Impact of Imperfect Channel Estimation on the Performance of Spatial Modulation MIMO Systems

Reginaldo Nunes, Bruno A. Angélico & Taufik Abrão

Abstract— **This paper aims to analyse the performance of spatial modulation (SM) techniques under imperfect channel state information (iCSI), i.e., errors in the estimation of channel coefficients. The results are compared with the classic spatial multiplexing technique V-BLAST. Furthermore, computational complexity for both SM and V-BLAST are evaluated in terms of complex-values operations under the same spectral efficiency. Simulation results show that SM is more robust to imperfect CSI than V-BLAST while maintaining lower computational complexity for binary modulation order and spectral efficiency $\mathcal{S}$ values of order of tens or smaller. This robustness is remarkable especially under a large number of transmit antennas condition, which is an important feature to be considered in the next Dense-MIMO system applications. In general, it is noted that the performance of both SM with ML detector and V-BLAST are degraded as the channel errors increase. However, spatial modulation is more robust while maintaining a reduced complexity for $\mathcal{S} \leq 13$ bps/Hz. For instance, under a BER of 10^{-4} and a channel percentage error of $\varepsilon_{\%} = 10\%$, the increasing in SNR is about 1.2 dB for SM with $N_t = 16$, while for V-BLAST this SNR degradation is ≈ 3 dB.**

Keywords— **Spatial modulation, MIMO, ML detection, V-BLAST.**

I. Introduction

MIMO systems can be classified into three different groups. In the first one, space-time coding is capable to yield diversity from multiple transmitting antennas, as well to generate temporal redundancy data, allowing reliable decoding at the receiver side. Therefore, this group reaches diversity gain but not multiplexing gain; however it presents clear advantages such as simplicity of implementation with maintenance of the coding rate equal to one (Alamouti space-time block coding scheme) [1]. In the second MIMO group, the channel state information (CSI) knowledge in the transmitter is assumed, which the deployment of the singular value decomposition (SVD) is used to obtain the capacity gain [2]. Finally, in the third group, namely spatial multiplexing, an increasing in data rate is achieved, but not necessarily provide diversity transmission gain; Bell Labs layered space-time scheme (BLAST) is the when-known scheme for this group [3].

Among these three groups, the spatial multiplexing technique becomes an appropriate choice for future implementations due to the increasing demand for high data rates, which can be easily achieved with this technique [4]. However, the spatial multiplexing technique presents serious limitations, such as high interchannel interference (ICI) on the receiver side, error propagation and high complexity in the detection [5].

As an alternative to these background, recently Mesleh *et al.* proposed a low complexity transmission technique equally applicable to MIMO wireless channels, namely spatial modulation (SM) [6]. This is a relatively new scheme which exploits the spatial multiplexing gain for transmission systems with multiple antennas, whose goal is to avoid the above limitations of conventional spatial multiplexing transmission scheme. In SM, a block of information bits is mapped into a point of signal constellation combined to a point of spatial constellation. At each time-symbol instant, only one transmitting antenna of the set is turned on, while the other antennas has no signal-power transmission. This allows the SM scheme entirely avoid ICI, while use only one radio frequency chain and it does not require synchronization between the transmitter antennas.

In SM scheme, the position of each antenna set of antennas is used as an information source, i.e., the index of the active antenna also maps a part of the bits to be transmitted. This feature allows SM to obtain multiplexing gain compared to conventional transmission schemes with a single transmission antenna. Furthermore, despite of a single antenna activation at each instant, the SM scheme also achieves high data throughput. In reception, the maximum ratio combining (MRC) rule can be used to identify the index of transmit antenna, and then the transmitted symbol can be estimated. These two stages are combined at the demodulator in order to recover the block of information bits originally transmitted.

Recently, several schemes for SM signal detection have been proposed. For not very large number of transmit antennas and modulation order, maximum likelihood-based (ML) SM detectors with affordable computational complexity could be obtained. In [7] a SM optimal detection scheme based on ML detector was proposed, which jointly identifies the index of the transmitting antenna and the transmitted symbol. The optimal detection performs better than the previously proposed in [6], with a gain of ≈ 4 dB. It is also shown that spatial modulation with optimal detector achieves a gain in the range of $1.5 \sim 3$ dB over conventional MIMO systems, such as the vertical BLAST (V-BLAST) scheme [8].

A new SM scheme combined to space-time block coding [1], namely STBC-SM, which explores the SM high-spectral gain and also the diversity and code gain of STBC is proposed in [9]. By simulation results the authors show that STBC-

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This work was supported in part by Araucaria Foundation (25/2012), by the National Council for Scientific and Technological Development (CNPq) of Brazil and in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES).

SM provides BER performance gains ranging from 3 to 5 dB (depending on the spectral efficiency) over the schemes SM and V-BLAST, with a linear increasing on decoder complexity.

Recently, a simple spatial modulation scheme in the absence of spatial mapping and/or coding symbol in the transmission namely space shift keying (SSK) was proposed in [10]. Regarding the classical SM, in the simplest SSK transmission scheme the information to be transmitted is mapped only by the antennas, i.e., the transmitted waveform does is not modulated. This feature makes the SSK detection less complex than the SM detection, but the SM multiplexing gain is held [4].

Moreover, when the deployment of antennas is a limiting factor, a variant of the SSK scheme can be used, namely generalized SSK (GSSK) proposed in [11]. In this spatial transmission scheme a combination of multiple transmit antenna indexes is allowed, in contrast to the use of a single-index used in SSK. The gain achieved with SSK remains in GSSK, but at the cost of maintaining synchronism between the transmitted antenna and also requires multiple radio frequency chains. In fact, it is observed that the SSK scheme is a particular case of GSSK, when only one antenna is used at the transmitter side at each symbol period. In this way, very recently Wang *et al.* proposed a transmission scheme namely multiple active-spatial modulation (MA-SM) in which multiple antennas are activated at each instant of transmission [12]. In this scheme the symbols transmitted by multiple transmitting antennas carry information signals from the M-ary constellation, unlike GSSK which multiple antennas transmit the same signal at a given symbol-time without modulation. Thus, MA-SM exploits the inherent properties of SM and also obtains high multiplexing gain of V-BLAST. Performance gains in the range of $2 \sim 5$ dB at bit error rate of 10^{-2} (depending on the spectral efficiency) is attainable over SM and STBC schemes with low-complexity detection scheme based on signal vector space.

Notation: bold lowercase symbols represent vectors and bold uppercase, matrices. Italicized symbols denote scalar values. The notations $(\cdot)^T$, $(\cdot)^H$, $\|\cdot\|$ and $\|\cdot\|_F$ hold for transpose, conjugate transpose, two norm and Frobenius norm of a matrix or vector, respectively. The operator $|\cdot|$ denote absolute value of a scalar. $\mathcal{CN}\left(\mu, \sigma^2\right)$ represents a complex Gaussian distribution of a random variable with mean μ e variance σ^2. $P(\cdot)$ is the probability of an event; $p_{\mathbf{Y}}$ denotes the probability density function (PDF) of a random variable $\mathbf{y}$ and $\mathbb{E}_{\mathrm{x}}[.]$ denotes statistical expectation with respect to x.

II. System Model for SM System

A general diagram for MIMO systems is shown in Fig. 1 [6] with N_r receive and N_t transmit antennas. The channel gain between the τth transmitting antenna and the νth receiving antenna is assigned by $h_{\nu,\tau}$; $\mathbf{b}$ is a vector of n bits transmitted at each symbol-time. The binary vector is mapped into another vector $\mathbf{x} = [0 \ x_\iota \ \cdots \ 0]^T$ of size N_t in which only one element is nonzero. The symbol number ι in the resulting vector $\mathbf{x}$ is x_ι, where ι is the mapped transmit antenna number, $\iota \in [1 : N_t]$.

The symbol x_ι is transmitted by the ιth antenna on the MIMO channel, denoted by $\mathbf{H}$ matrix, which is characterized through a frequency non-selective (flat) Rayleigh channel with independent and identically distributed (i.i.d.) entries according to the complex Gaussian distribution $\mathcal{CN}(0,1)$. The received vector is given by:

$$\mathbf{y} = \mathbf{h}_{(\nu=\iota)} x_\iota + \boldsymbol{\eta} \tag{1}$$

where $\mathbf{h}_\nu$ is the ν-th column of $\mathbf{H}$ and $\boldsymbol{\eta}$ is the additive white Gaussian noise (AWGN) vector $\boldsymbol{\eta} = [\eta_1 \ \eta_2 \ \cdots \ \eta_{N_r}]^T \sim \mathcal{CN}(0, \sigma_n^2)$. The number of bits that can be transmitted using spatial modulation is given by $n = \log_2(N_t) + m = \log_2(MN_t)$, where $m = \log_2(M)$ is the number of bits/symbol for M-QAM modulation. As can be seen, the number of transmitted information bits can be adjusted in two different ways: a) changing the modulation order of transmit signal; b) adjusting the number of symbols associated with each antenna (changing the spatial modulation).

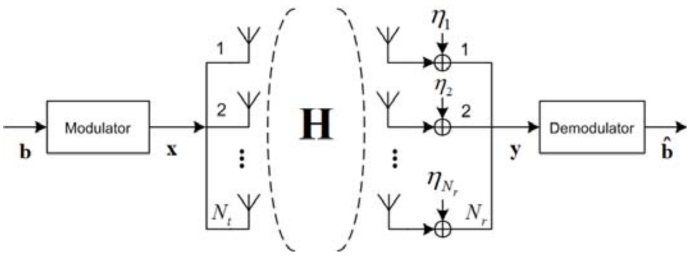

Fig. 1. General MIMO system topology. N_t transmit antennas and N_r receive antennas.

A. Imperfect Channel Estimation

In communication systems with coherent detection the knowledge of channel coefficients at the receiver side is of paramount importance to recover the transmitted information with a high degree of confidence. However, in practical systems, the channel can not be accurately estimated. In order to study the impact of this imperfection on the MIMO system performance, in this subsection appropriate procedures to emulate the channel estimation errors have been described.

In literature there are several methods to estimate channel coefficients, as the technique of minimum mean square error (MMSE) [13], [14], the least squares (LS) [15], among others. In general, the attainable mean square error (MSE) between the estimated and true channel coefficients is higher for MMSE regarding the LS method, but the system performance is also dependent on detector that is used at receiver. In [15] it has been shown that when the detection with optimum diversity combining is deployed, the MIMO system performance under LS channel estimates method is almost the same as obtained with the MMSE technique. In this work, the LS channel estimation technique has been used. Thus, the channel coefficient matrix estimated at the receiver $\mathbf{H}'$ can be expressed as:

$$\mathbf{H}' = \mathbf{H} + \boldsymbol{\varepsilon} \tag{2}$$

where $\mathbf{H}'$ is the estimation for $\mathbf{H}$. The matrices $\mathbf{H}$ and $\boldsymbol{\varepsilon}$ with dimensions $N_r \times N_t$ have i.i.d. circularly symmetric

Gaussian entries with distributions $\mathcal{CN}(0,1)$ and $\mathcal{CN}(0,\sigma_\varepsilon^2)$, respectively; matrix $\boldsymbol{\varepsilon}$ denotes the channel estimation errors. Since the matrix $\boldsymbol{\varepsilon}$ is independent of $\mathbf{H}$, from (2) we have that the statistical distribution for the samples of the matrix $\mathbf{H}'$ is given by $\mathcal{CN}\left[0,(1+\sigma_\varepsilon^2)\right]$. Thus, $\mathbf{H}'$ and $\mathbf{H}$ have joint circularly symmetric Gaussian samples with correlation coefficient $\rho_{\mathbf{h}_\nu,\mathbf{h}'}$, given by [16]:

$$\rho_{\mathbf{h}_\nu,\mathbf{h}'} = \frac{\mathbb{COV}\left[\mathbf{h}_\nu,\mathbf{h}'\right]}{\sqrt{\mathbb{VAR}\left[\mathbf{h}_\nu\right]\mathbb{VAR}\left[\mathbf{h}'\right]}} = \frac{1}{\sqrt{1+\sigma_\varepsilon^2}} \tag{3}$$

Under ideal channel estimation conditions, the error is zero, i.e. $\sigma_\varepsilon^2 = 0$; hence, from (2) and (3) it is obtained that $\mathbf{H}' = \mathbf{H}$ and $\rho_{\mathbf{h}_\nu,\mathbf{h}'} = 1$, respectively.

III. Optimal Detection

Since the entries of channel are equally likely, the optimal detector [7] can be based on the jointly maximum likelihood principle, i.e., in terms of optimization problem, one needs to find the j and q indexes such that:

$$\begin{aligned}[\hat{\imath}_{ML}, \hat{x}_{\imath ML}] &= \arg\max_{j,q} p_{\mathbf{Y}}(\mathbf{y}|\mathbf{x}_{jq},\mathbf{H}) \\ &= \arg\min_{j,q}(\left\|\mathbf{g}_{jq}\right\|_F^2 - 2\mathrm{Re}\{\mathbf{y}^H\mathbf{g}_{jq}\}) \end{aligned} \tag{4}$$

where $\mathbf{g}_{jq} = \mathbf{h}_j x_q$, with $1 \leq j \leq N_t$, $1 \leq q \leq M$, and $p_{\mathbf{Y}}(\mathbf{y}|\mathbf{x}_{jq},\mathbf{H}) = \pi^{-N_r}\exp(-\left\|\mathbf{y}-\mathbf{H}\mathbf{x}_{jq}\right\|_F^2)$ is the probability density function of $\mathbf{y}$, conditioned on $\mathbf{x}_{jq}$ and $\mathbf{H}$. Thus, it can be seen that optimal detection requires a joint detection of the symbol and antenna index.

IV. Numerical Results

This section presents simulation results to evaluate the SM performance loss when there are imperfect channel state information at receiver. These results for SM optimal detection (SM-OD) are compared with the performance of V-BLAST MMSE OSIC under the same spectral efficiency. The Fig. 2.a and 2.b show the SM-OD performance for $N_t = 4$ with 16QAM modulation and $N_t = 16$ with 4QAM, respectively, while the Fig. 2.c shows V-BLAST MMSE OSIC performance with $N_t = 3$ and 4QAM. In all system configurations analysed in this subsection, four receive antennas, uncorrelated Rayleigh channel and spectral efficiency $\mathcal{S} = 6$ [bps/Hz] have been used. Moreover, the estimation errors have been fixed for the entire SNR range; it was assumed channel coefficient errors with Gaussian distribution for both amplitudes and phases. These errors are the same for all three system configurations and were generated according to $\sigma_\varepsilon^2 \in [0.0025\ \ 0.01\ \ 0.0225\ \ 0.04]$, i.e., percentage errors of $\varepsilon_\% \in [5\ \ 10\ \ 15\ \ 20]\,\%$, respectively. In general, it is noted that the performances of both SM-OD and V-BLAST are degraded as the error increase. However, spatial modulation is more robust to errors on channel estimates while maintaining a reduced complexity for this spectral efficiency value. For example, the increase in SNR for the bit error rate of BER$=10^{-4}$ and error percentage of $\varepsilon_\% = 10\%$ is 2 [dB] for SM with $N_t = 4$, and 1.2 [dB] for SM with $N_t = 16$, while for V-BLAST this SNR degradation is ≈ 3 [dB]. Thus, it can be seen that the best performance (reduced degradation) is achieved by the SM-OD system with higher number of transmit antennas, i.e., $N_t = 16$.

V. Computational Complexity

This section provides a comprehensive analysis of complexity for spatial modulation and V-BLAST. The computational complexity analysis is of paramount importance in determining the deployment feasibility for these schemes, as well as allows one to establish a fair comparison among different spatial modulation schemes, mainly with regard to the complexity $\times$ performance tradeoff. In this paper the computational complexity analysis is similar to the analysis performed in [6] and [17], where multiplications and sums of complex numbers are considered as operations in the detection process.

A. SM Complexity

The complexity of optimal SM detector (SM–OD) is obtained by analyzing the ML detection metric given by eq. (4). The first term can be simplified [7] as $\left\|\mathbf{h}_j x_q\right\|_F^2 = \left\|\mathbf{h}_j\right\|_F^2 |x_q|^2$. The squared operation from the Frobenius norm $\left\|\mathbf{h}_j\right\|_F^2$ requires N_r complex multiplications and needs to be evaluated for all N_t transmit antennas, thereby obtaining $N_r N_t$ complex operations. Similarly to the procedure adopted for the sub-optimal detector, the squared operation of the module $|x_q|^2$ requires one complex multiplication. As this operation is evaluated for each $q \in [1:M]$, M complex multiplications are obtained. Note that the complexity of the multiplication in $\left\|\mathbf{h}_j x_q\right\|_F^2 = \left\|\mathbf{h}_j\right\|_F^2 |x_q|^2$ is not considered, because it involves only real values and does not add to the overall complexity. Thus, the attained complexity to the first term is given by $N_r N_t + M$.

The complexity of the second term in eq. (4) is dependent on the computation of $\mathbf{y}^H\mathbf{h}_j x_q$ [17]. The calculation of $\mathbf{y}^H\mathbf{h}_j$ requires N_r complex multiplications and $N_r - 1$ complex additions. Evaluating this operation over $j \in [1:N_t]$ results in $N_t(2N_r - 1)$ complex operations. Since $\mathbf{y}^H\mathbf{h}_j$ has been previously calculated, its multiplication by x_q further requires only one complex multiplication. This operation is evaluated M times for each $j \in [1:N_t]$, resulting in $N_t M$ complex operations. Therefore, the second term calculation requires $2N_r N_t + N_t M - N_t$ complex operations. Adding these complexities of the two terms, the total complexity of the optimal SM detector is given as:

$$\delta_{\text{SM-OD}} = 3N_r N_t + N_t M - N_t + M \tag{5}$$

B. V-BLAST Complexity

As reference comparison purpose, the computational complexity of minimum mean squared error (MMSE) V-BLAST receiver was obtained from [18]. The MMSE criterion requires two matrix multiplications, one inversion and one addition [19]. The first multiplication requires $N_t^2 N_r$ complex multiplications and $N_t^2(N_r - 1)$ complex additions. In turn, the matrix addition requires N_t^2 complex additions. The matrix inversion is performed using elimination method of Gauss. In [20],

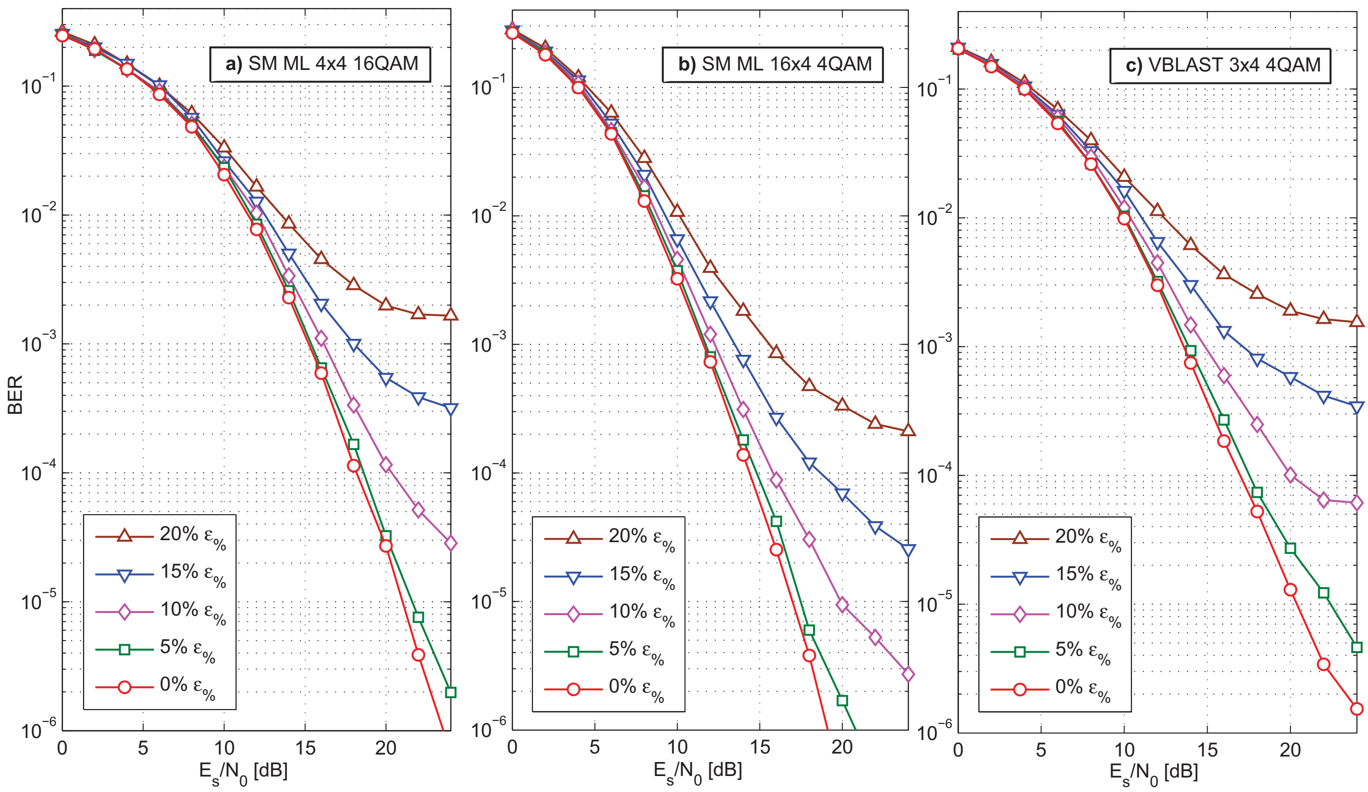

Fig. 2. BER performance for SM-OD and V-BLAST MMSE OSIC with imperfect CSI at receiver; $\mathcal{S} = 6$ [bps/Hz], $N_r = 4$ e $\varepsilon_{\%} \in [5 \;\; 10 \;\; 15 \;\; 20]\,\%$. a) SM: $N_t = 4$, $M = 16$. b) SM: $N_t = 16$, $M = 4$. c) V-BLAST: $N_t = 3$, $M = 4$.

the cost for this method is $2n^3/3$ flops[1] for matrices which contain real numbers. For the computational complexity analysis, where only complex numbers operations are considered, it is assumed that one complex multiplication and addition corresponds to the six and two flops, respectively. Thus, for the worst case, the matrix inversion requires $4N_t^3$ complex operations. The second matrix multiplication requires N_t^3 complex multiplications and $N_t^2(N_t - 1)$ complex additions. Hence, $(6N_t^3 + 2N_r N_t^2 - N_t^2)$ complex operations are needed for MMSE criterion. Since V-BLAST performs this operations for each $j \in [1 : N_t]$, the total number of complex operations at the receiver side is given by:

$$\delta_{\text{V-BLAST}} = \sum_{j=1}^{N_t} \left(6j^3 + 2N_r j^2 - j^2\right) \tag{6}$$

Table I concatenates those complexities for SM and V-BLAST in terms of complex-values operations (sums and multiplications).

TABLE I

NUMBER OF COMPLEX-VALUES OPERATIONS FOR SM AND V-BLAST.

Scheme	Sum and Multiplication
SM-OD	$3N_r N_t + N_t M - N_t + M$
V-BLAST	$\sum_{j=1}^{N_t} \left(6j^3 + 2N_r j^2 - j^2\right)$

[1]floating point operation (flop) is defined as one addition, subtraction, multiplication or division of two real floating-point numbers.

C. *Complexities under Equal Transmission Rate*

In order to achieve the same transmitted information rate the SM and V-BLAST should deploy different number of transmit antennas; thus, the associated complexities of these spatial diversity schemes are analysed parameterised in the spectral efficiency $\mathcal{S}$. Fig. 3 depicts the complex-values complexity in terms of equivalent number of multiplications and sums as a function of spectral efficiency ranging from $\mathcal{S} = 3$ [bps/Hz] to $\mathcal{S} = 15$ [bps/Hz], considering BPSK and 8-QAM modulation formats.

The first notable observation from Fig. 3 is that SM complexity is lower than the complexity of V-BLAST for $\mathcal{S} < 13$ [bps/Hz] when BPSK modulation is used. On the other hand, when the modulation is 8QAM, the VBLAST complexity is always lower than the spatial modulation, since with the increasing of modulation order a lower number of transmit antennas is required for V-BLAST, which spectral efficiency is $N_t \log_2 M/BW$ [bps/Hz], where BW is the bandwidth. As one can see from Fig. 3, allowable spectral efficiency for 8QAM V-BLAST are in range $\mathcal{S} \geq 6$ [bps/Hz], while for SM scheme there in no constraint on this regarding, once the spectral efficiency can be adjusted either by changing the modulation order (M) of signal constellation (at the cost of power transmission increase) or by changing the number of transmit antennas. For the system configurations adopted in Fig. 3, BPSK and 8QAM modulation formats have been used. Hence, for SM with BPSK modulation, a large number of transmitting antennas is required in order to achieve high

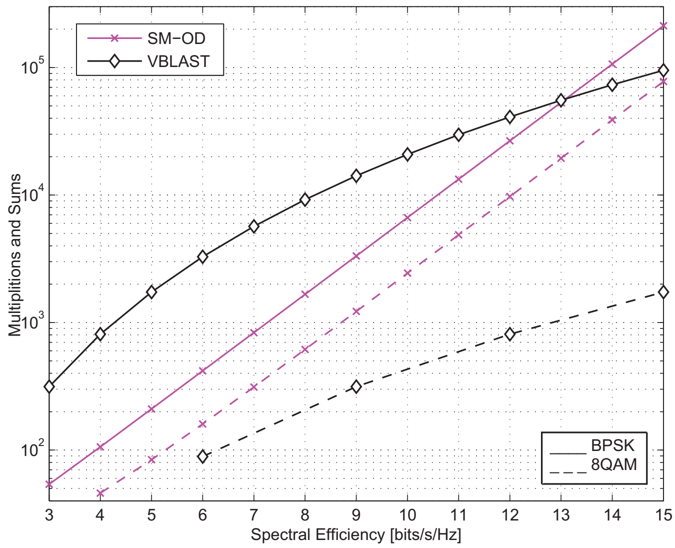

Fig. 3. Equivalent complex-valued number of operations for SM-OD and V-BLAST MMSE under same spectral efficiency.

spectral efficiency. By changing the modulation order to 8-QAM, the same spectral efficiency is reached with 25% of the total transmit antennas used in the system with BPSK modulation, thereby reducing computational complexity at cost of some increase in transmit power need to achieve the same performance achieved with BPSK modulation.

VI. Conclusions

In this work, performance-complexity trade-off of SM-OD and V-BLAST were analysed under imperfect channel coefficient estimations for a wide range of equal spectral efficiencies. It was observed that SM is more robust to channel errors than V-BLAST while maintaining lower computational complexity for spectral efficiency $\mathcal{S}$ values of order of tens or smaller. This robustness is noted especially when a large number of transmit antennas is deployed, which is an important characteristic to be considered in the future Dense-MIMO applications, i.e., when a large number of transmit antennas is available.

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