

On the Performance of Trellis Coded Spatial Modulation

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Abstract—Trellis coded modulation (TCM) is a well known scheme that applies mapping by set partitioning. The key idea is to group the constellation symbols into sets with each set having the maximum free distance between its symbols. In this paper, a similar approach is applied to antenna constellation points of spatial modulation (SM) in order to enhance its performance in correlated channel conditions. In SM, multiple antennas exist at the transmitter side, but only one of them is active at any particular time instant. The incoming data bits determine the active transmit antenna and the signal constellation point transmitted from it. At the receiver side, the active antenna index and the transmitted symbol are estimated and used together to decode the transmitted information bits. The locations of the transmit antennas are considered as spatial constellation points, and TCM is applied to enhance the bit error ratio (BER) performance of SM and coded V-BLAST (vertical Bell Labs layered space-time) applying optimum sphere decoder algorithm. It is shown that under the same spectral efficiency, TCSM performs nearly the same as SM and V-BLAST in idealistic channel conditions. However, a significant enhancement is reported in the presence of realistic channels performance such as Rician fading and spatial correlation (SC).

Index Terms—MIMO, Spatial modulation, Trellis coded modulation, V-BLAST, Sphere decoder, Correlated channel conditions, Rician fading, Spatial correlation.

I. INTRODUCTION

Wireless radio frequency channel generally poses several challenges on the system design. The physical layer of such systems has to deal with multipath propagation, interference and limited available spectrum. MIMO (multiple-input-multiple-output) transmission technology constructively exploits multipath propagation to provide higher data throughput for the same given bandwidth [1].

One of the most promising MIMO techniques to achieve the expected high data rate is the proposed V-BLAST (vertical Bell Labs layered space-time) architecture [2]. In V-BLAST, the information bit stream is separated in substreams. All the symbols of a certain stream are transmitted through the same antenna (one stream per antenna). The substreams are co-channel signals, that is, they have the same frequency band. Therefore, as compared to a SISO system, a linear increase of

the data rate with the number of transmit antennas is achieved. The major task at the receiver is to resolve the inter-channel-interference (ICI) between the transmitted symbols. There are several detection algorithms available in the literature for V-BLAST. The optimum solution is to use maximum likelihood (ML) decoder. The problem of ML algorithm is the high complexity required to search over all possible combinations. Therefore, other algorithms are proposed trying to achieve similar performance as ML detection but with a significant reduction in receiver complexity. A highly potential technique is the proposed sphere decoder (SD) algorithm in [3]. The main idea behind SD is to limit the number of possible codewords by considering only those codewords that are within a sphere centered at the received signal vector. The complexity of separating these signals should be small enough such that the overall complexity of the sphere decoding is lower than that of the full search. In this paper, coded V-BLAST with the SD algorithm is considered.

Traditional MIMO systems use all transmit antennas to simultaneously transmit data to the receiver side. The aim is to improve power efficiency by maximizing spatial diversity [4], or to boost the data rate by transmitting independent streams from each transmit antenna (as in V-BLAST) [1, 2, 5], or to achieve both of them at the same time at the expense of increasing complexity [6].

An alternative multiple antenna transmission technique, called spatial modulation (SM), utilizes the multiple transmit antennas in a different way [7, 8]. Multiple antennas are considered as additional constellation points that are used to carry information bits as seen in Fig. 1. At one time instant, only one transmit antenna is active. Part of the incoming bit sequence determines the active antenna. The active antenna transmits the data symbol and both the transmitted symbol and the active antenna index are estimated at the receiver and used to decode the original information bits.

TCM is a modulation scheme which allows highly efficient and reliable digital transmission without bandwidth expansion or data rate reduction [9]. TCM combines the function of convolutional encoder of rate $R = k/(k+1)$ and M-ary signal mapper that maps $M = 2^{(k+1)}$ constellation points. Unlike conventional coding techniques only certain sequences of successive constellation points are allowed (mapping by set partitioning). The key idea is to group symbols into sets

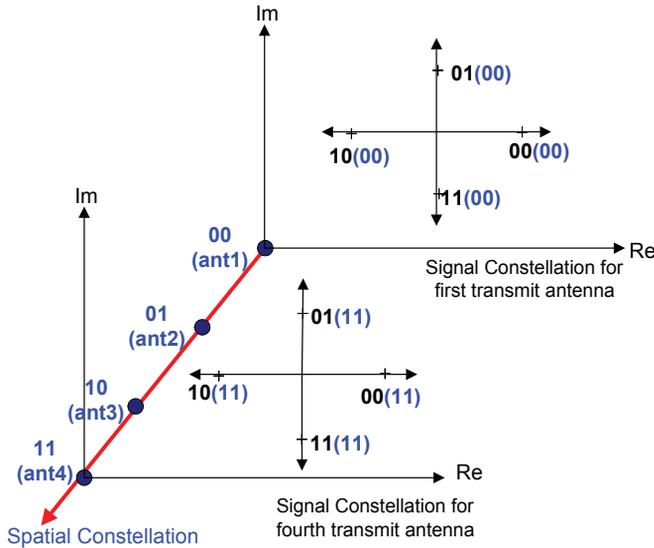


Fig. 1. Spatial modulation maps a sequence of bits into a signal constellation and into a spatial constellation point. The spatial constellation point data is shown inside brackets in the figure. In this example 4-PSK and four transmit antennas are considered. Each spatial constellation point defines an independent complex plane of signal constellation points. For illustration purpose, two such planes, for the sequences (00) and (11), are shown in the figure.

of equal sizes where each set maximizes the free distance between its symbols.

In this paper, the key idea of TCM is applied to the antenna constellation points of SM. This novel scheme is called trellis coded spatial modulation (TCSM). In TCSM, the transmit antennas are partitioned into sub-sets in such a way that the spatial spacing between antennas in the same sub-set is maximized. Therefore, the effect of correlated channels on the performance of SM is reduced. This fact is significant when considering portable devices with multiple antennas installed in compact space and enough separation between them cannot be guaranteed. The performance of the proposed idea is analyzed in the presence of Rician fading and spatial correlation (SC) channels and major enhancements in BER is reported as compared to SM and V-BLAST with the same spectral efficiency.

The rest of the paper is organized as follows: In Section II, the system model of TCSM is presented. V-BLAST system model is discussed in Section III. Section IV present the channel models. Simulation results are discussed in Section V. Finally, Section VI concludes the paper.

II. TRELLIS CODED SPATIAL MODULATION (TCSM) SYSTEM MODEL

The TCSM system model is depicted in Fig. 2. A MIMO system consisting of four transmit antennas ($N_t = 4$) and four receive antennas ($N_r = 4$) is considered as an example. The transmitted bits at each time instant are grouped as the row vectors of the matrix $\mathbf{x}(t)$. For illustration purposes, the incoming bit sequences are considered $\mathbf{x}(t) =$

$\begin{bmatrix} 001 & 110 & 111 \end{bmatrix}^T$, where $(\cdot)^T$ denotes the transpose of a vector or a matrix. The first step is to split this matrix into two matrices. The first matrix $\mathbf{x}_1(t)$ contains the bits that are mapped to spatial constellation points. While the second matrix contains the bits that are mapped to signal constellation points¹. In the considered example, $\mathbf{x}_1(t) = \begin{bmatrix} 0 & 1 & 1 \end{bmatrix}^T$ and $\mathbf{x}_2(t) = \begin{bmatrix} 01 & 10 & 11 \end{bmatrix}^T$. Assuming 4-PSK (phase shift keying) constellation, as seen in Fig. 1, the second matrix is mapped to $\begin{bmatrix} i & -1 & -i \end{bmatrix}^T$, where each element in this matrix corresponds to the symbol that is transmitted from one antenna among the set of existing transmit antennas at one time instant. The first matrix, $\mathbf{x}_1(t)$, is then used to select the active transmit antenna. However, before mapping the bits in the first matrix to the spatial constellation points (the transmit antenna indexes), the bits are processed by a rate 1/2 TCM encoder. The TCM encoder block consists of a convolutional encoder followed by a random block interleaver. The TCM encoder, state transition, and spatial mapping are depicted in Fig. 3. TCM groups the antenna indexes in a tree like fashion, then separates them into two limbs of equal size. At each limb of the tree, the indexes are further apart. In other words, TCM partitions the transmit antennas into sub-sets with the constraint of maximizing the spacing of antennas belonging to the same sub-set. In the given example and assuming all antennas are equally spaced on a vertical line, antennas one and three form a set and antennas two and four form the other set. The output of the TCM encoder is then used to select the active antenna. In the above example, $\mathbf{x}_1(t)$ is transformed into another matrix $l(t) = \begin{bmatrix} 00 & 01 & 11 \end{bmatrix}^T$ by the encoder of Fig. 3(c) assuming the initial state of the encoder is 00. The SM mapper operates on both $l(t)$ and $\mathbf{x}_2(t)$ matrices creating the output matrix

$$s(t) = \begin{bmatrix} i & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & -i \end{bmatrix}.$$

Each column from the output matrix is transmitted at a single time instant from the existing transmit antennas over the MIMO channel $\mathbf{H}(t)$. For instance, at the first time instant in the considered example, the elements of the first column are transmitted from the four transmit antennas. Since, however, only *one* element is different from zero, only *one* antenna emits a signal. This means, that only the first antenna is active at this particular time instant and is transmitting symbol i while all other antennas are switched off. The signal experiences an N_r - dim additive white Gaussian noise (AWGN). The channel and the noise are assumed to have independent and identically distributed (iid) entries according to $\mathcal{CN}(0, 1)$. In addition, Rician fading and Kronecker SC channel models are considered. The complete models for the channel with Rician fading and spatial correlation are discussed in Section IV.

At the receiver, the optimum SM decoder proposed in [10]

¹This is the basic working mechanism of SM, the reader is kindly requested to refer to [7] for detailed information.

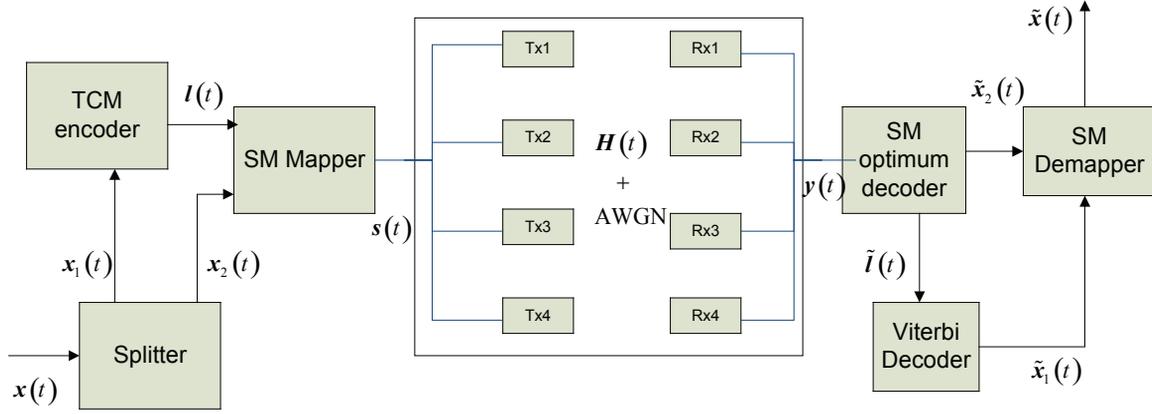


Fig. 2. Trellis coded spatial modulation (TCSM) system model

is considered to estimate the transmitted symbol $\tilde{x}_2(t)$ and the transmit antenna index $\tilde{l}(t)$ as follows:

$$\begin{aligned} [\tilde{x}_2, \tilde{l}] &= \arg \max_{\tilde{x}_2, \tilde{l}} p_{\mathbf{y}}(\mathbf{y} | s_{l,m}, \mathbf{H}) \\ &= \arg \max_{\tilde{x}_2, \tilde{l}} \sqrt{\rho} \|\mathbf{g}_{l,m}\|_{\mathbb{F}}^2 - 2 \operatorname{Re} \{ \mathbf{y}^H \mathbf{g}_{l,m} \}, \quad (1) \end{aligned}$$

where $\mathbf{g}_{l,m} = \mathbf{h}_l s_{l,m}$ is the received vector when transmitting the symbol $s_{l,m}$ from antenna index l where $1 \leq l \leq N_t$ and $1 \leq m \leq M$ and \mathbf{h}_l is the channel vector containing the channel path gains from transmit antenna l to all receive antennas; M is the size of the signal constellation diagram and Re is the real part of a complex number. In addition, ρ is the average signal to noise ratio (SNR) at each receive antenna, and

$$p_{\mathbf{y}}(\mathbf{y} | s_{l,m}, \mathbf{H}) = \pi^{-N_t} \exp \left(- \|\mathbf{y} - \sqrt{\rho} \mathbf{H} s_{l,m}\|_{\mathbb{F}}^2 \right) \quad (2)$$

is the probability density function (pdf) of \mathbf{y} conditioned on the transmitted symbol $s_{l,m}$ from antenna index l and the channel \mathbf{H} . The notation $\|\cdot\|_{\mathbb{F}}$ stands for the Frobenius norm of a vector or a matrix.

The estimated antenna number is de-mapped to the corresponding bits and the incoming data sequence of one complete frame is applied to a random block deinterleaver and then decoded using a hard decision Viterbi decoder. The output from the Viterbi decoder together with the estimated symbols are used to retrieve the original information bits.

In this paper, the performance of TCSM scheme is compared to SM and V-BLAST. SM applies no channel coding and uses a smaller number of transmit antennas or lower modulation order to achieve the same spectral efficiency as TCSM. V-BLAST system model, on the other hand, is discussed in the following section.

III. V-BLAST SYSTEM MODEL

The considered V-BLAST system in this paper is depicted in Fig. 4. The rate 1/2 convolutional encoder shown in Fig. 3 is considered. Coded V-BLAST system is generally termed

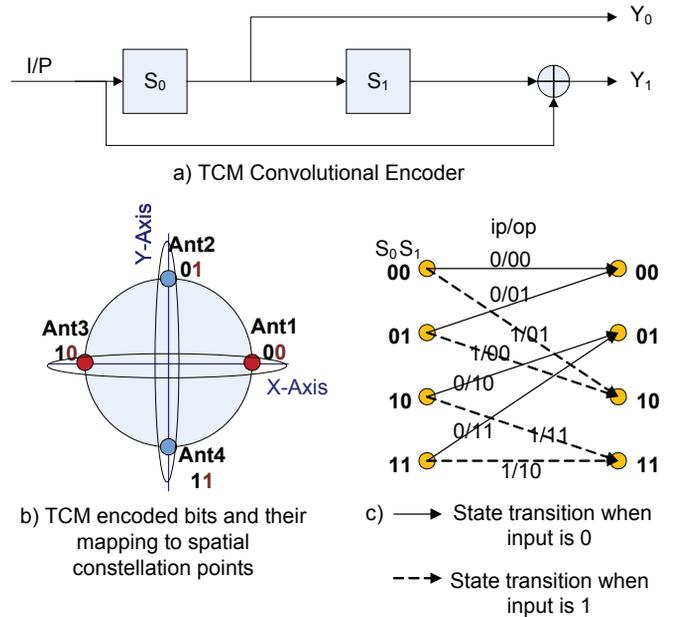


Fig. 3. Trellis coded encoder, spatial constellation mappings, and state transitions of the TCM encoder

horizontal BLAST (H-BLAST) [11]. In H-BLAST, the incoming bit stream is demultiplexed into N_t parallel substreams. Channel coding followed by interleaving is applied to each substream. The coded bits are modulated and then transmitted from the corresponding transmit antenna. If the interleaving depth is selected to be larger than the coherence time of the channel, additional diversity gain can be achieved [12].

Another way of applying channel coding to V-BLAST is to use a single channel code for all layers as shown in Fig. 4. This scheme is called single coded BLAST (SCBLAST) [12]. SCBLAST is simpler than H-BLAST in the sense that only a single channel encoder is needed for all layers. In addition, in correlated slow or block fading channel, SCBLAST outperforms H-BLAST since the demultiplexer (at the transmitter)

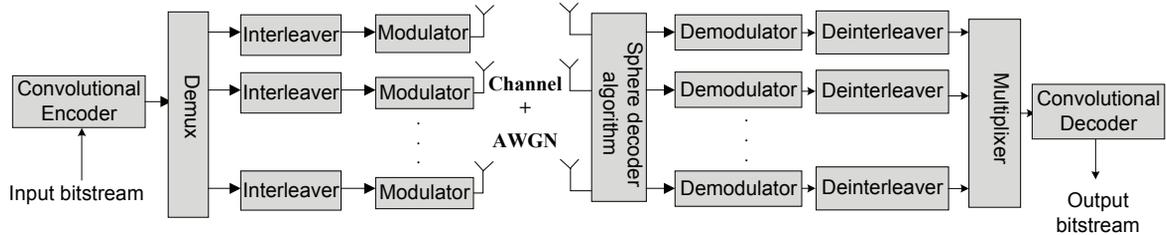


Fig. 4. V-BLAST system model

and multiplexer (at the receiver) act as spatial interleavers where they together help in breaking some of the correlation in the received signal [12]. In this paper, correlated slow fading channels are assumed and therefore, SCBLAST is considered for the comparisons used in this paper.

At the receiver, SD algorithm is employed to detect the transmitted symbols from all layers. In simulations, SD algorithm based on integer lattice theory is implemented. A complex MIMO system is decoupled into its real and imaginary parts so as to form an equivalent real-valued system. This approach is most appropriate for lattice-based modulation schemes such as quadrature amplitude modulation (QAM) or pulse amplitude modulation (PAM) [3, 13, 14]. For other complex constellations such as phase-shift keying (PSK), the SD based on integer lattice theory are inefficient due to the existence of invalid candidates. A solution is to avoid decoupling of the complex system by applying complex SD algorithms [15].

The SD algorithm avoids an exhaustive search by examining only those points that lie inside a sphere with radius C . The performance of the SD algorithm is closely tied to the choice of the initial radius. The radius should be chosen large enough so that the sphere contains the solution. However, the larger the radius is, the longer the search takes which increases the complexity. On the other hand, a small radius may cause the algorithm to fail finding any point inside the sphere. In this paper, the initial radius of the SD algorithm is adjusted according to the noise level assuming the knowledge of the SNR at the receiver side. If no point is found inside the sphere, the search is repeated with a larger radius ($C = C + 1$) [16]. This approach is shown to perform near optimum maximum likelihood detection [16].

SD receivers have been implemented in custom application-specific integrated circuits (ASICs) [17] and as simplified fixed complexity designs [18] conveniently realized in field-programmable gate arrays (FPGAs) [19].

The output symbols from SD are demodulated and the bits are deinterleaved. The bits from all layers are multiplexed and hard decision Viterbi decoder is then applied.

IV. CHANNEL MODELS

In this paper, \mathbf{H} is an $N_r \times N_t$ flat fading channel matrix representing the path gains h_{ij} between transmit antenna j

and receive antenna i .

$$\begin{bmatrix} h_{11} & h_{12} & \cdots & h_{1N_t} \\ h_{21} & h_{22} & \cdots & h_{2N_t} \\ \vdots & \vdots & \ddots & \vdots \\ h_{N_r,1} & h_{N_r,2} & \cdots & h_{N_r,N_t} \end{bmatrix} \quad (3)$$

In case of NLOS (non-line-of-sight), the sum of all scattered components of the received signal is modeled as a zero mean complex Gaussian random process given by $\alpha(t) = \alpha_1(t) + \sqrt{-1}\alpha_2(t)$, where $\alpha_1(t)$ and $\alpha_2(t)$ are assumed to be real valued statistically independent Gaussian random processes. As a result, the phase of the random process $\alpha(t)$ takes a uniform distribution and the amplitude takes a Rayleigh distribution. Therefore, a static fading Rayleigh channel matrix that is flat for all frequency components is modeled.

A. Rician fading channel

If a LOS path exists between the transmit and receive antennas, the channel amplitude gain is characterized by a Rician distribution and the channel is said to exhibit Rician fading. The Rician fading MIMO channel matrix can be modeled as the sum of the fixed LOS matrix and a Rayleigh fading channel matrix as follows [20]:

$$\mathbf{H}_{\text{Ricean}}(t) = \sqrt{\frac{K}{1+K}}\bar{\mathbf{H}}(t) + \sqrt{\frac{1}{1+K}}\mathbf{H}(t), \quad (4)$$

where $\sqrt{\frac{K}{1+K}}\bar{\mathbf{H}}$ is the LOS component, $\sqrt{\frac{1}{1+K}}\mathbf{H}$ is the fading component, and K is the Rician K -factor. The Rician K -factor is defined as the ratio of the LOS and the scatter power components and $\bar{\mathbf{H}}$ is a matrix with all elements being one.

B. Spatial correlation (Kronecker model)

The channel correlation depends on both the environment and the spacing of the antenna elements. It is assumed that correlations at the transmitter and receiver array are independent of each other because the distance between the transmit and receive array is large compared to the antenna element spacing.

To incorporate the SC into the channel model, the correlation among channels at multiple elements needs to be calculated. The correlated channel matrix is then modeled using the Kronecker model [21].

$$\mathbf{H}^{\text{corr}}(t) = \mathbf{R}_{\text{rx}}^{1/2}\mathbf{H}(t)\mathbf{R}_{\text{tx}}^{1/2} \quad (5)$$

The correlation matrices are computed analytically based on the power azimuth spectrum (PAS) distribution and array geometry [21]. A clustered channel model, in which groups of scatterers are modeled as clusters located around the transmit and receive antennas, is assumed. The clustered channel model is validated through measurements [22] and adopted by various wireless system standard bodies such as the IEEE 802.11n Technical Group (TG) [23] and the 3GPP/3GPP2 Technical Specification Group (TSG) [24].

V. SIMULATION RESULTS

In order to validate the proposed TCSM idea, Monte Carlo simulation results for at least 10^6 channel realizations are obtained and the average BER is plotted versus the average SNR at each receiver input. In all simulations where Rician fading is considered, channel correlation due to antenna spacing is zero, but the Rician K factor is set to $K = 3$. This value is within the range of the measured values in indoor wireless communication [25]. For SC channel model, similar parameters as discussed in [7] are adopted here as well, except that the element spacing at the transmitter and the receiver are set to 0.1λ and 0.5λ , respectively. The 0.5λ separation between the antennas can achieve relatively low correlation assuming the receiver is surrounded by a large number of local scatterers [26]. The 0.1λ element spacing at the transmitter results in high correlation which models a small mobile device with multiple antennas where large separation between the antennas cannot be achieved.

A. TCSM and SM performance comparison

In the first results, depicted in Figs. 5, 6 and 7, TCSM performance under ideal, Rician fading, and SC channel conditions are plotted, respectively, and compared to SM performance under similar channel conditions. TCSM transmits 4QAM symbol from a 4x4 MIMO system and applies the rate 1/2 TCM encoder. Therefore, TCSM achieves 4 b/s/Hz but only 3 bits are data bits and the fourth one is a coding bit. SM transmits a BPSK symbol from a 4x4 MIMO system achieving 3 b/s/Hz spectral efficiency. Thus, the two systems have the same spectral efficiency.

In ideal channel conditions (the channel paths are uncorrelated), the BER of the two systems are compared in Fig. 5. SM performs slightly better than TCSM. The reason for this behavior is that the TCM coding gain and the set partitioning of the transmit antennas has no advantage since all channel paths are uncorrelated. However, the situation is different if correlated channel paths are considered, i.e. when Rician fading and SC channels are considered. The advantage of TCSM over SM is obvious from Figs. 6 and 7. A SNR gain of about 6 dB in Rician fading channel at a BER of 10^{-4} can be noticed in Fig. 6. In addition, similar gain in SNR at the same BER is noticed in Fig. 7 for SC channel. The significant gains in the presence of channel correlations due to Rician fading or SC can be attributed to TCM encoding and the underlying partitioning of the transmit antennas. The fact that the transmit antennas with larger separation distance

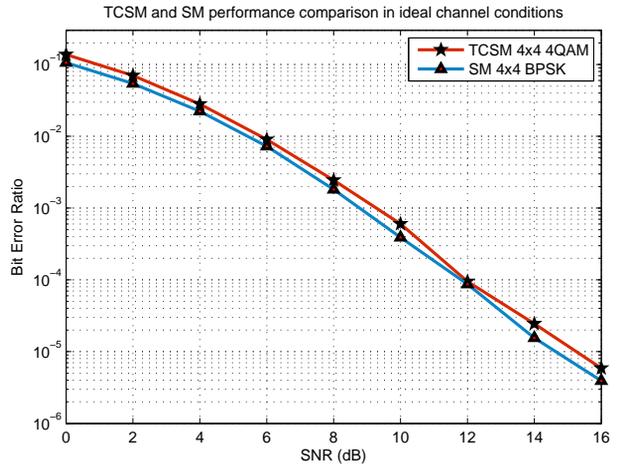


Fig. 5. Performance comparison of SM 4x4 BPSK and TCSM 4x4 4QAM for ideal channel

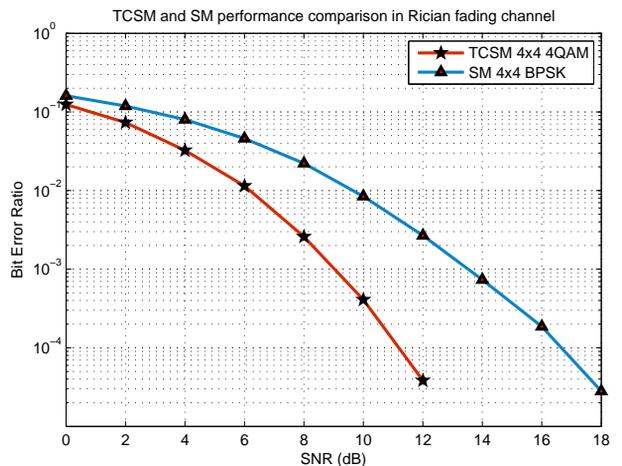


Fig. 6. Performance comparison of SM 4x4 BPSK and TCSM 4x4 4QAM in Rician fading channel with Rician K -factor of 3

are grouped in one set, reduces the effect of correlation and results in a better performance.

B. TCSM and V-BLAST performance comparison

In the second set of results, the BER of TCSM and V-BLAST² are compared in ideal, Rician fading, and SC channel conditions as depicted in Figs. 8, 9, and 10, respectively. Two spectral efficiencies are studied for each system. TCSM transmits 4QAM and 32QAM symbols from 4x4 MIMO system achieving a spectral efficiencies of 3 b/s/Hz and 6 b/s/Hz, respectively. V-BLAST system transmits 4QAM and 16QAM symbols from a 3x4 MIMO system and applying the rate 1/2 channel encoder, therefore, achieving 3 b/s/Hz and 6 b/s/Hz spectral efficiencies, respectively.

²V-BLAST here refers to SCBLAST discussed in Section III. The name of V-BLAST is retained here for consistency.

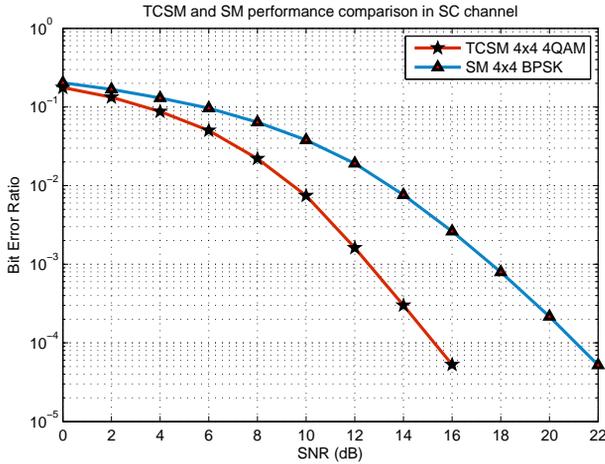


Fig. 7. Performance comparison of SM 4x4 BPSK and TCSM 4x4 4QAM in SC channel with transmit antenna element spacing of 0.1λ at the transmitter and 0.5λ at the receiver

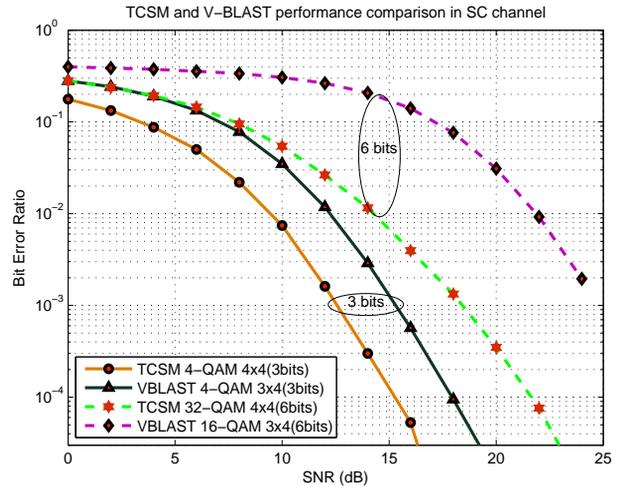


Fig. 10. Performance comparison of TCSM and V-BLAST in SC channel with transmit antenna element spacing of 0.1λ and receive antenna element spacing of 0.5λ

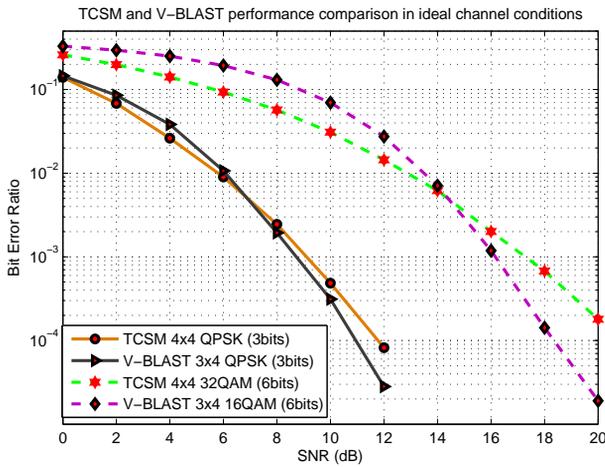


Fig. 8. Performance comparison of TCSM and V-BLAST in ideal channel conditions

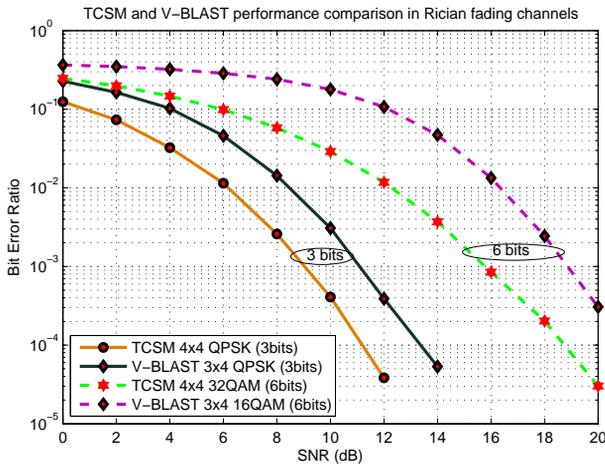


Fig. 9. Performance comparison of TCSM and V-BLAST in Rician fading channel with Rician K -factor of 3

In ideal channel condition, TCSM and V-BLAST outperform each other in a range of SNRs. The BER curves intersect at 7 dB for 3 b/s/Hz and at 14 dB for 6 b/s/Hz as shown in Fig. 8. The channel coding gain in V-BLAST causes BER enhancements at high SNR. In addition, and as discussed previously, the effect of TCM coding and set partitioning are insignificant as the channel paths are uncorrelated in this scenario. The BER gain of V-BLAST over TCSM at high SNR is larger for the case of 6 b/s/Hz. This is mainly because the higher coding gain of V-BLAST at high SNR and the fact that TCSM uses higher order modulation in order to achieve similar spectral efficiency as V-BLAST. The improvements of TCSM over V-BLAST at low SNR is not related to the TCM coding and set partitioning. It is mainly due to the underlying working mechanism of SM and the fact that it completely avoids inter-channel-interference (ICI) at the receiver side [7].

In Fig. 9, the performance of V-BLAST and TCSM is compared in the presence of line of sight (LOS) path between transmitter and receiver (Rician fading channel). Rician fading enhances the SNR at the receiving antennas, but increases the correlation between the antenna elements [27]. Therefore, Rician fading significantly degrades the performance of V-BLAST and SM [7]. This degradation can be observed for V-BLAST in the results depicted in Fig. 9. As compared to the obtained results in ideal channel conditions, V-BLAST requires 2 dB and 3 dB increase in SNR to achieve a BER of 10^{-3} for 3 b/s/Hz and 6 b/s/Hz, respectively. However, TCSM seems to be less affected by the presence of Rician fading. In fact, it demonstrates even better performance as compared to ideal channel conditions results. For instance, the 32QAM 4x4 TCSM achieves a BER of 10^{-3} at a SNR of about 19 dB in ideal channel condition. Though, it achieves the same BER at a SNR of 16 dB in the presence of Rician fading channel. Indeed, TCSM demonstrates better performance in the presence

of LOS path between the transmitter and the receiver. This can be explained by the fact that Rician fading increases the SNR at the receiver side and the underlying set partitioning together with TCM coding eliminates the correlation between transmit antennas. Nevertheless, it should be mentioned that the performance of TCSM in Rician fading channels depends on the number of transmit antennas, the considered modulation order, and the Rician K -factor. However, for the systems considered in this paper and in the presence of Rician fading, TCSM outperforms V-BLAST by 2 dB and 3 dB in SNR at a BER of 10^{-3} for 3 b/s/Hz and 6 b/s/Hz, respectively.

Finally, the effect of SC on the performance of TCSM and V-BLAST is studied and the results are shown in Fig. 10. The presence of correlation degrades the performance of the two systems. Again, TCSM is significantly less affected by the presence of SC as compared to V-BLAST. As compared to the results obtained in ideal channel conditions, SC degrades the performance of TCSM by 3 dB and 1 dB in SNR at a BER of 10^{-3} for 3 b/s/Hz and 6 b/s/Hz, respectively. While V-BLAST system performance degrades by about 5 dB and 9 dB in SNR at a BER of 10^{-3} for 3 b/s/Hz and 6 b/s/Hz, respectively. TCSM outperforms V-BLAST by about 3 dB and 6 dB in SNR at a BER of 10^{-3} for 3 b/s/Hz and 6 b/s/Hz, respectively.

In summary, the basic idea of the proposed scheme is to divide the existing antennas into sets using TCM such that each set maximizes the spatial distance between its antennas, and therefore minimizes the effect of correlation fading.

VI. SUMMARY AND CONCLUSION

SM is a radically different and relatively new MIMO approach. It has the important feature that it fully *avoids* inter-channel interference while it still enables the system to benefit from spatial multiplexing gains. The key to achieving this goal is the exploitation of the relative dislocation of the antennas within an antenna array. This dislocation is used to *implicitly* convey extra data bits. At the receiver a new block, namely an antenna detector, is required. This paper, for the first time, proposes the use of trellis coded modulation for the correction of data errors that occur within the antenna detector block, *i.e.*, the correction of erroneous data bits that are implicitly encoded into the location of the antenna.

TCM concept is adopted in a novel way in this paper to combat performance degradation of SM in correlated channel conditions. TCM is applied to the spatial constellation points of SM. In the proposed TCSM, only certain sequences of successive spatial constellation points are allowed which reduces the correlation between neighboring antennas. TCSM performance is analysed in this paper and compared to the performance of SM and V-BLAST. Major enhancements in SNR are reported in Rician fading and spatially correlated channel conditions. The proposed TCSM allows the integration of multiple antenna system in small devices with antenna separations as low as 0.1λ . It is also suitable for indoor applications with direct LOS between transmitter and receivers.

Future work will consider different channel conditions and TCM encoders with different states.

ACKNOWLEDGMENT

Harald Haas acknowledges the Scottish Funding Council support of his position within the Edinburgh Research Partnership in Engineering and Mathematics between the University of Edinburgh and Heriot Watt University.

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