On Coordinated Multi-Point Transmission for Cellular Environments

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Abstract— Current and emergent services are demanding higher data rates, improved spectral efficiency and increased network capacity. To face these new requirements, it is important to find schemes able to reduce the effects of fading and to exploit new types of diversity.

Coordinated Multi-Point transmission (CoMP) comprises the coordinated transmission of signals from adjacent base stations (BS), and the corresponding reception from user equipments (UE). CoMP transmission is an important technique that can mitigate inter-cell interference, improve the throughput, exploit diversity and, therefore, improve the spectrum efficiency.

This paper performs a comparison between different multi-antenna techniques that can be employed in CoMP to achieve the requirements of the Fourth Generation Cellular Systems (4G).

1. INTRODUCTION

An important requirement of 4G systems is the ability to deliver a homogenous service, regardless the users' positions. Users located at the cell edge may experience a degradation of the Signal-to-Noise Ratio (SNR) due to inter-cell interference, additional path loss or limited BS transmit power. In these scenarios, Coordinated Multi-Point Transmission plays an important role, as it allows the exploitation of additional diversity or the delivery of a high and constant throughput, regardless the users' positions.

The basic concept of Multiple Input Multiple Output (MIMO) relies on the transmission of signals through multiple paths, between multiple transmit and multiple receive antennas.

Multi-antenna systems are used in order to push the performance or capacity/throughput limits as high as possible without an increase of the spectrum bandwidth, although at the cost of an obvious increase of complexity. In the case of frequency selective fading channel, different symbols suffer from interference from each other, whose effect is usually known as Intersymbol Interference (ISI). This effect tends to increase with the used bandwidth. By exploiting diversity, multi-antenna systems can be employed to mitigate the effects of ISI.

Instead of representing an additional interference level, the multiple paths of MIMO signals can be used as an advantage. Moreover, while in MIMO the multiple transmit or the multiple receive antennas are co-located, advanced cellular network architectures may also achieve the same level of diversity, but using antennas belonging to different base stations or relay nodes. Nevertheless, a certain level of synchronization or coordination is normally required between those stations.

The various multi-antenna configurations are referred to as Single Input Single Output (SISO), Multiple Input Single Output (MISO), Single Input Multiple Output (SIMO) or MIMO. The SIMO and MISO architectures are forms of receive and transmit diversity schemes, respectively. MIMO architectures can be used for combined transmit and receive diversity, for the parallel transmission of data or for spatial multiplexing. When used for spatial multiplexing, MIMO technology promises high bit rates in a narrow bandwidth. Therefore, it is of high significance to spectrum users. In this case, MIMO system considers the transmission of different signals from each transmit antenna element so that the receiving antenna array receives a superposition of all transmitted signals.

Most common CoMP techniques present the following configurations [1–3]:

- Space-Time Block Coding (STBC)
- Multi-layer Transmission

Although STBC is essentially a MISO system, the use of receive diversity makes it a MIMO, which corresponds to the most common configuration for this type of diversity. STBC based schemes focus on achieving a performance improvement through the exploitation of additional diversity, while keeping the symbol rate unchanged [2, 4]. On the other hand, multi-layer transmission and Space-Division Multiple Access (SDMA) belong to another group, entitled Spatial Multiplexing (SM), whose principles are similar but whose purposes are quite different. The goal of the MIMO based on multi-layer transmission scheme relies on achieving higher data rates in a given bandwidth, whose increase rate corresponds to the number of transmit antennas [1]. In this case, the number of receive antennas must be equal or higher than the number of transmit antennas. The increase of symbol rate is achieved by logically "steering" the receive antennas to each one (separately) of the transmit antennas, in order to receive the corresponding data stream [5, 6]. This is achieved through the use of the nulling algorithm.

1.1. Single-User MIMO and Multi-User MIMO

The MIMO techniques previously exposed are typically employed in the concept of Single-User MIMO (SU-MIMO). SU-MIMO considers data being transmitted from a single user into another individual user. An alternative concept is the Multi-User MIMO (MU-MIMO) where multiple streams of data are simultaneously allocated to different users, using the same frequency bands.

The approach behind MU-MIMO is similar to Space-Division Multiple Access (SDMA). Nevertheless, while SDMA is typically employed in the uplink (because the nulling algorithm requires higher number of antennas), the MU-MIMO can also be implemented in the downlink. This allows sending different data streams into different UE. In this case, instead of performing the nulling algorithm at the receiver side, the nulling algorithm is performed using a pre-coding approach at the transmitter side (BS). This is possible because the BS can accommodate a high number of transmit antennas and the UE can only accommodate a single or reduced number (lower) of receive antennas. In the downlink of a MU-MIMO configuration, the number of transmit antennas must be higher than the number of multiple data streams that is sent to multiple users, at the same time and occupying the same frequency bands (the opposite of the SDMA approach). In this configuration, the nulling algorithm is implemented at the transmitter side using a pre-processing algorithm such as Zero Forcing (ZF), Minimum Mean Square Error (MMSE), dirty paper coding, etc.. Alternatively, instead of implementing the above described spatial multiplexing principle, the MU-MIMO can be performed using the beamforming algorithm. In any case, MU-MIMO requires accurate downlink Channel State Information (CSI) at the transmitter side. Obtaining CSI is trivial using Time Division Duplexing (TDD) mode, being more difficult to be achieved when Frequency Division Duplexing (FDD) is employed. In FDD mode, CSI is normally obtained using a feedback link in the opposite direction.

Note that when the aim relies on achieving a performance improvement, a SU-MIMO is normally employed using an algorithm such as STBC. On the other hand, when the aim is to achieve higher through puts using a constrained spectrum, we have two options: in the downlink, the MU-MIMO is typically the solution; in the uplink, SDMA is normally employed.

It is worth noting that users located at the cell edge, served by MU-MIMO, may experience a degradation of the SNR due to inter-cell interference, inter-user interference[1], due to additional path loss or due to limited BS transmit power (which results from the use of a pre-coding). A mechanism that can be implemented to mitigate such limitation relies on employing a dynamic MIMO system, where MU-MIMO is employed everywhere, except at the cell edge. In this location, the BS switches into SU-MIMO using STBC, translating in a performance improvement [7] at the cost of a reduced throughput. Alternatively, base station cooperation is known as an effective mechanism which improves the performance at the cell edge, resulting in a more homogenous service quality, regardless the users' positions.

This paper is organized as follows: different MIMO systems possible for CoMP use are described in Section 2; in Section 3, a description about coordinated multipoint transmission is presented, while Section 4 presents a set of performance results; finally, Section 5 summarizes this paper.

2. MIMO CHARACTERIZATION

This section describes different multi-antenna techniques which can be used to improve the performance, spectral efficiency or to achieve an increased network capacity in CoMP.

2.1. Space-Time Block Coding

Although Space-Time Block Coding (STBC) is essentially a MISO system, the use of receiver diversity makes it a MIMO, which corresponds to the most common configuration for this type of

[1] Users that share the spectrum and that are separated by the MU-MIMO spatial multiplexing.

diversity. Transmit diversity (TD) techniques are particularly interesting for fading channels where it is difficult to have multiple receive antennas (as in conventional receiver diversity schemes). A possible scenario is the downlink transmission where the base station uses several transmit antennas and the mobile terminal only has a single one [2].

STBC based schemes focus on achieving a performance improvement through the exploitation of additional diversity, while keeping the symbol rate unchanged [2, 3]. Symbols are transmitted using an orthogonal block structure, which enables simple decoding algorithm at the receiver [2, 3].

2.1.1. Open Loop Techniques

Open Loop Transmit Diversity schemes are performed without previous knowledge of the channel state by the transmitter. Space Time Block Coding, also known as the Alamouti scheme, is the most known open loop technique [2].

If we employ Alamouti's transmit diversity we need some processing at the transmitter. The Alamouti's coding can be implemented either in the time domain or in the frequency domain. In this paper we consider time-domain coding (the extension to frequency domain coding is straightforward). By considering the STBC with two transmit antennas, the lth time-domain block to be transmitted by the mth antenna ($m = 1$ or 2) is $s_l^{(m)}$, with [2, 8]

$$s_{2l-1}^{(1)} = a_{2l-1} \qquad s_{2l-1}^{(2)} = -a_{2l}^* \qquad s_{2l}^{(1)} = a_{2l} \qquad s_{2l}^{(2)} = a_{2l-1}^* \tag{1}$$

where a_l refers to the symbol selected from a given constellation, to be transmitted in the lth time domain block. Considering the matrix-vector representation, we define $\mathbf{s}_l^{[1,2]}$

$$\mathbf{s}_l^{[1,2]} = \begin{bmatrix} a_{2l-1} & a_{2l} \\ -a_{2l}^* & a_{2l-1}^* \end{bmatrix} \tag{2}$$

where different rows of the matrix refer to transmit antenna order and different columns refer to symbol period orders. The Alamouti's post-processing for two antennas comes [8],

$$\tilde{A}_{2l-1} = \left[Y_{2l-1}H_l^{(1)*} + Y_{2l}^* H_l^{(2)}\right]\beta \qquad \tilde{A}_{2l} = \left[Y_{2l}H_l^{(1)*} - Y_{2l-1}^* H_l^{(2)}\right]\beta \tag{3}$$

where $\beta = [\sum_{m=1}^{M} |H_l^{(m)}|^2]^{-1}$. Defining $\mathbf{Y}_l^{[1,2]} = [\begin{smallmatrix} Y_{2l-1} & Y_{2l}^* \\ Y_{2l} & -Y_{2l-1}^* \end{smallmatrix}]$ and $\mathbf{H}_l^{[1,2]} = [\ H_l^{(1)*} \quad H_l^{(2)}\ ]^T$, (3) can be expressed in matrix-vector representation as $\tilde{\mathbf{A}}_l^{[1,2]} = [\mathbf{Y}_l^{[1,2]} \times \mathbf{H}_l^{[1,2]}] \times \beta$, where $\tilde{\mathbf{A}}_l^{[1,2]} = [\ \tilde{A}_{2l-1} \quad \tilde{A}_{2l}\ ]^T$.

Finally, the decoded symbols come

$$\tilde{A}_{2l-j} = \overbrace{A_{2l-j}\sum_{m=1}^{M}\left|H_l^{(m)}\right|^2\beta}^{\text{Desired Symbol}} + \overbrace{N_{2l-j}^{eq}}^{\text{Noise Component}} \qquad j = 0, 1 \tag{4}$$

where $N_{k,l}^{eq}$ denotes the equivalent noise for detection purposes.

Orthogonal code of rate 1 using more than two antennas does not exist. Schemes with 4 and 8 antennas with code rate one only exist in the case of binary transmission. If orthogonality is essential (fully loaded systems with significant interference levels), a code with $R < 1$ should be employed for such cases.

The signal processing for non-orthogonal 4 and 8 transmit antennas is defined in [8] and in the references therein. In both cases, the decoding does not achieve the maximum possible path diversity since in the decoding of all symbols there is always inter-symbolic interference from one symbol in the case of 4 antennas (c_0), and from 3 symbols in the case of 8 antennas (c_0, c_1, c_2).

It is worth noting that although the described STBC scheme is a MISO, by adopting receive diversity, this can be viewed as a MIMO system.

2.1.2. Closed Loop Techniques

In the case of the downlink, the space diversity provided by the Selective Transmit Diversity (STD) scheme presents a low rate feedback link from the receiver (UE) informing the transmitter (BS)

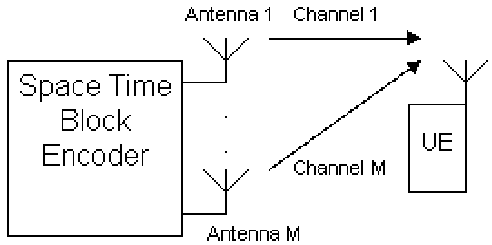

Figure 1: Generic block diagram of an open loop transmitter scheme.

which antenna should be employed for transmission. There is a common or dedicated pilot sequence being transmitted. Different antennas with specific pilot patterns/codes enable antenna selection. Once the UE sends back to the transmitter the information about the M link qualities (number of transmit antennas), the BS transmits a single symbol stream over the best antenna. The receiver is supposed to re-acquire the carrier phase $\theta_k(t)$ after every switch between antennas. Moreover, the Antenna Switch (AS) has the capability to switch every slot duration. Note that STD can be viewed as a type of CoMP, using a scheduling technique.

2.2. Spatial Multiplexing

Multi-layer Transmission and SDMA belong to group entitled Spatial Multiplexing (SM), whose principles are similar but whose purposes are quite different. As long as the antennas are located sufficiently far apart, the transmitted and received signals from each antenna undergo independent fading.

The primary goal of the MIMO based on multi-layer transmission scheme relies on achieving higher data rates in a given bandwidth, whose increase rate corresponds to the number of transmit antennas [1, 3]. An example of a receiving algorithm employed in multi-layer transmission is the Vertical — Bell Laboratories Layered Space-Time (V-BLAST) algorithm. In the Multi-Layer MIMO, the number of receive antennas N must be equal or higher than the number of transmit antennas M. The increase of symbol rate is achieved by logically "steering" the receive antennas to each one (separately) of the transmit antennas, in order to receive the corresponding data stream. This is achieved through the use of the nulling algorithm [3].

As depicted in Figure 2, two different Multi-Layer MIMO schemes are considered: scheme 1 and scheme 2 [3]. Scheme 1 directly allows an increase of the data rate whose increase rate corresponds to the number of transmit antennas. Scheme 2 allows the exploitation of diversity, without achieving an increase of data rate. The transmit diversity combining is achieved using any combining algorithm, namely the Mean-Square Error (MSE) based or the Maximum Ratio Combining (MRC). In the case of scheme 2 (depicted in Figure 2(b))), the antenna switching is performed at a symbol rate, where the red dashed lines represent the signal path at even symbol periods, in case of two transmit antennas. The diversity is achieved because each symbol is transmitted by different antennas, at different symbol periods. Output signals are then properly delayed and combined to

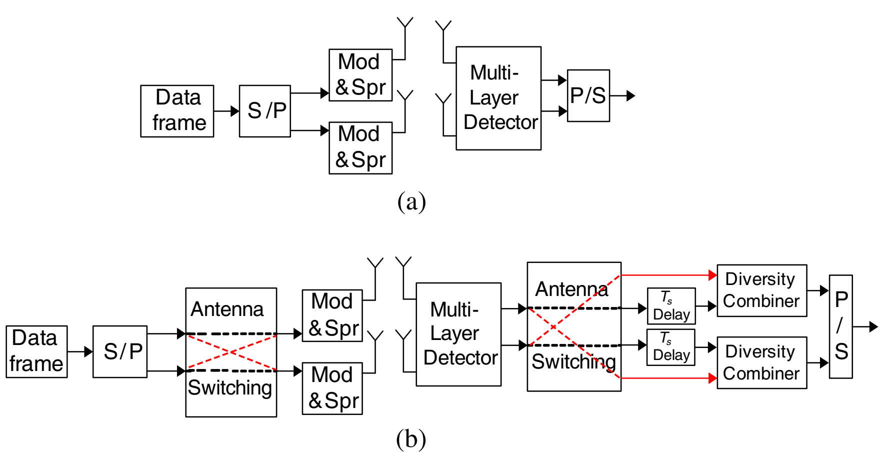

Figure 2: Generic diagram of the 2 × 2 multi-layer MIMO, (a) scheme 1 and (b) scheme 2.

provide diversity.

In Multi-Layer MIMO, the symbol with the highest SNR is first detected using a linear nulling algorithm such as zero forcing (ZF) or minimum mean square error (MMSE) [1, 9]. The detected symbol is regenerated, and the corresponding signal portion is subtracted from the received signal vector using typically a Successive Interference Cancellation (SIC) algorithm. This cancellation process results in a modified received signal vector with fewer interfering signal components left. This process is repeated, until all symbols from different transmit antennas are detected. [1] provides the signal description for the V-BLAST receiver, while in [5] it is proposed an advanced receiver for the Multi-Layer MIMO scheme applied to Wideband Code Division Multiple Access (WCDMA) signals.

3. COORDINATED MULTI-POINT TRANSMISSION

Using CoMP transmission, independent antenna elements of different BSs are grouped together, forming a cluster, and the UEs can experience a throughput increase or performance improvement. A pre-processing is typically employed at the BSs side such that the signals that reach the UE do not require any type of post-processing.

In case each BS uses the MIMO scheme, the resulting MIMO can be viewed as a "giant MIMO", consisting of a combination of independent antenna elements from different BSs (see Figure 3).

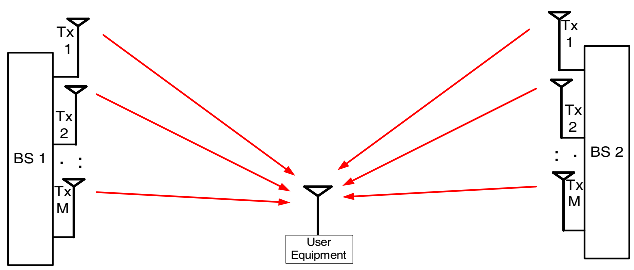

Figure 3: CoMP implemented as a downlink MIMO.

Coordinated multi-point transmission comprises the coordinated transmission of signals from adjacent BSs, and the corresponding reception from a UE. The signal received at the UE side consists of the sum of independent signals sent by different BSs.

CoMP transmission is an important technique that can mitigate inter-cell interference, improve the throughput, exploit diversity and, therefore, improve the spectrum efficiency. Note that CoMP transmission allows a spectrum efficiency improvement, even at the cell edge. CoMP transmission can be viewed as a special type of MU-MIMO.

Similar to MU-MIMO, a pre-processing such as beamforming, ZF, MMSE or dirty-paper coding is employed, in order to assure that the UE receives a combined signal coming from multiple BSs. In this case, the UE commonly employs a low-complexity and regular detector. Alternatively, a single-user like MIMO detector can be employed at the receiver (UE) or a coordinated scheduling can also be employed. In the latter case, CoMP transmission can be associated to carrier aggregation, activating or de-activating some carriers in order to optimize the performance.

Similar to MU-MIMO, accurate downlink CSI is typically required at BSs side, which consists of an implementation difficulty. In case of TDD, obtaining CSI is trivial, as the uplink and downlink channels are almost the same. Nevertheless, in case of FDD, obtaining CSI at the transmitter side is a complex task.

Depending on the way the coordination between different BSs is performed, and the way CSI is obtained (in FDD mode), two different architectures can be implemented:

- Centralized architecture: in this architecture there is a central Control Unit (CU) which decides about the transmission scheme and resources allocation to be used by different BSs. In this case, the CU is connected to different BSs of the cluster. Each UE estimates the downlink CSI of the signals received from each BS. Then, the CSI is sent back to the corresponding BS. At a third stage, CSI is sent from different BSs of the cluster to the CU through backhaul links. Based on CSI, the CU decides about the transmission scheme and resources allocation to be used by each BS, and sends this information to different BSs of the cluster. A major limitation of this architecture relies on the latency, whose factor may result in performance degradation due to fast CSI variations [10].

- Distributed architecture: in this architecture, each BS is associated to a different CU, and the decision about the transmission scheme and resources allocation is performed independently at the BS level. Then, this information is exchanged between the cluster's BSs. In this case, each UE estimates the downlink CSI to different BSs and sends this joint data back not only to the BS of reference, but to all BSs. This way the CU associated to each BS has information about different downlink CSI and makes the decision accordingly. An advantage of this architecture relies on the fact that latency is much reduced, and there is no need to use backhaul links for the purpose of exchanging CSI. Nevertheless, this architecture is more subject to errors caused by the uplink transmission [11].

4. PERFORMANCE RESULTS

In this section we present a set of performance results concerning the proposed CoMP using different configurations, namely with one and two receive antennas, for a regular single carrier transmission (that is, without any advanced transmission technique such as multi-carrier or CDMA), and for the Pedestrian A and Vehicular A propagation environments (corresponds to a rich multipath propagation). Uncoded Bit Error Rate (BER) performance is considered, which is expressed as a function of the bit signal-to-noise ratio E_b/N_0, employing the QPSK constellation under a Gray mapping rule. Concerning the system level simulation, a total of four mobile terminals were considered in the cell. Different multi-antenna systems were considered in the simulations: the "no CoMP" corresponds to the SISO, that is, using a single BS (CoMP is not employed), where the receiver comprises a single receive antenna; the CoMP STBC and CoMP STBC 2×2 correspond to the Alamouti-like scheme with two transmit antennas and a single or two receive antennas, respectively; the CoMP STD corresponds to the closed loop technique, that is, corresponds to two BS's and a single receive antenna; finally, CoMP SPATIAL MUX 2×2 corresponds to spatial multiplexing with two transmit and two receive antennas (see Figure 2 for layers 1 and 2).

Figure 4 shows the performance results concerning the Pedestrian A propagation environment, and assuming a single receive antenna. As can be seen, through the exploitation of diversity the CoMP STBC and CoMP STD allows a performance improvement relating to the "No CoMP". Note that the STD performs better than the STBC for E_b/N_0 below 12 dB. Since the Pedestrian A presents a propagation environment close to the single path (flat fading), the selective diversity allows selecting the antenna that presents less instantaneous frequency selectivity, leading to good results even under noisy conditions. Nevertheless, since the STBC always transmits the signals by the two antennas (antenna diversity), and since the corresponding channel presents low level of multipath diversity, it is only able to perform better than the STD for low levels of noise, that is, for high E_b/N_0 levels.

Figure 5 presents the performance for the Pedestrian A, but with two receive antennas. As expected, the performance obtained with the layer 2 is better than that of layer 1 due to its ability to exploit diversity, but the throughput is not duplicated. Moreover, the CoMP based on the Alamouti-like MIMO scheme (CoMP STBC 2×2) achieves a performance improvement relating to the layer 2, achieving the best overall performance.

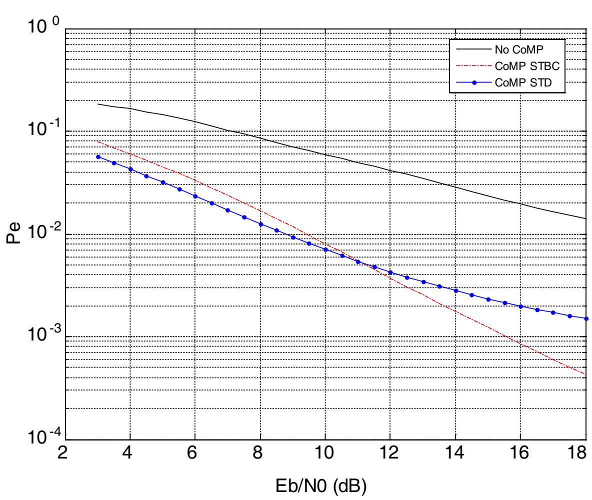

Figure 4: Pedestrian A propagation model (single receive antenna).

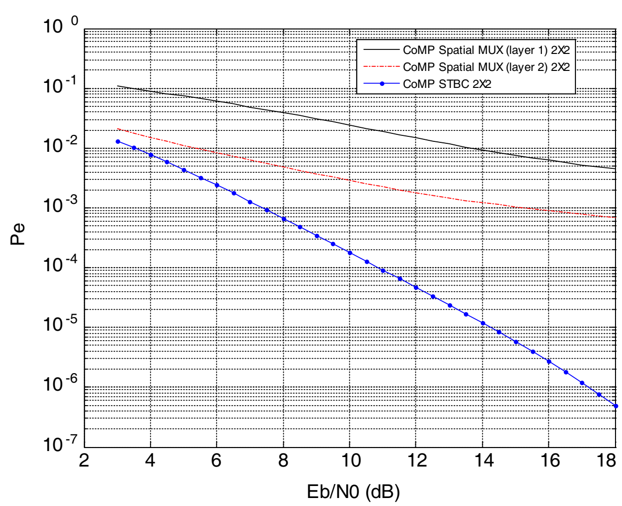

Figure 5: Pedestrian A propagation model (two receive antennas).

Figure 6 corresponds to the results plotted in Figure 4 but concerning the Vehicular A, which is a rich multipath propagation. In this case, the best overall performance is achieved by CoMP STBC for all levels of E_b/N_0.

Figure 7 corresponds to Figure 5 but for the Vehicular A propagation environment. As before, the best overall performance is achieved by CoMP STBC 2×2. Nevertheless, comparing the results of Vehicular A against those of Pedestrian A, it is viewed that the difference of performance between CoMP MUX layer 2 and CoMP STBC is reduced.

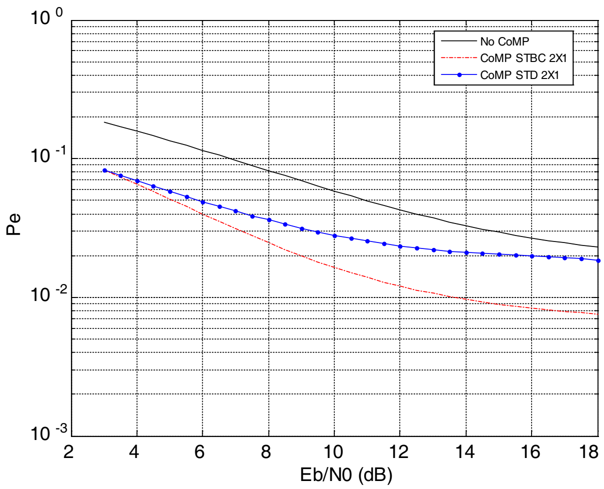

Figure 6: Vehicular A propagation model (single receive antenna).

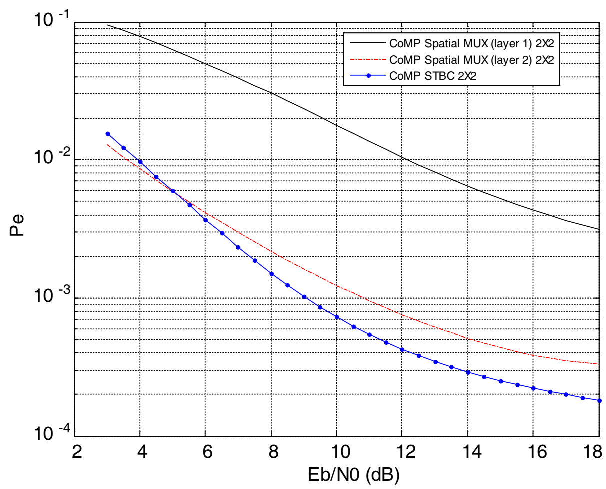

Figure 7: Vehicular A propagation model (two receive antennas).

5. CONCLUSIONS

This paper performed a comparison between different coordinated multi-point transmission techniques. It was shown that the best overall performance tends to be achieved by the CoMP using the Alamouti-like scheme (STBC). Naturally, when the aim is the increase of throughput, instead of performance improvement, CoMP implementing spatial multiplexing (layer 1) should be viewed as an option.

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