On the Effect of Gaussian Imperfect Channel Estimations on the Performance of Space Modulation Techniques

Raed Mesleh* and Salama S. Ikki‡

*University of Tabuk, Electrical Engineering Department and Sensor Networks and Cellular Systems (SNCS) research Center, P.O.Box: 6592-2, 47315/4031 Tabuk, Saudi Arabia, Email: rmesleh.sncs@ut.edu.sa

‡INRS, Montreal, Canada and a collaborate researcher at SNCS research center, Email: sikki.sncs@ut.edu.sa

***Abstract*—Space modulation techniques, such as spatial modulation (SM) and space shift keying (SSK), are efficient low-complexity implementation of multiple input multiple output (MIMO) systems. In such techniques, a single transmit-antenna is activated during each time instant and the activated antenna index is used to convey information. Due to the novel method of conveying information, a major criticism arises on the practicality of such techniques in the presence of real-time imperfections such as channel estimation errors. Therefore, the aim of this paper is to shed light on this issue. The performance of such systems are analyzed in the presence of Gaussian imperfect channel estimations. More specifically, the performance of SSK system consisting of N_t transmit and N_r receive antennas with maximum-likelihood (ML) detection and imperfect channel state information (CSI) at the receiver is studied. The exact average bit error probability (ABEP) over Rayleigh fading channels is obtained in closed-form for $N_t = 2$ and arbitrary N_r; while union upper bound is used to compute the ABEP when $N_t > 2$ and arbitrary N_r. Furthermore, simple and general asymptotic expression for the ABEP is derived and analyzed. Besides, the effect of imperfect CSI on the performance of SM, Alamouti and SSK schemes considering different number of channel estimation pilots are studied and compared via numerical Monte Carlo simulations. It is shown that, on the contrary to the raised criticism, space modulation techniques are more robust to channel estimation errors than Alamouti since the probability of error is determined by the differences between channels associated with the different transmit antennas rather than the actual channel realization.**

***Index Terms*—SSK, SM, channel estimation errors, MIMO.**

I. Introduction

Multiple-input multiple-output (MIMO) technique is one of the most important contributions to the progress in wireless communications in recent years. As such, it has been considered in many recent standards such as, 3rd Generation Partnership Project (3GPP) [1], Wireless World Initiative New Radio (WINNER) [2], and Long Term Evolution (LTE) [3]. The aim of MIMO techniques is to improve power efficiency by maximizing spatial diversity (as in space-time coding (STC)) [4, 5], or to boost the data rate by transmitting independent streams from each transmit antenna (as in V-BLAST (vertical Bell Labs layered space-time)) [6], or to achieve both of them at the same time at the expense of increasing complexity [7].

SSK is a MIMO technique which activates a single transmit-antenna during each time instant and uses the activated antenna index to implicitly convey information [8]. The fundamental idea of SSK is originally proposed in [9], which was further developed into spatial modulation in [10, 11]. Activating single transmit-antenna at a time eliminates inter-channel interference, relaxes inter-antenna synchronization requirements, reduces receiver complexity, and allows the use of a single RF chain at the transmitter. In addition, SSK is shown to enhance error performance with moderate number of transmit antennas as compared to other conventional MIMO techniques such as STC and V-BLAST. Hence, it has been investigated widely by several researchers and variant schemes based on its concept have been proposed [12–14, and references therein]. However, a common assumption in the earlier literature is the availability of perfect channel state information (CSI) at the receiver, and a major criticism arises on the practicality of SSK system in the presence of real-time imperfections such as channel estimation errors. A recent study in [15] revealed that space modulation techniques are more robust to channel estimation errors as compared to V-BLAST and require less training symbols. However, the comparisons in [15] are studied only through Monte Carlo simulations, which does not give too much insights for performance analysis and system optimization.

In this paper, the ABEP for an SSK system in the presence of imperfect CSI is computed in closed-form without resorting to Monte Carlo numerical simulations, which besides being computationally intensive, only yield limited insights about the system performance and cannot be exploited for a systematic optimization of it. Also, a simple and accurate asymptotic high signal to noise ratio (SNR) expression is obtained, which has not been considered before even for perfect estimation. The performance of SSK, Alamouti, and SM techniques are compared in the presence of imperfect CSI and for different system configurations and different number of channel estimation pilots. It is shown that space modulation techniques are more robust to channel estimation errors as compared to Alamouti scheme and require less training symbols. This behavior is well explained from the derived conditional error probability where it will be shown that the probability of error is determined by the differences between channels associated with the different transmit antennas rather than the actual channel realization.

The remainder of this paper is organized as follows: SSK system and channel models are presented in Section II. In Section III, analysis of SSK with imperfect CSI is conducted and analytical and simulation results are compared. In Section IV,

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SSK, Alamouti, and SM simulation results are compared and Section V concludes the paper.

Notations: Italicized symbols denote scalar values while bold lower/upper case symbols denote vectors/matrices. We use $(.)^T$ for transpose, $(.)^H$ for conjugate transpose, $\binom{\cdot}{\cdot}$ for the binomial coefficient and $||.||_F$ for the Frobenius norm of a vector/matrix. We use $\Pr(.)$ for the probability of an event and $\Re\{.\}$ for the real part of a complex variable.

II. System and Channel Models

A. SSK Modulation

Let us consider a generic $N_t \times N_r$ MIMO system, with N_t and N_r being the number of transmit and receive antennas, respectively. In SSK modulation, the transmitter encodes blocks of $\log_2(N_t)$ data bits into the index of a single transmit-antenna, which is switched on for data transmission while all other antennas are kept silent. Therefore, the number of transmit antennas must be a power of 2. However, there are different schemes reported in literature that apply SSK for any number of transmit antennas [16, 17]. The receiver solves a N_t-hypothesis detection problem to estimate the active transmit-antenna, which results in the estimation of the unique sequence of bits emitted by the encoder. The N_t signals are assumed to be emitted with equal probability.

The signal is transmitted over an $N_r \times N_t$ wireless channel $\mathbf{H}$, and experiences an N_r-dim additive white Gaussian (AWGN) noise, $\mathbf{n}$. $\mathbf{H}$ is a complex channel matrix with $N_r \times N_t$ dimension. Its element $h_{m,n}$ denotes the complex channel path gain between the n^{th} transmit antenna and m^{th} receive antenna. The channel entries are assumed to be i.i.d. complex Gaussian random variables with zero mean and variance σ_h^2. The $\mathbf{n} = [n_1, n_2, \cdots, n_{N_r}]^T$ is the complex Gaussian noise vector with zero mean and variance N_0 (both real and imaginary parts having a double-sided power spectral density equal to $N_0/2$). Since only one transmit antenna is active, the output of the channel is given by

$$\mathbf{y} = \sqrt{E}\mathbf{h}_j + \mathbf{n}, \tag{1}$$

where $\mathbf{h}_j$ is the j^{th} column of $\mathbf{H}$, i.e., $\mathbf{h}_j = [h_{1,j}, \cdots, h_{N_r,j}]^T$ and E denotes the transmitted energy.

B. SSK Detection

Let the estimate of the $h_{i,j}$ channel be $\widetilde{h}_{i,j}$. We assume that $h_{i,j}$ and $\widetilde{h}_{i,j}$ are jointly ergodic and stationary Gaussian processes. Further, assuming orthogonality between the channel estimate and the estimation error, we have

$$h_{i,j} = \widetilde{h}_{i,j} + e_{h_{i,j}}, \tag{2}$$

where $e_{h_{i,j}}$ is the channel-estimation error, which is complex Gaussian with zero mean and variance σ_e^2. Note that σ_e^2 is a parameter that captures the quality of the channel estimation and can be appropriately chosen depending on the channel dynamics and estimation schemes. Assuming orthogonal pilot channel estimation sequences, the estimation error reduces linearly with increasing the number of pilots.

The detector's main function is to determine the active transmit antenna index. In particular, a detector estimates the complex channel gains as in (2) and uses the result in the same metric that would be applied if the channel were perfectly known. Given that the channel inputs are assumed equally likely, the optimal detector is a maximum likelihood (ML), which is given by

$$u = \arg \max_{n=1,2,\cdots,N_t} \{D_n\}, \tag{3}$$

where D_n is the decision metric defined in what follows

$$\begin{aligned} D_n &= \Re\left\{\mathbf{y}^H \times \sqrt{E}\widetilde{\mathbf{h}}_n\right\} - \frac{1}{2}\sqrt{E}\widetilde{\mathbf{h}}_n^H \times \sqrt{E}\widetilde{\mathbf{h}}_n \\ &= \Re\left\{\mathbf{y}^H \times \sqrt{E}\widetilde{\mathbf{h}}_n\right\} - \frac{1}{2}E||\widetilde{\mathbf{h}}_n||_F^2, \end{aligned} \tag{4}$$

where $\widetilde{\mathbf{h}}_n = [\widetilde{h}_{1,n}, \cdots, \widetilde{h}_{N_r,n}]^T$. From (2), we can write $\mathbf{h}_n = \widetilde{\mathbf{h}}_n + \mathbf{e}_n$. In particular, (4) states that, if the transmitted message is j, the detector will be successful in detecting it, i.e., $u = D_j$ if and only if arg $\max_{n=1,\cdots,N_t}\{D_n\} = D_j$.

From (1), the decision metrics in (4) conditioned upon activating the j^{th} transmit antenna, i.e., $D_{n|j}$, can be written as

$$\begin{aligned} D_n|_{n=j} &= \Re\left\{\left(\sqrt{E}\mathbf{h}_j + \mathbf{n}\right)^H \times \sqrt{E}\widetilde{\mathbf{h}}_j\right\} - \frac{1}{2}E||\widetilde{\mathbf{h}}_j||_F^2 \\ &= \Re\left\{\left(\sqrt{E}(\widetilde{\mathbf{h}}_j + \mathbf{e}_j) + \mathbf{n}\right)^H \times \sqrt{E}\widetilde{\mathbf{h}}_j\right\} - \frac{E}{2}||\widetilde{\mathbf{h}}_j||_F^2 \\ &= \frac{E}{2}||\widetilde{\mathbf{h}}_j||_F^2 + E\Re\left\{\mathbf{e}_j^H\widetilde{\mathbf{h}}_j\right\} + \sqrt{E}\Re\left\{\mathbf{n}^H\widetilde{\mathbf{h}}_j\right\}, \end{aligned} \tag{5}$$

and

$$\begin{aligned} D_n|_{n\neq j} &= \Re\left\{\left(\sqrt{E}\mathbf{h}_j + \mathbf{n}\right)^H \times \sqrt{E}\widetilde{\mathbf{h}}_n\right\} - \frac{1}{2}E||\widetilde{\mathbf{h}}_n||_F^2 \\ &= E\Re\left\{\widetilde{\mathbf{h}}_j^H\widetilde{\mathbf{h}}_n\right\} + E\Re\left\{\mathbf{e}_j^H\widetilde{\mathbf{h}}_n\right\} + \sqrt{E}\Re\left\{\mathbf{n}^H\widetilde{\mathbf{h}}_n\right\} \\ &\quad - \frac{1}{2}E||\widetilde{\mathbf{h}}_n||_F^2. \end{aligned} \tag{6}$$

III. ABEP over Rayleigh Fading Channels

A. The $2 \times N_r$ MIMO Case

1) Conditional Error Probability: Let us consider $N_t = 2$. From the decision rule in (3), the probability of wrong detecting the index of the active transmit-antenna, $P_b(.,.)$, when conditioning upon the channel impulse responses $\widetilde{\mathbf{h}}_1 = [\widetilde{h}_{1,1}, \widetilde{h}_{2,1}, \cdots, \widetilde{h}_{N_r,1}]^T$ and $\widetilde{\mathbf{h}}_2 = [\widetilde{h}_{1,2}, \widetilde{h}_{2,2}, \cdots, \widetilde{h}_{N_r,2}]^T$ can be explicitly written as

$$P_b(\widetilde{\mathbf{h}}_1, \widetilde{\mathbf{h}}_2) = \frac{1}{2}\Pr\left(D_1|_1 < D_2|_1\right) + \frac{1}{2}\Pr\left(D_2|_2 < D_1|_2\right). \tag{7}$$

After a few algebraic manipulations, $P_b(.,.)$ in (7) can be expressed as

$$P_b(\widetilde{\mathbf{h}}_1, \widetilde{\mathbf{h}}_2) = Q\left(\sqrt{\frac{E\sum_{i=1}^{N_r}|\widetilde{h}_{i,1} - \widetilde{h}_{i,2}|^2}{2\left(E\sigma_e^2 + N_0\right)}}\right) = Q\left(\sqrt{\lambda}\right), \tag{8}$$

where $Q(.)$ is the Q-function defined as $Q(x) = \int_x^\infty (\exp(-x^2/2)/2\pi)dx$ and $\lambda = \frac{E\sum_{i=1}^{N_r}|\widetilde{h}_{i,1}-\widetilde{h}_{i,2}|^2}{2(E\sigma_e^2+N_0)}$. It can be easily seen from (2) that $\widetilde{h}_{i,1}$ and $\widetilde{h}_{i,2}$ are complex Gaussian random variables with zero mean and variance $\sigma_{\widetilde{h}}^2 = \sigma_h^2 - \sigma_e^2$. We can see from (8) that the conditional probability depends on the difference (Euclidean distance) between the estimated complex gains, $\widetilde{h}_{i,1}$ and $\widetilde{h}_{i,2}$ and from (2) this difference (Euclidean distance) decreases as the estimation error increases. Furthermore, the denominator in the Q-function increases as the accuracy of the estimation decreases resulting in a degradation in the system performance.

A significant notice from (8) is that the probability of error is not determined by the actual channel realization, rather by the differences between channels associated with the different transmit antennas. Thereby, it is anticipated that SSK technique is more robust to channel estimation errors as compared to other MIMO techniques. This will be shown later in Section IV.

2) Average Error Probability: The average error probability can be written as

$$\bar{P}_b = \int_0^\infty Q\left(\sqrt{\upsilon}\right) f_\lambda(\upsilon) d\upsilon, \tag{9}$$

where $f_\lambda(\upsilon)$ is the probability density function (PDF) of λ. The PDF of λ with the help of [18, pp. 41] can be written as

$$f_\lambda(\upsilon) = \frac{1}{(N_r-1)!}\frac{1}{a^{N_r}}\upsilon^{N_r-1}\exp\left(-\frac{\upsilon}{a}\right), \tag{10}$$

where $a = \frac{E\sigma_{\widetilde{h}}^2}{E\sigma_e^2+N_0}$. By substituting (10) into (9) and solve the integration, the exact ABEP can be written as

$$\bar{P}_b = \gamma_a^{N_r}\sum_{k=0}^{N_r-1}\binom{N_r-1+k}{k}[1-\gamma_a]^k, \tag{11}$$

where $\gamma_a = \frac{1}{2}\left[1-\sqrt{\frac{a}{2+a}}\right]$.

3) Diversity Gain: In order to clearly show the system diversity, we re-derive the error probability as follows. According to [19], the asymptotic error probability can be derived based on the behavior of the PDF of λ around the origin. By using Taylor's series, $f_\lambda(\upsilon)$ given in (10) can be rewritten as

$$f_\lambda(\upsilon) \approx \frac{1}{(N_r-1)!}\frac{1}{a^{N_r}}\upsilon^{N_r-1} + \text{H.O.T}, \tag{12}$$

where H.O.T. stands for higher order terms. Therefore, the error probability can be written as [18]

$$\begin{aligned}\bar{P}_b &\approx \int_0^\infty Q\left(\sqrt{\upsilon}\right)\frac{1}{(N_r-1)!}\frac{1}{a}\upsilon^{N_r-1}d\upsilon \\ &\approx \frac{2^{N_r-1}\Gamma(N_r+0.5)}{\left(\sigma_{\widetilde{h}}^2\right)^{N_r}\sqrt{\pi}N_r!}\left(\frac{E/N_0}{(E/N_0)\sigma_e^2+1}\right)^{-N_r} \\ &= C(N_r)\left(\frac{E/N_0}{(E/N_0)\sigma_e^2+1}\right)^{-N_r},\end{aligned} \tag{13}$$

with $C(N_r) = \frac{2^{N_r-1}\Gamma(N_r+0.5)\left(\sigma_{\widetilde{h}}^2\right)^{-N_r}}{\sqrt{\pi}N_r!}$ being a constant depends on the number of receive antennas, N_r. Two interesting results can be seen from (13). First, in the case of perfect channel estimations, i.e., $\sigma_e^2 = 0$, a diversity order of N_r can be obtained which equals the number of receive-antennas at the receiver. Second, error floors could happen if the estimation error is independent of E/N_0. However, if the Gaussian estimation errors decrease as E/N_0 increases, then (13) can be approximated (by neglecting the 1st term) as $\bar{P}_b \approx C(N_r)(E/2N_0)^{-N_r}$ and a diversity gain of N_r is obtained.

B. The $N_t \times N_r$ MIMO Case

Previously, we have provided exact closed-form expressions for the average error probability when the source is equipped with two transmit-antennas. In this section, the frameworks are generalized to account for a higher number of transmit antennas. The ABEP is derived using the well known union bounding technique [18, pp. 261-262]. The ABEP for the system under consideration is union bounded as

$$\bar{P}_b \le \sum_{m=1}^{N_t}\sum_{\hat{m}=m+1}^{N_t}\frac{2N(m,\hat{m})}{N_t}\text{PEP}\left(TX_m \to TX_{\hat{m}}\right), \tag{14}$$

where $N(m,\hat{m})$ is the number of bits in error between TX_m and $TX_{\hat{m}}$, $\text{PEP}\left(TX_m \to TX_{\hat{m}}\right)$ denotes the pairwise error probability (PEP) of deciding on $TX_{\hat{m}}$ given that TX_m is transmitted, and the index in the summation is simplified since $N(m,\hat{m})$ is symmetric.

In particular, $\text{PEP}\left(TX_m \to TX_{\hat{m}}\right)$ is the ABEP of an equivalent $N_t = 2$ system where only the transmit-antennas TX_m and $TX_{\hat{m}}$ can be activated for transmission. In other words, $\text{PEP}\left(TX_m \to TX_{\hat{m}}\right)$ in (14) is the ABEP computed in the previous Section when $N_t = 2$.

C. Analytical results validation

In Fig. 1, the exact error probability (obtained through simulations) is plotted along with the analytical expression given in (11) and the asymptotical expression obtained in (13) considering $\sigma_e^2 = 0.01$ and different number of receive antennas. As observed, the derived analytical expression is in good agreement with the exact results. Furthermore, the asymptotical expression for the error probability provides an excellent match in the moderate-to-high SNR range ($\geq$10 dB).

Observe that the channel uncertainties (imperfect channel estimations) result in a degradation of the diversity order (the negative slope of the plots). Error floors can be clearly seen when the estimation errors' variances are non-zero. Furthermore, in the low and medium range of SNR, increasing SNR improves the error probability since the dominant noise in this range is the AWGN. On the other hand, in the high SNR regime, error floors appear due to channel estimation error which is independent of the SNR.

When decreasing the variance of the Gaussian estimation errors as the SNR of the data symbols increases (the pilot symbols have the same energy as the data symbols), i.e., $\sigma_e^2 = (E/N_0)^{-1}$, we observe no error floor phenomenon as illustrated in Fig. 2. However, channel uncertainties result in a degradation in the error performance since the gap between

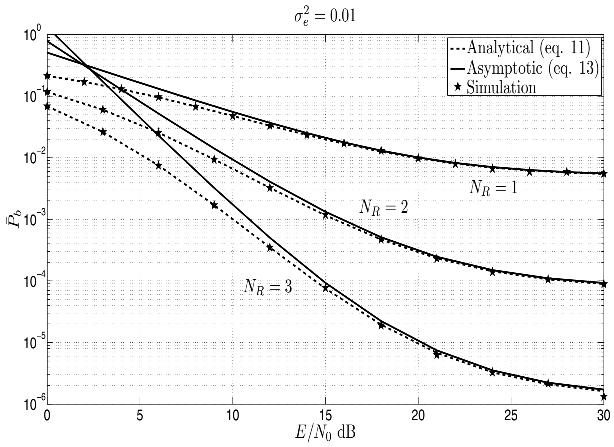

Fig. 1. Average error probability with two transmit antennas and different number of receive antennas with fixed estimation variance.

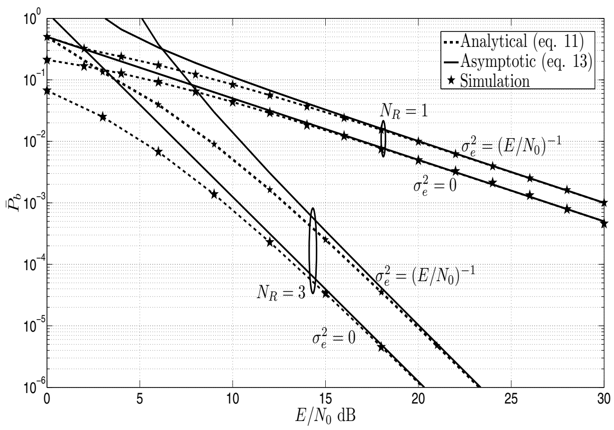

Fig. 2. Average error probability with two transmit antennas and different number of receive antennas with perfect estimations and variable estimation variance.

the results pertaining to the imperfect estimations and the ones for the ideal estimation increases as the number of receive antennas increase.

IV. Simulation results

In the following, the performance of SSK, SM [10], and Alamouti [4] schemes are simulated via Monte Carlo simulation and compared in the presence of imperfect CSI at the receiver. At least 10^6 channel realizations are simulated for each E/N_0 value. The channel is assumed to be static for each frame and a frame length of 100 symbols is considered. Orthogonal Hadamard pilot symbols are inserted at the beginning of each frame for channel estimation purposes. The pilot sequences, each of length N_h symbols, are transmitted simultaneously from the multiple transmit antennas, and the variance of the Gaussian estimation error decreases as the number of transmitted pilots increases, $\breve{\sigma}_e^2 = \sigma_e^2/N_h$.

The ABEP versus E/N_0 for 2×2 SSK scheme assuming one, four, and eight pilots are depicted in Fig. 3. A degradation

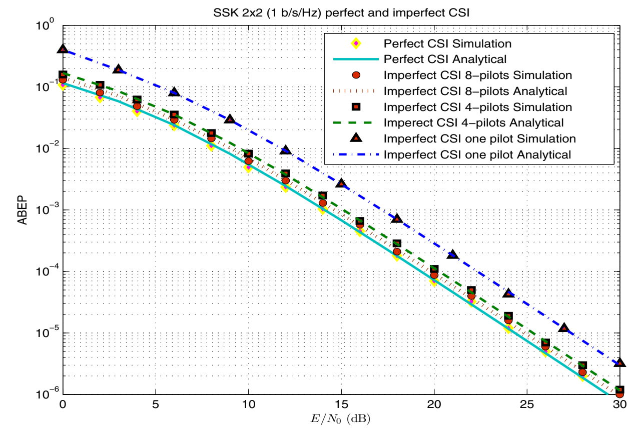

Fig. 3. Analytical and simulation average error probability for SSK system with two transmit and receive antennas and different numbers of channel estimation pilots.

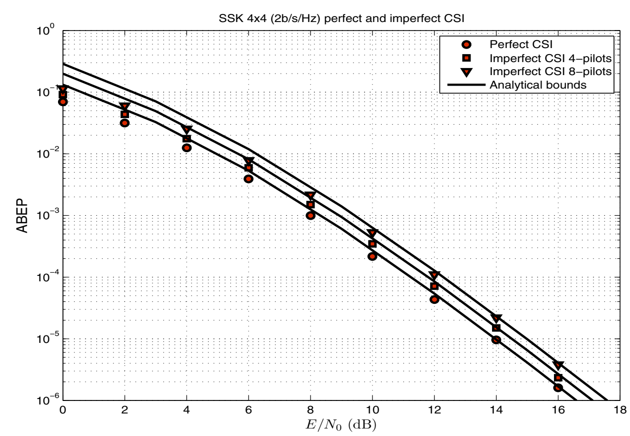

Fig. 4. Analytical and simulation average error probability for SSK system with four transmit and four receive antennas and four and eight channel estimation pilots.

of about 3 dB in E/N_0 for certain ABEP is noticed when using a single pilot as compared to the case of perfect CSI. However, increasing the number of pilots enhances the performance and reduces the estimation error where a very close performance to the case of perfect CSI is achieved with four and eight pilots as shown in the figure. Analytical results are also depicted in Fig. 3 and an exact matching with the simulation results is noticed here as well.

Analytical and simulation ABEP results for 4×4 SSK system are depicted in Fig. 4 where the upper bound in (14) is used to compute the analytical results and four and eight pilots are considered. The union bound is shown to be tight for pragmatic SNR values and achieves almost similar performance to simulation results.

Results for Alamouti scheme are shown in Fig. 5 assuming 2×2 and 2×4 MIMO configurations and BPSK modulation. Performance degradation due to imperfect channel knowledge at the receiver is more significant as compared to previous SSK

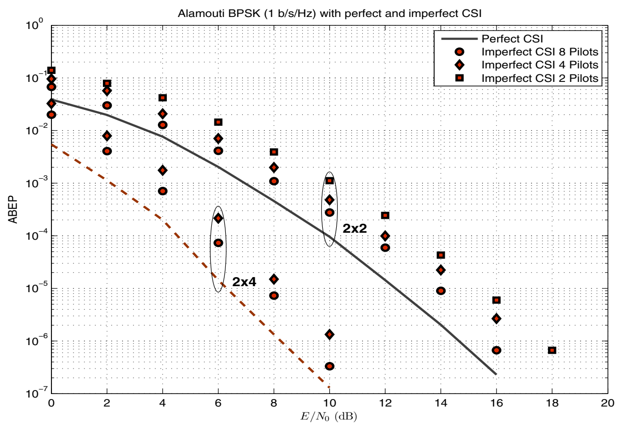

Fig. 5. Average error probability with two transmit antennas and different number of receive antennas with perfect and imperfect channel estimations for BPSK Alamouti scheme.

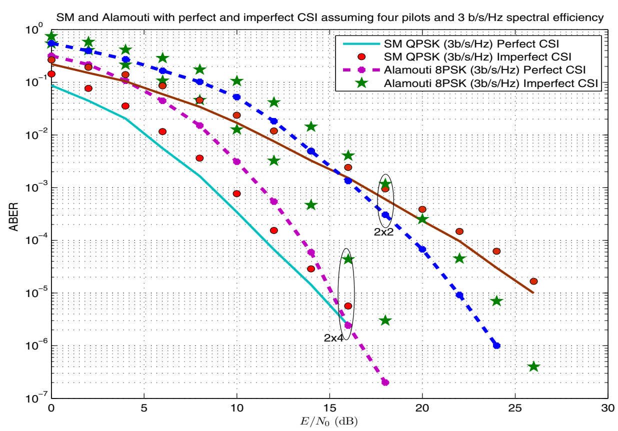

Fig. 6. Alamouti and SM performance comparison with perfect and imperfect channel estimations. A spectral efficiency of 3 b/s/Hz and four channel estimation pilots are assumed.

results. For instance, 1 dB degradation can be noticed for 8 pilots and about 2 dB for four pilots; while 2 pilots degrades the performance by about 3 dB.

In the last comparison shown in Fig. 6, the ABEP for SM with QPSK modulation and Alamouti scheme with 8-PSK modulation assuming 2×2 and 2×4 MIMO configurations are shown. Again, SM is shown to be more robust to channel estimation errors as compared to Alamouti. For instance, imperfect channel knowledge degrades SM performance by about 0.5 dB while Alamouti scheme performance degrades by 1-2 dB.

V. Conclusion

This paper analyzes the effect of imperfect channel knowledge at the receiver on the performance of space modulation techniques. It is shown that these novel techniques are more robust to channel estimation errors as compared to Alamouti scheme. It is also shown that the overall probability of error of SSK scheme depends on the Euclidian distance between the channel paths associated with different number of transmit antennas rather than the actual channel realizations. Hence, the effect of channel estimation errors on the performance of such techniques are insignificant. Future work will focus on generalizing the conducted analysis to other space modulation techniques such as SM.

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