Repetition Time-Switched Transmit Diversity as an Alternative to Alamouti Space-Time Coding for Wireless Communication Systems

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Abstract – We present a simple transmit diversity technique, called repetition time-switched transmit diversity (R-TSTD), which is a modified version of the well-known time-switched transmit diversity (TSTD) algorithm. Throughout the paper, we focus on the scenario of a transmitter with $n_T = 2$ antennas. The idea behind R-TSTD is to use only one antenna at a time while still ensuring that all constellation symbols are transmitted via both antennas. Thus, unlike the classical TSTD technique, R-TSTD does provide a transmit diversity effect similar to that achieved with space-time coding (STC) algorithms. The error performance of the proposed R-TSTD system is compared to that of the Alamouti STC scheme via Monte Carlo computer simulations. It is shown that, in the absence of any outer error-correcting code, Alamouti STC slightly outperforms R-TSTD. However, when a near-capacity channel code is employed as an outer code, the error performance achieved using R-TSTD is significantly better than that obtained with Alamouti STC, provided that the desired spectral efficiency is sufficiently low.

Keywords – space-time coding; time-switched transmit diversity; bit-interleaved coded modulation; turbo codes.

I. INTRODUCTION

Space-time coding (STC) techniques can be used to design power-efficient wireless communication systems when two or more transmit antennas are available [1]-[3]. Among all the STC algorithms that have been introduced, the Alamouti scheme is probably the one that has so far received the greatest amount of attention, due to its particularly attractive features for practical applications such as simplicity of implementation, excellent error performance, and the absence of requirement for channel state information at the transmitter side [3]. Another approach that could be considered to improve the error performance of wireless communication systems with multiple transmit antennas is the time-switched transmit diversity (TSTD) algorithm [4], [5]. This approach consists of cycling the sequence of constellation symbols through the transmit antennas in a round ribbon fashion so that only one antenna is actually used at a time. This merely introduces an artificial time selectivity which is only exploitable when a channel code is used in conjunction with TSTD. Unlike STC, TSTD cannot provide any transmit diversity in the absence of channel coding. As a result, TSTD is not generally considered as an interesting alternative to STC.

In this paper, we propose a modified version of the TSTD technique, called repetition time-switched transmit diversity (R-TSTD), that, unlike TSTD, can provide a transmit diversity gain even in the absence of channel coding. Throughout the paper, we focus on the case where $n_T = 2$ transmit antennas are available. The error performance obtained with R-TSTD is then investigated via Monte Carlo computer simulations and compared to that achieved with an equivalent Alamouti STC scheme, assuming that either no channel code is employed or a binary turbo code [6] is used as an outer channel code.

The remainder of the paper is organized as follows. The structure of the proposed R-TSTD scheme is described in Section II. Computer simulation results are shown in Section III. In order to illustrate the potential of R-TSTD for practical wireless communication applications, we consider in Section IV the example of an adaptive modulation and coding system and explain how its overall error performance could be improved by using R-TSTD under certain channel conditions. Finally, conclusions are drawn in Section V.

II. STRUCTURE OF THE PROPOSED R-TSTD SYSTEM

Fig. 1.a shows the block diagram of the proposed R-TSTD transmitter with $n_T = 2$ antennas. Note that, in Fig. 1, we have depicted the structure of a coded R-TSTD system, i.e. a system employing an outer binary channel code in association with the R-TSTD algorithm proposed in this paper. However, the use of a channel code is optional and, as will be shown later, the R-TSTD algorithm can still display a good error performance in the absence of channel coding. An R-TSTD scheme without any outer channel code will hereafter be referred to as uncoded R-TSTD.

The sequence of data bits to be transmitted, which can be either information bits (in the case of an uncoded R-TSTD scheme) or coded bits (in the case of a coded R-TSTD system, as shown in Fig. 1), is fed into a mapper using Gray labeling.
Note that the coded bits are actually interleaved (π) before mapping as the coded R-TSTD system is designed according to the bit-interleaved coded modulation (BICM) approach [7], [8]. The function of the mapper is to associate each group of $\log_2(M)$ successive data bits with a complex symbol drawn from an $M$-ary constellation. The sequence produced by the mapper is thus composed of $N/\log_2(M)$ complex symbols $x_n, n \in \{1, \ldots, N/\log_2(M)\}$, where $N$ designates the number of data bits used to generate this sequence.

![Diagram](image)

Fig. 1 – Structure of a coded R-TSTD scheme. (a) Transmitter, (b) Receiver. The notations $Tx_i, n \in \{1, 2\}$, and $Rx_m, m \in \{1, \ldots, n_R\}$, refer to the $n$th transmit antenna and $m$th receive antenna, respectively.

With the proposed R-TSTD algorithm, a frame of $N/\log_2(M)$ symbols $x_n$ is transmitted using $2N/\log_2(M)$ time intervals $t_p, p \in \{1, \ldots, 2N/\log_2(M)\}$ as follows: A particular constellation symbol $x_n, n \in \{1, \ldots, N/\log_2(M)\}$, is transmitted using antenna 1 at time $t_p$, with $p = 2n - 1$, and transmitted again using antenna 2 during the following time interval $t_{p+1}$. The transmission of each constellation symbol via both antennas provides a transmit diversity similar to that achieved by STC. However, unlike STC, the R-TSTD scheme uses only one antenna at a time. Note that the implementation of the R-TSTD algorithm requires the repetition of each symbol $x_n$ in two successive time slots $t_p$ and $t_{p+1}$, with $p = 2n - 1$. This is the reason why the algorithm introduced in this paper is termed repetition time-switched transmit diversity. The inherent loss in spectral efficiency resulting from the use of one antenna instead of two during a time interval can be compensated for by increasing the size of the signal constellation and/or, in case a channel code is employed, the rate of this code.

Note that an R-TSTD transmitter requires the use of only one RF chain combined with a simple switch whereas a classical STC transmitter is implemented using two RF chains. This can be seen as a significant practical advantage of R-TSTD over STC since it is well known that reducing the number of RF chains in a mobile wireless terminal is an efficient strategy to minimize its power consumption (see, e.g., [9]).

Assume that $n_R$ antennas are used at the R-TSTD receiver side (see Fig. 1.b). The channel sample received by a particular antenna $i \in \{1, \ldots, n_R\}$ at time $t_p$, with $p = 2n - 1$, is given by

$$y_{n_1}^i = h_{n_1}^i \cdot x_n + w_{n_1}^i,$$

whereas the next channel sample received by the same antenna (at time $t_{p+1}$) can be expressed as

$$y_{n_2}^i = h_{n_2}^i \cdot x_n + w_{n_2}^i.$$ (2)

In these equations, $h_{n_1}^i$ and $h_{n_2}^i$ are two independent complex Rayleigh fading samples while $w_{n_1}^i$ and $w_{n_2}^i$ are two independent complex Gaussian noise samples with zero mean and variance $\sigma^2 = N_0$, where $N_0$ denotes the one-sided power spectral density of the complex additive white Gaussian noise (AWGN). We assume that perfect channel state information is available at the receiver side.

The $2n_R$ received samples $y_{n,j}^i, i \in \{1, \ldots, n_R\}$ and $j \in \{1, 2\}$, are subsequently processed using a maximum-ratio combiner (MRC). We can easily show that the MRC produces an estimate $\hat{y}_n$ of the transmitted constellation symbol $x_n$ which is computed as follows:

$$\hat{y}_n = \frac{\sum_{i=1}^{n_R} \sum_{j=1}^{2} |h_{n,j}^i|^2 \cdot y_{n,j}^i}{\sum_{i=1}^{n_R} \sum_{j=1}^{2} |h_{n,j}^i|^2},$$ (3)

where the operators $(\cdot)^*$ and $|\cdot|^2$ designate the “complex conjugate of” and “modulus of”, respectively. The sample $\hat{y}_n$ is fed either to a decision block in the case of an uncoded R-TSTD system or to the soft-output demapper in the case of a coded system [7], [8], [10]. This demapper generates estimates of the coded bits that need to be de-interleaved (π⁻¹) before finally being sent to the binary soft-decision channel decoder.
III. EXAMPLES AND SIMULATION RESULTS

In this Section, we present some bit error rate (BER) results obtained via Monte Carlo computer simulations for various R-TSTD schemes using $n_R = 1$ or 2 receive antenna(s).

A. Uncoded R-TSTD scheme using 16-QAM

Consider first the case of an uncoded R-TSTD scheme using a 16-QAM signal constellation, hereafter referred to as uncoded 16-QAM R-TSTD. Fig. 2 shows the BER versus $E_b/N_0$ curves obtained with this uncoded 16-QAM R-TSTD system when $n_R = 1$ and 2. We recall that $E_b$ denotes the energy per information bit and $N_0$ designates the one-sided power spectral density of white Gaussian noise. For comparison sake, we have also plotted in Fig. 2 the BER curves corresponding to two uncoded Alamouti STC systems using a QPSK signal constellation [3] and either one or two received antenna(s).

In the uncoded 16-QAM R-TSTD system, two time intervals are actually necessary to transmit a 16-QAM constellation symbol, i.e. four information bits, which implies that two information bits are transmitted during one time interval. The resulting spectral efficiency obtained with the uncoded 16-QAM R-TSTD system is thus equal to 2 bits/s/Hz, and therefore identical to that achieved with an Alamouti STC scheme employing a QPSK constellation.

![Fig. 2 – BER performance of two uncoded 16-QAM R-TSTD schemes using $n_R = 1$ or 2 receive antenna(s). For comparison purposes, the BER curves obtained with two equivalent uncoded Alamouti QPSK STC systems are also plotted.](image)

The results displayed in Fig. 2 show that the simple R-TSTD algorithm proposed in this paper is able to provide a diversity order similar to that offered by the Alamouti STC technique. However, it appears that, at high SNR ($E_b/N_0 > 2 - 4$ dB), both uncoded Alamouti QPSK STC schemes actually outperform their corresponding uncoded 16-QAM R-TSTD systems by a fraction of a decibel. Such result indicates that R-TSTD is not a particularly attractive alternative to Alamouti STC in the absence of an outer channel code. Note that the small performance gap between both approaches could actually make R-TSTD a better option than Alamouti-STC for some specific applications where power consumption is so critical that using only one RF chain instead of two would be a significant advantage.

When no channel code is employed, the main drawback of R-TSTD compared to, say, Alamouti STC is the significant increase in constellation size required to compensate for the loss in spectral efficiency due to the use of only one antenna at a time. For instance, if $M$-QAM is used by an uncoded Alamouti STC scheme, then an uncoded R-TSTD system must employ an $M^2$-QAM in order to be able to provide the same spectral efficiency. This means that, in practice, the R-TSTD algorithm is only suitable for systems with low spectral efficiencies (since employing huge signal constellations is not a realistic option in wireless communications).

We can also observe from Fig. 2 that, at low SNR ($E_b/N_0 < 2 - 4$ dB), the uncoded 16-QAM R-TSTD system does actually outperform the Alamouti QPSK STC scheme. In the context of uncoded systems, this result does not constitute a particularly interesting finding. However, it clearly implies that, if a near-capacity outer channel code is employed in conjunction with the transmit diversity algorithm, a coded R-TSTD system could perform significantly better than its equivalent Alamouti STC scheme. It has indeed been shown that, for near-capacity BICM, the error performance at the channel decoder output mainly depends on the error rate on the sequence of estimates processed by this decoder in the low-SNR region (see, e.g., [11]). This will be illustrated and confirmed by results shown in the next sub-Section.

As a summary, we can state that the 16-QAM R-TSTD and Alamouti QPSK STC schemes display similar error performances in the absence of any outer channel code. This result can be explained as follows: With R-TSTD, each of the transmit antennas can radiate using full energy since only one antenna operates at any given time. This is a clear advantage over Alamouti STC for which each transmit antenna can only radiate half of the available energy. On the other hand, the fact that R-TSTD has to employ 16-QAM instead of QPSK represents an obvious drawback with respect to STC. As it happens, we can show that the advantage provided by the ability of each antenna to radiate with full energy does not fully compensate for the use of 16-QAM in place of QPSK at high SNR, which explains the small performance degradation obtained when using R-TSTD instead of STC in this SNR range.

However, it is also worth mentioning that the performance gap between 16-QAM and QPSK actually decreases as the SNR is reduced. In other words, the performance penalty resulting from the use of 16-QAM instead of QPSK is less severe at low SNR than it is in the higher SNR range. This is the reason why the uncoded 16-QAM R-TSTD system is able
to outperform the uncoded Alamouti QPSK STC scheme at SNR values that are sufficiently low ($E_b/N_0 < 2 - 4$ dB).

**B. Turbo-coded R-TSTD scheme using 16-QAM**

Let us now consider the case of a coded R-TSTD scheme using a 16-QAM signal constellation as well as a binary turbo code [6], hereafter referred to as turbo-coded 16-QAM R-TSTD. The parameters of the turbo code considered in this sub-Section are as follows: The frame size, i.e. the size of the random interleaving/de-interleaving functions used inside both encoder and decoder, is equal to 2000 information bits. A rate-$R_c$ turbo-code, with $R_c > 1/3$, is obtained by periodically puncturing a rate-1/3 mother turbo code built from two parallel-concatenated 16-state recursive and systematic convolutional (RSC) codes with polynomials (23, 31). Turbo decoding is performed in 10 iterations and the log-MAP algorithm is used for the decoding of each RSC code.

Figs. 3 and 4 show the BER versus $E_b/N_0$ curves obtained with a turbo-coded 16-QAM R-TSTD system for two different values of the coding rate $R_c$ (= 1/2 or 2/3), when the number of receive antennas is $n_R = 1$ and 2, respectively. Depending on the value of $R_c$, the spectral efficiency of the turbo-coded 16-QAM R-TSTD scheme is thus equal to either 1 bit/s/Hz (when $R_c = 1/2$) or $\approx 1.33$ bits/s/Hz (when $R_c = 2/3$). For comparison purposes, we have also plotted in Figs. 3 and 4 the BER curves corresponding to two equivalent turbo-coded Alamouti QPSK STC systems with the same parameters ($n_R = 1$ or 2, $R_c = 1/2$ or 2/3).

It is seen from Figs. 3 and 4 that the turbo-coded 16-QAM R-TSTD scheme does outperform the turbo-coded Alamouti QPSK STC system in all cases. For instance, at BER $= 10^{-4}$ and for a spectral efficiency of 1 bit/s/Hz, the performance gap between both schemes is approximately equal to 1.33 dB and 0.54 dB, when the number of receive antennas is $n_R = 1$ and 2, respectively. Those results clearly indicate that, for low spectral efficiencies, i.e. when the wireless communication system operates at low average SNR, a turbo-coded R-TSTD system can perform significantly better than a turbo-coded Alamouti STC system. Such finding is not surprising given the superiority in terms of error performance of the uncoded 16-QAM R-TSTD system over the uncoded Alamouti QPSK STC scheme at low SNR (see sub-Section III.A). Note that we would have obtained similar conclusions if the turbo code was replaced by any other type of near-capacity channel code.

The conclusion of this sub-Section is that a significant error performance improvement can be obtained by using a coded R-TSTD scheme instead of its equivalent Alamouti STC system. We must keep in mind that such conclusion is only valid when the wireless communication system operates at low average SNR values. If operation at higher SNR values was required, e.g. because the desired spectral efficiency was larger than, say, 1.5 bits/s/Hz, then a coded Alamouti STC system would remain the best choice for the system designer. This has been confirmed by some computer simulations whose results are not reported here due to the lack of space.
IV. A POSSIBLE APPLICATION OF R-TSTD: ADAPTIVE MODULATION AND CODING SYSTEMS

The main purpose of this Section is to show, through an example, how our R-TSTD algorithm could be used to improve the error performance of a practical state-of-the-art wireless communication system.

Let us thus consider the example of a simple adaptive modulation and coding (AMC) scheme using Alamouti STC transmit diversity and assume that the transmitter can select, depending on the channel SNR, a particular modulation and coding scheme among several possible combinations. In the context of the work described above, we can for instance assume that the Alamouti STC transmitter has the choice between three different QAM modulation schemes, namely QPSK, 16-QAM, and 64-QAM, and various puncturing patterns applied to the same mother turbo code.

As an illustration, if the average SNR is high, the transmitter can use the 64-QAM constellation combined with, say, a rate-5/6 turbo code in order to take advantage of the excellent channel conditions to maximize the spectral efficiency (equal to 5 bits/s/Hz in this case). On the other hand, under very poor channel conditions, i.e. when the average channel SNR is very low, the transmitter must use the most robust modulation and coding scheme among all those available, i.e. the QPSK constellation combined with, for instance, a rate-1/2 turbo-code. The resulting spectral efficiency will be reduced to 1 bit/s/Hz in this case.

The R-TSTD algorithm can be employed to improve the error performance of the AMC system under very poor channel conditions. As shown in the previous Section, when the spectral efficiency is low (around 1 bit/s/Hz), better error performance is obtained by using, for example, the turbo-coded 16-QAM R-TSTD system rather than the turbo-coded QPSK Alamouti STC scheme. In other words, we would achieve better overall error performance if the AMC wireless communication system was given the option to employ either R-TSTD or Alamouti STC depending on the channel conditions: Alamouti STC would be used as long as the channel SNR was above a certain threshold, i.e. probably most of the time as this threshold is expected to be quite low. But, as soon as the channel SNR would fall below the threshold, the transmitter and receiver would then switch from the Alamouti STC to the R-TSTD mode of operation.

It is worth noting that employing two transmit diversity algorithms instead of one in the same AMC system implies a further degree of adaptability. However, since the AMC Alamouti STC system is already equipped with all the hardware blocks needed to implement R-TSTD (ability to switch from one modulation scheme to another, turbo code with a programmable puncturing function, etc...), it actually appears that this strategy could be implemented at very little cost in terms of added complexity at both transmitter and receiver sides.

V. CONCLUSIONS

We have proposed the R-TSTD technique which is a modified version of the well-known time-switched transmit diversity. It has been shown that, when combined with a near-capacity channel code (e.g., turbo code), R-TSTD can actually outperform the standard Alamouti STC algorithm, provided that the desired spectral efficiency is low (smaller than, say, 1.5 bits/s/Hz). Therefore, R-TSTD could be a very interesting alternative to Alamouti STC for some specific applications. To illustrate this, we have considered the example of an AMC wireless communication scheme using Alamouti STC and shown how the overall error performance of such system could be improved by making it possible to switch from Alamouti STC to R-TSTD when the channel conditions become very poor.

All the work described throughout this paper has been carried out by assuming the use of two transmit antennas. In the future, it will also be interesting to investigate the results obtained when more than two transmit antennas are available.

REFERENCES