Joint Interference Cancellation and Subtraction for a Hybrid Receiver in Kronecker Correlated MIMO Wireless Channels

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***Abstract*— Several works have evaluated the performance of MIMO transmission structures using the uncorrelated fading assumption. This idealized consideration may not be true in a typical downlink outdoor wireless system. In this type of scenario higher fading correlations are present at the transmitter due to the height of the base-station relative to the ground. In this work we present a Hybrid MIMO receiver for combined spatial multiplexing - transmit diversity and evaluate its performance when fading correlation is present at the transmitter. MIMO fading correlation is simulated according to a recently proposed Kronecker model and our results show the performance behavior of our hybrid receiver due to correlation.**

***Index Terms*— MIMO, spatial multiplexing, space-time coding, hybrid receiver, Kronecker model**

I. Introduction

Over the consideration of uncorrelated fading Multiple-Input Multiple-Output (MIMO) wireless channels are known to offer unprecedent spectral efficiency. With this assumption, each element of the MIMO channel fades independently and $r = min(M, N)$ uncouple parallel sub-channels between pairs of transmit and receive antennas are created, where M is the number of transmit and N is the number of receive antennas. The creation of r uncoupled parallel sub-channels represent a capacity gain that increases linearly with the lower number of antennas [1]. However, the uncorrelated fading assumption may not be true in the real world. In a typical downlink outdoor wireless system there is not rich scattering around the base-station (BS) antennas due to the height of the BS relative to the ground, which induces correlation at the BS transmit array. At the other link end, i.e., around the Mobile Terminal (MT), the uncorrelated fading characteristic is maintained due to rich local scattering. Several studies have proved that fading correlation leads to a performance degradation of MIMO antenna systems [2].

The MIMO transmission structures can be classified in two classes in agreement with the gain captured by the channel characteristics. The two possible gains are: *diversity gain* and *spatial multiplexing gain*. The first one is associated with the provision of link-reliability to the system, which can be measured in terms of a lower Bit Error Rate (BER) while the second one concerns the maximization of the spectral efficiency of the overall system as much as possible. Until the advent of hybrid MIMO schemes, MIMO transmission structures worked in one of these two pure transmissions classes. However, it is well known that the focus in a particular gain implies a sacrifice of the other one [3, 4].

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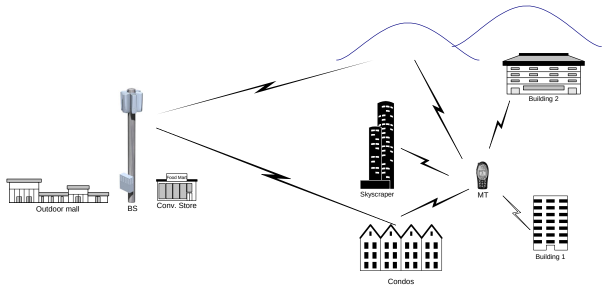

Fig. 1. Downlink Scenario

Hybrid MIMO transmission schemes apply pure diversity schemes (e.g. STBC) jointly with pure spatial multiplexing schemes (e.g. BLAST). In these schemes, some layers are space-time coded across two, three or four antennas. For the remaining layers, a V-BLAST approach is considered. With this idea, hybrid MIMO scheme arises as a solution to achieve a compromise between spatial multiplexing and transmit diversity gains. In other words, with hybrid MIMO schemes it can be possible to considerably increase the data rate while keeping a satisfactory link quality in terms of BER. As spatially-multiplexed layers see each other as Multiple Access Interference (MAI), some signal processing is mandatory in the receiver in order to cancel MAI.

In this work we consider approaches that combine cancellation and subtraction of the MAI, this approach is denoted Successive Interference Cancellation (SIC). Other solution is achieved by the Ordered Successive Interference Cancellation (OSIC).

In this work we present a hybrid MIMO receiver with combined cancellation and subtraction of the MAI that arises from hybrid spatial multiplexing - transmit diversity systems. We employ the so-called Successive Interference Cancellation (SIC) for MAI subtraction and evaluate link performance of the proposed receiver when fading correlation is present at the transmitter. Correlation is simulated according to the recently proposed Kronecker model [5]. Our simulation results show how performance of the proposed hybrid receiver is degraded when different levels of fading correlation are present at the transmitter.

The remainder of this paper is organized as follows. Section II is dedicated to MIMO correlated channel model as well as the system model adopted. In section III we present the hybrid MIMO receiver structure called G2+1. In section IV we describe the interference cancellation algorithm for this receiver along with SIC and OSIC interference cancellation and subtraction strategies. Section IV contains our simulation results. Finally, in section V we conclude this paper and draw some perspectives.

II. Channel and System Model

In this section the Kronecker correlated MIMO channel model used for performance evaluation is discussed and the system model is presented.

A. Correlated MIMO Channel Model

Consider that the transmitter is equipped with an M-element antenna array, while the receiver is equipped with an N-element antenna array. The MIMO channel matrix $\mathbf{H}[k]$ has size N x M, with k a generic time-instant. In this work we assume a typical downlink outdoor wireless scenario, as shown in Fig. 1. In this context, the assumption that the transmitted signals undergo independent fading is no more valid. For example, at the Mobile Terminal (MT) the multipath propagation is more perceived due to several local scatterers and this leads to uncorrelated fading. On the other hand in the transmitter (BS), a correlation is present due to the height of BS located high above the ground and no presence of local scatterers. In such an environment, the MIMO channel at a time-instant k can be written as

$$\mathbf{H}[k] = \mathbf{K}_{\mathrm{R}}\mathbf{H}_w\mathbf{K}_{\mathrm{T}}, \tag{1}$$

where $\mathbf{H}_w$ is the channel matrix with uncorrelated complex gaussian entries and the matrices $\mathbf{K}_{\mathrm{R}}$ and $\mathbf{K}_{\mathrm{T}}$ are N x N and M x M lower triangular matrices, respectively, with positive diagonal entries. They can be obtained from their correlation matrices Θ_{R} and Θ_{T} by Cholesky decomposition [6], where Θ_{T} and Θ_{R} represent the correlation matrix at the transmitter and receiver, respectively. We also assume that the correlation between the receiver antenna elements does not depend on the transmit antenna elements and vice versa. In such a case, we have

$$\Theta_{\mathrm{R}} = \mathbf{K}_{\mathrm{R}}\mathbf{K}_{\mathrm{R}}^H, \tag{2}$$

$$\Theta_{\mathrm{T}} = \mathbf{K}_{\mathrm{T}}\mathbf{K}_{\mathrm{T}}^H, \tag{3}$$

where $(\cdot)^H$ denotes conjugate transpose. In our correlated channel model, $\Theta_{\mathrm{R}} = \mathbf{I}_{N\mathrm{x}N}$. This means that there are many scatterers around the mobile terminal and the received signal appears uncorrelated due to multipaths reflected from the several scatterers. And

$$\Theta_{\mathrm{T}} = \begin{bmatrix} 1 & \rho & \dots & \rho \\ \rho & 1 & \dots & \rho \\ \vdots & \vdots & \ddots & \vdots \\ \rho & \rho & \dots & 1 \end{bmatrix}, \tag{4}$$

in this case all channel correlations are equal to ρ. This model is also denoted in the literature as Kronecker model since the full autocorrelation matrix Θ is given by

$$\Theta = \Theta_{\mathrm{T}}^T \otimes \Theta_{\mathrm{R}}, \tag{5}$$

where $(\cdot)^T$ denotes transposition and $\otimes$ is the Kronecker product. It has been shown the validity of this model through measurements results, see [5].

B. System Model

Consider a downlink system model assuming flat fading channel and let the transmitter be equipped with a 3-element antenna array while the receiver is equipped with an N-element antenna array. At any time-instant k, the received signal vector can be expressed as

$$\mathbf{x}[k] = \mathbf{H}\mathbf{s}[k] + \mathbf{n}[k], \tag{6}$$

where $\mathbf{H}$ is defined in accordance of Eq. (1) and is represented as

$$\mathbf{H} = \begin{bmatrix} h_{11} & h_{12} & h_{13} \\ h_{21} & h_{22} & h_{23} \\ \vdots & \vdots & \vdots \\ h_{n1} & h_{n2} & h_{n3} \end{bmatrix}, \tag{7}$$

the element h_{nm}, with $1 \leq n \leq N$ and $1 \leq m \leq 3$ is the complex scalar channel that links the *n*th receive antenna and the *m*th transmit antenna. The 3×1 vector $\mathbf{s}[k]$ contains the symbols transmitted from all antennas at time-instant k. The envelope of each element in the vector h_{nm} follows a Rayleigh distribution. The composition of vector $\mathbf{s}[k]$ depends on the specific hybrid scheme considered. In this paper we choose the hybrid receiver G2+1 $(M = 3)$ that is presented in the next section. This limitation is motivated by the practical feasibility of utilizing this number of antenna elements in nowaday's base station-to-mobile transmissions. The $N \times 1$ vector $\mathbf{n}[k]$ denotes the temporally and spatially Additive White Gaussian Noise (AWGN) which $\mathbf{R}_{\mathbf{nn}}[k] = E\{\mathbf{n}[k]\mathbf{n}^H[k]\} = \sigma^2 \cdot \mathbf{I}_{N\mathrm{x}N}$.

III. G2+1 MIMO Hybrid Structure

In this section we present a hybrid MIMO transmission scheme, i.e., a MIMO antenna scheme that makes simultaneous use of spatial multiplexing and transmit diversity. In a general way, the transmission process of a hybrid scheme can be divided in layers, where each layer is characterized by the provided gain, multiplexing or diversity gain. Figure 2 shows the architecture of the G2+1 hybrid MIMO structure with SIC detection.

This hybrid scheme employs a 3-element transmit antenna array with two spatial multiplexing layers. A standard G2 (Alamouti's) [7] space-time block code is used at the first layer while the other layer is non-space-time-coded and operate in a co-channel way with the first one. In the G2+1 scheme, the transmitted signals can be organized in a equivalent space-time coding matrix as described below

$$\mathbf{\Omega}_{G2+1}[k, k+1] = \begin{bmatrix} s_1[k] & s_1[k+1] & s_2[k] \\ -s_1[k+1]^* & s_1[k]^* & s_2[k+1] \end{bmatrix}, \tag{8}$$

where the spatial dimension varies column-wise and the temporal dimension row-wise. The symbol vector transmitted by the transmit array in two consecutive time-instants, say k and $k+1$, are given by

$$\begin{aligned} \mathbf{s}_{11}[k] &= \mathbf{s}_1[k], & (9)\\ \mathbf{s}_{11}[k+1] &= -\mathbf{s}_1[k+1]^*, & (10)\\ \mathbf{s}_{12}[k] &= \mathbf{s}_1[k+1], & (11)\\ \mathbf{s}_{12}[k+1] &= \mathbf{s}_1[k]^*, & (12)\\ \mathbf{s}_2[k] &= \mathbf{s}_2[k], & (13)\\ \mathbf{s}_2[k+1] &= \mathbf{s}_2[k+1]. & (14) \end{aligned}$$

From Eq. (8), it can be seen that $n_s = 4$ useful symbols (two from each multiplexing layer) are transmitted in $n_t = 2$ consecutive symbol intervals. Thus, the effective symbol rate

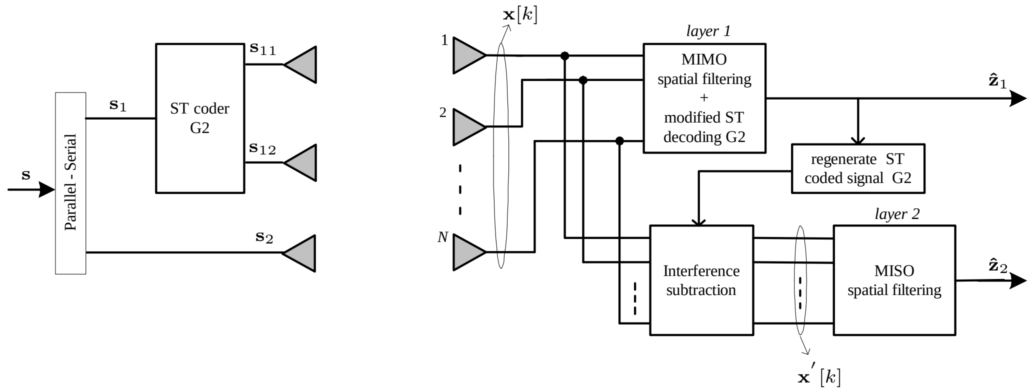

Fig. 2. G2+1(SIC) transmitter-receiver structure

of this scheme is equal to $n_s/n_t = 2$ symbols per channel use (pcu).

Considering the first layer of G2+1 scheme as the desired signal, we can expand Eq. (6) as the sum of a MIMO desired signal and a Single-Input Multiple-Output (SIMO) interferer signal as follows

$$\mathbf{x}_{G2+1}[k] = \mathbf{H}_d^{G2}\mathbf{z}_1[k] + \mathbf{h}_I\mathbf{z}_2[k] + \mathbf{n}[k], \tag{15}$$

where $\mathbf{H}_d^{G2}$ and $\mathbf{h}_I$ are MIMO and SIMO channel matrices of dimension $N \times 2$ and $N \times 1$, respectively and $\mathbf{z}_1[k] = \begin{bmatrix} \mathbf{s}_{11}[k] & \mathbf{s}_{12}[k] \end{bmatrix}^T$ and $\mathbf{z}_2[k] = \mathbf{s}_2[k]$ are multiplexing sub-sequences for each layer at time-instant k.

IV. Interference Cancellation Algorithm

Classical solutions for pure BLAST-based systems consider either Zero-Forcing (ZF) or Minimum Mean Square Error (MMSE) as the detection algorithm. On the other hand, for a pure STBC system with Alamouti's code, a simple maximum likelihood linear processing receiver is usually employed. Since we deal here with a hybrid of BLAST and Alamouti's STBC a modified interference cancellation algorithm with the property of both interference cancellation and space-time decoding is necessary, see [8]. In the following we formulate a modified MMSE algorithm that performs the following tasks

1) estimate the overall MIMO channel matrix $\mathbf{H}$;
2) cancel multiple access interference from channel estimation;
3) perform space-time decoding after interference cancellation.

The proposed algorithm optimizes the coefficients of a MIMO-MMSE spatial filter (as shown in Fig. 2) in such a way that the orthogonality of the space-time code is preserved as much as possible in its output signal.

At any time-instant k, the output signal vector of the $N \times N$ MIMO-MMSE spatial filter is given by

$$\mathbf{y}[k] = \mathbf{W}\mathbf{x}[k], \tag{16}$$

where

$$\mathbf{W} = \begin{bmatrix} w_{11} & w_{12} & \dots & w_{1N} \\ w_{21} & w_{22} & \dots & w_{2N} \\ \vdots & \vdots & \ddots & \vdots \\ w_{N1} & w_{N2} & \dots & w_{NN} \end{bmatrix}. \tag{17}$$

We obtain the error vector at the output of the MIMO-MMSE spatial filter as

$$\mathbf{e}[k] = \mathbf{W}\mathbf{x}[k] - \mathbf{H}_d\mathbf{s}_1[k] = \mathbf{W}\mathbf{x}[k] - \mathbf{x}_d[k], \tag{18}$$

where $\mathbf{x}_d[k] = \mathbf{H}_d\mathbf{s}_1[k]$ is the desired space-time coded signal associated to the first multiplexing layer of a particular hybrid transmission scheme. Contrarily to the classical MIMO-MMSE spatial filter (where the desired signal is $\mathbf{s}_1[k]$), here the desired signal consists of the original transmitted signal modified by desired MIMO channel impulse response $\mathbf{H}_d$.

The MMSE cost function be formalized as follows

$$J_{MMSE} = E\{\|\mathbf{W}\mathbf{x}[k] - \mathbf{x}_d[k]\|^2\}. \tag{19}$$

Solving this unconstraint optimization problem, the obtained solution with respect to $\mathbf{W}$ is given by

$$\mathbf{W} = \mathbf{R}_{\mathbf{x}_d\mathbf{x}} \cdot (\mathbf{R}_{\mathbf{x}\mathbf{x}})^{-1}, \tag{20}$$

where $\mathbf{R}_{\mathbf{x}\mathbf{x}} = E\{\mathbf{x}[k]\mathbf{x}^H[k]\}$ and $\mathbf{R}_{\mathbf{x}_d\mathbf{x}} = E\{\mathbf{x}_d[k]\mathbf{x}^H[k]\}$ are the input covariance matrix and a cross-correlation matrix, respectively.

The coefficients of the MIMO-MMSE spatial filter can be computed after direct least square (LS) estimate of the MIMO channel impulse response.

A. *Successive Interference Cancellation (SIC)*

Interference cancellation can be done either in parallel or in a serial way. Here, we consider the serial approach which jointly performs interference cancellation and subtraction. Considering the so-called SIC approach, just one layer is detected at each time. Interference contributions of previously detected layers are subtracted out prior to signal detection of subsequent layers. After interference cancellation and decision at the i-th layer, its hard estimate $\hat{\mathbf{z}}_i[k]$ is subtracted out from the received signal $\mathbf{x}[k]$ and this modified received signal, denoted by $\mathbf{x}_{i+1}[k]$, is fed into the spatial filter of the $i+1$-th layer:

$$\mathbf{x}_{i+1}[k] = \mathbf{x}_i - \hat{\mathbf{z}}_i\mathbf{h}_i \tag{21}$$

where $\mathbf{h}_i$ is the ith column of the matrix channel $\mathbf{H}$, corresponding to the channel gains associated to layer i and $\hat{\mathbf{z}}_i\mathbf{h}_i$ represents the estimated symbol of the i-th layer. As result, $\mathbf{x}_{i+1}$ is free from the interference coming from layers $1, \dots, i$.

In this work, where we consider the specific case of the G2+1 hybrid receiver, the detection follows the natural order, i.e., the G2 space-time coded layer is detected first, followed by the non-coded multiplexing layer. This choice is based on the fact that the G2 layer exhibits some detection reliability, provided by the space-time code, compared to the other (non-space-time coded) layer.

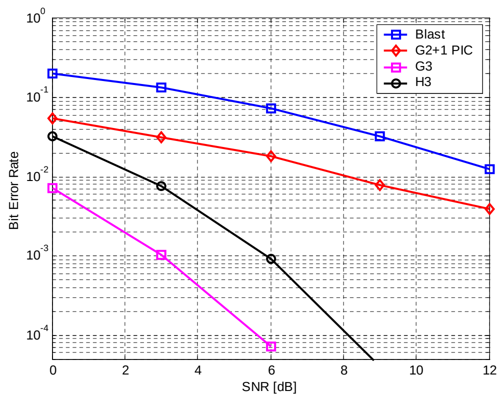

Fig. 3. Hybrid tradeoff characterization 3Tx-4Rx architecture.

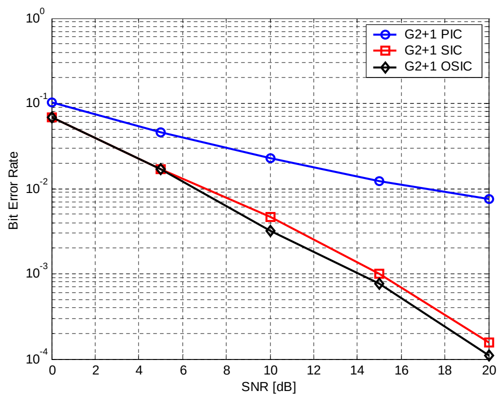

Fig. 4. Performance of the G2+1 scheme comparing the strategies PIC, SIC and OSIC in the receiver.

B. Ordered Successive Interference Cancellation (OSIC)

One of the disadvantages of SIC is that the signal associated to first detection layer may eventually exhibits a lower received SNR than that of the other layers. In this case, detection errors propagate throughout the serial detection process, degrading performance of the overall receiver. These problem can be alleviated as long as optimal detection ordering of layers is made. When detection ordering is assumed, the first layer to be detected is that with the higher SNR. In this situation, the SIC approach turns into Ordered Successive Interference Cancellation (OSIC).

TABLE I

OSIC POSSIBILITIES.

Diversity Order 1st Possibility	1st Layer	G2†	$2\cdot(N-1)$
	2nd Layer	1‡	$1\cdot(N)$
	TOTAL		$3\cdot N-2$
Diversity Order 2nd Possibility	1st Layer	1	$1\cdot(N-2)$
	2nd Layer	G2	$2\cdot(N)$
	TOTAL		$3\cdot N-2$

† G2 represents Alamouti's STBC layer.
‡ 1 denotes a layer following BLAST approach.

V. SIMULATION RESULTS

The BER performance of the G2+1 hybrid MIMO receiver is evaluated here by means of numerical results from Monte-Carlo simulations with Successive Interference Cancellation (SIC) and Ordered SIC (OSIC), respectively. The transmitted symbols are modulated with Binary-Phase Shift-Keying (BPSK). The BER curves are plotted according to the average SNR per receive antenna. Perfect channel estimation is assumed, since the consideration of imperfect channel estimation is degraded by about 0.3 dB compared to the ideal channel state information, see [9]. Still in [9], if the number os transmit antennas is small, the performance degradation due to the channel estimation error is small. However, as the number of transmit antennas increases, the sensitivity of the system to channel estimation error increases, [10]. Thus, as we assume $M = 3$, the degradation due to the perfect channel estimation is negligible.

Figure 3 first shows the BER results comparing the traditional MIMO schemes, V-BLAST, G3 and H3 [11] for 3 transmit antennas against the hybrid scheme G2+1. We remember that the V-BLAST scheme is designed to provide multiplexing gain only, while the STBC schemes G3 and H3 have as objective to provide diversity gain only. Considering the 3Tx-4Rx architecture, the V-BLAST scheme achieves a spectral efficiency of 3 symbols pcu in opposition to the 1/2 symbols pcu and 3/4 symbols pcu reached by schemes G3 and H3, respectively. From this results we can conclude that the hybrid scheme G2+1 achieves its objective, i.e., it reaches a higher spectral efficiency (2 symbols pcu since 4 symbols are transmitted in 2 channel realizations) than pure STBC scheme while it maintains an acceptable BER level that is better than that of a pure BLAST system.

Now we show the effect of our interference cancellation algorithm with joint interference cancellation and subtraction, assuming both ordering (OSIC) end (non)-ordering (SIC). Until here, uncorrelated fading is assumed and $N = 3$ receive antennas are employed. As benchmark for comparisons the traditional PIC approach was also simulated. Figure 4 shows that the combined effect of interference suppression and subtraction provides to the system an additional diversity gain for the second layer, which turns out into an improved overall performance. In fact, in the PIC approach the second layer perceives a diversity gain of $N-2 = 3-2 = 1$ while in the SIC ones a full diversity gain of $N = 3$ is perceived at this layer (i.e., equivalent to a single-transmit maximal ratio combiner - MRC).

Comparing OSIC and SIC approaches we get similar results. This can be explained by the fact that in the G2+1 scheme, similar diversity gains are offered with both strategies. For example, assuming that the first layer to be detected is the G2 space-time-coded layer, we get a diversity order of $\mathcal{D}_{G2} = 2\cdot(N-1)$. With perfect interference subtraction, the second layer will perceive a diversity order of $\mathcal{D}_1 = 1\cdot N$ and thus the whole system has a diversity order of $\mathcal{D}_{G2+1} = 2\cdot(N-1)+1\cdot N = 3\cdot N-2$. By now, if the first layer to be detected be the BLAST based (non-coded) one, we have $\mathcal{D}_1 = 1\cdot(N-2)$ for this layer and $\mathcal{D}_{G2} = 2\cdot(N)$ for the other one, which gives a total diversity order of $\mathcal{D}_{1+G2} = 1\cdot(N-2)+2\cdot(N) = 3\cdot N-2$. Table I summarizes the conclusion about this topic.

As a conclusion of this interesting result we should say that, since it is the diversity order that controls the slope of the BER vs. SNR curve, the use of OSIC is not important in the G2+1 receiver as it gives only a very slight performance improved over SIC, which is considerably less complex.

Now we consider a more realistic MIMO channel model, given by the Kronecker model detailed in Section II-A.

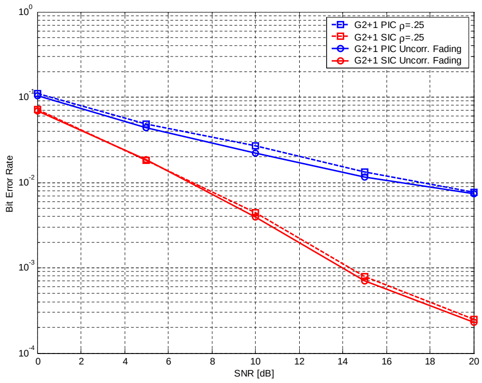

Fig. 5. Performance of the hybrid scheme G2+1 on correlated MIMO channel, correlation factor is $\rho = 0.25$.

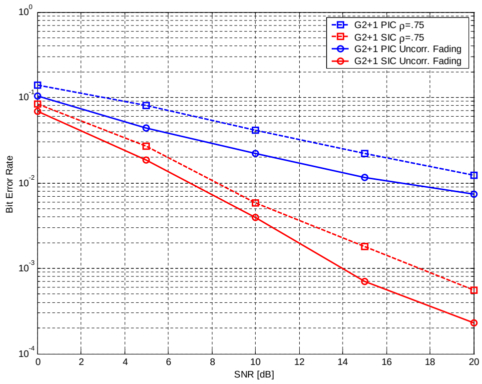

Fig. 6. Performance of the hybrid scheme G2+1 on correlated MIMO channel, correlation factor is $\rho = 0.75$.

Figures 5 and 6 show the performance of the G2+1 scheme considering the 3Tx-3Rx architecture on a Kronecker correlated MIMO channel, assuming that all correlation comes from the transmit side. We can see that in a low correlation level $(\rho = 0.25)$, the results are nearly the same of those with no correlation. Furthermore, the SIC approach continues to provide better results then the PIC one. On the other hand, in a higher correlation level $(\rho = 0.75)$, see Fig. 6, a decreasing in performance of an order of 3 dB for BER$= 10^{-2}$ is perceived for PIC, while that for SIC the same order of decreasing is perceived for BER$= 10^{-3}$. The reason for this result resides in the loss of space-time coding gain when correlation is present.

A solution for this drawback is the use of linear precoding at the transmitter to recuperate the coding gain of this scheme. This will be discussed in a future contribution. Still in Fig. 6, we can conclude that the SIC solution is still a good choice for this correlated MIMO channel model. Comparing the correlated and uncorrelated cases, we can see that for BER$= 10^{-3}$ the SIC solution has just 3 dB degradation while providing an enormous gain when compared to the PIC in the uncorrelated channel.

VI. Conclusions

In this work we have evaluated the performance of the G2+1 hybrid MIMO transmission scheme in a Kronecker correlated MIMO channel. We have shown that hybrid schemes arise as a solution for the inherent diversity-multiplexing trade-off of MIMO channels. We have also shown that the joint use of cancellation and subtraction of interference can provide a remarkable improvement in performance, compared to the PIC approach. On the other hand, the OSIC approach for this scheme is not recommended since the ordering of the layers to be detected has no influence in the diversity order.

Over the Kronecker correlated MIMO channel, for a low correlation level the PIC and SIC have similar performances, i.e., the correlation level has no great influence. Contrarily, for a high correlation level we conclude that the SIC approach is a good choice since it exhibit just a 3 dB degradation due to correlation, while providing an enormous gain when compared to the PIC in an uncorrelated channel.

The perspectives of this work include the investigation of linear precoding schemes to give back to the space-time code the gain lost due the correlation in the MIMO channel. Upcoming results also include link-performance evaluation of linear-precoded hybrid schemes in a typical indoor wireless environment. This will be done through the use of processed data obtained from MIMO indoor channel measurements carried out by a joint UFC-Ericsson research team at an Ericsson Research building in Kista, Sweden.

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