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Wireless Systems

On transmission techniques for multi-antenna W-CDMA systems

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SUMMARY

In this paper we present and evaluate a new pre-processing scheme for Multiple Input Multiple Output (MIMO) channels. Its performance is compared with other MIMO schemes proposed for the downlink of Wideband-Code Division Multiple Access (W-CDMA) systems, namely a variation of the Beam Forming (BF), entitled Beam-Selective Transmit Diversity (BSTD) or post-processing schemes, such as the Alamouti-like MIMO or the Vertical Bell Laboratories Layered Space-Time (V-BLAST) MIMO scheme. It is assumed that the Base Station (BS) has $M \geqslant 2$ transmit antennas and the Mobile Station (MS) receiver has space enough to accommodate $N = 2$ uncorrelated receive antennas.

It is shown that the proposed pre-processing scheme allows receivers with very low complexity, contrarily to the case where a post-processing approach is followed, simplifying the MS receiver. Therefore, the proposed $M \times N$ MIMO pre-processing scheme can be seen as an alternative to post-processing schemes. It is also shown that the pre-processing scheme for MIMO channels tends to achieve the best performance in most scenarios, being followed by the BSTD, which allows interference cancellation and provides diversity. Copyright © 2007 John Wiley & Sons, Ltd.

1. INTRODUCTION

Emergent services are demanding higher data rates, especially in the downlink. Wideband Code Division Multiple Access (W-CDMA) is a proven technology to reach this in cellular communications. To obtain this, it is important to find schemes that are able to reduce the effects of fading and explore new type of diversity, as well as to reduce Inter-Path Interference (IPI) and Multiple Access Interference (MAI). In the case of frequency selective fading, it can be observed that different symbols suffer from interference from each other, whose effect is usually known as Intersymbol Interference (ISI), which tends to increase with the used bandwidth. In the case of spread spectrum signals, a multipath environment also originates some level of self-interference. This happens because the replicas of the transmitted signal are not synchronized with the decorrelator of the receiver, which leads to loss of the orthogonality as well as ISI. In the case of W-CDMA, this is also called IPI or self-MAI. When there is more than one user, the multipath channel originates MAI, even for synchronized networks with orthogonal spreading sequences. The RAKE receiver, usually considered for DS-CDMA receivers, takes advantage of the multipath channel to provide multipath diversity. (RAKE stands for coherent combination of multipath components)

The use of multiple antennas at both the transmitter and receiver (also known as Multiple Input Multiple Output (MIMO) techniques) aims to improve the performance of systems, but it usually requires higher implementation complexity. Moreover, the antenna spacing must be larger than the coherence distance to ensure independent fading across different antennas. This coherence distance depends on the environment conditions, e.g. for the indoor environ-

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ment the coherence distance is lower than for the rural area environment [1].

Since conventional detection techniques for MIMO systems are based on the assumption of a flat propagation channel they are usually employed for modulations as the Orthogonal Frequency Division Multiplexing (OFDM) schemes, which have a flat fading channel behaviour at the sub-carrier level. Its extension to W-CDMA systems is not straightforward, especially when severely time-dispersive channels are considered [2, 3].

If the Channel Impulse Response (CIR) information associated to different MS is available at the BS, the use of pre-processing schemes at the transmitter (BS) allows simpler MS receiver implementations (and, eventually better performances). By reducing the signal processing requirements at the MS, we can reduce the battery drainage and decrease the terminal cost, key aspects in the MS design. Therefore, the complexity should be transferred from the MS receiver into the BS.

In this paper, we propose and analyse a new frequency domain pre-processing scheme for frequency-selective fading MIMO channels. This MIMO pre-processing scheme (for the sake of simplicity also called, in this paper, Pre-MIMO) is compared with the Beam-Selective Transmit Diversity (BSTD) [4, 5] that can be seen as a composite scheme where the MAI reduction is performed jointly with the exploitation of transmit diversity, without additional MS receiver complexity. To make a fair comparison, we consider two receive antennas to provide receive diversity, and therefore the BSTD can also be seen as a MIMO scheme. It is worth noting that the BSTD may also be seen as a pre-processing scheme, as most of the processing is performed at the BS side (transmitter). Both the MIMO pre-processing and the BSTD schemes allow low-complexity receivers. To improve the performance of the BSTD, we employ a decorrelating Multi-User Detector (MUD) [6]. Nevertheless, this association presents the disadvantage that the complexity of the MS receiver is increased related to the BSTD alone, or pre-processing MIMO scheme.

We also consider, for comparison purposes, two additional post-processing schemes: the V-BLAST MIMO scheme [7, 8], and the Alamouti-like MIMO scheme [9, 10], both optimised for W-CDMA signals subject to frequency selective fading. All of these four schemes are compared with the 1 × 2 Single Input Multiple Output (SIMO), which considers a RAKE receiver associated to each one of the two receive antennas to provide multipath diversity.

This paper is organised as follows. Section 2 describes the BSTD, the Alamouti-like MIMO and the V-BLAST MIMO schemes. Section 3 introduces the new proposed MIMO pre-processing scheme, while Section 4 presents the performance results and analysis of the different MIMO schemes. Finally, the conclusions are drawn in Section 5.

2. SOME MIMO TECHNIQUES FOR W-CDMA

This section describes the BSTD [4, 5] the 2×2 Alamouti-like MIMO Scheme [11] and the V-BLAST MIMO Scheme optimised for W-CDMA signals subject to Frequency Selective Fading channels (FSFC) [7, 8]. These schemes are later compared in Section 4 using different propagation models and multi-user scenarios.

2.1. BSTD—Beam-Selective Transmit Diversity

Making use of spatial isolation of different users with transmit BF is an effective solution to mitigate MAI at the receiver. Therefore, transmit BF can be seen as an alternative to MUD, without complexity increase at the MS side. Generally speaking, both Selective Transmit Diversity (STD) and BF can be implemented by antenna array with certain array elements at the BS. For STD, those array elements are usually widely separated to form a transmit diversity array with low correlation among them. In BF, all the array elements are closely located to form a beamforming array with antenna elements typically spaced half wavelength.

With the BSTD scheme, several sub-beamforming arrays are equipped at the BS and they are combined to implement the STD technique. In fact, the BSTD scheme can be viewed as a composite of the BF scheme and the STD scheme [4, 5].

The BS configuration for BSTD is shown in Figure 1. There is a total K MS randomly distributed along the arc boundary of a 120° cell sector (the kth MS is denoted as MS_k for $k = 1, \ldots, K$). There are N sub-beamforming arrays (SBFA) equipped at the BS for this cell sector. Each SBFA has antenna elements spaced half wavelength ($d = \lambda/2$), while the distance between adjacent SBFAs is large enough to keep them uncorrelated [12]. The number of array elements in each SBFA is M_{b}, and thus the total elements number of the N SBFAs is $M = M_{\mathrm{b}} \times N$.

The BSTD scheme exploits several parallel sub-beamforming arrays equipped at the BS which are combined to implement the selective transmit diversity technique

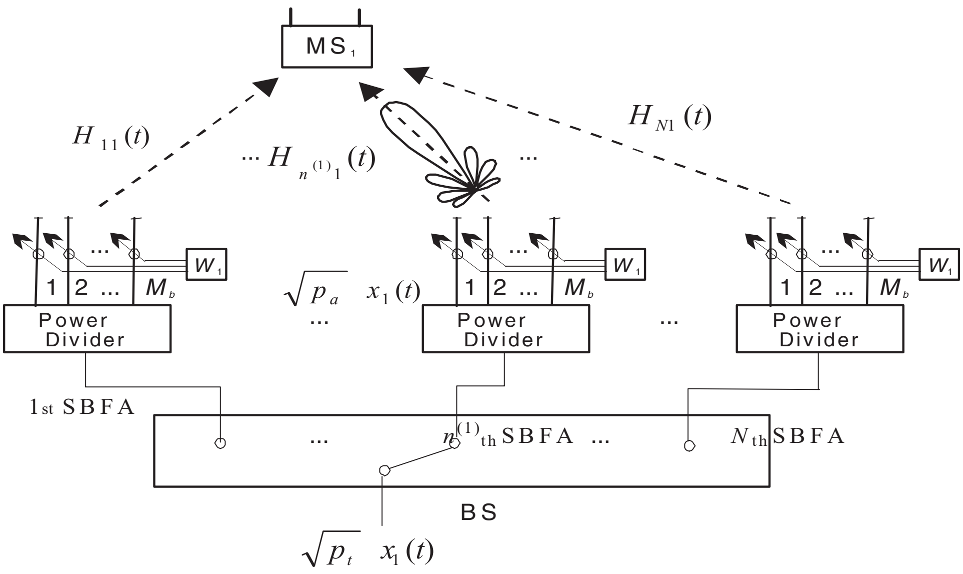

Figure 1. Base station configuration for BSTD.

[13]. To allow the exploitation of multipath diversity, a RAKE is also considered at the receiver.

The BSTD adaptively chooses the sub-beamforming array that better fits the environment based on the pilot sequences (one for each sub-beam). The MS estimates the Channel State Information (CSI) of the several beams of the BSTD and informs the BS about the best beam array through a feedback information channel.

In References [4, 5, 7] the detailed system is described and signal model for the BSTD considered a single receive antenna. However, by considering multiple receive antennas, the BSTD is seen as a MIMO system, where the signals from different antennas must be properly combined (e.g. with a Maximum Ratio Combiner (MRC) or Mean Square Error (MSE) combiner). By using this principle, we may use the single receive antenna model for multiple receive antennas. The results presented in this paper for the BSTD will consider two receive antennas. Since the BF component of the BSTD only partially removes the MAI, a Decorrelating MUD was added to the BSTD [6, 7]. A Decorrelating MUD was selected instead of a Parallel Interference Cancellation (PIC), because it does not require any special modification to work with the BSTD. Furthermore, while the PIC suffers from propagation errors [12], the Decorrelating MUD does not [6]. Moreover, the PIC introduces a delay in the signal proportional to the number of iterations, while the Decorrelating MUD does not. The Decorrelating MUD not only allows MAI cancellation, but also considers several IPI vectors, allowing interpath interference cancellation [6].

2.2. 2×2 Alamouti-like MIMO scheme

To mitigate the effects of fading and exploit diversity, the use of Space-Time Coding (STC)/MIMO schemes, like that proposed by Alamouti in References [9, 10], has been widely explored [11, 13, 14]. Within the 2×2 Alamouti-like MIMO scheme, the BS uses $M = 2$ transmit antennas and the MS also uses $N = 2$ receive antennas. As long as the spacing between antennas is large enough, the transmitted and received signals from each antenna undergo independent fading. Figure 2 shows a dual-antenna transmitter and receiver. The extension to higher number of receive antennas is straightforward. By considering transmit diversity of order higher than 2, we have ISI, although it results from only one symbol when detecting any other symbol, as shown in References [14, 15]. For this reason, the number of transmit antennas tends to be limited to 2.

The encoding performed by the proposed MIMO scheme is the same as applied by 2×1 STC initially proposed by Alamouti, as described in Reference [9] (Figure 2(a)). The additional receive antenna is used to provide receive diversity. In the 2×2 Alamouti-like MIMO scheme decoding, two 2D_RAKE receivers are considered [11], one associated to each receive antenna (a 2D_RAKE receiver is required to decode the Alamouti-like STC) [9].

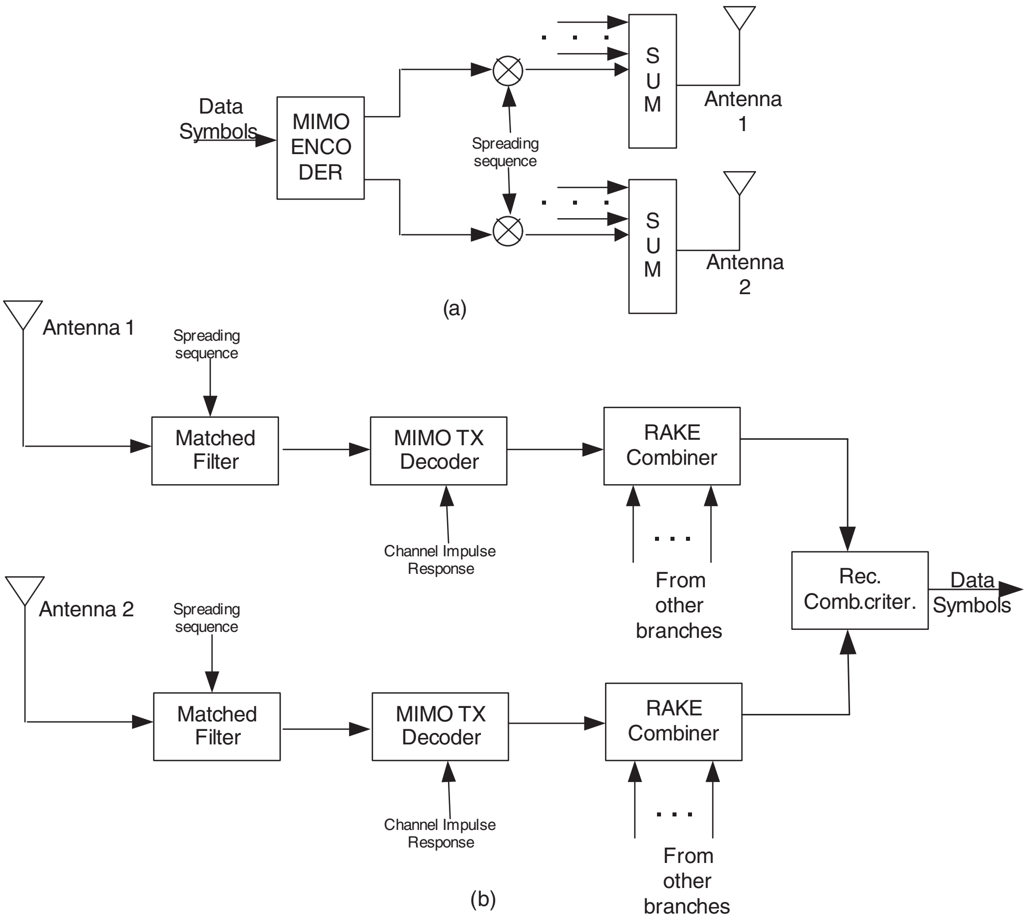

Figure 2. Alamouti-like 2 × 2. MIMO scheme: (a) Transmitter (encoder) and (b) Receiver (decoder).

This corresponds to each branch of the receiver (decoder) depicted in Figure 2(b). The receiver combiner criteria used may be the MSE based combiner, the Equal Gain Combiner (EGC), the MRC, etc. For a deeper analysis of the Alamouti-like MIMO scheme, the reader should relate to the system and signal models of References [7, 9].

In a multi-user environment, the frequency selectivity of the channel associated to the multipath propagation gives rise to MAI, even for synchronized W-CDMA systems employing orthogonal spreading sequences. In fact, even if just a single user was considered, the multipath environment originates IPI, whose effect is similar to the loss of orthogonality in multi-user environment. This is especially serious when larger constellations are employed (e.g. 16-QAM constellations). For this reason, the use of a MUD such as the PIC or Multipath PIC (MPIC) schemes is usually recommended to improve the performance [11].

It is known that Alamouti STC and MIMO schemes achieve better performances for channel profiles closer to uniform power profile, while schemes based on STD tend to perform better in channel profiles closer to single path [13]. Nevertheless, these former channel profiles originate a higher level of IPI and MAI [11, 16]. For this reason, the PIC [12] was selected to cancel the MAI in the Alamouti-like MIMO scheme. The block diagram of the PIC adapted to the Alamouti-like MIMO scheme is depicted in Figure 3, where a Clipped Soft Decision (CSD) is employed with growing subtractive coefficients [1]. The piecewise linear CSD is a good approximation of the hyperbolic tangent, which is applied to the matched filter statistics, independently to the in-phase and quadrature components [1]. The CSD increases the value of the subtractive coefficients as the precision of the MAI estimation is improved [7]. The Decorrelating MUD presented in Reference [6] was not associated to the Alamouti-like

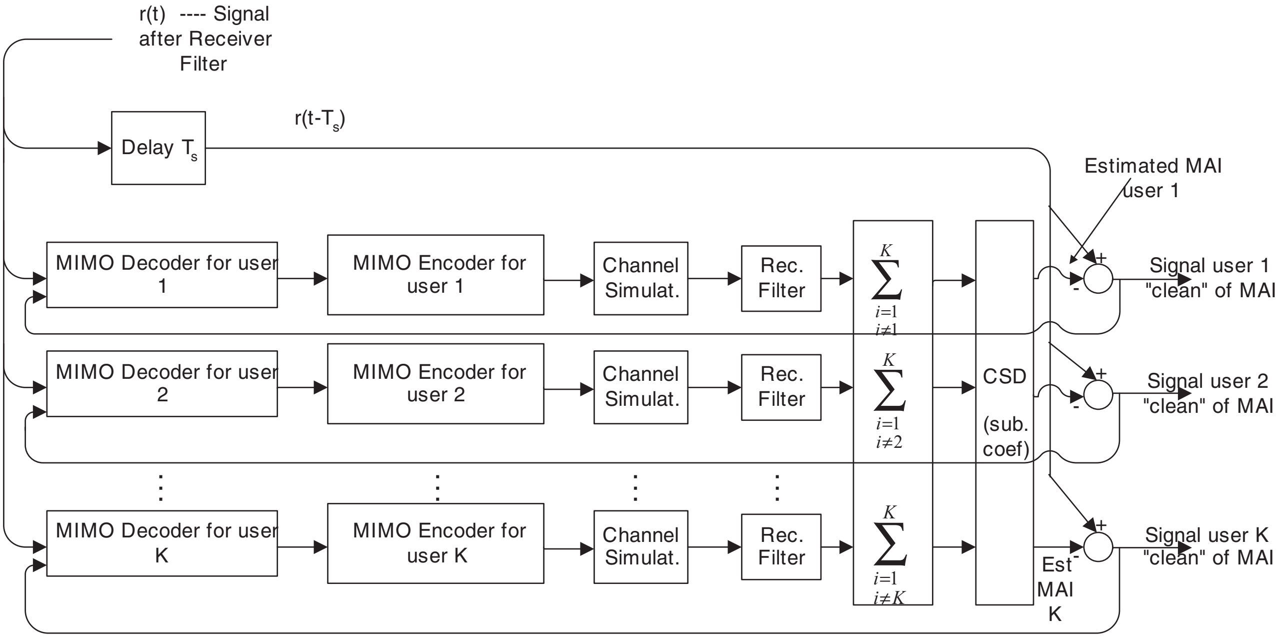

Figure 3. Scheme of the modified PIC detector.

MIMO scheme because it was designed to process signals originated from a single transmit antenna.

2.3. *V-BLAST MIMO scheme for W-CDMA signals with frequency selective fading*

Spatial Multiplexing (SM) schemes employ multiple antennas at both the transmitter and receiver, and send independent data streams over the individual transmit antennas. The data streams are separated by an interference cancellation type of algorithm. In this context, the number of receive antennas should not be lower than the number of transmit antennas. With SM schemes, the overall data rate can be increased significantly (it is proportional to the number of transmit antennas) while maintaining the spectral occupation. A well-known example of an SM scheme is the Bell Labs Layered Space-Time (BLAST) scheme. Nevertheless, due to the multipath propagation, W-CDMA channels are typically subject to frequency-selective fading. For this reason, conventional Vertical-BLAST (V-BLAST) detection techniques are not suitable for W-CDMA based MIMO systems, since they were originally proposed for flat fading scenarios [2, 3].

Figure 4 presents a generic diagram of the V-BLAST MIMO scheme. As depicted in Figure 5, two different V-BLAST MIMO schemes can be considered: scheme 1 and scheme 2 [2, 7]. Scheme 1 (Figure 5(a)) directly allows an increase in the data rate whose increase rate corresponds to the number of transmit antennas. Scheme 2 (Figure 5(b)) allows the exploitation of a higher diversity order, without increase in data rate.

In case of scheme 2, the transmit diversity combining is performed using any combining algorithm, preferably the MSE-based combining algorithm [7]. Antenna switching is performed at a symbol rate, where the red dashed lines represent the signal path at even symbol periods, in the case of two transmit antennas. Output signals are then properly delayed and combined to provide diversity. Therefore, contrary to scheme 1, the described scheme 2 is not an SM scheme.

In this subsection, the V-BLAST MIMO scheme is considered for W-CDMA systems. For this purpose, we consider a V-BLAST detector suitable for multipath frequency-selective channels, where the individual detection of each path is performed using a single Decorrelator

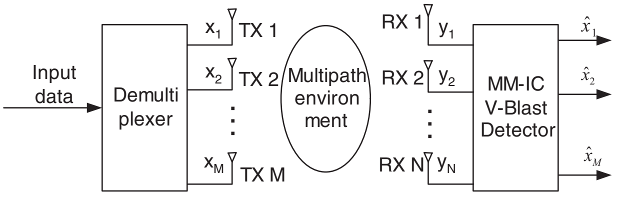

Figure 4. Generic diagram of the $M \times N$ V-BLAST MIMO scheme.

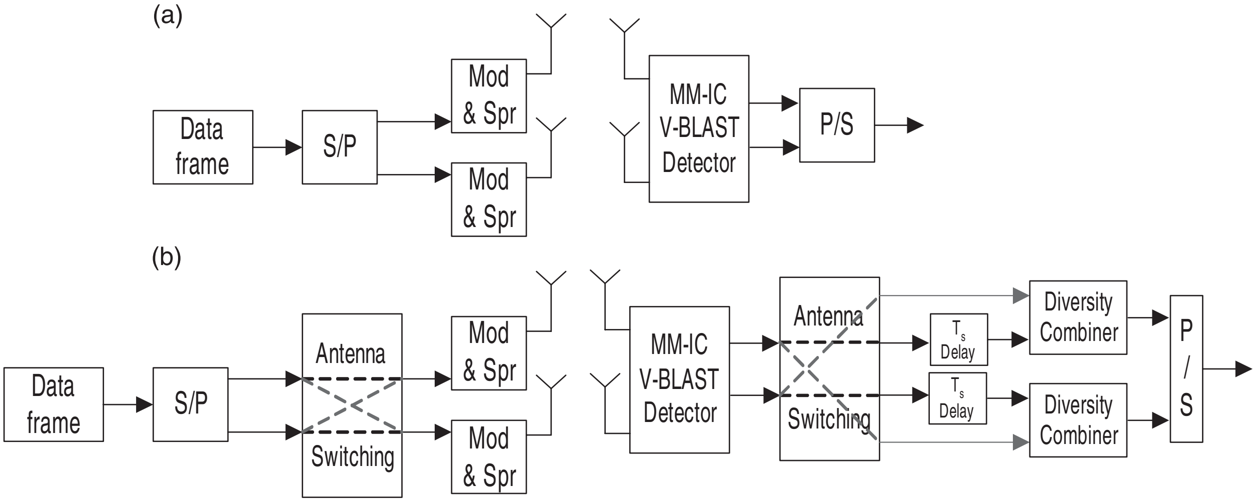

Figure 5. Diagram of the 2 × 2 V-BLAST MIMO alternatives. (a) scheme 1 and (b) scheme 2.

(instead of a RAKE receiver), and the resulting signals are combined through an MSE-based multipath combining algorithm [7, 8]. As it is usually considered for V-BLAST MIMO schemes, the current scheme is equipped with M transmit and N receive antennas, with $N \geqslant M$.

The detection algorithm of a conventional V-BLAST system consists of a linear nulling and Successive Interference Cancellation (SIC) process to estimate the N transmitted symbols from the received signal. The signal with the highest Signal to Noise plus Interference Ratio (SNIR) is first detected using a linear nulling process such as zero-forcing (ZF) or Minimum Mean Square Error (MMSE) [2]. The detected symbol is regenerated, and the corresponding signal portion is subtracted from the received signal. This cancellation process results in a modified received signal, with fewer interfering signal components left. This process is repeated, until all N symbols are detected.

It can be understood that the described conventional V-BLAST detection algorithm based on the nulling algorithm combined with a SIC is not adequate for W-CDMA transmission over multipath frequency selective channels, since the 'best antenna' (most powerful) differs from path to path [3]. For this reason, it is preferable to detect signals without regarding its SNIR. Since, with this non-optimum

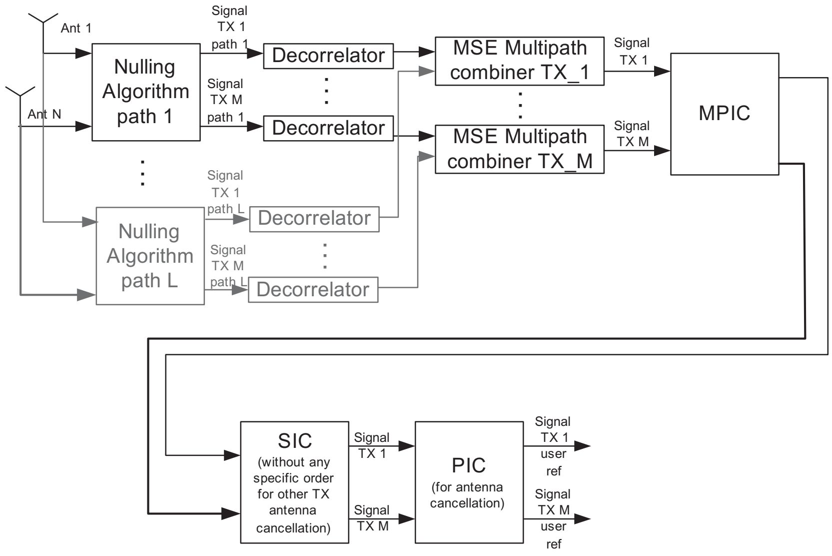

Figure 6. Generic scheme of the $M \times N$ MM-IC V-BLAST MIMO detector.

nulling sequence, the detection with the SIC is not optimum, the proposed Multipath Multipass Interference Cancellation (MM-IC) detector implements a multipass PIC externally to remove interferences from the previous iterations of the SIC.

Due to high sensitiveness of the conventional detector to IPI, the proposed MM-IC V-BLAST detector [7] incorporates an MPIC, an iterative SIC and a PIC, besides the nulling algorithm, into the conventional V-BLAST detection. This can be seen from Figure 6.

This sub-optimal subtractive detector considers the individual detection of each path using a single decorrelator, the multipath combining being performed by an MSE based combining algorithm. This results from the fact that the conventional MRC combining algorithm of the RAKE receiver is far from optimum in the case of the multipath V-BLAST detection. With this approach, the V-BLAST scheme can be applied to multipath frequency selective fading channels, while keeping the ability of W-CDMA signals to provide multipath diversity. The detailed description of the MM-IC detector can be found in Reference [7].

3. NEW PROPOSED MIMO PRE-PROCESSING SCHEME

If the CIR associated to different MS receivers is available at the BS side (as in slow-varying, closed loop systems or in Time Division Duplex (TDD) networks), we can employ pre-processing schemes at the transmitter (BS) so as to reduce the receiver complexity and/or improve system performance. In this paper, we consider the downlink transmission within W-CDMA systems.

A pre-processing scheme was applied in References [17, 18] to a single-path propagation model, allowing the exploitation of Space Division Multiple Access (SDMA) in the downlink. It was assumed that the number of transmit antennas at the BS side was higher than the number of MS ($M > K$, with K denoting the number of MSs), each one having a single receive antenna. In Reference [19] a different pre-processing technique was considered, where a Singular Value Decomposition (SVD) was employed for channel inversion.

Contrary to Reference [19], this paper considers a W-CDMA system and a multi-user scenario, therefore including multiple access interference. Furthermore, the calculation of the pre-processing coefficients considers a different approach. The proposed pre-processing technique used in the downlink transmission allows performance improvement without increasing MS complexity (e.g. without the use of either a RAKE receiver or a MUD). The generic diagram of the proposed scheme is depicted in Figure 7.

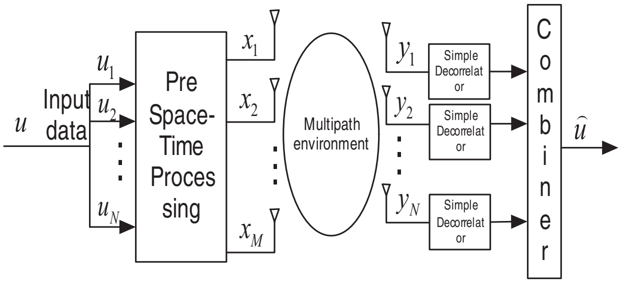

Figure 7. Proposed pre-processing scheme for MIMO channel.

The signal processing requirements inherent to the use of MIMO techniques in frequency-selective, multipath propagation channels, as is the typical case of W-CDMA systems, are much higher than for flat fading channels. If MIMO schemes are combined with post-processing methods, we can perform the antenna separation for each propagation path (i.e. we can define a RAKE-type receiver for MIMO systems) [10, 11]. For pre-processing schemes, the situation is much more complex, since it is not possible to directly pre-process the different paths, at least in the time domain. For this reason, we will perform the pre-processing in the frequency domain.

Our pre-processing technique assures that the several multipaths arrive the receiver superimposed and in phase, allowing the exploitation of multipath diversity, even by employing a simple decorrelator at the receiver.

Considering the signals depicted in Figure 7, the received signal $y_n^{(k)}(t)$ at the nth receive antenna of the kth MS is expressed as

$$y_n^{(k)}(t) = \sum_{m=1}^{M} x_m^{(k)}(t) * h_{n,m}^{(k)}(t) + z_n^{(k)}(t) \tag{1}$$

($*$ denotes the convolution operation), where $z_n^{(k)}(t)$ denotes the Gaussian channel noise (with zero mean and variance σ_n^2) seen at the nth receive antenna of the kth MS, $x_m^{(k)}(t)$ denotes the signal transmitted to the kth MS by mth antenna of the BS. The impulse response of the multipath channel between the mth transmit antenna of the BS and the nth receive antenna of the kth MS is given by

$$h_{n,m}^{(k)}(t) = \sum_{l=1}^{L} h_{n,m,l}^{(k)} \delta\left(t - \tau_{n,m,l}^{(k)}\right), \tag{2}$$

where $h_{n,m,l}^{(k)}$ is the complex gain associated to the lth multipath and $\tau_{n,m,l}^{(k)}$ is the corresponding delay.

The time domain signal at the output of the pre-processor is given by

$$x_m^{(k)}(t) = \sum_{n=1}^{N} u_n^{(k)}(t) * p_{m,n}^{(k)}(t) \tag{3}$$

where $p_{m,n}^{(k)}(t)$ is the pre-processing filter associated to pre-processing link between the nth data stream and the mth transmit antennas.

For the computation of $p_{m,n}^{(k)}(t)$, let us first consider a flat channel where $h_{n,m}^{(k)}(t) = \alpha_{n,m}^{(k)} e^{j\theta_{m,n}}(k)\delta(t-\tau)$ (i.e. there is a single path between each transmit and receive antenna and $\tau_{n,m} = \tau$). In this case, the pre-processor is such that $y_n^{(k)}(t) = u_n^{(k)}(t-\tau) + z_n^{(k)}(t)$ (i.e. the pre-processor inverts the MIMO channel coefficients). This means that, for $M \geqslant N$, the transmitted signal would be $x_m^{(k)}(t) = \sum_{n=1}^{N} u_n^{(k)}(t) p_{m,n}^{(k)}$, where the coefficients $p_{m,n}^{(k)}$ are obtained using 'channel inversion and regularization' [17, 18] and where $u_n^{(k)}(t) = u^{(k)}(t)$ $(n = 1 \ldots N)$, i.e. the same signal is applied to the input of the several branches of the pre-processor.

However, for W-CDMA signals within a multipath channel environment, the 'MIMO channel inversion' is no longer straightforward; at the BS side there is a lower degree of freedom related to the post-processing carried out by the MS, where the post-processing approach is able to process and combine the several multipaths to provide multipath diversity. Therefore, to jointly achieve the MIMO pre-processing for the multipath channel environment, we will consider a frequency domain approach. Hence, Equation (1) becomes

$$Y_n^{(k)}(f) = \sum_{m=1}^{M} X_m^{(k)}(f) \cdot H_{n,m}^{(k)}(f) + Z_n^{(k)}(f) \tag{4}$$

where $X_m^{(k)}(f) = \mathcal{F}[x_m^{(k)}(t)]$ and $H_{n,m}^{(k)}(f) = \mathcal{F}[h_{n,m}^{(k)}(t)]$ ($\mathcal{F}[x]$ denotes 'Fourier transform' of x). In the frequency domain, the matrix-vector representation is given by

$$\mathbf{Y}^{(k)}(f) = \mathbf{H}^{(k)}(f) \cdot \mathbf{X}^{(k)}(f) + \mathbf{Z}^{(k)}(f) \tag{5}$$

where $\mathbf{Y}^{(k)}(f)$ and $\mathbf{Z}^{(k)}(f)$ are size N-column vectors, $\mathbf{H}^{(k)}(f)$ is an $N \times M$ matrix whose element of the nth line and mth column is $H_{n,m}^{(k)}(f) = \mathcal{F}(h_{n,m}^{(k)}(t))$ and $\mathbf{X}^{(k)}(f)$ is a size-M column vector. By performing this operation, we have transformed a convolution operation into a multiplication (performed at the frequency sample level), making the previous difficult to pre-process signals subject to multipaths easier, although a delay is introduced in the received signal. Now, a similar approach of the single-path will be followed, but in the frequency domain, instead of time domain.

As can be seen from Figure 7, each symbol u is repeated over the several N branches $(u_1(t) = u_2(t) = \cdots = u_N(t))$. Moreover, signals from different receive antennas are then combined to provide diversity, using an MRC or MSE based combiner algorithm.

Now, the pre-processing scheme intends to force the following relation:

$$\mathbf{Y}^{(k)}(f) = \mathbf{U}^{(k)}(f) + \mathbf{Z}^{(k)}(f) \tag{6}$$

Therefore, the pre-processed signals to be transmitted should follow the relationship:

$$\mathbf{X}^{(k)}(f) = \mathbf{P}^{(k)}(f) \cdot \mathbf{U}^{(k)}(f) \tag{7}$$

where $\mathbf{P}^{(k)}(f)$ is an $M \times N$ matrix with the element of the mth line and nth column given by $P_{m,n}^{(k)}(f)$, i.e., the frequency response of the pre-processor associated to the mth transmit and nth receive antennas, and $\mathbf{U}^{(k)}(f)$ has the same size as $\mathbf{Y}^{(k)}(f)$. This originates:

$$\begin{aligned}\mathbf{Y}^{(k)}(f) &= \mathbf{H}^{(k)}(f) \cdot \mathbf{X}^{(k)}(f) + \mathbf{Z}^{(k)}(f) \\ &= \underbrace{\mathbf{H}^{(k)}(f) \cdot \mathbf{P}^{(k)}(f)}_{\mathbf{I}_N} \cdot \mathbf{U}^{(k)}(f) + \mathbf{Z}^{(k)}(f)\end{aligned} \tag{8}$$

where $\mathbf{I}_N$ is the identity matrix of size $N \times N$. Considering equations (8) and (6) the solution would be $\mathbf{P}^{(k)}(f) = [\mathbf{H}^{(k)}(f)]^{-1}$. However, $[\mathbf{H}^{(k)}(f)]^{-1}$ cannot be directly computed when $\mathbf{H}^{(k)}(f)$ is not a square matrix ($M > N$). Therefore, the inversion matrix can be computed using the linear least-mean square algorithm [20]. Considering the frequency domain approach, the computation of the frequency domain pre-processing coefficients becomes

$$\mathbf{P}^{(k)}(f) = \left[\mathbf{H}^{(k)}(f)\right]^H \cdot \left\{\mathbf{H}^{(k)}(f) \cdot \left[\mathbf{H}^{(k)}(f)\right]^H\right\}^{-1} \tag{9}$$

where H denotes 'Hermitian operation'.

A power constraint should be imposed to the signals to be transmitted such that $E\|x^{(k)}\|^2 = 1$ (considering normalized transmitted power), assuring that the total power of the transmitted signal corresponding to the kth user over the M antennas is not subject to a variation as a function of channel coefficients.

By pre-processing the signal with such filters, we are forcing the several multipaths to arrive at the single Decorrelator receiver superimposed and in phase.

The proposed pre-processing approach is suitable for channels selective in the frequency, being able to exploit multipath diversity, even without a Rake in the receiver (low complexity MS). Another advantage comes from the fact that the number of receive antennas is smaller than the number of transmit antennas, allowing MS of lower dimensions related to other post-processing MIMO schemes [8]. In addition, the new proposed MIMO pre-processing scheme requires a much simpler receiver (single decorrelator), as compared to the post-processing schemes described in Section 2.

4. PERFORMANCE RESULTS

In this section we present a set of performance results, obtained by simulation, concerning the proposed pre-processing technique, as well as other MIMO techniques for W-CDMA systems. In our simulations we considered the downlink of W-CDMA using Quadrature Phase Shift Keying (QPSK) modulation in a frequency selective Rayleigh fading channel. Both the Pedestrian A and the Vehicular A propagation models of Third Generation Partnership Project (3GPP) [21] were considered (see Table 1). Only uncoded Bit Error Rate (BER) performances were considered. We adopted Walsh–Hadamard spreading sequences with spreading factor $S_{\mathrm{F}} = 16$. The chip period is $Tc = 1/3.84\,\mu\mathrm{s}$ and the number of users can be either $K = 4$ or $K = 15$. The channels associated to different antennas are uncorrelated and perfect channel knowledge is assumed at the receiver and the transmitter (for the MIMO pre-processing case). For all schemes, an MSE-based receiver combiner was assumed to combine the signals from different receive antennas.

Instead of a RAKE receiver, the proposed MIMO pre-processing approach (in the figures entitled pre-MIMO, which corresponds to the scheme described in Section 3) considers a single decorrelator associated to each receiver antenna, and thus, its detection process is very simple. The MIMO pre-processing filters $p_{m,n}^{(k)}(t)$ can be digitally implemented by a set of tap-delay lines (TDLs). These TDLs have $g = 2$ samples per chip, and the impulse responses were truncated to the limit $3(\tau_{n,m}^{(k)})_{\max}$.

Table 1. Propagation conditions for Vehicular A and Pedestrian A multipath fading environments [22].

ITU vehicular speed 30 km/h		ITU Pedestrian A speed 3 km/h	
Relative delay (ns)	Relative mean power (dB)	Relative delay (ns)	Relative mean power (dB)
0	0	0	0
310	−1.0	110	−9.7
710	−9.0	190	−19.2
1090	−10.0	410	−22.8
1730	−15.0		
2510	−20.0		

4.1. $M \times N$ *MIMO pre-processing scheme*

Figure 8 presents the simulated results obtained with four users, for the Pedestrian A propagation model of 3GPP for the MIMO pre-processing scheme, which is described in Section 3. Comparing the performances obtained with the 4×1 Pre-MIMO with the 2×2 Pre-MIMO, it is observed that the latter configuration achieves better results due to higher receive diversity order. The 2×2 Pre-MIMO scheme may also be seen as an alternative to the 2×2 Alamouti-like MIMO scheme [11]. The same happens with the 4×2 Pre-MIMO scheme related to the 8×1 Pre-MIMO scheme. It can be generically stated that the advantage of MIMO systems is significant in terms of spectral efficiency. As an example, for a large $M = N$, $\mathbf{HH}^{H}/N \rightarrow \mathbf{I}_N$, so the spectral efficiency C is asymptotic to $C \approx N\log_2[1 + \mathrm{SNIR}]$ [bit/s/Hz] [7] (where $\mathbf{H}$ stands for the matrix containing the channel coefficients). From these results it can be stated that it is beneficial to also consider diversity at the receiver side. However, if it is not possible to provide receive diversity, the selection of a configuration with only transmit diversity also achieves a performance improvement related to lower diversity orders.

As can be seen, due to the diversity order provided, the proposed scheme with two transmit and a single receive antenna (2×1 Pre-MIMO scheme) achieves a performance improvement over the Single Input Single Output (SISO) scheme (1×1 Only RAKE) for the Pedestrian A propagation model. This scheme may also be seen as an alternative to the Selective Transmit Diversity with two antennas or Space Time Transmit Diversity with two

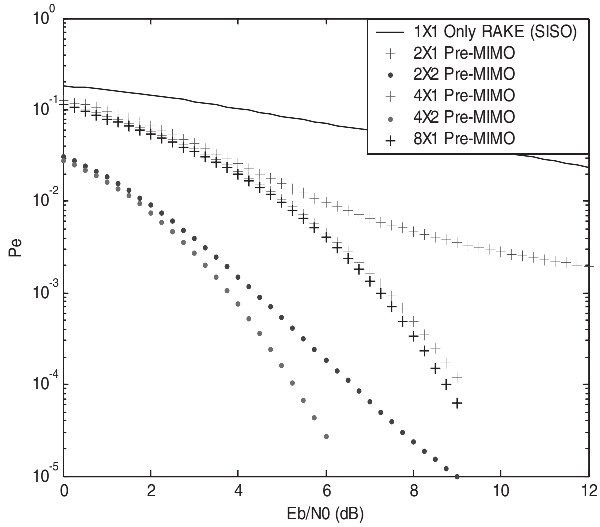

Figure 8. BER performance of the Pre-MIMO with four users for the Pedestrian A (with or without receive diversity).

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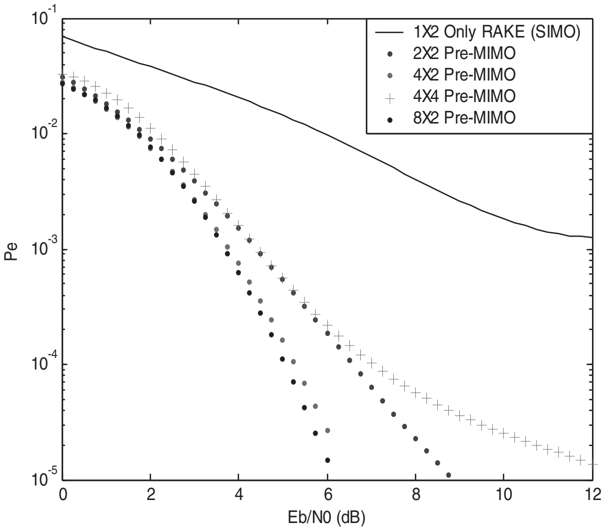

Figure 9. BER performance of the Pre-MIMO with four users for the Pedestrian A (with receive diversity).

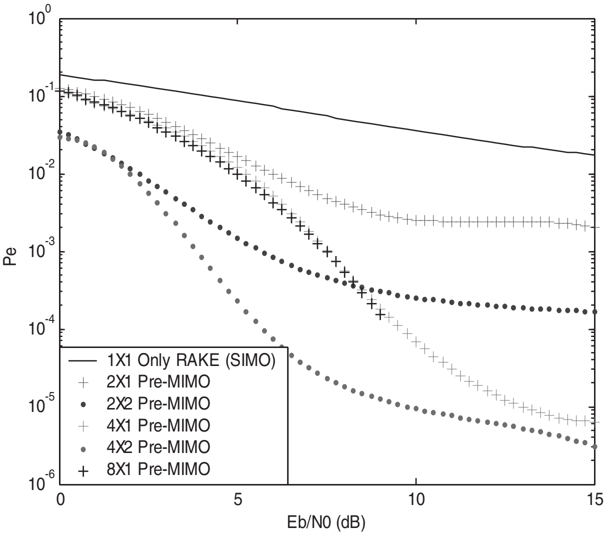

Figure 10. BER performance of the Pre-MIMO with 15 users for the Pedestrian A (with or without receive diversity).

antennas [15]. As expected, for the single receiver antenna case, the performance improves as the transmit diversity order is increased.

It can also be concluded that, in this scenario, the performance improvement achieved with the 8 × 1 Pre-MIMO scheme related to the 4 × 1 Pre-MIMO scheme is low. This happens because this propagation model presents the low level of multipath interference, and thus, the performance improvement achieved with the 4 × 1 Pre-MIMO scheme is already good enough.

Figure 9 presents similar simulated results as those presented in Figure 8 but considering always receive diversity, i.e. $N > 1$. As can be seen, all configurations present a performance improvement over the Single Input Multiple Output (SIMO) scheme (two receiver antennas associated to two RAKE receivers, whose outputs are combined using an MSE based combiner). It is also seen that the 2 × 2 Pre-MIMO scheme outperforms the 4 × 4 Pre-MIMO. This occurs because the pre-processing coefficients calculated using equation (9) start presenting singularities for $M = N$, these singularities being more likely to occur for higher number of antennas.

As for the case with a single antenna at the receiver, the performance improvement from 4 × 2 Pre-MIMO to 8 × 2 Pre-MIMO is small, once again due to the fact that the level of multipath interference present is low.

Figures 10 and 11 present results similar to those presented in the two previous graphs, but considering 15 users. As expected, due to the higher level of MAI, these scenarios lead to worse performances. A difference can be observed when we compare Figure 10 with Figure 8. In fact, in this new scenario the 8 × 1 and 4 × 1 Pre-MIMO schemes start performing better than the 2 × 2 Pre-MIMO scheme for E_b/N_0 values higher than 8.5 dB. This happens because the receive diversity provided by the 2 × 2 Pre-MIMO scheme suffers more of MAI, since a combination of two interfered signals is performed. Furthermore, the 4 × 1 Pre-MIMO scheme also has the same overall number of antennas, but only at the transmitter side, and hence, the level of interferences is not present with so much strength, leading to better performance than the 2 × 2

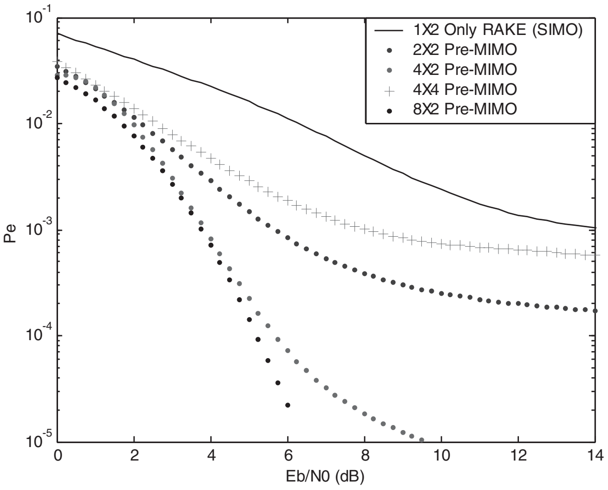

Figure 11. BER performance of the Pre-MIMO with 15 users for the Pedestrian A (with receive diversity).

Pre-MIMO scheme. From this, it can be concluded that, for the MIMO pre-processing scheme, the receive diversity tends to be a better choice than transmit diversity, except for higher levels of MAI and higher levels of E_b/N_0.

4.2. $M \times 2$ MIMO pre-processing vs other $M \times 2$ MIMO schemes

Let us assume that the MS can accommodate only two receive antennas. In this case, it is reasonable to make a comparison among the proposed $M \times 2$ MIMO pre-processing (Pre-MIMO) scheme (as introduced in Section 3), the 'Only RAKE' with two receive antennas (SIMO), the BSTD with two receive antennas (with and without the Decorrelating MUD), and the 2×2 MIMO post-processing schemes: Alamouti scheme (with and without the PIC) and V-BLAST scheme 2.

Regarding the $M \times 2$ Pre-MIMO scheme, it was shown in the previous subsection that the performance achieved, for the Pedestrian A, with the 4×2 Pre-MIMO configuration was very close to the other configurations with higher diversity order (8×2). Furthermore, due to singularities, the 2×2 Pre-MIMO configuration can have poor performance. For these reasons, the 4×2 Pre-MIMO scheme is considered in the present comparison for the Pedestrian A, since it already achieves a good order of diversity. However, for the Vehicular A, the 8×2 Pre-MIMO configuration is considered due to the gain achieved, related to the 4×2 Pre-MIMO configuration [7]. The Alamouti-like MIMO scheme did not consider the 4×2 configuration since it is based on space-time coding and it was seen that these codes with four transmit antennas generate ISI in the decoding process.

In Reference [4], a comparison was performed among the BF using eight antenna elements and the BSTD considering two sub-beams of four antenna elements each. It was shown that, in most propagation conditions and multi-user scenarios, the BSTD tends to outperform the BF. Therefore, only the BSTD with such a configuration is considered here. The BSTD with two receive antennas may also be seen as a MIMO scheme, since it is composed of several antennas at the transmitter and receiver. As it was mentioned, some additional results consider the combination of the Decorrelating MUD with the BSTD.

The V-BLAST MIMO scheme considered in this subsection is scheme 2 (scheme 1 has higher spectral efficiency, but worse performance). In the case of the 2×2 Alamouti-like MIMO scheme two 2D_RAKE receivers are considered [7, 11], one 2D_RAKE receiver associated to each receive antenna. The PIC with three levels of cancellation were considered associated to the 2×2 Alamouti-like MIMO scheme. Three levels of cancellation were considered for the PIC because the performance achieved was better than that obtained with two levels of cancellation, but almost the same performance as that reached with four levels of cancellation (and with one less symbol period of delay) [16].

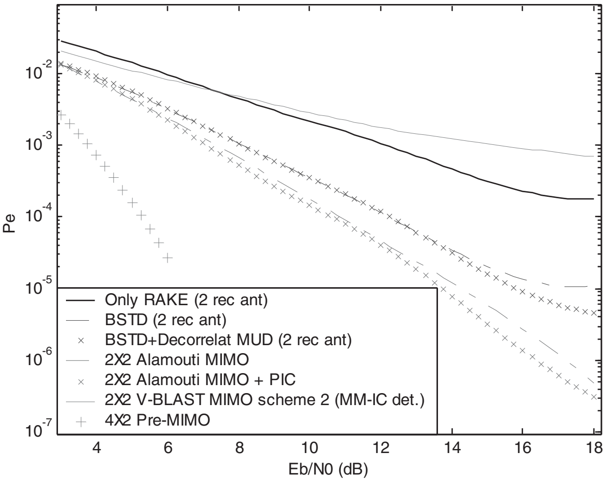

Figure 12. BER performance of the several proposed schemes with two receive antennas or MIMO schemes and four users, for the Pedestrian A.

Figure 12 shows the performance with four users, for the Pedestrian A channel. All the schemes achieve a performance improvement relative to the 'Only RAKE' (SIMO), except the V-BLAST scheme 2, which only outperforms the 'Only RAKE' for lower levels of E_b/N_0. Since we consider four users and the Pedestrian A generates low level of multipath interference and low level of MAI, the performance obtained with the BSTD is worse than that of the Alamouti-like MIMO scheme and the 4×2 Pre-MIMO scheme, because the latter schemes provide a higher diversity order. The best overall performance is achieved by the 4×2 Pre-MIMO scheme.

The 2×2 Alamouti-like MIMO scheme performs well because the level of MAI is low and the level of multipath diversity (captured by the RAKE receiver) is also low. Therefore, the diversity provided by the MIMO leads to a good performance improvement.

The performance improvement of BSTD or Alamouti-like MIMO scheme jointly with the corresponding MUD, related to the corresponding schemes without MUD, is moderate. It occurs because the considered scenario introduces low level of MAI.

The scheme that achieves the best overall performance is the new introduced 4×2 Pre-MIMO scheme, which is followed by the 2 × 2 Alamouti-like MIMO scheme combined with the PIC. This happens because the Pre-MIMO scheme presents a higher order of diversity. Moreover, the Pre-MIMO scheme requires lower level of complexity from the MS since only a simple decorrelator is required associated to each receive antenna (and an MSE based receiver combiner). Since Figure 12 considers four users with the Pedestrian A, low level of MAI occurs, which also contributes for the good performances achieved. However, since the Pre-MIMO requires the knowledge of CIR of all users at the BS side, namely the channel attenuations, phase shifts and delays of the several multipaths, and since errors may occur in the feedback link from the MS to the BS, these optimum performances may be degraded in real scenarios. Furthermore, it requires the assignment of some bandwidth in the uplink to assure the transmission of CIR with the required rate (depending on the rate of variation of the channel). Nevertheless, this information also tends to be required for advanced downlink power control purposes.

It is also worth noting that the considered 4 × 2 Pre-MIMO scheme considers four transmit antennas at the BS side sufficiently spaced to assure uncorrelated signals (at each antenna of the MS). Therefore, the dimensions of the array considered in this case are higher than those considered in the BSTD (BF4 + BF4), since the latter considers two sub-beams of four antenna elements spaced $\lambda/2$. The spacing between the centre of the two sub-beamforming arrays of the BSTD should be sufficient to assure uncorrelated signals or, at least, to reach a good level of cross-correlation coefficients.

When one imposes the constraint that the MS receiver cannot accommodate the MUD complexity, the best performance keeps being achieved by the 4 × 2 Pre-MIMO scheme followed by the Alamouti-like MIMO scheme (without the PIC).

Figure 13 shows the BER obtained with 15 users for the Pedestrian A. As before, when there are no constraints regarding the installation of two receive antennas, the 4 × 2 Pre-MIMO scheme achieves the best overall performance. Since the pre-processing is receiver oriented, it also allows the exploitation of SDMA, which randomises the loss of orthogonality to which different spreading sequences (corresponding to different users) are subject to. Therefore, it implicitly tends to decrease the level of interferences. In this scenario, even with higher level of MAI, the new introduced Pre-MIMO scheme outperforms the other schemes, even those that consider a MUD in the receiver.

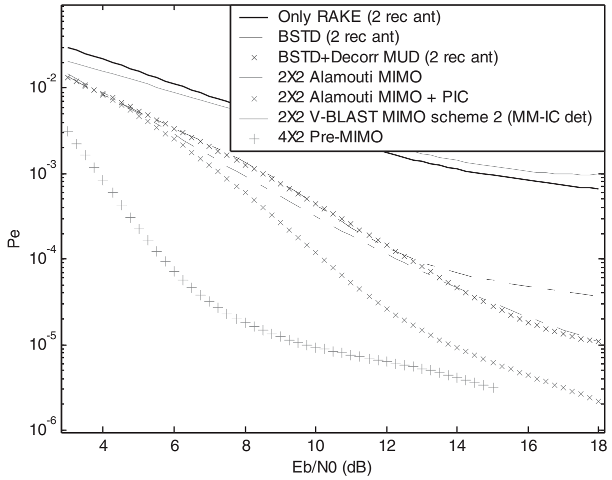

Figure 13. BER performance of the several proposed schemes with two receive antennas or MIMO schemes and 15 users, for the Pedestrian A.

The Alamouti-like 2 × 2 MIMO scheme combined with the PIC is the second scheme that achieves the best performance. This happens because the diversity order provided by the multipath channel is low (Pedestrian A) which makes the diversity exploitation provided by the MIMO an important issue. In addition, since the Pedestrian A propagation model originates low level of MAI, the use of the BSTD with its ability to mitigate MAI is not the most effective solution for this environment.

Finally, the performance obtained with the V-BLAST scheme 2 is quite low, approximating the ‘Only RAKE’ case.

Figures 14 and 15 present the BER performance obtained with 4 and 15 users, respectively, for the Vehicular A.

Regarding the four users case (Figure 14), the 8 × 2 Pre-MIMO scheme achieves the best overall performance. The 4 × 2 Pre-MIMO also outperforms the other schemes but

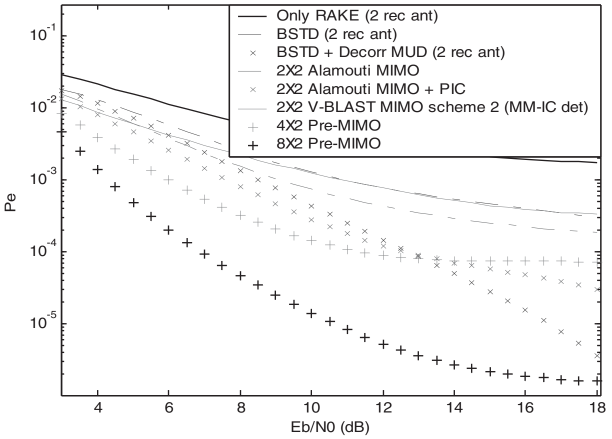

Figure 14. BER performance of the several proposed schemes with two receive antennas or MIMO schemes and four users, for the Vehicular A.

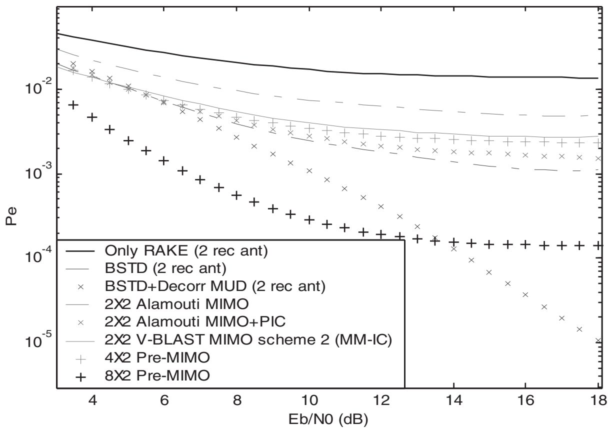

Figure 15. BER performance of the several proposed schemes with two receive antennas or MIMO schemes and 15 users, for the Vehicular A.

only for E_b/N_0 levels lower than 13 dB [$P_e = 10^{-4}$]. Nevertheless, the BSTD combined with the Decorrelating MUD achieves, for higher levels of E_b/N_0, better performance than the 4×2 Pre-MIMO scheme and the 2×2 Alamouti-like MIMO combined with the PIC. This happens for several reasons, namely for the following reasons:

- Vehicular A propagation model has a higher number of multipaths, which originates a higher level of MAI (for the same number of users, related to Pedestrian A), and therefore, the BSTD already cleans a part of the MAI with its beamforming component;
- The diversity order provided by the multipath channel is already high (since the BSTD uses a RAKE receiver), making the system interference dependent, originating that the increase in diversity order provided by the other MIMO schemes not determinant to improve the performance;
- The PIC of the Alamouti-like MIMO scheme starts presenting propagation errors, due to multipath interference;
- The Decorrelating MUD also cancels the interpath interference [6], which is an important issue in the case of the Vehicular A propagation model.

When it is considered that the MS cannot accommodate a MUD, the $M \times 2$ Pre-MIMO scheme with $M = 4$ is already enough to achieve better performance than the other schemes. However, due to possible feedback errors that may occur, this performance may be lowered related to that presented in this graph.

When Vehicular A with 15 users is considered (Figure 15), the scheme that achieves the best performance is the 8×2 Pre-MIMO scheme for E_b/N_0 levels lower than 14 dB [$P_e = 10^{-4}$]. For higher levels of E_b/N_0 the BSTD combined with the Decorrelating MUD performs better. This happens because this scenario presents a high level of MAI and the BSTD cancels part of it. Moreover, the Decorrelating MUD also cancels part of the remaining MAI, improving its performance.

By performing a comparison among schemes without the MUD, the 8×2 Pre-MIMO scheme is the one that achieves the best overall performance. It is followed by the BSTD, due to its inherent ability to combat the MAI, which performs better than the 2×2 Alamouti-like MIMO scheme. Furthermore, the V-BLAST MIMO scheme 2 outperforms the Alamouti-like MIMO scheme. From all of this, it can be concluded that the MM-IC detector makes the V-BLAST MIMO scheme 2 achieve a good performance when in the presence of a higher level of multipath interference, as well as higher number of users.

Looking at the $M \times 2$ Pre-MIMO scheme, it is clear that it tends to achieve the best performance, but it requires a higher number of transmit antennas for the Vehicular A ($M = 8$).

On the other hand, when in the presence of a propagation environment with lower level of multipath diversity (Pedestrian A), the Pre-MIMO scheme with four transmit antennas has better performance than the other schemes. For these reasons, one may conclude that the $M \times N$ Pre-MIMO scheme is a good option to achieve good performances. If CIR cannot be considered at the BS side with accuracy, the BSTD (if possible combined with the Decorrelating MUD) is also a good option to achieve good performances.

5. CONCLUSIONS

In this paper, we introduced and evaluated a new pre-processing technique for the downlink of W-CDMA systems. To cope with multipath frequency selective channels, we adopted a frequency-domain approach to compute the coefficients of the pre-processing filter. It was assumed that the BS has M transmit antennas and that the MS has N receive antennas, with $M \geqslant N$, which allows a MS of lower size, related to other MIMO schemes. It was also shown that the MIMO pre-processing scheme also allows a MS of lower size, due to the use of a low complexity receiver (which consists of a single Decorrelator), instead of the more common and complex receiver structure normally considered for the MIMO post-processing schemes.

It was shown that the new introduced MIMO pre-processing scheme tends to improve its performance with the increase in transmit or receive diversity order.

Considering the $M \times 1$ MIMO pre-processing configuration, this scheme may also be seen as an alternative to the Selective Transmit Diversity or Space Time Transmit Diversity [15]. The $2 \times N$ Pre-MIMO ($N = 1, 2$) scheme may also be seen as an alternative to the $2 \times N$ Alamouti-like MIMO scheme. It was also shown that the number of antennas needed to reach a gain needs to be higher for higher levels of multipath interference.

Assuming that the BS has $M \geqslant 2$ transmit antennas and that the MS has space enough to accommodate $N = 2$ receive antennas, the new introduced MIMO Pre-processing scheme (Pre-MIMO) was compared, considering W-CDMA signals, with other schemes, namely with the BSTD and with post-processing schemes (Alamouti-like MIMO scheme and V-BLAST scheme).

It was also shown that the best performance tends to be achieved by the $M \times 2$ Pre-MIMO. This scheme is followed by the BSTD combined with the MUD, which also achieves good performance results. If downlink CIR cannot be considered at the BS side (transmitter) with accuracy, the BSTD (if possible combined with the Decorrelating MUD) is also a good option to achieve good performances. The BSTD only requires feedback information about the sub-beamforming that presents better conditions.

By imposing the MS receiver complexity as a constraint, and considering that it cannot accommodate a MUD, it was also shown that the MIMO pre-processing is, once again, the scheme that achieves the best overall performance in all scenarios and levels of E_b/N_0, namely due to its antenna and multipath diversity capabilities.

It is worth noting that both the new proposed MIMO pre-processing scheme and the BSTD are very promising schemes for the downlink of a W-CDMA system, without demanding an additional complexity from the MS. Nevertheless, the influence of feedback errors in the transmission from the MS into the BS of the downlink CIR in the MIMO pre-processing scheme performance may be considered as a future work. This restriction is not so serious in the case of TDD networks since the downlink and uplink CIR are highly correlated.

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