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Performance Analysis of Extended RASK under Imperfect Channel Estimation and Antenna Correlation

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Abstract—Spatial modulations (SM) use the index of the transmit (or the receive) antennas to allow for additional spectral efficiency in MIMO systems by transmitting spatial data on top of classical IQ modulations. Extended Receive Antenna Shift Keying (ERASK) exploits the SM concept at the receiver side and yields the highest overall spectral efficiency in terms of spatial bits compared to the conventional SM schemes. To perform efficiently, ERASK may use zero-forcing precoding to target spatial streams towards the selected receive antennas, therefore requiring the Channel State Information CSI at the transmitter. In this paper, we evaluate the theoretical performance degradation of the ERASK scheme under imperfect CSI. In addition, correlation between antennas at the transmitter and the receiver using the Kronecker correlation model is integrated in our analysis. Analytical approach for the Bit Error Rate performance is provided and validated through simulations.

Index Terms—ERASK, MIMO, Spatial Modulation, Space Shift Keying, Zero Forcing, Channel Estimation Error, channel correlation

I. INTRODUCTION

Since their introduction about 20 years ago, multiple-input and multiple-output (MIMO) wireless systems have been proved to allow for an impressive increase in system capacity in the presence of multipath fading environments [1]. Indeed, MIMO technology represents today one of the major steps in the enhancement of many wireless communication systems [2]. One sub-branch of MIMO schemes referred to as Spatial Modulation (SM) appeared in the early 2000s, with the idea of exploiting the index of the transmit (TA) or receive antennas (RA) to transmit information bits. In such techniques, transmit or receive antenna selection is used as a spatial mapping function to carry information bits over a MIMO channel in addition to common IQ symbols.

SM schemes have initially been designed to activate one single spatial stream at a time, thereby overcoming inter-channel interference and considerably reducing the radio-frequency chain complexity [3]. One of the first proposed SM scheme known as space shift keying (SSK) [4][5], applies the SM concept at the transmitter side by simply selecting one TA out of N_t to transmit $\log_2 N_t$ spatial bits. The main idea behind such a concept is to recognize spatial bits from the various propagation signatures of the spatial streams associated to each TA activation [6]. With SSK hence, the receiver has to exhaustively learn the whole set of spatial signatures before being able to process the spatial demodulation. The SSK concept can also be applied at the receiver side thus leading

to the so-called Receive-Spatial Modulation (RSM) [7] or Receive Antenna Shift Keying (RASK) [8] schemes. In such cases, one out of N_r RA is targeted (instead of being activated) and the index of the targeted RA carries the additional spatial bits, thus yielding a spectral efficiency of $\log_2 N_r$. RSM and RASK hence rely on particular preprocessing techniques able to focus the propagated waves to the selected RA, such as Time Reversal (TR), Zero-Forcing (ZF) or other beamforming schemes [8][9][10]. As such, RSM schemes assume that the MIMO channel response is known at the transmitter. From a receiver point of view however, spatial demodulation amounts to simply detecting the targeted antenna which is considered as a low-complexity processing compared to conventional MIMO detection schemes [3].

A generalization of the RSM principle, further referred to as GPSM (Generalised Pre-coding aided Spatial Modulation), is proposed in [11] where the TA array concentrates the signal energy towards a subset of RAs of fixed size $N_a \geq 2$. This allows the SM-MIMO system to reach an increased spectral efficiency compared to conventional SM schemes, but, opposed to them where a single RF chains is deployed, all the RAs have to be active (in parallel or through switches) with generalized RSM in order to enable the detection of the subset of targeted RAs. Ultimately extending the concept of RSM by enabling all possible combinations of different numbers of targeted antennas leads to the ERASK (Extended RASK) scheme as proposed in [12]–[14]. Eventually, ERASK yields the highest possible spectral efficiency (spatial bits) for a SM scheme, i.e. N_r , while being possibly applied with reasonable decoding complexity through a threshold detector at the receiver side.

As any RSM system, ERASK however relies on beamforming techniques meaning that channel state information (CSI) is needed at the transmitter side. In real cases, supplying the transmitter with accurate CSIT is a difficult task. The negative effects of channel estimation errors on the performance of SM at the transmitter when operating over flat Rayleigh fading channels is investigated in [15], and authors in [7] addressed the problem of imperfect or partial CSIT on the transmit precoding for RSM. In this paper, we evaluate the effect of imperfect CSIT on the ERASK scheme assuming ZF preprocessing and using a real amplitude threshold as proposed and justified in [12]. In addition, we integrate in our model the impact of antenna correlation which may also have strong im-

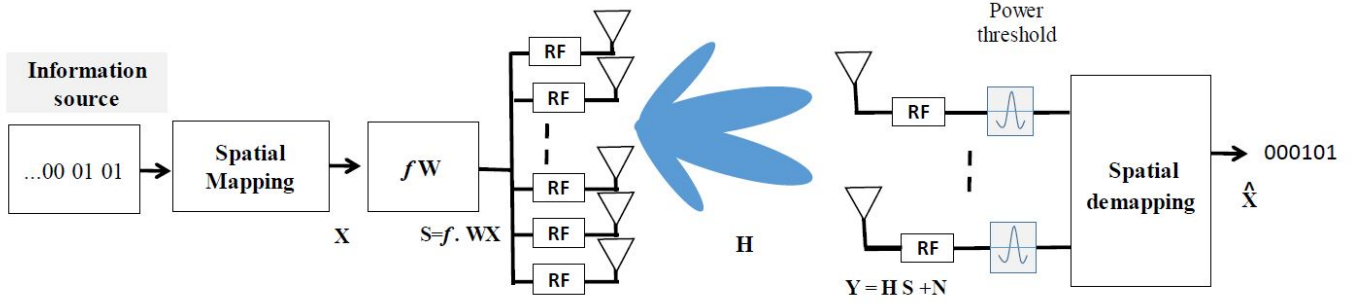


Figure 1. Block diagram of Extended-RASK

impact on the performance of SM systems. Theoretical Bit Error Rate (BER) is derived and validated through simulations, and various MIMO topologies with different number of antennas are compared giving many insights on the sensitivity of the ERASK scheme to imperfect CSIT and antenna correlation.

The rest of the paper is organized as follows. In Section II, the system model and the block diagram of the ERASK scheme are detailed. The models for imperfect CSIT and for transmit/receive spatial correlation are modeled in Section III. The theoretical computation of the BER is detailed in Section IV. Simulation results are provided in Section V, and a conclusion is drawn in Section VI.

II. SYSTEM MODEL

In this section, we set up the model for a communication system making use of the ERASK scheme. As any SM scheme, ERASK is based on a classical MIMO system topology. We denote by N_t the number of TAs and N_r the number of RAs. Assuming flat fading channels between the transmitter and the receiver, the input-output matrix form signal representation involving all the spatial links of the MIMO channel is commonly written as:

$$\mathbf{Y} = \mathbf{H} \mathbf{S} + \mathbf{N} \quad (1)$$

where $\mathbf{S} \in \mathbb{C}^{N_t \times 1}$ and $\mathbf{Y} \in \mathbb{C}^{N_r \times 1}$ are the transmit and receive symbol vectors and $\mathbf{H} \in \mathbb{C}^{N_r \times N_t}$ is the MIMO channel matrix with elements $H_{j,i}$ representing the complex channel coefficient between the i th transmit antenna T_i , and the j th receive antenna R_j . Finally, $\mathbf{N} \in \mathbb{C}^{N_r \times 1}$ is the vector of additive white Gaussian noise (AWGN) samples η_j such that $\eta_j \sim \mathcal{CN}(0, \sigma_n^2)$.

On that basis, SM schemes define particular mechanisms to exploit the MIMO channel to map symbols onto spatial links. Fig. 1 presents the block diagram of the studied ERASK system. With ERASK, a group of $m = N_r$ bits is associated to a spatial symbol $\mathbf{X} \in \mathbb{N}^{N_r \times 1}$ which is written as:

$$\mathbf{X} = [x_1 \ x_2 \ \dots \ x_{N_r}]^T \text{ where } x_j \in \{0, A\},$$

each x_j entry determining the set of targeted RAs such that:

$$x_j = \begin{cases} 0 & \text{if } R_j \text{ is not targeted,} \\ A & \text{if } R_j \text{ is targeted.} \end{cases} \quad (2)$$

Contrary to other RSM schemes, ERASK considers any combinations of targeted antennas, so that each antenna have the same probability to be targeted or not, i.e. $\frac{1}{2}$. The target mechanism is then obtained through the pre-processing block which transforms the vector of spatial symbols \mathbf{X} into the vector of transmitted signals $\mathbf{S} \in \mathbb{C}^{N_t \times 1}$ as,

$$\mathbf{S} = f \mathbf{W} \mathbf{X} \quad (3)$$

where $\mathbf{W} \in \mathbb{C}^{N_t \times N_r}$ is the pre-processing matrix, of entries $w_{i,j}$, $i \in [1 \ N_t]$ and $j \in [1 \ N_r]$ and f is a normalization factor defined as,

$$f = \frac{1}{\sqrt{\sigma_x^2 \text{Tr}(\mathbf{W} \mathbf{W}^H)}} \quad (4)$$

where $\text{Tr}(\cdot)$ holds for the trace of matrix and $\sigma_x^2 = \mathbb{E}_x [x_j x_j^*]$ is independent on j since \mathbf{X} has i.i.d. entries. As each entry of \mathbf{X} is of amplitude A with a probability $\frac{1}{2}$, we can further state that $\sigma_x^2 = \frac{A^2}{2}$.

As argued in [12], ZF beamforming is the best pre-processing strategy for ERASK. Indeed, supposing that the number of antennas satisfies the constraint $N_r \leq N_t$, it can annihilate all interference on the received signal and then leads to the best antenna detection performance. Assuming perfect CSIT, $\mathbf{W} = \mathbf{H}^\dagger (\mathbf{H} \mathbf{H}^\dagger)^{-1}$ so that the received signal vector is given by,

$$\mathbf{Y} = f \mathbf{X} + \mathbf{N} \quad (5)$$

and the received signal y_j at antenna R_j then writes,

$$y_j = f \times x_j + \eta_j. \quad (6)$$

Hence, under perfect CSIT assumption, no interference is added to the received signal at each RA, and a simple amplitude threshold detector can be used to recover the spatial symbols by detecting whether each RA is targeted by the transmit array or not. One may use a coherent detector as proposed in [12] leading to a demodulation process carried out through an independent and parallel signal analysis per antenna. Considering that the target signal $x_j = A$ is of known phase ϕ_A at the receiver, the receiver can compensate the phase

of the received signal and compare the real part obtained to a predefined amplitude threshold ν as,

$$\hat{x}_j = \begin{cases} 0, & \text{if } \Re\{y_j \times e^{-\phi_A}\} \leq \nu, \\ A, & \text{if } \Re\{y_j \times e^{-\phi_A}\} \geq \nu. \end{cases} \quad (7)$$

where the threshold is [12]:

$$\nu = \frac{f \cdot A}{2}. \quad (8)$$

From such antenna detection process, a simple look-up table based spatial demapping is finally employed to decode the binary information.

III. IMPERFECT CSIT AND CHANNEL CORRELATION

In the sequel, we first introduce the channel state information error model and its effect on the received signal. Then, antenna correlation at the transmitter and the receiver is incorporated in our model. Finally, the resulting received signal expression is given.

A. Imperfect CSIT

A perfect channel knowledge at any side of the transmission system is impossible in practical situations. In this paper, the transmitter is assumed to be capable of accurately tracking the long term average Channel State Information (CSI). This can be for instance plausible in time-division duplexing (TDD) mode, where the reciprocity of the channel can apply. However, we consider in the sequel that an instantaneous CSI error is added to the long term channel estimation, such that we have,

$$\mathbf{H} = \bar{\mathbf{H}} + \tilde{\mathbf{H}} \quad (9)$$

where $\bar{\mathbf{H}}$ represents the average long term CSI that is accurately estimated at the transmitter, and $\tilde{\mathbf{H}}$ denotes the instantaneous CSI deviation matrix where all entries obey the complex Gaussian distribution $\tilde{h}_{j,i} \sim \mathcal{CN}(0, \sigma_{\tilde{H}}^2)$. Since $\bar{\mathbf{H}}$ is estimated at the transmitter, then the pseudo-inverse of $\bar{\mathbf{H}}$ is used as a pre-filter as,

$$\mathbf{W} = \bar{\mathbf{H}}^\dagger (\bar{\mathbf{H}} \bar{\mathbf{H}}^\dagger)^{-1}. \quad (10)$$

B. Transmit and Receive Spatial Correlation

Performance of SM schemes are often evaluated over a independent Rayleigh fading per antenna link. In this work the correlation between TAs and between RAs is taken into account to evaluate the robustness of the system ERASK. Employing the Kronecker correlation model [16] for that purpose, the MIMO channel can be rewritten as:

$$\mathbf{H} = \mathbf{R}_r^{1/2} \mathbf{H}_I (\mathbf{R}_t^{1/2})^T \quad (11)$$

where $\mathbf{H}_I \sim \mathcal{CN}(\mathbf{0}, \mathbf{I})$ is the channel matrix with independent entries, and \mathbf{R}_r and \mathbf{R}_t represent the receive and transmit spatial correlation matrices at the receive and transmit arrays, respectively. The correlation matrices are generated using the exponential model, such that $\mathbf{R}_r(i, j) = \rho_r^{|i-j|}$ and $\mathbf{R}_t(i, j) = \rho_t^{|i-j|}$, where $0 \leq \rho_r, \rho_t \leq 1$. Then combining the correlation

model with the imperfect channel estimation model, we may write the MIMO channel as:

$$\mathbf{H} = \underbrace{\mathbf{R}_R^{1/2} \bar{\mathbf{H}}_I (\mathbf{R}_T^{1/2})^T}_{\bar{\mathbf{H}}} + \underbrace{\mathbf{R}_R^{1/2} \tilde{\mathbf{H}}_I (\mathbf{R}_T^{1/2})^T}_{\tilde{\mathbf{H}}} \quad (12)$$

where matrix $\bar{\mathbf{H}}$ represents the full known part of the channel and matrix $\tilde{\mathbf{H}}$ represents the unknown part of the channel, both integrating correlation effects.

C. Received Signal and Detection Algorithm

From the above model, in which the estimation of the channel includes errors, the equation of the received signal (5) becomes :

$$\mathbf{Y} = f \mathbf{X} + f \tilde{\mathbf{H}} \mathbf{W} \mathbf{X} + \mathbf{N} \quad (13)$$

which can be re-expressed at each received antenna as,

$$y_j = f \times x_j + f \times \sum_{k=1}^{N_r} \sum_{i=1}^{N_t} \tilde{h}_{j,i} w_{i,k} x_k + \eta_j. \quad (14)$$

As expected from the erroneous channel knowledge, ZF beamforming fails in properly isolating the entries of the spatial symbol vector which gives rise to a residual interference term in the latter two expressions.

IV. PERFORMANCE ANALYSIS

Based on the obtained receive signal in Eq. (14), we provide in this section the analytical derivation for the theoretical BER performance of the ERASK system under imperfect channel estimation. The generic expression of the BER \mathcal{P}_e can be written as,

$$\mathcal{P}_e = \frac{1}{m} \cdot \mathbb{E} \left\{ \sum_k^{N_r} \sum_{j \neq k}^{N_r} \mathcal{P}(\mathbf{X}_k \rightarrow \mathbf{X}_j) \cdot d(\mathbf{X}_k, \mathbf{X}_j) \right\}. \quad (15)$$

where $d(\mathbf{X}_k, \mathbf{X}_j)$ is the Hamming distance between two spatial symbols \mathbf{X}_k and \mathbf{X}_j , and $\mathcal{P}(\mathbf{X}_k \rightarrow \mathbf{X}_j)$ is the probability to transmit \mathbf{X}_k and detect \mathbf{X}_j . All spatial signatures are possible and equally likely in ERASK scheme, so that for each RA, the probability of being targeted or not is independent on the fact that any other RA is also targeted. Consequently, evaluating the global BER of the ERASK system amounts to get the BER on each RA antenna. Let us define $\mathcal{P}(y_{j1})$ (resp. $\mathcal{P}(y_{j0})$) as the probability that one particular antenna R_j is targeted (resp. not targeted), and $\mathcal{P}(y_{j0} \rightarrow y_{j1})$ (resp. $\mathcal{P}(y_{j1} \rightarrow y_{j0})$) the conditional probability that one particular antenna R_j is detected as being targeted (not targeted) knowing that it was not (resp. it was). We then have,

$$\mathcal{P}_e = \mathcal{P}(y_{j0}) \cdot \mathcal{P}(y_{j0} \rightarrow y_{j1}) + \mathcal{P}(y_{j1}) \cdot \mathcal{P}(y_{j1} \rightarrow y_{j0}). \quad (16)$$

Since $x_k \in \{0, A\}$ with a probability of $\frac{1}{2}$, we have $\mathcal{P}(y_{j0}) = \mathcal{P}(y_{j1}) = \frac{1}{2}$. In addition, following the threshold criteria introduced in Eq. (8), We can then simply restate the BER expression as,

$$\mathcal{P}_e = \frac{1}{2} \cdot \mathcal{P} \left(y_{j0} > \frac{f \cdot A}{2} \right) + \frac{1}{2} \cdot \mathcal{P} \left(y_{j1} < \frac{f \cdot A}{2} \right). \quad (17)$$

The probabilities of false detection in Eq. (17) have to be analyzed from the expression of the received signal at antenna R_j given in Eq. (6). It is important to keep in mind that the interference term embedded in Eq. (6) depends on the other targeted antennas. It can be statistically represented as,

$$f \times \sum_{k=1}^{N_r} \sum_{i=1}^{N_t} \tilde{h}_{j,i} w_{i,k} x_k \sim \mathcal{CN}(0, \sigma_l^2). \quad (18)$$

$$\text{where } \sigma_l^2 = \sum_{k=1}^{N_r} x_k^2 \sum_{i=1}^{N_t} f^2 \|w_{i,k}\|^2 \sigma_H^2. \quad (19)$$

Now expressing the normalization factor f as,

$$f^2 = 2/(A^2 \times \sum_{i=1}^{N_t} \sum_{j=1}^{N_r} \|w_{i,j}\|^2), \quad (20)$$

the expression of the interference variance in (19) becomes:

$$\sigma_l^2 = \sum_{k=1}^{N_r} x_k^2 \frac{2}{A^2 \times N_r} \sigma_H^2 \quad (21)$$

in average over all possible spatial symbols. We can then decompose all possible spatial signatures to determine the distribution of the interference and the additive white noise depending on the number N_a of targeted antennas as,

$$\sigma_l^2 = 2\sigma_H^2 \times N_a/N_r, \quad (22)$$

where $0 \leq N_a \leq N_r$. Then, defining $\mathcal{P}(N_a)$ as the probability of error detection if N_a antennas are targeted, we have from Eq. (17):

$$\begin{aligned} \mathcal{P}(N_a) &= \frac{1}{2} \cdot \mathcal{P}\left(\Re\{f.A + \mathcal{CN}(0, \sigma_l^2 + \sigma_n^2)\} < \frac{f.A}{2}\right) \\ &+ \frac{1}{2} \cdot \mathcal{P}\left(\Re\{\mathcal{CN}(0, \sigma_l^2 + \sigma_n^2)\} > \frac{f.A}{2}\right) \\ &= Q\left(f.A/2\sqrt{\sigma_n^2 + \sigma_l^2}\right) \end{aligned} \quad (23)$$

where $Q(\cdot)$ denotes the Gaussian Q-function. As a result, the general equation of the BER taking every subset of targeted antennas is given as:

$$\mathcal{P}_e = \frac{1}{2^{N_r}} \sum_{N_a=0}^{N_r} C_{N_r}^{N_a} Q\left(f.A/2\sqrt{\sigma_n^2 + 2\sigma_H^2 \times N_a/N_r}\right) \quad (24)$$

where $C_{N_r}^{N_a}$ is the binomial coefficient giving the number of subsets of N_a elements of a set of N_r elements. Finally introducing the ratio between the average transmit power level to the interference and noise level as:

$$\text{SNR} = \frac{\bar{P}_t}{\sigma_n^2 + \sigma_l^2} = \frac{1}{\sigma_n^2 + \sigma_l^2}, \quad (25)$$

the equation of the BER performance given in Eq. (24) becomes:

$$\mathcal{P}_e = \frac{1}{2^{N_r}} \sum_{N_a=0}^{N_r} C_{N_r}^{N_a} Q\left(\frac{f.A}{2}\sqrt{\text{SNR}}\right) \quad (26)$$

Such a result indicates that the system performance is driven by f , which directly depends on the MIMO channel characteristics, the number of RAs and the deviation of the channel estimation error (embedded in the SNR). Hence, it can already been anticipated that the BER will degrade as :

- f decreases. This will occur as the antenna correlation increases, since f becomes weak when the channel matrix is bad conditioned.
- N_r increases. This translates the fact that a higher amount of antenna interference has to be canceled with large receive antenna arrays.
- σ_l^2 increases. This is a direct consequence of the channel estimation impairments.

V. SIMULATION RESULTS

The performance of the ERASK system based on a parallel threshold detection and under imperfect CSIT is evaluated through the measurement of the BER versus SNR. More precisely, in the following curves the variance of the CSIT deviation is set to a constant value and the level of the Gaussian noise at the receiver changes to illustrate the BER in terms of the SNR. It is assumed that $\bar{\mathbf{H}}$ is a MIMO flat fading channel matrix where $\bar{h}_{j,i}$ are complex coefficients following i.i.d. Rayleigh distribution, and the entries of the matrix of instantaneous CSI deviation are complex coefficients following the complex Gaussian distribution with a variance σ_H^2 . The power for each sub-channel is normalized as,

$$E[\|\bar{h}_{j,i}\|^2] + \sigma_H^2 = 1,$$

and the correlated model described in Eq. (12) is used for various values of ρ . Simulations are carried out by implementing a sufficient number of iterations for different channel realizations.

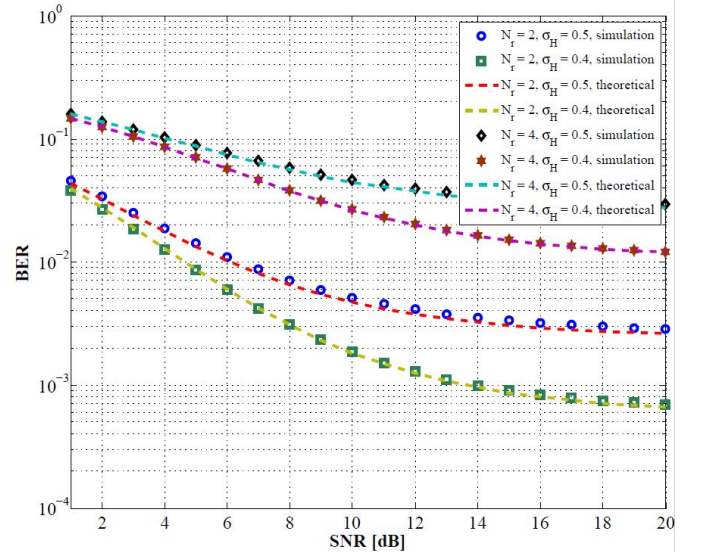


Figure 2. Theoretical and simulation comparison of BER Vs SNR performance of ERASK over uncorrelated Rayleigh fading channels. $N_t = 8$, $N_r = 2$ and 4, $\sigma_H = 0$ and 0.2

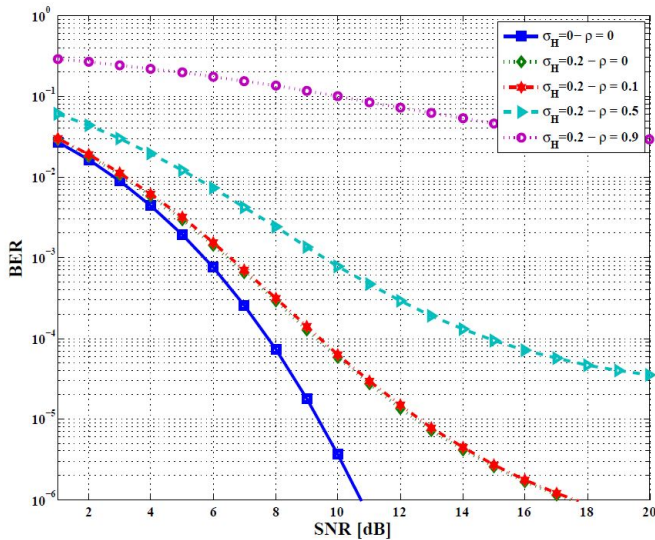


Figure 3. BER Vs SNR performance of ERASK with $N_t = 8$ and $N_r = 2$ over Rayleigh fading channels for perfect channel estimation and no correlation, and for $\sigma_H = 0.2$ with correlation factor $\rho = 0, 0.1, 0.5$ and 0.9 .

In Fig. 2, we first compare the simulated (markers) and theoretical (dashed lines) BER values for a ERASK system with $N_t = 8$, and $N_r = 2$ and 4 . For each N_r , results are given for two different channel estimation accuracies, namely $\sigma_H = 0.4$ and 0.5 . No antenna correlation is used in this figure. As evident from the obtained curves, theoretical results perfectly match simulation results for any configuration. Then, as expected from the analysis of Eq. (24), it is observed that increasing the order of the spatial modulation (i.e. increasing N_r), or degrading the CSIT quality leads to strong performance losses. In both cases indeed, the sum of added interference increases which translates into the form of error floors at high SNR.

The effect of the correlation at the transmitter and the receiver of the system, combined with the impact of channel estimation errors, is shown in Fig. 3. The considered ERASK system is set with $N_t = 8$ and $N_r = 2$. Two configurations are compared. The first one, used as a reference, assumes perfect CSIT and no correlation. The second one, considers a deviation of the estimation error of $\sigma_H = 0.2$ and different correlation factor levels ($\rho = 0, 0.1, 0.5$ and 0.9). The ERASK performance obviously degrades when the correlation factor increases (lower f), and when channel estimation error is added (higher σ_l^2). Nevertheless, the degradation remains still acceptable for $\rho \leq 0.5$ with a performance degradation of less than 4 dB at a 10^{-3} BER compared to the perfect conditions, and less than 3 dB when only the channel estimation error is included ($\sigma_H = 0.2, \rho = 0$). Interestingly, the curves obtained without correlation and with $\rho = 0.1$ are almost undistinguished, which indicates that under a given quality of the channel estimation, the antenna correlation has no impact on the performance.

In Fig. 4, various ERASK system settings (i.e. various $N_t \times N_r$) are compared with and without channel estimation

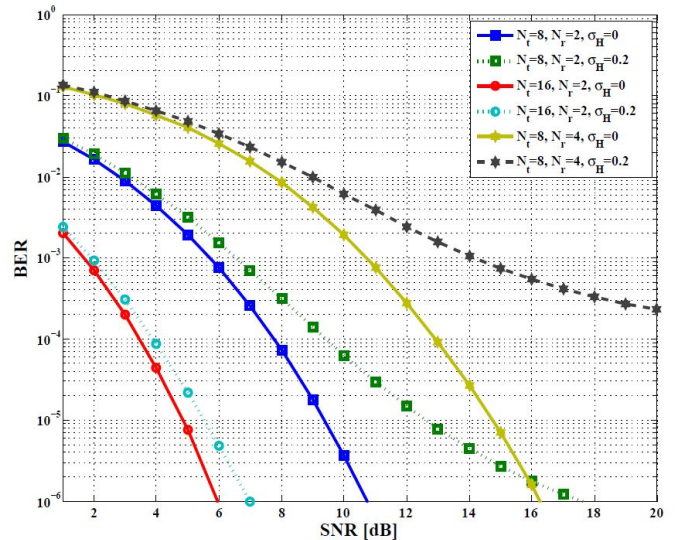


Figure 4. BER Vs SNR performance of ERASK over Rayleigh fading channels with antenna correlation factor $\rho = 0.1$. $N_t = 8$ and 16 , $N_r = 2$ and 4 , $\sigma_H = 0$ and 0.2 .

inaccuracies, and fixing the correlation factor to $\rho = 0.1$. First comparing the curves with $N_t = 8$, it is verified that the larger the RA array, the stronger the degradation of the performance. Indeed, as the number of RAs increases, the amount of inter-antenna interference becomes higher at the receiver side and the defect of interference cancellation of the ZF scheme due the channel estimation errors becomes more significant. This fact corroborates the analysis made on Eq. (26). Reversely, analyzing the curves with $N_r = 2$ but changing N_t leads to the conclusion that the ZF beamforming is less sensitive to poor CSIT when a larger number of TAs is used. This indicates that using large transmit arrays, and thus exploiting higher spatial focusing gains, is favorable to channel estimation inaccuracies.

VI. CONCLUSION

In this paper, we have evaluated the performance of the ERASK spatial modulation scheme based on ZF preprocessing under the impact of imperfect CSIT. We have followed an analytical approach to derive a closed-form expression of the BER of the ERASK scheme by integrating channel estimation errors in the system model. Also, the effect of the correlation between transmit antennas and receive antennas has been taken into account. Our theoretical results have been validated through simulations and have allowed for many insights in the analysis of the ERASK BER performance. Namely, it has been shown that the higher number of receive antennas, the stronger the degradation of the performance. However, the exposed results have also highlighted how more robust the ERASK scheme is against channel estimation impairments and antenna correlation when the number of transmit antennas increases. From our study, we can then conclude that the ERASK scheme can adapt many situations dealing with imperfect channel knowledge and antenna correlation as soon as some

compensation is brought from the use of a sufficient number of transmit antennas.

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