may now employ a maximum a posteriori (MAP) equalizer for a SIMO system, which is a straightforward extension of the MAP equalizer for SISO systems, obtained at the cost of a linear (in M) increase in complexity. Note that, in this case, the resulting computational complexity does not depend on the number of transmit antennas.

Without loss of generality, in this paper we focus on the case of $M = 1$ receive antenna and use the turbo equalizer proposed in [17], which is depicted in Fig. 2. This receiver consists of three blocks: a MAP equalizer, which is based on the trellis of the SISO equivalent channel given in (3); and two decoders, each corresponding

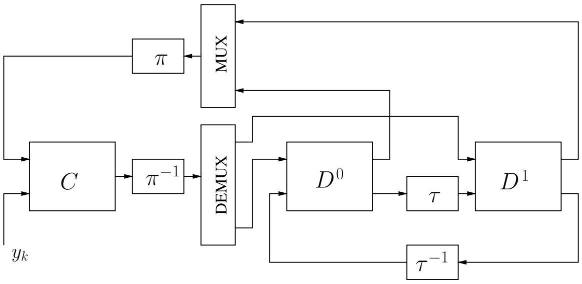

Fig. 2. Receiver block diagram, where D^0 and D^1 represent the constituent decoders, C is the MAP channel equalizer, y_k are the received symbols, τ is the code interleaver, and π is the channel interleaver (for the case of non-binary modulation a mapper should follow the channel interleaver).

to a constituent encoder of the turbo code.[1] Each of these blocks computes extrinsic information on the transmitted symbols. This information is passed to the other blocks, where it is used as *a priori* probabilities on the transmitted symbols [17]. Note that in this paper, we focus on classical MAP equalization, but reduced complexity schemes such as the one proposed in [18], which is based on a modified BCJR algorithm and yields a small performance loss, can be directly applied to the proposed scheme.

3. Simulation results

In this section, we investigate the performance of the proposed scheme in terms of the number of transmit antennas and ISI length, and compare it to the outage probability. In the computer simulations we consider that the input data are channel encoded using a systematic rate-1/3 parallel turbo code, with constituent encoders $G(D) = \left[\frac{1+D+D^2+D^3}{1+D^2+D^3}\right]$. We consider BPSK modulation, $M = 1$ receive antenna, ISI lengths $D = 2(\sigma_0^2 = \sigma_1^2 = 0.5)$ and $D = 5(\sigma_0^2 = 0.45, \sigma_1^2 = 0.25, \sigma_2^2 = 0.15, \sigma_3^2 = 0.10, \sigma_4^2 = 0.05)$, perfect channel state information at the receiver, pseudo-random interleavers, and 10 iterations of the turbo equalizer.

3.1. Comparison with outage probability

In order to show that the proposed scheme is able to achieve full diversity ($N \times M \times D$), we compare its performance with the outage probability, which is the theoretical limit to be considered in the case of block fading channels [1]. The performance of the proposed system is evaluated in terms of frame error rate (FER) vs. E_b/N_0, where E_b is the energy per information bit. The interleaver length is set to $I = 97$, which means that the frame size is $S = 300$ symbols. Fig. 3 shows the FER vs. E_b/N_0, for $N = 2$ and 8, for the case of ISI length $D = 2$. In the figure we also show the corresponding outage probabilities (for $N = 2$ and 8), which were numerically evaluated according to [19, Section III].

From the figure, we can see that the slope of the outage probability and of the FER are the same, which means that the proposed scheme achieves full diversity. In Fig. 4, we present similar results, but for the case of $D = 5$, where it is also clear that the proposed scheme achieves full diversity. Note that the relative loss with respect to the outage probability increases with the increase of the number of transmit antennas, although this increase is very moderate. The loss, for the case of $D = 2$ and $N = 2$ is around 2 dB, which is similar to the one obtained for this channel (two i.i.d taps per channel) in [12] (for an STBC based scheme) and in [19] (for an STTC based scheme). In [12] and [19] the authors also utilize iterative (turbo) equalization, but do not present results for a large number of transmit antennas such as $N = 8$, or for ISI length $D = 5$.

3.2. BER performance

We investigate the effect of the number of transmit antennas, N, in the performance of the proposed system in terms of bit error rate (BER). The interleaver length is set to $I = 97$. Fig. 5 shows the BER vs. E_b/N_0, as a function of N, for the case of ISI length $D = 2$. From the figure, we can see that the proposed scheme achieves large gains when compared with the case of only one transmit antenna. Specifically, at a BER of 10^{-3}, the gain over a system with only one transmit antenna is around 10, 15, 17.5 and 19 dB for $N = 2$, 4, 8 and 16, respectively. As a reference, we also show the BER for the case of a static (no-fading) SISO link with the same ISI pattern. Fig. 6 shows similar results but for the case of $D = 5$, where at a BER of 10^{-3} the gain over a system with only one transmit antenna is around 4, 6 and 7 dB for $N = 2$, 4 and 8, respectively. We can see that performance gets near to that of a static ISI SISO link for ($D = 2$; $N = 16$) and ($D = 5$; $N = 8$), which means that the proposed system is able to overcome most of the fading degradation. Note that, as shown in [20, Chapter 5], in the limit, when the number of antennas goes to infinity, the MIMO fading channel is perfectly stabilized and approaches an static (linear Gaussian) link. It is interesting to remark that, as can be seen from the figures, for $D = 2$, we need more antennas to achieve a diversity level ($N \times M \times D$) similar to that of $D = 5$.

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[1] In the case of non-binary modulation, iterative demapping and decoding can be performed, avoiding the use of a non-binary turbo encoder.

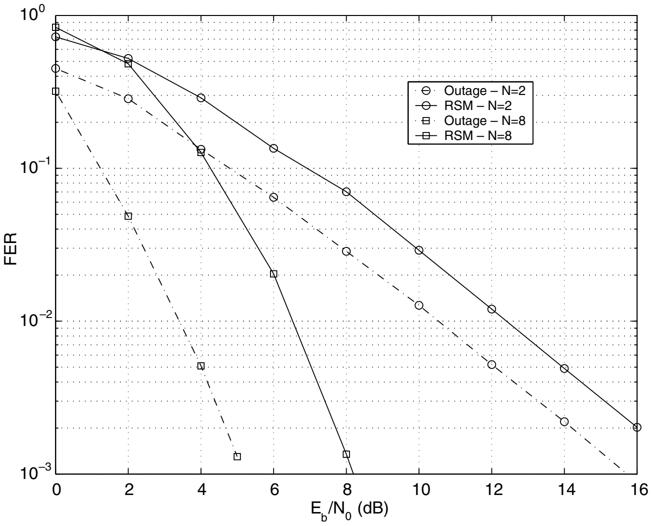

Fig. 3. FER vs. E_b/N_0 for $N = 2$, 8, interleaver of length $I = 97$, and ISI length $D = 2$. The figure also shows the outage probability for $N = 2$, 8 and $D = 2$.

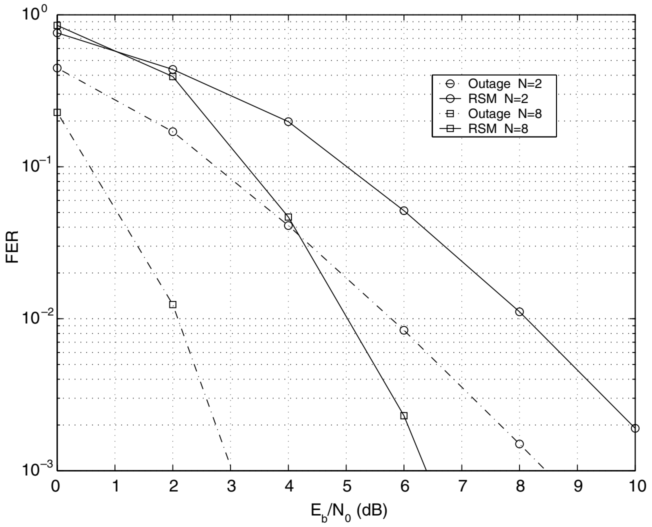

Fig. 4. FER vs. E_b/N_0 for $N = 2$, 8, interleaver of length $I = 97$, and ISI length $D = 5$. The figure also shows the outage probability for $N = 2$, 8 and $D = 5$.

3.3. *Effect of imperfect channel knowledge*

In the previous simulations, we considered that the channel is perfectly known at the receiver site. However, in practice, it is necessary to estimate the channel before (or during) equalization and decoding. For RSM, and $M = 1$ receive antennas as considered in the previous simulations, one needs to first estimate the MISO block-fading channel and then generate the equivalent SISO time-varying channel using the same pseudo-random sequence utilized in the random signal mappers at the transmitter. Thus, since the pseudo-random sequence is assumed to be known at the receiver, channel estimation reduces to the estimation of the MISO block-fading channel, which can be obtained with the aid of some pilots inserted in the beginning of each data frame.

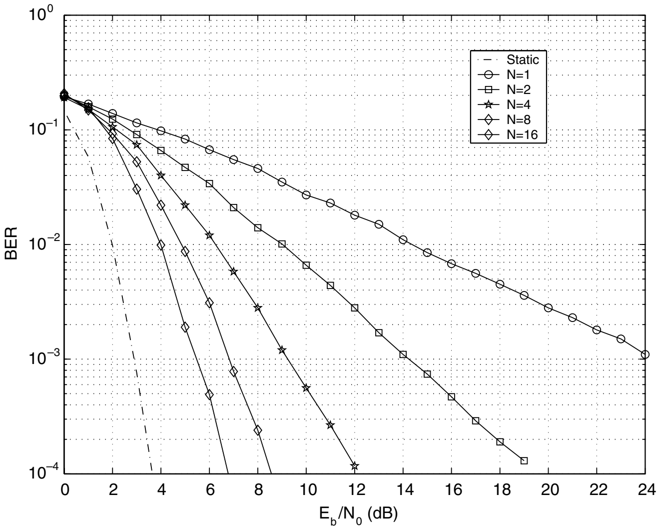

Fig. 5. BER vs. E_b/N_0 for different numbers of transmit antennas ($N = 1, 2, 4, 8, 16$), interleaver of length $I = 97$, and ISI length $D = 2$. The figure also shows the BER for a SISO static (no-fading) ISI link.

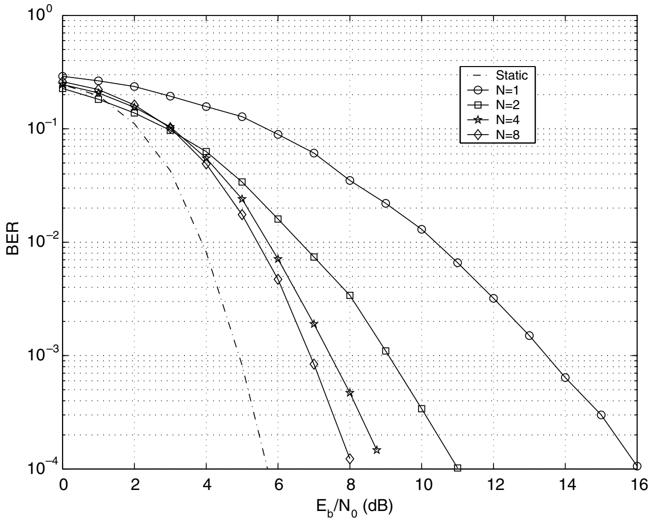

Fig. 6. BER vs. E_b/N_0 for different numbers of transmit antennas ($N = 1, 2, 4, 8$), interleaver of length $I = 97$, and ISI length $D = 5$. The figure also shows the BER for a SISO static (no-fading) ISI link.

In [21], the authors determine the Cramér-Rao bound for a series of different estimation schemes. The Cramér-Rao is a lower bound for the mean square error (MSE) of a non-biased estimation process. Specifically, we consider the case of where a given number of P pilots is inserted in the beginning of a frame of S symbols to be transmitted through the channel. In this case, the Cramér-Rao bound is given by [21, Eq. (11)]:

$$\mathrm{MSE}[h_{i,j}(d)] \geqslant \frac{\sigma_{\mathrm{n}}^2}{\sigma_{\mathrm{n}}^2 \rho_h^2 + S\sigma_{\mathrm{s}}^2 + P\sigma_{\mathrm{p}}^2}, \tag{5}$$

where σ_{n}^2 is the noise variance, $\rho_h^2 = 1/\sigma_{\mathrm{d}}^2$, σ_{s}^2 is the average energy used in the data transmission, and σ_{p}^2 is the average energy used in the pilots transmission.

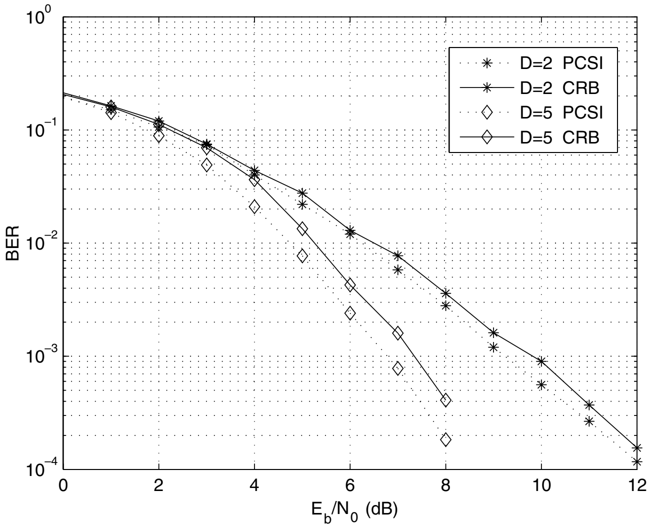

Fig. 7. BER vs. E_b/N_0 for $N = 4$, $I = 97$, $D = 2$, 5 for the cases of perfect channel state information (PCSI) at the receiver, and for the Cramér-Rao bound (CRB) considering $P = 10$ pilots.

In Fig. 7, we show the BER vs. E_b/N_0 for the cases of $N = 4$, $S = 300$ ($I = 97$), $P = 10$, $D = (2,5)$, for the cases of perfect channel state information (PCSI) and for the case where the estimation error is a Gaussian random variable with zero mean and variance given by the Cramér-Rao bound (5). From the figure, we can see that the loss increases with the ISI length, but it is relatively low for both cases ($D = 2$ and $D = 5$). Thus, the performance of the proposed scheme presents a very small degradation in the practical case where the channel has to be estimated at the receiver site.

4. Comparison with other schemes

The results in Sections 3.1 and 3.2 empirically show that the proposed scheme achieves full diversity ($N \times M \times D$), while having about the same gap from outage capacity as other schemes presented in the literature [10–12,19]. In this section we compare, in terms of computational complexity, the proposed scheme with these alternative systems, which are based on either STTC or STBC. We do not draw a direct comparison with multi-carrier schemes because, as stated in [12], most multi-carrier systems do not achieve full diversity, and present a non-constant modulus transmission that reduces power efficiency.

4.1. STTC-based schemes

McEliece and Lin [22] showed that the computational effort required by a Viterbi or BCJR like algorithm is proportional to the total edge count in the channel/code trellis. Thus, for a space–time trellis coded system,

Table 1
Total edge count for MAP equalization for a space–time trellis coded system (STTC) and for the proposed system (RSM), for several values of ISI length D, number of transmit antennas N, and BPSK modulation

D	RSM	STTC	
	$N = 2, 8$	$N = 2$	$N = 8$
2	4	16	65,536
3	8	64	1.67×10^7
4	16	256	4.29×10^9
5	32	1024	1.09×10^{12}
6	64	4096	2.81×10^{14}

such as [16,23,19], the complexity of MAP equalization is proportional to $(m^N)^D$ [24,25]. Due to the equivalent SIMO model given by (2), for the proposed system the complexity of MAP equalization is independent of the number of transmit antennas and proportional only to $(m)^D$, yielding a savings that increases exponentially with the number of transmit antennas. Table 1 shows the total edge count for MAP equalization in the case of a space–time trellis coded system (STTC) and of the proposed system (RSM), for several values of ISI length D, number of transmit antennas N, and BPSK modulation. We can see that the savings in computational complexity are large and rapidly increase with N and D.

4.2. STBC-based schemes

TR-STBC [10,11] and its generalizations [12] are considered to present one of the best complexity/performance trade-off when dealing with ISI MIMO channels. One of its advantages, besides the fact that it shares the simplicity and efficiency of STBC for flat channels, is that the complexity of the equalization process is not a function of the number of transmit antennas. Thus, when using TR-STBC like schemes in a multiple transmit antenna system, the equalization demands the same computational effort as in the case of a single transmit antenna. However, as in the case of STBC for flat channels [6], TR-STBC like schemes suffer from rate loss when more than two transmit antennas and complex constellations are used [11,12]. The highest rate achieved by STBCs from complex orthogonal design [6], which are the basis of the schemes presented in [11,12], is 1/2 when $N > 4$. TR-STBC based on complex non-orthogonal design could overcome the rate loss, but with a complexity larger than the complexity of TR-STBC based on complex orthogonal design.

We have empirically shown that, similar to the schemes presented in [10–12], the proposed system achieves full diversity, while its equalization complexity is not a function of the number of transmit antennas. Additionally, the proposed scheme does not suffer from rate loss when the number of transmit antennas is increased (for either real or complex constellations), which can be seen as an interesting advantage over [10–12].

5. Conclusion

We have presented a novel scheme for space–time transmission over frequency selective fading MIMO channels. Transmit diversity is obtained through the use of random signal mapping. Simulation results showed that the proposed scheme achieves full diversity and that large improvements can be obtained over a SISO system even with very short frame lengths. When compared with STTC based systems, the proposed scheme achieves similar performance, while yielding very large savings in computational complexity. Finally, the proposed method presents a computational complexity similar to that of TR-STBC and its generalizations, but does not suffer from the rate loss inherent to orthogonal-STBC based schemes.[2]

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