Analysis of the Performance of a Non-Coherent Large Scale SIMO System Based on M-DPSK Under Rician Fading

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***Abstract*—In this paper we extend the analysis of the performance of a non-coherent large-scale single input multiple output (LS-SIMO) uplink system based on M-DPSK to consider Rician-K fading channel conditions. The interference is analyzed for a generalized $K-$factor and we provide analytical expressions of the signal to interference plus noise ratio (SINR) for a single user. We demonstrate that for Rician fading our proposed system is independent of the channel statistics, which simplifies the receiver design. The performance is evaluated in terms of the required number of antennas and the error probability. Finally, we provide numerical results showing that our proposal require a lower number of receive antennas to achieve a given error probability than other non-coherent benchmark schemes available in the literature. As the results show an increase in the spectral efficiency using DPSK modulation combined with NC LS-SIMO, this makes it a good candidate for 5G and beyond.**

I. Introduction

The emerging wireless technologies like immersive video, Machine to Machine communications (M2M) or Internet of Things (IoT) are constantly demanding higher user densities and data rates. Hence, the industry is forced to deploy the future 5th Generation of wireless communication systems, 5G [1]. One of the key enabling technologies for 5G is large scale (or massive) multiple-input multiple-output (LS-MIMO) technology [2][3], where the Base Stations (BS) are equipped with a vast number of antennas to achieve multiple orders of energy and spectral efficiency gains beyond those of the current operational standards [4].

In general, the conventional coherent detection for LS-MIMO technology requieres the knowledge of the Channel State Information (CSI) at the BS for a large number of channels. The CSI may be estimated using pilot signals transmitted from each user to the BS, assuming reciprocity in the radio link when utilizing time division duplexing (TDD). Due to the fact that the pilot signals used in adjacent cells are not completely orthogonal, the performance of the LS-MIMO systems is degraded due to pilot contamination [5].

In this context, in order to tackle this impediment, we propose to use non-coherent (NC) detection as a design alternative, for avoiding channel estimation. The NC detection has indeed compelling benefits in terms of dispensing with power-thirsty channel estimation, as also argued in [7]-[8]. In our previous work [8], we demonstrated these advantages of NC LS-single input multiple output (LS-SIMO) under Rayleigh propagation conditions. Here in this paper we generalize the analysis taking into account the Rician channel. The authors in [11] presented a comparison between coherent and NC detection for LS-SIMO and single-user systems, demonstrating that NC systems are potentially capable of outperforming their coherent counterparts. Furthermore, [10] shows that CSI estimation is not needed,while in [13] a new constellation design for NC detection is shown. However, the designs there proposed are based on energy detection which still requires an impractically enormous number of receive antennas to guarantee a reasonable performance.

Another recent scheme for NC SIMO is focused on uniquely factorable constellation [9]. However, it is not developed for LS systems. For single- user MIMO systems, Gohary and Davidson [12] proposed a transmitter and a receiver for NC communication based on Grassmanian constellation, which works well for a frequency-flat MIMO channel and for high Signal Noise Ratio (SNR), but cannot exploit differential detection.

In this contribution we extend the previous analysis to obtain a thorough characterization of the LS-SIMO system under Rician fading channel. We will demonstrate that using a design based on DPSK constellation the statistics of the channel do not need to be known in contrast to [13]. Furthermore, the gain with respect to other works that also consider Rician channel is shown both according to the required number of antennas and the spectral efficiency.

The rest of the paper is organized as follows. The proposed system model is introduced in Section II. The interference and SINR are analyzed in Section III. The performance is analyzed in Section IV and compared to previous work. Finally, Section V presents the conclusions.

II. System Model

In this contribution, we consider an uplink scenario for a single-user single input multiple output system (SIMO), where a BS equipped with R receive antennas (RA) receives a transmitted signal by a single antenna transmitter. The

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proposed block diagram for the complete system is shown in Fig. 1.

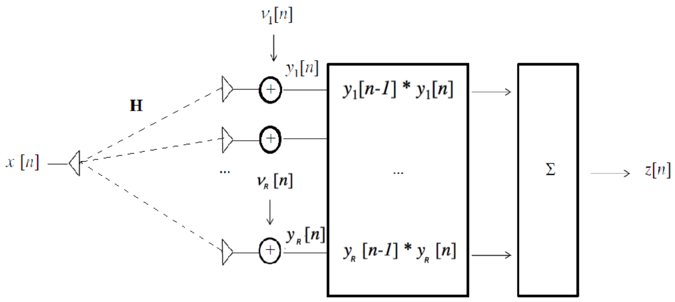

Fig. 1. **System block diagram.**

A user transmits a signal $x[n]$ at time instant n, which is a differentially encoded version of $s[n]$ formulated as

$$x[n] = s[n]x[n-1], \ n > 1. \tag{1}$$

The symbols $s[n]$ belong to an M-ary PSK constellation, $\mathfrak{M} = \{s_m, \ m = 0, 1, ..., \ M-1\}$, where $|s_m[n]| = 1$ and M is the order of the constellation. The $x[0]$ is a known first symbol at the transmitter and receiver which is taken from the constellation $\mathfrak{M}$. The LS-MIMO wireless channel is modeled by the $(R \times 1)$-element channel matrix $\widetilde{\boldsymbol{H}} = \boldsymbol{H} + \mu$, whose components $\widetilde{h_j}$ representing the propagation from the user to the j-th antenna of the BS. These elements $\widetilde{h_j} = h_j + \mu$, where $h_j \sim CN(0, \sigma_h^2)$, are circularly symmetric complex Gaussian random variables. We assume that the statistics of the channel are defined as follows

$$|\mu|^2 = \frac{K}{K+1} \tag{2}$$

and

$$\sigma_h^2 = \frac{1}{K+1}, \tag{3}$$

where K is the Rician factor ($K > 0$), which characterizes the fading model [14]. This factor represents a propagation direction with line-of-sight (LOS) between the Base Station and the user. Note that when K=0 we have a Rayleigh channel in which there is no dominant propagation along the LOS and in this case, the system model is equivalent to that presented in [8]. For simplicity of the presentation, we assume that all the channels experience Rician fading with the same K-factor. Each of the antennas at the BS receives the vector $\mathbf{y}[n]$ at time instant n. Then the signal received at the BS is obtained as follows

$$\mathbf{y} = \widetilde{\boldsymbol{H}}x + \mathbf{v}, \tag{4}$$

where we will remove the time dependency n to facilitate the notation. Here the AWGN components $\mathbf{v}$ is the $(R \times 1)$-element vector, $\nu_j[n] \sim CN(0, \sigma^2)$.

The power of the signal received at each antenna is $E\{|\boldsymbol{H}\boldsymbol{x}|^2\} = |s|^2(\sigma_h^2 + \mu^2)$, as $|s|^2 = 1$ and $(\sigma_h^2 + \mu^2) = 1$, then we define the reference SNR as

$$\rho = \frac{E\{||\boldsymbol{H}x||^2\}}{\sigma^2} = \frac{(\sigma_h^2 + \mu^2)}{\sigma^2} = \frac{1}{\sigma^2}. \tag{5}$$

At the receiver shown in Fig. 1, we assume that $h_j[n-1] = h_j[n] = h_j, \ j = 1, ..., R$. This assumption is that the channel stays time-invariant for two consecutive symbols. Hence, the phase difference is non-coherently detected for these two symbols received at each antenna. The resulting received symbol is the decision variable $z[n]$ defined as follows

$$z[n] = \frac{1}{R} \sum_{j=1}^{R} y_j[n-1]^* y_j[n], \tag{6}$$

that contains information and interference gleaned from all antennas

$$\begin{aligned} z[n] =& \left(\frac{1}{R}\sum_{j=1}^{R}|h_j|^2 + \frac{2\mu}{R}\sum_{j=1}^{R}Re\{h_j\} + \mu^2\right)s[n] \\ &+ \frac{1}{R}\sum_{j=1}^{R}h_j x[n]v_j^*[n-1] + \frac{1}{R}\sum_{j=1}^{R}h_j^* x^*[n-1]v_j[n] \\ &+ \frac{\mu}{R}\Big[\sum_{j=1}^{R}x^*[n-1]v_j[n] + \sum_{j=1}^{R}x[n]v_j^*[n-1]\Big] \\ &+ \frac{1}{R}\sum_{j=1}^{R}v_j[n]v_j^*[n-1]. \end{aligned} \tag{7}$$

We know using the Law of Large Numbers that

$$\frac{1}{R}\sum_{j=1}^{R}|h_j|^2 \overset{R\to\infty}{=} \sigma_h^2, \tag{8}$$

$$\frac{1}{R}\sum_{j=1}^{R}Re\{h_j\} \overset{R\to\infty}{=} 0, \tag{9}$$

$$\frac{\mu}{R}\Big[\sum_{j=1}^{R}x^*[n-1]v_j[n] + \sum_{j=1}^{R}x[n]v_j^*[n-1]\Big] \overset{R\to\infty}{=} 0, \tag{10}$$

almost surely. Taking into account $(\sigma_h^2 + \mu^2) = 1$, then we have

$$z[n] \overset{R\to\infty}{=} s[n] + i[n] \tag{11}$$

where $i[n]$ are the noise terms and and the interference explained in the Section III. We can calculate an estimate of $s[n]$ from $z[n]$ as follows

$$\hat{s}[n] = \arg\ \min\{|s[n] - z[n]|, s[n] \in \mathfrak{M}\}, \tag{12}$$

In the next section and the performance analysis, we will show that as R grows bigger this low-complexity estimate guarantees a good performance.

III. Evaluation of the Signal to Interference plus Noise Ratio

We define the Signal to Interference plus Noise Ratio (SINR) as the ratio of the signal power to the power of additive white gaussian noise (AWGN) plus interference created by the multiple antennas at the BS and the detection process in LS-SIMO. When detecting $\hat{s}[n]$ from $z[n]$, due to a finite value of R, the interference plus noise arises from the noise terms in (11) and from expressions (8), (9) and (10). Hence the interference plus noise term $i[n]$ is shown in (13).

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$$i[n] = z[n] - s[n] = \underbrace{s[n](\frac{1}{R}\sum_{j=1}^{R}|h_j|^2 + \frac{2\mu}{R}\sum_{j=1}^{R}Re\{h_j\} + \mu^2 - 1)}_{i_1[n]} + \underbrace{\frac{1}{R}\sum_{j=1}^{R}h_j x[n]v_j^*[n-1] + \frac{1}{R}\sum_{j=1}^{R}h_j^* x^*[n-1]v_j[n]}_{i_2[n]}$$
$$\underbrace{+\frac{\mu}{R}[\sum_{j=1}^{R}x^*[n-1]v_j[n] + \sum_{j=1}^{R}x[n]v_j^*[n-1]]}_{i_3[n]} \underbrace{+\frac{1}{R}\sum_{j=1}^{R}\nu_j^*[n-1]\nu_j[n])}_{i_4[n]} \tag{13}$$

The four terms $i_1[n]$, $i_2[n]$, $i_3[n]$ and $i_4[n]$ are independent because the channel and noise are independent as it is shown in the Appendix A, therefore we can add independently the power of the interference terms $I = I_1 + I_2 + I_3 + I_4$. We calculate the expectation of the power of the different terms of $i[n]$ in (13), $I = E\{|i[n]^2|\}$, based on the Wishart and Gaussian matrices, omitted for the sake of conciseness. I is formulated as follows

$$I_1 = \frac{(\sigma_h^2 + \mu^2)^2}{R} = \frac{1}{R} \tag{14}$$

$$I_2 = \frac{2\sigma_h^2\sigma^2}{R} \tag{15}$$

$$I_3 = \frac{2\mu^2\sigma^2}{R} \tag{16}$$

$$I_4 = \frac{1}{R}\sigma^4. \tag{17}$$

Therefore, the SINR obeys

$$SINR = \frac{E\{|s|^2\}}{I} = \frac{R}{1 + 2\sigma^2(\sigma_h^2 + \mu^2) + \sigma^4} = \frac{R}{1 + 2\sigma^2 + \sigma^4}. \tag{18}$$

As we can see in (18), the interference is independent of K. Therefore, it is equivalent for both Rice and Rayleigh [8] channels. This will be further demonstrated in the Section IV with numerical results. Because of this equivalence, we can use the bounds shown in [8] for the error probability of the received symbol. The upper bound as

$$P_e \leq (M-1)\, Q\left(\sqrt{\frac{d_{min}^2}{2I}}\right) \tag{19}$$

being d_{min} the minimum constellation distance and the lower bound as

$$Pe \geq \frac{1}{M}\sum_{m=0}^{M-1} Q\left(\frac{d_{min}^m}{\sqrt{2I}}\right). \tag{20}$$

where d_{min}^m is the minimum distance defined as the distance between each constellation point $m \in \mathfrak{M}$ from its nearest symbol.

In Fig. 2 the SINR obtained by simulation is compared to that in the theoretical expression (18) for a reference SNR (ρ) of -4 and -2 dB.

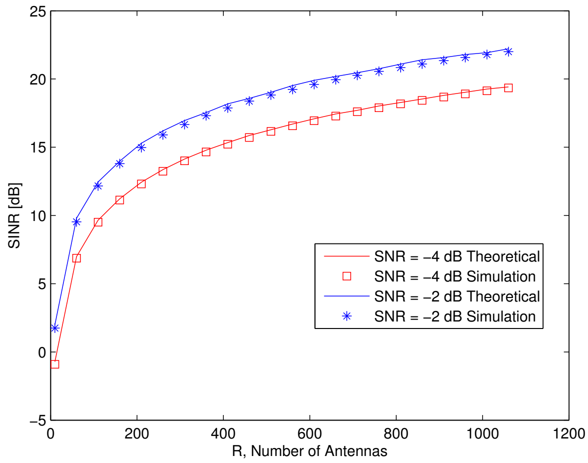

Fig. 2. **SINR versus the required number of antennas.**

IV. Performance Evaluation

In this section, numerical results by simulations are presented to assess the performance of the DPSK LS-SIMO design. We assume a block fading, where during the transmission of a long symbol burst the channels stay invariant, varying randomly between bursts.

In Fig. 3 we plot the bit error rate (BER) for SNR=-8, -5 and 0 dB with a constellation size of $M = 4$ and $M = 16$ symbols. For $M = 4$, we compare the performance in two different Rician channels ($K = 10$ and $K = 100$) and Rayleigh channel ($K = 0$. As observed the K-factor does not influence in the performance when we use the DPSK design. Therefore, in contrast to previous works [13], we would not need to know the statistics of the channel. This is an advantage over energy-detection-based constellation designs. We can also see that an increase of the constellation order is possible at the expense of a higher number of antennas. In Fig. 4, we analyse the BER versus the reference SNR of the 32$-$DPSK scheme with regard to different R of the BS under Rician propagation. The receiving number of antennas is set to $R = 500$, 256 and 128. We can verify that the K-factor does not change the results with respect to the Rayleigh case. With this figure we show that it is feasible to increase the constellation order, by increasing the SNR or R.

In order to compare the performance to previous work [13]

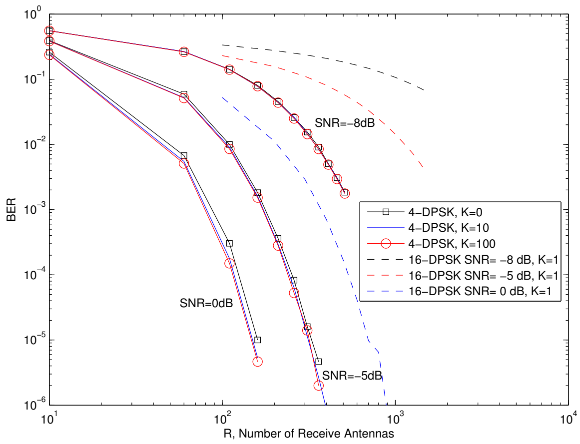

Fig. 3. **Performance of 4-DPSK and 16-DPSK for several *SNR* and different *K* factors.**

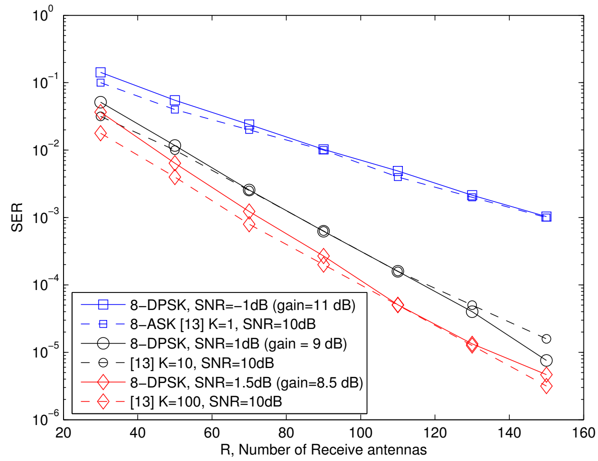

Fig. 5. **SER comparison of DPSK constellation with energy based design.**

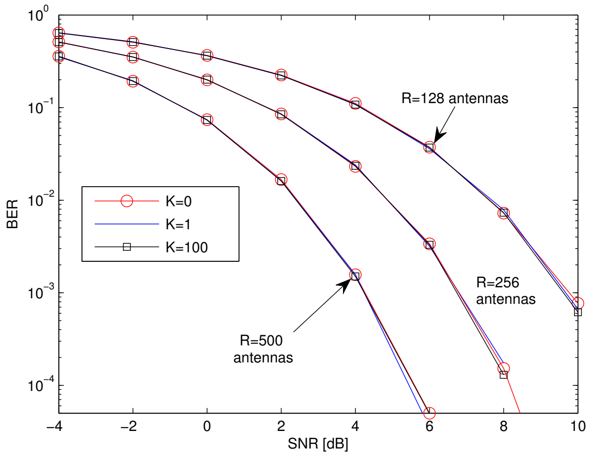

Fig. 4. **Performance of 32-DPSK for different R.**

we plot now the symbol error rate (SER) in Fig. 5. It shows a performance comparison between the DPSK scheme and the energy detection scheme [13], both with $M = 8$ under Rician channels. We can see that the DPSK scheme exhibits better SER performance than the energy detection. In order to obtain the same performance as [13] with K=1 and SNR=10dB, our system requires an SNR of -1 dB. This means that we have an SNR gain of 11 dB for K=1. Similarly, we have 9 dB gain for $K = 10$ and 8.5 dB in the case of $K = 100$.

In Fig. 6 we compare our proposed system to [13] for both the same SNR = 10 dB and $M = 8$, where we show the performance of higher order DPSK modulation. Comparing the curves of DPSK and energy detection with $K = 1$ and for a target SER $= 10^{-3}$, we can see that with DPSK we can reduce in 140 the required number of antennas. If we wish to obtain the same performance with the same number of antennas, we can increase the order of constellation up to $M = 32$. The reduction is lower for higher K factor, because the energy detection of [13] works better for high K. Consequently our system can increase the spectral efficiency.

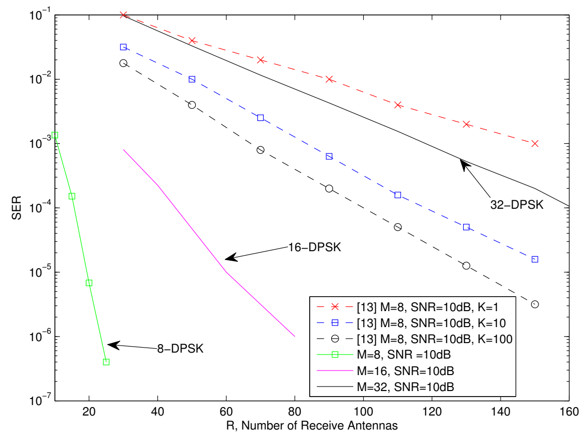

Fig. 6. **SER performance versus number of antennas.**

Fig. 7 shows the minimum required number of antennas R needed in order to achieve a target SER of 10^{-4} using different constellation size. We can see that the DPSK scheme with SNR=1dB is equivalent in performance to energy detection with SNR=10dB. Then we have an improvement of 9dB in SNR. For the same SNR = 10 dB, DPSK allows us to save approximately 100 antennas when $M = 8$. The reduction is even larger for higher constellation size. If we fix a number of antennas, DPSK can increase the spectral efficiency. For example, for R=20 we have M=3 with [13] and M=8 for DPSK.

V. Conclusions

We have extended the analysis of the performance of a non-coherent large scale SIMO system based on M-DPSK to consider Rician-K fading channel conditions. We have analyzed the interference for a generalized $K-$factor, demonstrating that our proposed system is independent of the statistics of the

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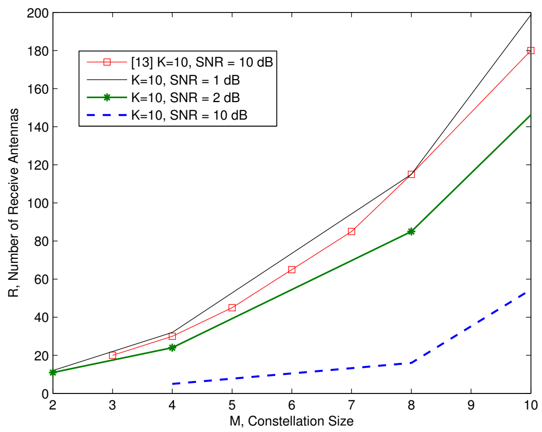

Fig. 7. **Minimum number of receive antennas R for a target SER$= 10^{-4}$ performance for two different constellation designs.**

channel, hence, simplifying the receiver design. Moreover, we provide analytical expressions of the signal to interference plus noise ratio (SINR) for a single user. The results of the performance analysis show a lower required number of antennas than other previous works based on energy detection. In addition, our system can increase the spectral efficiency making the proposed DPSK scheme a good candidate for the future 5G communication systems and beyond. As a future work, we are analyzing the performance increasing the number of users.

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APPENDIX
INDEPENDENCE OF THE INTERFERENCE PLUS NOISE TERMS

In this appendix, we demonstrate that the interference plus noise components which were presented in Section III are independent and uncorrelated. To this end, they have to fulfill

$$\begin{aligned} Cov(i_j, i_k) = E\{i_j[n]i_k[n]\} - E\{i_j[n]\}E\{i_k[n]\} = 0 \\ E\{i_j[n]i_k[n]\} = E\{i_j[n]\}E\{i_k[n]\} \end{aligned} \tag{21}$$

where $j,k = 1,\ldots,4$ are the interfering terms defined in (13) and $Cov(x,y)$ is the covariance between the random variables x and y.

Let us obtain the expectation for each term:

$$\begin{aligned} E\{i_1[n]\} =& E\{s[n](\frac{1}{R}\sum_{j=1}^{R}|h_j|^2 + \frac{2\mu}{R}\sum_{j=1}^{R}Re\{h_j\} + \mu^2 - 1)\} \\ =& \sigma_h^2 + \mu^2 - 1 \end{aligned} \tag{22}$$

as $(\sigma_h^2 + \mu^2) = 1$, then $E\{i_1[n]\} = 0$

$$\begin{aligned} E\{i_2[n]\} = &-\frac{1}{R}\sum_{j=1}^{R}E\{\nu_j^*[n-1]\}E\{h_j x[n]\} \\ &-\frac{1}{R}\sum_{j=1}^{R}E\{\nu_j[n]\}E\{h_j^* x^*[n-1]\} \end{aligned} \tag{23}$$

$$\begin{aligned} E\{i_3[n]\} = &\frac{\mu}{R}[\sum_{j=1}^{R}E\{x^*[n-1]\}E\{v_j[n]\} \\ &+\sum_{j=1}^{R}E\{x[n]\}E\{v_j^*[n-1]\}] \end{aligned} \tag{24}$$

$$E\{i_4[n]\} = \frac{1}{R}\sum_{j=1}^{R}E\{v_j^*[n-1]\}E\{v_j[n]\} \tag{25}$$

as $E\{v_j[n]\} = 0$ then (23), (24) and (25) are 0.

Regarding the cross expectations $E\{i_j[n]i_k[n]\}$, since all terms include $E\{v[n]\} = 0$, these terms cancel each other, giving $E\{i_j[n]i_k[n]\} = 0$ for any j and k.

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