HYBRID MAXIMUM-LIKELIHOOD DETECTOR FOR TRELLIS CODED SPATIAL MODULATION

CĂLIN VLĂDEANU[1], SAFWAN EL ASSAD[2]

Key words: Spatial modulation, Trellis coded spatial modulation (TCSM), Soft-output maximum-likelihood (ML) detectors.

Most spatial modulation (SM) schemes in the literature use hard-output maximum-likelihood (ML) antenna index detection. In trellis coded spatial modulation (TCSM) scheme, the detection should be also performed for the transmitted symbol, while the sequence decoding is performed using a hard-output Viterbi algorithm. We modified the hard-output ML-SM detector to determine a soft estimate of the transmit antenna index and a hard estimate of the transmitted symbol, and used it in conjunction with the logarithmic maximum a posteriori probability (log-MAP) sequence decoding algorithm. If at least four receive antennas are used, the soft-output and the less complex hybrid detectors offer a coding gain, over the hard-output detector, of at least 4 dB in Rician fading and 2 dB in spatially correlated (SC) fading channels.

1. INTRODUCTION

During the last decades, multiple-input multiple-output (MIMO) techniques emerged as high spectral efficiency solutions for wireless data transmissions. MIMO techniques, which perform a multiple-antenna transmission and reception, take advantage of the channel diversity in fading environments. However, a major drawback arising from this mechanism is the inter-channel interference (ICI), caused by the inter-antenna signals overlapping.

Spatial modulation (SM) was proposed recently for eliminating the ICI in multiple-antenna transmitters [1, 2]. The principle of SM consists in restricting the multiple-antenna transmitter to use only one antenna for signal transmission over a data symbol interval. Because only one transmit antenna is active during a data symbol interval, results that the ICI does not exist. In fact, the information

---

[1] "Politehnica" University of Bucharest, Telecommunications Department, 1–3 Iuliu Maniu, ZIP 061071, Bucharest, Romania, E-mail: calin@comm.pub.ro.

[2] École d'Ingénieurs de l'Université de Nantes, IETR Laboratory, UMR CNRS 6164, Image team Rue Christian Pauc, 44306 Nantes, cedex 3, France, E-mail: safwan.elassad@univ-nantes.fr.

Rev. Roum. Sci. Techn. – Électrotechn. et Énerg., 57, *4*, p. 383–393, Bucarest, 2012

sequence bits are used to select the transmit antenna. The information binary sequence is split into fixed length words that are used as address to select the transmit antenna. The SM concept is a generalization of space shift keying (SSK) modulation, where each selected transmit antenna issues the same unmodulated signal [3, 4].

A very successful method of reducing power requirements without increasing bandwidth is trellis coded modulation (TCM) [5]. TCM allows highly efficient and reliable digital transmissions, without any sacrifice in bandwidth.

In trellis coded spatial modulation (TCSM) schemes the key idea of TCM is applied to the antenna constellation points of SM [6, 7]. In TCSM schemes, the information address words of SM are convolutionally encoded. Moreover, 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, even though only one transmit antenna is active, the coded SM can achieve both multiplexing and coding gains as compared to the conventional MIMO techniques, especially in correlated channel environments. This advantage is significant when considering portable devices with multiple antennas installed in compact space. Other solutions for efficient wireless coded transmissions using the TCM principle can be found in the literature [8]. In the receiving part, the transmit antenna index should be determined first. Most schemes presented in the literature use hard-output maximum-likelihood (ML) detection for the antenna index identification [9]. In TCSM schemes, this detection should be also performed for the transmitted symbol. The ML detector for TCSM scheme jointly identifies the transmit antenna and symbol indexes. In the second step, the information sequence is reconstructed from the detected antenna and symbol indexes, employing a sequence decoding algorithm, such as the hard-output Viterbi algorithm. In [7] and [10] a soft-output ML-SM optimum detector is introduced, which estimates separately the log-likelihood ratio (LLR) per bit for the antenna index and the symbol index.

In this paper, we revised the well known hard-output ML-SM detector into a hybrid one. Thus, LLR values are determined only for the antenna indexes, while the symbol indexes are determined as hard estimates. We also used this hybrid LLR in conjunction with the logarithmic maximum a posteriori probability (log-MAP) sequence decoding algorithm. As a result, a coding gain of at least 4 dB is noticed for TCSM transmissions in Rician fading channels and 2 dB in spatially correlated (SC) fading channels, when using at least four receive antennas. The considered SC channel model is presented in [11]. The bit error rate (BER) is estimated by simulations for QPSK-TCSM transmissions over stationary Rayleigh, Rician, and SC fading channels with additive white Gaussian noise (AWGN).

The paper is organized as follows. Section 2 presents the TCSM system model. The ML-SM detectors are presented consecutively in Section 3. The simulated bit error rate (BER) is estimated in Section 4 for QPSK-TCSM transmissions over different fading channels. Finally, conclusions are drawn.

2. **TCSM SYSTEM MODEL**

The TCSM system block scheme is presented in Fig. 1 [6, 7]. In the transmitter, the information bit sequence $u(t)$ is first split into words of $k+s$ bits. The first k bits form the vector $\mathbf{u}_1(t)$, while the remaining s bits form the vector $\mathbf{u}_2(t)$. Here, t denotes the time variable. The first vector $\mathbf{u}_1(t)$ is encoded convolutionally by a rate $k/(k + 1)$ trellis-coded modulation encoder and the resulted vector is denoted by $\mathbf{v}_1(t)$. On the other hand, the s bits vector $\mathbf{u}_2(t)$ is modulated into a 2^s-ary two-dimensional modulation symbol, such as phase-shift keying (PSK), denoted by $\mathbf{v}_2(t)$. Finally, in the SM mapper, the 2^s-ary modulated symbol $\mathbf{v}_2(t)$ is issued over a unique transmit antenna that is selected by the convolutional encoder output $\mathbf{v}_1(t)$. This principle is named *spatial modulation* due to the fact that, at an instant, the information is used to select a unique transmit antenna from an antenna array. In fact, the transmit antenna index is obtained by converting the binary vector $\mathbf{v}_1(t)$ into decimal. Let's denote by n_T the number of transmit antennas, with $n_T = 2^{k+1}$, where $k + 1$ is the size of the vector $\mathbf{v}_1(t)$. Similar to the classical TCM [5], TCSM partitions the transmit antennas from the antenna array into sub-sets, maximizing the spacing of antennas belonging to the same sub-set [7].

In the receiver, several transmitted signal replicas are captured by n_R receive antennas. It is important to note that for TCSM n_R can take any value, but n_T should be at least four, because TCSM is a technique that exploits the antenna encoded position in the antenna array. Next, the SM decoder estimates in a ML manner both the transmit antenna index, denoted as $\tilde{\mathbf{v}}_1(t)$, and the transmitted constellation point index, $\tilde{\mathbf{v}}_2(t)$. These estimates can be soft-output values or hard-output ones, depending on the SM decoding method. In the Section 3 several distinct SM decoding methods are presented. The vector of the estimated transmit antenna indexes is applied to a sequence decoding block that recovers the vector $\tilde{\mathbf{u}}_1(t)$, which is an estimate of the convolutional encoder input $\mathbf{u}_1(t)$ from the transmitter. For each estimated transmit antenna index at the input, the sequence decoder outputs a k bit vector. The sequence decoding algorithms considered in this paper are either the hard-input hard-output Viterbi algorithm, or the soft-input hard-output log-MAP algorithm, depending on the SM decoder output, if it uses either hard estimation or a soft estimation, respectively. On the other hand, each estimated 2^s-ary constellation point $\tilde{\mathbf{v}}_2(t)$ is demodulated into s bits vector $\tilde{\mathbf{u}}_2(t)$. Finally, each k bits vector $\tilde{\mathbf{u}}_1(t)$ and s bits vector $\tilde{\mathbf{u}}_2(t)$ are joined into to a serial string, comprising the information sequence estimate $\tilde{u}(t)$.

The channel model assumes the presence of complex AWGN noise, denoted by $\mathbf{n}(t)$, and static flat fading denoted by an $n_R \times n_T$ matrix $\mathbf{H}(t)$ representing the path gains h_{ij} between transmit antenna j and receive antenna i, where $i \in \{0, 1, ..., n_R\}$ and $j \in \{0, 1, ..., n_T\}$.

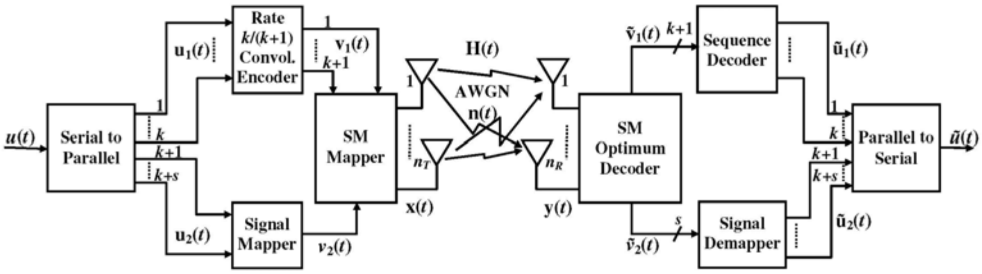

Fig. 1 – TCSM system block scheme.

The values of matrix $\mathbf{H}(t)$ elements determine the channel type. In this paper, we considered three different channel models, as in [6] and [7]. The first channel model is a static fading Rayleigh channel that is flat for all frequency components. The complex path gains h_{ij} have a uniformly distributed phase and a Rayleigh distributed amplitude. If a line-of-sight (LOS) path exists between transmit and receive antennas, the channel amplitude gain is characterized by a Rician distribution. The Rician fading MIMO channel matrix can be modeled as:

$$\mathbf{H}_{\text{Rician}}(t) = \sqrt{\frac{K}{K+1}}\mathbf{A}(t) + \sqrt{\frac{1}{K+1}}\mathbf{H}(t), \tag{1}$$

where K denotes the Rician factor, defined as the ratio between the LOS and the scatter power components, $\mathbf{A}(t)$ is a $n_R \times n_T$-matrix with all elements being one, and $\mathbf{H}(t)$ is a Rayleigh fading matrix, corresponding to the scatter components, which is defined as for the first channel model.

The third channel model takes into account the spatial correlation (SC) between the transmit antennas from the antenna array [7, 11]. Transmit antennas are considered to be equally spaced and linearly distributed into the antenna array. The channel correlation depends on both the environment and the spacing of the antenna elements. The correlated channel matrix is modeled as following [11]:

$$\mathbf{H}_{\text{SC}}(t) = \mathbf{R}_{\text{Rx}}^{1/2}\,\mathbf{H}(t)\,\mathbf{R}_{\text{Tx}}^{1/2}, \tag{2}$$

where $\mathbf{H}(t)$ is a Rayleigh fading matrix, while $\mathbf{R}_{\text{Rx}}$ and $\mathbf{R}_{\text{Tx}}$ are the spatial covariance matrices at the receiver and transmitter, respectively, expressing the correlation of the receive/transmit signals across the array elements. A closed-form expression for the coefficients of $\mathbf{R}_{\text{Rx}}$ and $\mathbf{R}_{\text{Tx}}$ is given in [11].

Considering all the notations above and the block scheme in Fig. 1, one can write the expression of the received signal, the n_R-dimensional vector $\mathbf{y}(t)$:

$$\mathbf{y}(t) = \sqrt{\rho}\,\mathbf{H}(t)\,\mathbf{x}(t) + \mathbf{n}(t), \tag{3}$$

where ρ is the average signal-to-noise ratio (SNR) per receive antenna, $\mathbf{n}(t)$ is the n_R – dimensional AWGN noise with an average power σ_n^2, and $\mathbf{x}(t)$ represents the n_T – dimensional transmitted signal pattern, at any moment t. Considering that in the SM transmitter, a single transmit antenna with the index v_1 is active at any moment t, issuing the 2^s-ary constellation point v_2 with the index u_2, the n_T – dimensional transmitted vector $\mathbf{x}$ is given by:

$$\mathbf{x}_{v_1,u_2}[k] \overset{\Delta}{=} \begin{cases} v_2, & \text{if } k = v_1 \\ 0, & \text{if } k \neq v_1,\ k \in \overline{1, n_T} \end{cases}. \tag{4}$$

3. **ML-SM DETECTORS**

As mentioned before, the SM detector is specific to all SM MIMO transmission techniques. A ML algorithm is used to identify the most probable transmit antenna index and transmitted symbol from the received signal replicas. In this section, three different ML algorithms are presented. The conventional hard-output ML-SM optimum detector is presented first. Then, our proposed hybrid ML-SM optimum detector is defined. Finally, the soft-output per bit ML-SM optimum detector is introduced.

3.1. ML OPTIMUM DETECTOR WITH HARD-OUTPUT

The hard-output optimum ML detector for TCSM scheme that jointly identifies the transmit antenna index $\tilde{\mathbf{v}}_1(t)$ and the transmitted symbol $\tilde{\mathbf{v}}_2(t)$ was introduced in [9]. For the sake of conciseness, the time variable denoted by t will be eliminated, starting with this section. The joint estimation is made as following:

$$[\tilde{\mathbf{v}}_1, \tilde{\mathbf{v}}_2] = \underset{\mathbf{v}_1,\mathbf{v}_2}{\arg\max}\ p_{\mathbf{y}}(\mathbf{y} \mid \mathbf{x}, \mathbf{H}) = \underset{\mathbf{v}_1,\mathbf{v}_2}{\arg\min}\left[\sqrt{\rho}\left\|\mathbf{z}_{\mathbf{v}_1,\mathbf{v}_2}\right\|_{\mathrm{F}}^2 - 2\,\mathrm{Re}\left(\mathbf{y}^H \mathbf{z}_{\mathbf{v}_1,\mathbf{v}_2}\right)\right], \tag{5}$$

where $\|\,.\,\|_{\mathrm{F}}^2$ denotes the Frobenius norm, $\mathrm{Re}(.)$ is the real part of a complex number, $(.)^H$ denotes the Hermitian of a vector or a matrix, and $\mathbf{z}_{\mathbf{v}_1,\mathbf{v}_2} = \mathbf{h}_{\mathbf{v}_1}\mathbf{v}_2$ represents the received vector when transmitting the 2^s-ary symbol $\mathbf{v}_2$ from the antenna with the index $\mathbf{v}_1$; $\mathbf{h}_{\mathbf{v}_1}$ is the channel path gains vector from the transmit antenna with index $\mathbf{v}_1$ to all n_R receive antennas. The probability density function (pdf) of $\mathbf{y}$ conditioned on transmitted vector $\mathbf{x}$ and channel matrix $\mathbf{H}$ is given by:

$$p_{\mathbf{y}}(\mathbf{y} \mid \mathbf{x}, \mathbf{H}) = \pi^{-n_T} \exp\left(-\left\|\mathbf{y} - \sqrt{\rho}\mathbf{H}\mathbf{x}\right\|_{\mathrm{F}}^2\right). \tag{6}$$

The vector of the hard decision transmit antenna indexes $\tilde{\mathbf{v}}_1$ is applied to a hard-input hard-output Viterbi algorithm that recovers the vector $\tilde{\mathbf{u}}_1$, which is an estimate of the convolutional encoder input $\mathbf{u}_1$ from the transmitter.

3.2. HYBRID ML OPTIMUM DETECTOR

In this subsection, a modified hybrid version of the ML optimum detector with hard-output, from subsection 3.1, is introduced. Instead of taking the hard decision for both the transmit antenna index and the transmitted symbol as in (5), we kept the hard decision only for the transmitted symbol $\tilde{\mathbf{v}}_2$, as follows:

$$[\tilde{\mathbf{v}}_2] = \arg\min_{\mathbf{v}_2} \mathbf{Z}_{\mathbf{v}_1,\mathbf{v}_2}, \tag{7}$$

where $\mathbf{Z}_{\mathbf{v}_1,\mathbf{v}_2} = \sqrt{\rho}\left\|\mathbf{z}_{\mathbf{v}_1,\mathbf{v}_2}\right\|_{\mathrm{F}}^2 - 2\,\mathrm{Re}\left(\mathbf{y}^H \mathbf{z}_{\mathbf{v}_1,\mathbf{v}_2}\right)$ is an $n_T \times 2^s$ decision matrix and all notations are identical to those introduced in subsection 3.1. Then, the decided transmitted symbol $\tilde{\mathbf{v}}_2$ from (7) is used to select the $\tilde{\mathbf{v}}_2$ column from the matrix $\mathbf{Z}_{\mathbf{v}_1,\mathbf{v}_2}$. Let's denote the $\tilde{\mathbf{v}}_2$ column from the matrix $\mathbf{Z}_{\mathbf{v}_1,\mathbf{v}_2}$ as $\mathbf{Z}_{\tilde{\mathbf{v}}_2} = \mathbf{Z}_{\mathbf{v}_1,\tilde{\mathbf{v}}_2}$. Hence, the vector $\mathbf{Z}_{\tilde{\mathbf{v}}_2}$ contains n_T elements that represent soft estimates of the transmit antenna indexes $\tilde{\mathbf{v}}_1$. Finally, we introduce the values of $\mathbf{Z}_{\tilde{\mathbf{v}}_2}$, with the opposite sign, as decision metrics for the soft-input log-MAP algorithm. It will be shown in Section 4 that this detection separation, *i.e.*, first a hard-output decision for the transmitted symbol, and then a soft-output decision for the antenna index, in conjunction with a soft-input sequence decoding algorithm, is offering a BER improvement over hard-output ML detector in Rician and SC fading channels.

3.3. ML OPTIMUM PER BIT JOINT DETECTOR WITH SOFT-OUTPUT

A soft-output ML-SM optimum detector, which estimates separately the log-likelihood ratio (LLR) per bit for the antenna index and the symbol index was proposed in [7]. The sequence of detected antenna indexes is then used as input for a hard-input Viterbi decoding algorithm. The BER simulation results in Section 4 will show some improvements over the hard-output ML detector.

The soft estimates of the transmit antenna index $\tilde{\mathbf{v}}_1$ and the transmitted constellation symbol index $\tilde{\mathbf{u}}_2$ are computed as log-likelihood ratios (LLRs) per binary representation element. The calculation of the LLR for the *i*-th bit of the transmit antenna index binary representation is as follows:

$$LLR\left(v_1^i\right) = \log \frac{P\left(v_1^i = 1 \middle| \mathbf{y}\right)}{P\left(v_1^i = 0 \middle| \mathbf{y}\right)} = \log \frac{\sum_{\tilde{\mathbf{v}}_1 \in \mathbf{V}_{1,1}^i} \sum_{\mathbf{v}_2 \in \mathbf{V}_2} \exp\left(- \left\| \mathbf{y} - \sqrt{\rho}\mathbf{h}_{\tilde{\mathbf{v}}_1} \mathbf{v}_2 \right\|_F^2 \Big/ \sigma_n^2 \right)}{\sum_{\tilde{\mathbf{v}}_1 \in \mathbf{V}_{1,0}^i} \sum_{\mathbf{v}_2 \in \mathbf{V}_2} \exp\left(- \left\| \mathbf{y} - \sqrt{\rho}\mathbf{h}_{\tilde{\mathbf{v}}_1} \mathbf{v}_2 \right\|_F^2 \Big/ \sigma_n^2 \right)}, \tag{8}$$

where v_1^i represents the i-th bit from the binary representation of the transmit antenna index $\mathbf{v}_1$, with $i = \overline{1, k+1}$, and all notations were kept as in subsection 3.1. Similarly, the LLR of the j-th bit in the binary representation of the transmitted constellation symbol index is as follows:

$$LLR\left(u_2^j\right) = \log \frac{P\left(u_2^j = 1 \middle| \mathbf{y}\right)}{P\left(u_2^j = 0 \middle| \mathbf{y}\right)} = \log \frac{\sum_{\tilde{\mathbf{u}}_2 \in \mathbf{U}_{2,1}^j} \sum_{\mathbf{v}_1 \in \mathbf{V}_1} \exp\left(- \left\| \mathbf{y} - \sqrt{\rho}\mathbf{h}_{\mathbf{v}_1} \tilde{\mathbf{v}}_2 \right\|_F^2 \Big/ \sigma_n^2 \right)}{\sum_{\tilde{\mathbf{u}}_2 \in \mathbf{U}_{2,0}^j} \sum_{\mathbf{v}_1 \in \mathbf{V}_1} \exp\left(- \left\| \mathbf{y} - \sqrt{\rho}\mathbf{h}_{\mathbf{v}_1} \tilde{\mathbf{v}}_2 \right\|_F^2 \Big/ \sigma_n^2 \right)}, \tag{9}$$

where u_2^j represents the j-th bit from binary representation of transmitted constellation symbol index $\mathbf{v}_2$, with $j = \overline{1, s}$. $\mathbf{V}_1$ and $\mathbf{V}_2$ denote the sets of all possible 2^n transmit antennas indexes and 2^s constellation symbols, respectively. $\mathbf{V}_{1,1}^i$ and $\mathbf{V}_{1,0}^i$ represent subsets from the set of transmit antennas indexes $\mathbf{V}_1$, which have "1" and "0" at the i-th bit; $\mathbf{U}_{2,1}^j$ and $\mathbf{U}_{2,0}^j$ represent subsets from the set of signal constellation symbols $\mathbf{V}_2$, which have "1" and "0" at the j-th bit.

4. **TCSM SYSTEM PERFORMANCES ANALYSIS**

The TCSM scheme presented in Section 2 using the ML-SM detectors in Section 3 were considered for simulations. The BER is estimated as a function of the average SNR per receive antenna using the Monte-Carlo method. For all simulations, we considered four transmit antennas (n_T = 4) and a variable number of receive antennas ($n_R = \overline{1, 4}$). It is assumed that all antennas, both at transmitter and receiver, are equally spaced on a vertical line. The transmitted signal is considered as QPSK (s = 2). The rate 1/2 convolutional encoder from [7], with the generator polynomials written in an octal form as [2, 5], was considered for encoding the transmit antenna index in a TCM manner. In order to implement the TCM principle over the transmit antenna position (or index), antennas one and three form a set and antennas two and four form the other set [7]. Therefore, for a spectral efficiency of 3 b/s/Hz three bits are processed in parallel by the TCSM transmitter, as follows: one bit (k = 1) enters the rate 1/2 TCM encoder, the other two bits select the transmitted signal symbol from the QPSK constellation (s = 2).

The pair of bits from the TCM encoder output select the transmit antenna during the current symbol interval. The three channel models presented in Section 2 are used for simulations. In all simulations with Rician fading, the Rician factor is set to K = 3, and in all simulations with SC channel, the distance between transmit antennas is fixed to 0.1λ, while the distance between receive antennas is 0.5λ [7].

The BER performances as a function of SNR per receive antenna for the TCSM transmission over a static Rayleigh fading channel are depicted in Fig. 2.

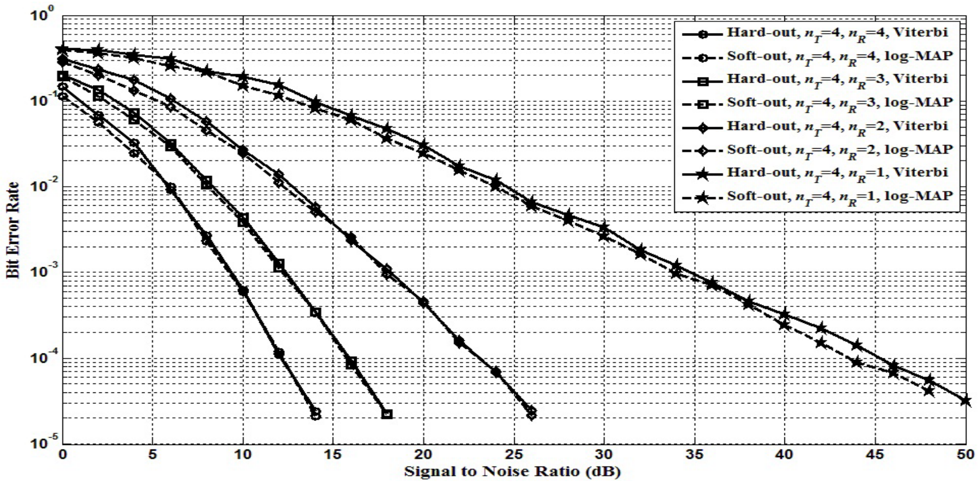

Fig. 2 – BER performances for QPSK-TCSM schemes over Rayleigh fading channel.

This is the case of the ideal channel conditions, because the channel paths are uncorrelated. All three SM detectors presented in Section 3 are considered. It is obvious from Fig. 2 that the BER performances for all combinations of SM detection and sequence decoding techniques overlap. For the sake of intelligibility, we considered in Fig. 2 only one hard-output SM receiver and only soft-output SM receiver, respectively. Hence, no matter what the number of receive antennas is, the BER performances for all three SM detection methods are identical.

In Fig. 3, the BER performances of the TCSM transmission over a static Rician fading channel are presented. As a general note, the soft-output SM detectors outperform the hard-output one. In fact, the coding gain of both soft-output receivers depends on the number of receive antennas, too. Also, for a small number of receive antennas, the joint per bit SM detector performs better than the hybrid SM detector. To be more specific, the coding gain of the joint per bit SM detector over the hard-output detector is of about 4 dB for all n_R values. However, the hybrid SM detector performs the same as the soft-output joint per bit SM detector only for at least four receive antennas. To be more specific, the coding gain of the joint per bit SM detector over the SM detector of antenna index is of about 0.2 dB for $n_R = 3$, 0.5 dB for $n_R = 2$, and 2 dB for $n_R = 1$.

The performances of the TCSM system over a SC fading channel are presented in Fig. 4. These plots show a similar relation between different SM detectors, as in the case of Rician fading channel. Hence, the coding gain of the joint per bit SM detector over the hard-output detector is of about 2 dB for $n_R = 4$, 1.5 dB for $n_R = 3$, 1 dB for $n_R = 2$. For $n_R = 1$ there is no coding gain. The coding gain of the joint per bit SM detector over the hybrid SM detector is of about 0.2 dB for $n_R = 4$, 0.3 dB for $n_R = 3$, 1 dB for $n_R = 2$, and 1.7 dB for $n_R = 1$. Similar to the Rician fading case, the SM detector of antenna index performs the same as the soft-output joint per bit SM detector for at least four receive antennas.

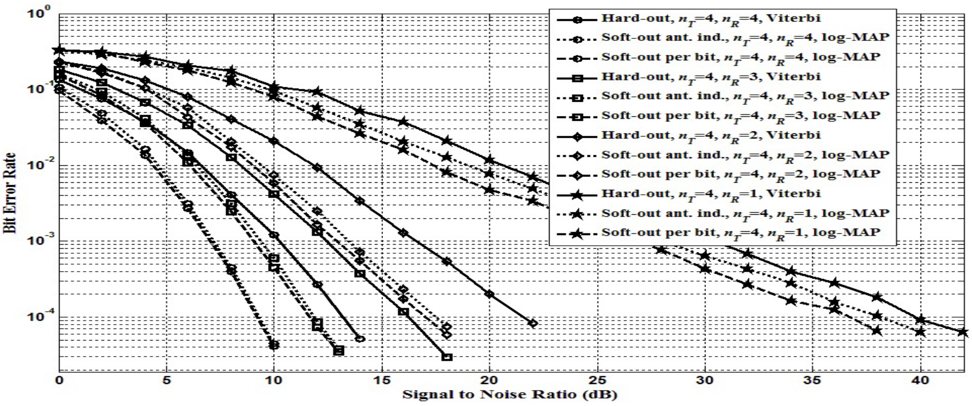

Fig. 3 – BER performances for QPSK-TCSM schemes over Rician fading channel.

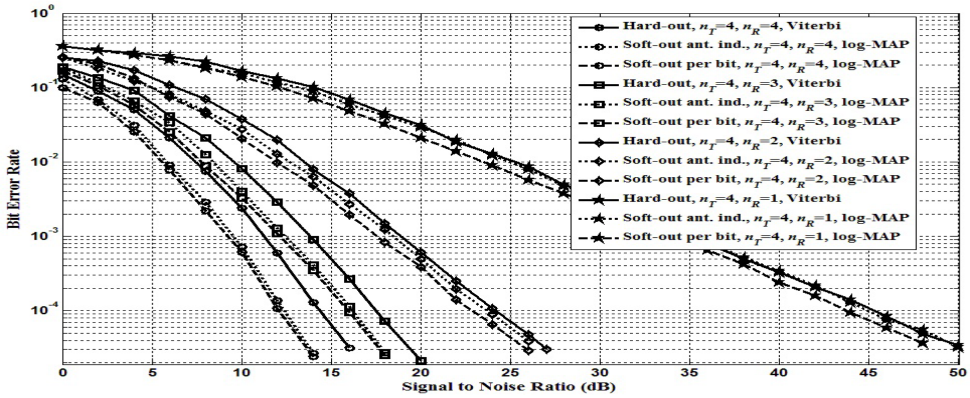

Fig. 4 – BER performances for QPSK-TCSM schemes over SC fading channel.

On the other hand, the soft-output SM detector of antenna index is less complex than the joint per bit SM detector because uses a soft-output estimation only for the antenna index, while the constellation symbol detection is a hard-output operation. The receiver diversity is an important requirement for a high data rate TCSM transmission. For such systems, the hybrid SM detector of antenna index offers a simpler solution, having the same performances as a more complex but fully soft-output detection method.

5. CONCLUSION

A hybrid ML-SM detector was proposed, which determines the soft estimate of transmit antenna index and the hard estimate of the transmitted symbol. The simulations proved that this hybrid detector performs better than the hard-output one and almost as the fully soft-output one. In fact, for high data rate MIMO-TCSM transmissions, *i.e.*, with a large number of receive antennas, the hybrid detector offers the same performances as the soft-output one. Nevertheless, the hybrid detector is less complex than a fully soft-output one. Also, we combined the soft-output detectors (including the hybrid one) with the soft-input hard-output log-MAP sequence decoding instead of the usual hard-input hard-output Viterbi decoding. These operations determined significant coding gains of the soft-output receivers over the hard-output one in Rician and SC fading channels.

In perspective, we intend to extend the performances analysis of the proposed hybrid SM detector used in conjunction with the log-MAP decoding to more complex channel models, as frequency-selective Nakagami fading channel.

ACKNOWLEDGEMENTS

This work was supported by the Romanian contract POSDRU/89/1.5/S/62557 and by the Romanian UEFISCSU PN-2 RU-TE Project no. 18/12.08.2010.

Received on February 5, 2012

REFERENCES

1. R. Mesleh, H. Haas, S. Sinanovic, C.W. Ahn, and S. Yun, *Spatial modulation*, IEEE Trans. Veh. Technol., **57**, *4*, pp. 2228–2241, 2008.
2. M.D. Renzo, H. Haas, and P.M. Grant, *Spatial modulation for multiple-antenna wireless systems: A survey*, IEEE Commun. Mag., **49**, *12*, pp. 182–191, 2011.
3. J. Jeganathan, A. Ghrayeb, L. Szczecinski, and A. Ceron, *Space shift keying modulation for MIMO channels*, IEEE Trans. Wireless Commun., **8**, *7*, pp. 3692–3703, 2009.

4. M.D. Renzo, H. Haas, *Improving the Performance of Space Shift Keying (SSK) Modulation via Opportunistic Power Allocation*, IEEE Commun. Lett., **14**, *6*, pp. 500–502, 2010.
5. G. Ungerboeck, *Channel coding with multilevel/phase signals*, IEEE Trans. on Information Theory, **IT-28**, *1*, pp. 55–67, 1982.
6. R. Mesleh, I. Ştefan, H. Haas, and P.M. Grant, *On the performance of trellis coded spatial modulation*, Int. ITG Workshop on Smart Antennas, Berlin, Germany, Feb. 16–18, 2009.
7. R. Mesleh, M. D. Renzo, H. Haas, and P. M. Grant, *Trellis coded spatial modulation*, IEEE Trans. Wireless Commun., **9**, *7*, pp. 2349–2361, 2010.
8. C. E. Sterian, M. Pätzold, and Y. Wu, *Super orthogonal and super quasi-orthogonal space-frequency trellis coding using OFDM for broadband wireless communications*, Rev. Roum. Sci. Techn. – Électrotechn. et Énerg., **56**, *1*, pp. 89–98, 2011.
9. J. Jeganathan, A. Ghrayeb, and L. Szczecinski, *Spatial modulation: optimal detection and performance analysis*, IEEE Commun. Lett., **12**, *8*, pp. 545–547, 2008.
10. S.U. Hwang, S. Jeon, S. Lee, and J. Seo, *Soft-Output ML Detector for Spatial Modulation OFDM Systems*, IEICE Electronics Express, **6**, *19*, pp. 1426–1231, 2009.
11. A. Forenza, D. Love, and R. Heath Jr., *A low complexity algorithm to simulate the spatial covariance matrix for clustered MIMO channel models*, IEEE Vehicular Technology Conference (VTC 2004-Fall), Los Angeles, CA, USA, May 2004.