Constant-rate Adaptive Space-time Code Selection Technique for Wireless Communications

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***Abstract*—A constant-rate space-time code selection technique for transmit antenna diversity systems is proposed. The proposed technique selects both the space-time code and the number of transmitter antennas through a comparison of equivalent SISO channels with a set of predetermined threshold levels, using only four bits for feedback. The constant-rate transmission is based in the inclusion of a complementary transmission mode, which is used whenever no equivalent SISO channel's envelope is found to be over the threshold levels. Simulation results show that the proposed technique outperforms other adaptive transmission techniques, while in comparison with its variable-rate counterpart, there is an increase in spectral efficiency with a slight penalty performance. Additionally to a constant-rate transmission, the new techniques makes BER performance almost independent of the relative velocity between the transmitter and the receiver.** [1 2] **.**

***Index Terms*—Space-time coding, adaptive transmission, antenna selection, wireless communications, baseband signal processing.**

I. Introduction

Transmit antenna diversity (TAD) is one of the tools to be applied to construct multiple-input multiple-out (MIMO) systems, which are expected to contribute to providing the high data rates needed by fourth generation wireless systems. One way to implement TAD is by using space-time block codes (STBC), obtaining an open loop system whenever channel state information (CSI) is not available at the transmitter end [1], [2]. Closed-loop systems are designed to take advantage of the CSI at the transmission end. However, they are limited by the need to maintain the amount of data in the feedback channel as low as possible. Channel feedback information is one important issue when designing transmit systems.

Several structures that combine antenna selection techniques with space-time coding have been proposed in [3]–[7]. In [7], it was shown that selection of antenna subsets in conjunction with space-time codes produces an increase in the mean signal to noise ratio (SNR), maintaining the diversity order. In this paper, a modification of the space-time code selection technique (STCS) described in [8], [9] is proposed, which allows to obtain a constant-rate transmission. In the former STCS technique, the STBC and the antennas to be used were selected through a comparison of the equivalent single-input single-output (SISO) channel envelopes (taken as a linear combination of Rayleigh channel envelopes) with a set of predetermined threshold levels. A no-transmission mode was selected whenever no equivalent SISO channel satisfied the predetermined conditions, producing a slight average spectral efficiency penalty, generally no higher than 10%. However, such non-constant rate transmission could prevent its use in constant-rate applications. The proposed modification corrects this drawback by sustituing the non-transmission mode by a complementary mode, which consist in transmitting with a predetermined code. In our test, it was found that transmitting with a single antenna was the most convenient choice, thanks to the fastest recovery of the Rayleigh channel compared to other equivalent SISO channels.

Monte Carlo simulations show that, using the complementary mode, almost the same bit-error rate (BER) performance than the variable-rate STCS (VR-STCS) is achieved, but without any spectral efficiency penalty. Additionally, simulations over a range of Doppler frequencies show that the performance of the new technique is almost independent of the relative velocity between the transmitter and the receiver.

The remainder of the paper is organized as follows. In Section II, the system model is introduced. Section III describes the new space-time code algorithm. In Section IV, simulation results are shown and discussed. Finally, Section V ends the paper with the conclusions.

II. System Model

In the communication system model, four transmitter and one receiver antennas are employed. Initially, the transmitter sends pilot symbols to perform the vector channel estimation at the receiver. The equivalent SISO channel envelopes are compared with a given set of threshold levels, which are previously chosen according to the mobile speed. Afterwards, the receiver decides on the space-time code and the transmit antennas to use, and sends this decision to the transmitter. Transmission is adapted to that decision, which is maintained until the next decision instant, when the process is repeated.

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The transmission is assumed to occur in flat frequency channels. The squared envelopes of the equivalent SISO channels using an orthogonal STBC (OSTBC) are given by

$$\alpha_{n_T}^2 = \sum_{k=1}^{n_T} r_k^2, \tag{1}$$

where n_T and r_k^2 represent the number of transmitter antennas and the square of Rayleigh distributed channel envelopes, respectively. It is well known that α_{n_T} follows a Nakagami-n_T distribution [10] with a mean value of $\Omega_{n_T} = 2n_T$. Its probability density function is given by

$$p_N(x) = \left(\frac{n_T}{\Omega_{2n_T}}\right)^{n_T} \frac{x^{n_T-1}}{\Gamma(n_T)}\, e^{-n_T x/\Omega_{2n_T}}. \tag{2}$$

The received signal can be expressed by the following input/output relationship:

$$\mathbf{Y} = \mathbf{S_{n_T}}\mathbf{F}\mathbf{H} + \mathbf{V}, \tag{3}$$

where $\mathbf{H}$ is the 4x1 channel vector, $\mathbf{S_{n_T}}$ is a 4x4 space-time coding matrix, $\mathbf{F}$ is a 4x4 permutation and selection matrix and $\mathbf{V}$ is the 1x4 noise vector. The matrix $\mathbf{S_{n_T}}$ may take the following structures, based on the space-time codes proposed in [1] and [2], depending on the number of selected antennas [8], [9]:

$$\mathbf{S_1} = \begin{pmatrix} s_0 & 0 & 0 & 0 \\ s_1 & 0 & 0 & 0 \\ s_2 & 0 & 0 & 0 \\ s_3 & 0 & 0 & 0 \end{pmatrix}, \tag{4}$$

$$\mathbf{S_2} = \begin{pmatrix} s_0 & s_1 & 0 & 0 \\ -s_1^* & s_0^* & 0 & 0 \\ s_2 & s_3 & 0 & 0 \\ -s_3^* & s_2^* & 0 & 0 \end{pmatrix}, \tag{5}$$

$$\mathbf{S_3} = \begin{pmatrix} s_0 & s_1 & \frac{s_2}{\sqrt{2}} & 0 \\ -s_1^* & s_0^* & \frac{s_2}{\sqrt{2}} & 0 \\ \frac{s_2^*}{\sqrt{2}} & \frac{s_2^*}{\sqrt{2}} & \frac{(-s_0-s_0^*+s_1-s_1^*)}{2} & 0 \\ \frac{s_2^*}{\sqrt{2}} & -\frac{s_2^*}{\sqrt{2}} & \frac{(s_1+s_1^*+s_0-s_0^*)}{2} & 0 \end{pmatrix}, \tag{6}$$

$$\mathbf{S_4} = \begin{pmatrix} s_0 & s_1 & \frac{s_2}{\sqrt{2}} & \frac{s_2}{\sqrt{2}} \\ -s_1^* & s_0^* & \frac{s_2}{\sqrt{2}} & -\frac{s_2}{\sqrt{2}} \\ \frac{s_2^*}{\sqrt{2}} & \frac{s_2^*}{\sqrt{2}} & \frac{(-s_0-s_0^*+s_1-s_1^*)}{2} & \frac{(s_0-s_0^*-s_1-s_1^*)}{2} \\ \frac{s_2^*}{\sqrt{2}} & -\frac{s_2^*}{\sqrt{2}} & \frac{(s_1+s_1^*+s_0-s_0^*)}{2} & -\frac{(s_0+s_0^*+s_1-s_1^*)}{2} \end{pmatrix}. \tag{7}$$

III. Selection algorithm

In this section, the selection algorithm, which is carried out at the receiver baseband in the discrete-time domain, is described. The selection algorithm is based on the comparison of possible equivalent SISO channels with a set of four threshold levels, which are selected depending on the maximum Doppler frequency. Since the decision should be maintained until new feedback information is available, it is not sufficient to make it based only on instantaneous CSI; it should also take into account the rate of change of the equivalent SISO channel envelope. As the rate of change of the fading envelope decreases with n_T, it could be established that, in order to select an equivalent SISO channel only when its envelope is above a predefined threshold level during a given period of time, the lower the number of antennas that comprise the channel, the higher the requirements for selecting it. For a given instantaneous BER objective, equivalent SISO channels for larger n_T values will take more time to drop to the envelope level that produces such an instantaneous BER objective. Therefore, the highest threshold level (ρ_1) will correspond to the one-antenna equivalent SISO channels, while the lowest threshold level (ρ_4) will correspond to the four-antennas equivalent SISO channel. Then, the selection algorithm proceeds as follows:

- *Step 1*: Once the receiver obtains the CSI (which can be estimated based on a pilot sequence sent by the transmitter using all the transmitter antennas), it compares individually the Rayleigh fading envelopes with threshold ρ_1. If one or more of these envelopes are detected to be over ρ_1, the corresponding transmitter antennas are marked as selected and the procedure jumps to step 6.
- *Step 2*: The receiver compares all the Nakagami-2 fading envelopes with ρ_2. If one or more of these envelopes are detected to be over ρ_2, all the transmitter antennas which compose the detected envelopes are marked as selected and the procedure jumps to step 6.
- *Step 3*: The receiver compares all the Nakagami-3 fading envelopes with ρ_3. If one or more of these envelopes are detected to be over ρ_3, all the transmitter antennas which compose the detected envelopes are marked as selected and the procedure jumps to step 6.
- *Step 4*: The receiver compares the Nakagami-4 fading envelope with ρ_4. If it is detected to be over ρ_4, all the transmitter antennas are marked as selected and the procedure jumps to step 6.
- *Step 5*: This step is reached only if no Nakagami-k fading envelope is detected to be over ρ_k. In this case, the highest envelope's Rayleigh channel is selected, that is, a single antenna is selected.
- *Step 6* The receiver constructs the permutation and selection matrix $\mathbf{F}$ and sends it to the transmitter.

The only form of feedback is given by the permutation and selection matrix $\mathbf{F}$. It is first set as a permutation matrix of order four with the first n_T columns of the identity matrix corresponding to the position of the selected antennas. Finally, as $\mathbf{F}$ should specify n_T (for selecting the corresponding $\mathbf{S_{n_T}}$), its last $4 - n_T$ rows are set to zero.

For example, if antennas 1 and 4 are selected, matrix $\mathbf{F}$ should permute columns 2 and 4 of $\mathbf{S_2}$. Then,

$$\mathbf{F} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}. \tag{8}$$

At the transmitter end, the number of ones in $\mathbf{F}$ specifies n_T, and the antenna selection into that code is performed

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directly through the product $\mathbf{S}_{\mathbf{n_T}}\mathbf{F}$. Notice that the overhead transmitting matrix $\mathbf{F}$ is limited to 4 bits.

The main difference between this procedure and that stated in [8] resides in the inclusion of step 5, in which the highest envelope's Rayleigh channel is selected whenever no Nakagami-k fading envelope is detected to be over ρ_k in previous steps. In this condition, it is likely that all SISO equivalent channels have a low instant envelope value. The selection of a single antenna is based on the fastest recovery of the Rayleigh channel, compared with Nakagami-k channels, for $k > 1$.

IV. Results

For the simulations, symbol-synchronous receiver sampling and ideal timing have been assumed. Uncorrelated narrow-band Rayleigh channels were used, modeled as a circular complex Gaussian variable with zero mean and unit standard deviation. For simplicity, a zero-delay feedback channel and perfect channel estimation at the receiver have been assumed. Maximum likelihood detection was employed in reception.

The transmitter power was maintained constant independently of the number of transmitter antennas in use, distributing it evenly over them. The symbol time was $T_s = 3.2\mu$s and the carrier frequency $f_c = 3.5$ GHz. The normalized Doppler frequency of the simulated channels was 1.28×10^{-4}, 3.84×10^{-4}, 6.4×10^{-4} y 8.95×10^{-4}, corresponding to mobile speeds of approximately $v = 12$ km/h, 37 km/h, 62 km/h and 86 km/h, respectively. Pilot symbols used for channel selection (feed-forward and feedback STCS information) were inserted every 140 symbols. Then, for the test channels, a fixed feedback spacing of 140 symbols was used, which corresponds to 10%, 30%, 50% and 70% of the channels' coherence time (T_C), when using the relationship between T_C and f_d stated by

$$T_C = \frac{9}{16\pi f_d}. \tag{9}$$

In order to obtain the same average spectral efficiency (3 b/s/Hz) when using the different $\mathbf{S}_{\mathbf{n_T}}$ matrices, an 8 phase shift keeing (8PSK) modulation was used when selecting one or two transmitters, while 16 quadrature amplitud modulation (16QAM) was used when selecting three or four transmitters. No channel coding was used. Threshold levels were found for an instantaneous BER objective equal to 1.2×10^{-3} (for details about the how theshold levels were obtained, see [8]). The threshold levels values used in the simulations were $\rho_1 = \rho_2 = -0.43$ dB,$\rho_3 = \rho_4 = -1$ dB.

To present the simulation results, comparisons should be make with closed loop multiple-input single output (MISO) system techniques that use four radio frequency (RF) chains, i.e., to use four tranmitter antennas and a single receiver antenna. A considerable effort has been focused on research regarding MIMO systems, such as in spatial multiplexing and linear precoding [11]–[16]. However, such systems require more than one receiver antenna; in fact, they usually require more receiver than transmitter antennas. The combination of beamforming and orthogonal STBC (OSTBC-BF) proposed in [17] and the combination of orthogonal STBC with adaptive sub-group antenna encoding (OSTBC-SGE) proposed in [18] are, to the authors' knowledge, two of the most recent closed loop MISO systems with four transmitter antennas found in the literature. As OSTBC-BF requires weighting the transmit signal with a complex channel vector, 512 bits (four complex numbers in standard IEEE 754 double precision) feedback were established for this technique, with the intention of disassociate system performance with feedback information accuracy. On the other hand, OSTBC-SGE requires only four bits feedback.

Figs. 1 to 4 show the BER performance of the constant-rate STCS (CR-STCS), that is, our proposed technique which uses the complementary transmission mode, in comparison with the variable rate STCS (VR-STCS), the OSTBC-SGE and the OSTBC-BF as a function of the SNR for different relative velocities between the transmitter and the receiver. Additionally, the VR-STCS average spectral efficiency is shown. In general, it can be seen that the CR-STCS slightly sacrifices the BER with respect to the VR-STCS, but this sacrifice is compensated with a larger and constant average spectral efficiency. Furthermore, it can be noticed that the BER performance of the CR-STCS hardly depends on the relative velocity of the receiver.

In Fig. 1 the aforementioned systems are compared for a velocity $v = 12$ km/h. It can be seen that the difference in performance between CR-STCS and VR-STCS is around 0.3dB for a BER$= 1 \times 10^{-3}$ and 1dB for a BER$= 1 \times 10^{-5}$. Compared to the OSTBC-BF and OSTBC-SGE techniques, a significant SNR gain is obtained. For example, for a BER$= 1 \times 10^{-3}$, 4.8dB and 6.2dB are respectively obtained.

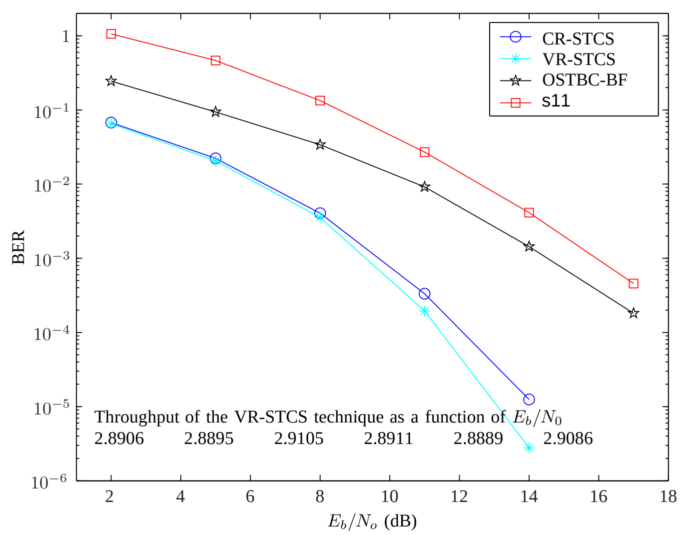

Fig. 1: BER and throughput comparison of the proposed technique (CR-STCS) with other schemes for a speed of 12 km/h. The throughputs of CR-STCS, OSTBC-BF and OSTBC-SGE techniques are constant at 3b/s/Hz.

In Fig. 2 the velocity is $v = 37$km/h, and when comparing CR-STCS and VR-STCS a difference of around 0.6 and 1.8dB

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can be observed for a BER equal to 1×10^{-3} and 1×10^{-5}, respectively. However, the spectral efficiency, besides being constant, is a 6% higher than with VR-STCS. Regarding OSTBC-BF y OSTBC-SGE, again it can be noticed a BER difference of around 5dB and 7dB for a BER$= 1 \times 10^{-3}$.

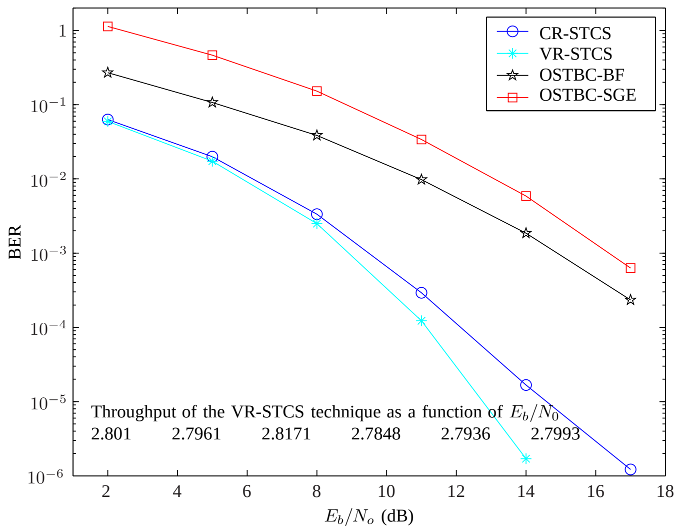

Fig. 2: BER and throughput comparison of the proposed technique (CR-STCS) with other schemes for a speed of 37 km/h. The throughputs of CR-STCS, OSTBC-BF and OSTBC-SGE techniques are constant at 3b/s/Hz.

Figs. 3 and 4, containing results for $v = 62$km/h and $v = 86$km/h, show the same trend. For $v = 62$km/h the CR-STCS suffers a performance degradation with respect to VR-STCS of around 0.7dB and 1.5dB, for a BER equal to 1×10^{-3} and 1×10^{-5}, respectively. For $v = 86$km/h, the degradation is around 1 and 2dB. In comparison with OSTBC-BF and OSTBC-SGE, SNR gains higher than 6dB are obtained for a BER$= 1 \times 10^{-3}$. The increase of spectral efficiency with respect to VR-STCS is higher than 10%. It can be noticed that VR-STCS achieves a high BER performance through the rate sacrifice. As CR-STCS maintains a constant rate, there is a higher degradation of CR-STCS in terms of SNR compared with VR-STCS. However, results show that BER performance and rate are maintained by the proposed technique.

Finally, Fig. 5 shows the confidence intervals with 95% of confidence for the Monte Carlo simulation for a velocity $v = 12$ km/h (see Fig. 1). The fluctuation of the results from the different simulations is noticeable only for the lowest BER values. In general, only BER results close to 1×10^{-6} or lower show a significant uncertainty. This is a consecuence of using a large amount of samples, which increments with the SNR. As a general rule, for low SNRs half a million samples were used, as no BER lower than 1×10^{-3} was expected. For medium SNRs 1 million samples were used, expecting a BER higher than 1×10^{-4}. Finally, for high SNRs 3 millions samples were used.

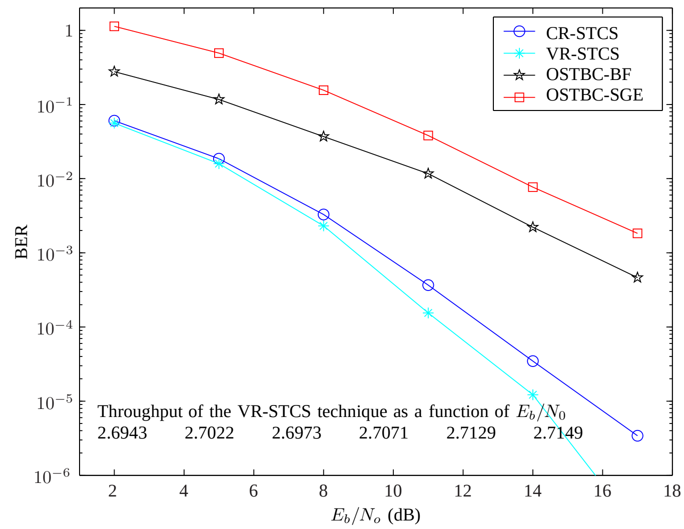

Fig. 3: BER and throughput comparison of the proposed technique (CR-STCS) with other schemes for a speed of 62 km/h. The throughputs of CR-STCS, OSTBC-BF and OSTBC-SGE techniques are constant at 3b/s/Hz.

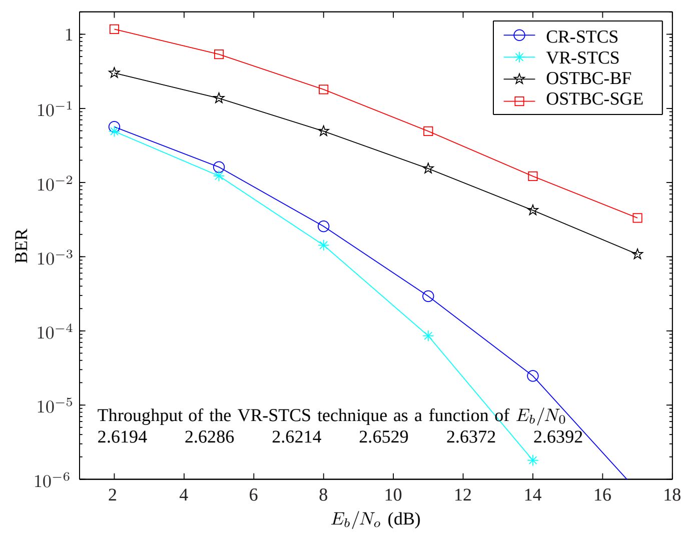

Fig. 4: BER and throughput comparison of the proposed technique (CR-STCS) with other schemes for a speed of 86 km/h. The throughputs of CR-STCS, OSTBC-BF and OSTBC-SGE techniques are constant at 3b/s/Hz.

V. Conclusions

An adaptive space-time code selection technique for constant-rate transmit diversity wireless systems has been proposed. The proposed technique selects both the space-time code and the antennas to be energized, using the instantaneous channel state information and comparing it with a set of predefined threshold levels. In case no channel satisfies the established conditions, a complementary mode is chosen, in

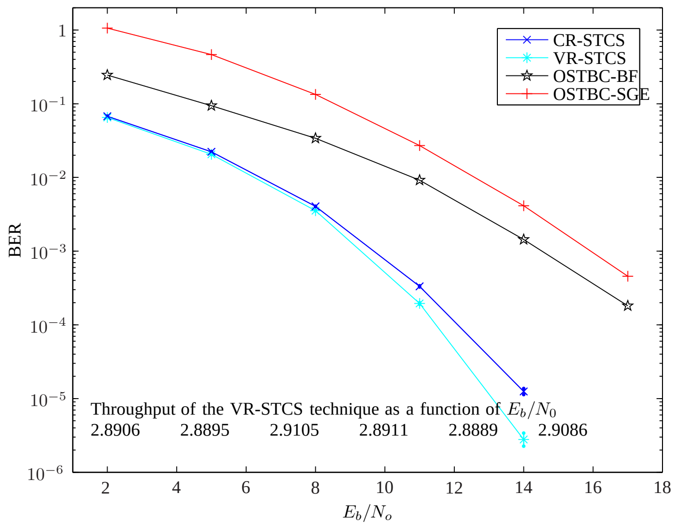

Fig. 5: Confidence intervals of the simulation results for a speed of 12 km/h (see Fig. 1).

which a single antenna is selected. The addition of the complementary mode allows to obtain a constant-rate transmission without sacrificing the spectral efficiency. Simulation results show that, when considering the channel state information obsolescence, the proposed technique widely outperforms other adaptive transmission techniques. Regarding the original space-time code selection technique, which provides a variable rate-transmission, the proposed technique slightly sacrifices the BER performance, in no more than 2dB in the worst case (for high relative velocity and high SNRs), but attains more than a 10% increment in spectral efficiency. Finally, the proposed technique achieves a more stable BER performance with respect to the relative velocity between transmitter and receiver.

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