Performance Evaluation and Comparison between Iterative DS-CDMA and NDMA

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***Abstract*—Multipacket Reception (MPR) techniques employing either Direct Sequence Code Division Multiple Access (DS-CDMA) or Network Diversity Multiple Access (NDMA) have great potential to deal with packet collisions from multiple Mobile Terminals (MTs). However, their performance evaluation in practical systems is difficult because lengthy simulations are needed to obtain the packet error rates for specific channel conditions. This paper considers MPR receivers based on the Iterative Block Decision Feedback Equalization (IB-DFE) concept. An analytical tool that computes the Bit Error Rate (BER) and Packet Error Rate (PER) for DS-CDMA is proposed, where its theoretical results have a good accuracy. This analytical approach, that provides a simple and relatively fast way to compute the BER and PER performance for DS-CDMA, is then employed for a comparison with NDMA.** [1]

***Index Terms*—SC-FDE, IB-DFE, Multipacket Detection, Analytical Performance, DS-CDMA, NDMA, ARQ.**

I. Introduction

Whenever two or more users try to send packets in a given channel, a collision occurs and the packets involved are usually too corrupt to detect. The traditional way of coping with collisions is to discard the involved packets and request an additional transmission. However, this leads to significant performance degradation - reduced throughput, increased delay and power inefficiency - that can be especially serious for saturated systems [1]. For this reason, there is a great interest in Multipacket Reception (MPR) techniques that detect packets involved in a collision [2], [3].

There are several methods to perform MPR for packets involved in a collision. One approach is to employ multiple receiving antennas as in Spatial Diversity Multiple Access (SDMA) systems [4]. Even though these techniques allow excellent performance, the maximum number of detectable users is limited by the number of receiving antennas, making these techniques very rigid from the hardware point of view. In fact, these techniques allow an increase of the number of scheduled users for a given channel, though unsuitable for random access.

The simplest way of coping with collisions is to employ Code Division Multiple Access (CDMA) techniques [3]. Provided that uncorrelated spreading sequences are assigned to each user, then it is possible to separate several users involved in a collision; this can be achieved with a spreading factor equal or higher than the number of users involved in the collision. However, the orthogonality between each sequence is lost when the users are not synchronous and/or the channel is selective, e.g. multipath propagation effects. This means that some correlation between spreading sequences is almost unavoidable in the uplink. Prefix-assisted block transmission techniques combined with frequency-domain receiver implementations are known to be appropriate for severely time-dispersive channels [5], [6]. This concept can be efficiently employed with Direct Sequence CDMA (DS-CDMA) systems [3], [7]. A promising multiuser receiver for severely time-dispersive channels was proposed in [7] that combines an iterative frequency-domain receiver based on the Iterative Block with Decision Feedback Equalization (IB-DFE) concept [8] with prefix-assisted DS-CDMA schemes, allowing an excellent performance in fully-loaded systems, i.e. when the number of users is equal to the spreading factor.

As an alternative to DS-CDMA-based MPR schemes, Network Diversity Multiple Access (NDMA) techniques [2], [9] can be employed to cope with collisions. In this case, the receiver, i.e. the Base Station (BS), requests all users involved in a collision to retransmit slightly modified versions of their packets several times. Usually the BS requires as many transmissions as the number of users involved in the collision. Once there are enough transmissions, the receiver is able to separate the packets involved [2], [9]. Although the performance of NDMA is excellent, the BS needs to know which users are involved in the collision and their corresponding channels. This can be especially difficult for severely time-dispersive channels [10]. There is also a variant of NDMA that requests additional redundancy until all packets are correctly received, it is known as Hybrid-ARQ NDMA (H-NDMA) [1].

The study of MPR techniques at the network level is difficult, since there are no closed formulas for the Bit Error Rate (BER) and Packet Error Rate (PER). In most studies, average BER and PER values are previously obtained from extensive physical layer simulations and then used by the network simulator, usually under specific conditions, e.g. perfect power control. Another option would be to implement the physical layer in the network simulator, however this would significantly increase the complexity and duration of the network simulations. The ideal, would be to implement simple

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formulas for the BER and PER for a given MPR scenario into the network simulator. A promising analytical approach for the performance evaluation of NDMA was presented in [11], [12] but, as far as the authors know, there is no equivalent analytical tool for MPR in DS-CDMA.

This paper evaluates a comparison between prefix-assisted DS-CDMA and NDMA techniques. In both cases, the receiver is implemented in the frequency domain and is based on the IB-DFE concept [8]. For this purpose, a simple and accurate analytical approach is proposed for the BER and PER performance evaluation of DS-CDMA where the receiver is based on the ones proposed in [7].

The paper assumes the following notation: $\mathbf{A}^T$, $\mathbf{A}^H$ and $\mathbf{A}^*$ denote the transpose, Hermitian (i.e., complex conjugate transpose) and complex conjugate of the matrix $\mathbf{A}$, respectively.

The structure of the paper is as follows: Section II characterizes the proposed system and Section III analyzes the receiver structure for DS-CDMA and provides an analytical tool for its performance evaluation. Section IV refers to the accuracy of the proposed analytical tool and a brief comparison between DS-CDMA and NDMA. Finally, Section V briefly comments the paper's conclusions.

II. System Characterization

The current section briefs a generalized characterization of the proposed analytical model for DS-CDMA. The paper considers a structured wireless system, where a set of Mobile Terminals (MTs) send data to a Base Station (BS) using a slotted data channel. MTs are low resource battery operated devices, whereas the BS is an high resource device that copes with packet errors either due to poor propagation conditions or collisions. The MTs send data frames on time slots defined by the BS (for the sake of simplicity, it is assumed that the packets associated to each MT have the same duration and a packet corresponds to a slot). Perfect channel estimation and synchronization is assumed with perfect time advance mechanisms to compensate different propagation times.

Multiple MTs may transmit packets during each slot using DS-CDMA, where data symbols are spread over the channel's bandwidth with a spreading factor K. It is assumed that the BS is capable of detecting the number of MTs transmitting in a given channel during a slot. The number of MTs transmitting in each slot will be at most P. The BS executes the detection algorithm at the end of each slot to acknowledge the correctly received packets.

Let us consider a data block on the time domain from a MT p, $\{a_{n,p}; n=0,...,M-1\}$, and its respective Discrete Fourier Transform (DFT) counterpart, $\{A_{k,p}; k=0,\dots,M-1\}$. Considering a spreading factor K, where $\mathbf{c}_p=[c_{1,p},\dots,c_{K,p}]$ is the spreading sequence assigned to a user p, then its respective DFT is $\mathbf{C}_p=[C_{1,p},\dots,C_{K,p}]$, and the transmitted symbol from a user p is $\mathbf{S}_{k,p}=\mathbf{C}_p^T A_{k,p}$ with size $K\times 1$. This is roughly equivalent of having K replicas of the same data block.

Let us describe a received symbol at the BS as $\mathbf{Y}_k=[Y_k^{(1)},\dots,Y_k^{(K)}]$ and the channel noise as $\mathbf{N}_k=[N_k^{(1)},\dots,N_k^{(K)}]$ for a given transmission. The channel realizations for a given MT p to transmit $\mathbf{S}_{k,p}$ are $\mathbf{H}_{k,p}{}'=diag(H_{k,p}^{(1)}{}',H_{k,p}^{(2)}{}',\dots,H_{k,p}^{(K)}{}')$.

For the sake of simplicity it will be assumed that $\mathbf{H}_{k,p}=[H_{k,p}^{(1)}{}'C_{1,p},\dots,H_{k,p}^{(K)}{}'C_{K,p}]^T$. Grouping the channel realizations of the P users results $\mathbf{H}_k=[\mathbf{H}_{k,1},\dots,\mathbf{H}_{k,P}]$.

The received content at the BS is $\{\mathbf{Y}_k; k=0,\dots,M-1\}$, where $\mathbf{Y}_k=\mathbf{H}_k^T\mathbf{A}_k+\mathbf{N}_k$.

For each channel realization, $\mathbf{H}_k$, based on the FDE receiver structure and the Signal-to-Noise Ratio (SNR), it is shown in the following sections that the BER and the PER can be computed from a function f, where $<BER_p,PER_p>=f(\mathbf{H}_k,SNR)$. This function is generic and applies to any system employing MPR for DS-CDMA. It is independent of the MAC protocol used, since the MAC protocol behavior can be modeled in $\mathbf{H}_{k,p}$.

The analytical model proposed in this paper makes the proposed work quite versatile, without relying on previous simulations of the physical medium to test network applications. It allows a precise estimation of the PER, simplifying the performance estimation for system level models, which run on top of a physical layer.

III. Receiver Design and Performance Analysis

The analytical model of the receiver design is based on a uniform presentation of the model from [7]. This model assumes that the overall interference that affects the symbol estimation has a Gaussian behavior, and in general, the analysis of the receiver structure assumes perfect synchronization between the MTs and the BS, and perfect channel estimation.

The IB-DFE receiver decodes the MTs' transmissions up to N_{iter} iterations. The estimated data symbol, $\tilde{A}_{k,p}^{(i)}$, for a given iteration i and MT p is $\mathbf{F}_{k,p}^{(i)}{}^T\mathbf{Y}_k-\mathbf{B}_{k,p}^{(i)}{}^T\bar{\mathbf{A}}_k^{(i-1)}$, where $\mathbf{F}_{k,p}^{(i)}{}^T=\left[F_{k,p}^{(i,1)},\dots,F_{k,p}^{(i,K)}\right]$ are the feedforward coefficients and $\mathbf{B}_{k,p}^{(i)}{}^T=\left[B_{k,p}^{(i,1)},\dots,B_{k,p}^{(i,P)}\right]$ are the feedback coefficients. $\bar{\mathbf{A}}_k^{(i-1)}=\left[\bar{A}_{k,1}^{(i-1)},\dots,\bar{A}_{k,P}^{(i-1)}\right]^T$ are the soft decision estimates from the previous iteration for all users. $\bar{\mathbf{A}}_k^{(i-1)}$ can be related to the symbols' hard decisions, $\hat{\mathbf{A}}_k^{(i-1)}$, where according to [13], [14] results $\bar{\mathbf{A}}_k^{(i-1)}\simeq\mathbf{P}^{(i-1)}\hat{\mathbf{A}}_k^{(i-1)}$ and $\hat{\mathbf{A}}_k^{(i-1)}=\mathbf{P}^{(i-1)}+\boldsymbol{\Delta}_k$. $\mathbf{P}^{(i-1)}=diag\left(\rho_1^{(i-1)},\dots,\rho_P^{(i-1)}\right)$ are the correlation coefficients and $\boldsymbol{\Delta}_k=\left[\Delta_k^{(1)},\dots,\Delta_k^{(P)}\right]^T$ is a zero mean error vector. For more information on $\bar{\mathbf{A}}_k^{(i-1)}$ and $\hat{\mathbf{A}}_k^{(i-1)}$ calculus refer to [14]–[16].

Expanding $\rho_p^{(i-1)}$ for a given MT p, assuming a QPSK constellation, where according to [16] results $\rho_p^{(i-1)}=\frac{1}{2M}\sum_{n=0}^{M-1}\left|\rho_{n,p}^{I}{}^{(i-1)}\right|+\left|\rho_{n,p}^{Q}{}^{(i-1)}\right|$, so that $\rho_{n,p}^{I}{}^{(i-1)}=tanh\left(\frac{\left|L_{n,p}^{I}{}^{(i-1)}\right|}{2}\right)$, and $\rho_{n,p}^{Q}{}^{(i-1)}=tanh\left(\frac{\left|L_{n,p}^{Q}{}^{(i-1)}\right|}{2}\right)$.

This results the likelihood estimation, where $L_{n,p}^{I}{}^{(i-1)} = \frac{2}{\sigma_{n,p}^{2}{}^{(i-1)}} Re\left\{\tilde{a}_{n,p}^{(i-1)}\right\}$, $L_{n,p}^{Q}{}^{(i-1)} = \frac{2}{\sigma_{n,p}^{2}{}^{(i-1)}} Im\left\{\tilde{a}_{n,p}^{(i-1)}\right\}$, and $\sigma_{n,p}^{2}{}^{(i-1)} \simeq \frac{1}{2M}\sum_{n'=0}^{M-1}\left|\hat{a}_{n',p}^{(i-1)} - \tilde{a}_{n',p}\right|^2$.

For the first iteration, i.e. $i = 1$, $\bar{\mathbf{A}}_k^{(i-1)}$ is a null vector and $\mathbf{P}^{(i-1)}$ is a null matrix. Assuming that $\mathbf{R}_A$, $\mathbf{R}_N$ and $\mathbf{R}_\Delta$, are respectively, the correlation of $\mathbf{A}_k$, $\mathbf{N}_k$ and $\mathbf{\Delta}_k$, where $\mathbf{R}_A = \mathbb{E}\left[\mathbf{A}_k\mathbf{A}_k^H\right] = 2\sigma_A^2\mathbf{I}_P$, $\mathbf{R}_N = \mathbb{E}\left[\mathbf{N}_k\mathbf{N}_k^H\right] = 2\sigma_N^2\mathbf{I}_K$, $\mathbf{R}_\Delta = \mathbb{E}\left[\mathbf{\Delta}_k\mathbf{\Delta}_k^H\right] \simeq 2\sigma_A^2\left(\mathbf{I}_P - \mathbf{P}^{(i-1)^2}\right)$. σ_A^2 is the symbol's variance and σ_N^2 is the noise's variance.

Knowing that $\mathbf{\Gamma}_p = [\Gamma_{p,1} = 0, \ldots, \Gamma_{p,p} = 1, \ldots, \Gamma_{p,P} = 0]^T$ and $\alpha_{k,p}^{(i)} = \mathbf{F}_{k,p}^{(i)}\mathbf{H}_k^T - \mathbf{B}_{k,p}^{(i)}\mathbf{P}^{(i-1)^2} - \mathbf{\Gamma}_p$, $\beta_{k,p}^{(i)} = \mathbf{B}_{k,p}^{(i)}{}^T\mathbf{P}^{(i-1)}$, the Mean Square Error (MSE), $\mathbb{E}\left[\left|A_{k,p} - \tilde{A}_{k,p}^{(i)}\right|^2\right]$, of $A_{k,p}$ is

$$\mathbb{E}\left[\left|A_{k,p} - \tilde{A}_{k,p}^{(i)}\right|^2\right] = \alpha_{k,p}^{(i)}{}^{*}\mathbf{R}_A\alpha_{k,p}^{(i)}{}^{T} + \mathbf{F}_{k,p}^{(i)}{}^{H}\mathbf{R}_N\mathbf{F}_{k,p}^{(i)} + \beta_{k,p}^{(i)}{}^{*}\mathbf{R}_\Delta\beta_{k,p}^{(i)}{}^{T}. \quad (1)$$

To obtain the optimal coefficients, $\mathbf{F}_{k,p}^{(i)}$ and $\mathbf{B}_{k,p}^{(i)}$, under the minimum Mean Square Error (MSE) criterion, the Lagrange function is applied to (1). So

$$\nabla J = \nabla\left(\mathbb{E}\left[\left|A_{k,p} - \tilde{A}_{k,p}^{(i)}\right|^2\right] + \left(\gamma_p^{(i)} - 1\right)\lambda_p^{(i)}\right), \quad (2)$$

where the Lagrange multipliers are constrained to $\gamma_p^{(i)} = \frac{1}{M}\sum_{k=0}^{M-1}\sum_{n=1}^{K} F_{k,p}^{(i,n)} H_{k,p}^{(n)'} C_{n,p}$. From the following set of equations,

$$\begin{cases} \nabla_{\mathbf{F}_{k,p}^{(i)}} J = 0 \\ \nabla_{\mathbf{B}_{k,p}^{(i)}} J = 0 \\ \nabla_{\lambda_p^{(i)}} J = 0 \end{cases}, \quad (3)$$

$\nabla_{\mathbf{F}_{k,p}^{(i)}} J = 0$ is

$$\mathbf{H}_k^H\mathbf{R}_A\mathbf{H}_k\mathbf{F}_{k,p}^{(i)} - \mathbf{H}_k^H\mathbf{R}_A\mathbf{P}^{(i-1)^2}\mathbf{B}_{k,p}^{(i)} - \mathbf{H}_k^H\mathbf{R}_A + \mathbf{R}_N\mathbf{F}_{k,p}^{(i)} + \frac{1}{M}\mathbf{H}_k^H\lambda_p^{(i)}\mathbf{\Gamma}_p = 0, \quad (4)$$

$\nabla_{\mathbf{B}_{k,p}^{(i)}} J = 0$ is

$$\left(\mathbf{P}^{(i-1)^2}\mathbf{R}_A + \mathbf{R}_\Delta\right)\mathbf{B}_{k,p}^{(i)} = \mathbf{R}_A\mathbf{H}_k\mathbf{F}_{k,p}^{(i)} - \mathbf{R}_A\mathbf{\Gamma}_p, \quad (5)$$

and $\nabla_{\lambda_p^{(i)}} J$ is $\gamma_p^{(i)} = 1$. So the optimal coefficients are

$$\begin{cases} \mathbf{B}_{k,p}^{(i)} = \mathbf{H}_k\mathbf{F}_{k,p}^{(i)} - \mathbf{\Gamma}_p \\ \mathbf{F}_{k,p}^{(i)} = \mathbf{\Lambda}_{k,p}^{(i)}\mathbf{H}_k^H\mathbf{\Theta}_{k,p}^{(i)} \end{cases}. \quad (6)$$

$\mathbf{\Lambda}_{k,p}^{(i)} = \left(\mathbf{H}_k^H\left(\mathbf{I}_P - \mathbf{P}^{(i-1)^2}\right)\mathbf{H}_k + \frac{\sigma_N^2}{\sigma_S^2}\mathbf{I}_K\right)^{-1}$ and $\mathbf{\Theta}_{k,p}^{(i)} = \left(\mathbf{I}_P - \mathbf{P}^{(i-1)^2}\right)\mathbf{\Gamma}_p - \frac{\lambda_p^{(i)}}{2\sigma_A^2 N}\mathbf{\Gamma}_p$. For a single user p transmitting data, i.e. without collisions, this leads to

$$\gamma_p^{(i)} = 1, \quad (7a)$$

$$B_{k,p}^{(i,1)} = \sum_{n=1}^{K} F_{k,p}^{(i,n)} H_{k,p}^{(n)'} C_{n,p} - 1, \quad (7b)$$

$$F_{k,p}^{(i,n)} = \frac{\gamma_p^{(i)}\left(H_{k,p}^{(n)'} C_{n,p}\right)^*}{\frac{\sigma_N^2}{\sigma_A^2} + \sum_{n=1}^{K}\left|H_{k,p}^{(n)'} C_{n,p}\right|^2}. \quad (7c)$$

From (1), and the optimal $\mathbf{F}_{k,p}^{(i)}$ and $\mathbf{B}_{k,p}^{(i)}$ coefficients given by (6), it is possible to compute the minimum MSE. Defining

$$\sigma_p^{2\,(i)} = \frac{1}{M^2}\sum_{k=0}^{M-1}\mathbb{E}\left[\left|\tilde{A}_{k,p}^{(i)} - A_{k,p}\right|^2\right], \quad (8)$$

from the Gaussian error function, $Q(x)$, the Bit Error Rate (BER) of user p at the ith iteration for a QPSK constellation is

$$BER_p^{(i)} \simeq Q\left(\frac{1}{\sigma_p{}^{(i)}}\right). \quad (9)$$

For an uncoded system with independent and isolated errors, the Packet Error Rate (PER) for a fixed packet size of $2M$ bits is $PER_p^{(i)} \simeq 1 - \left(1 - BER_p^{(i)}\right)^{2M}$.

IV. Performance Results

The performance of the proposed analytical tool is evaluated for a given ratio range of the bit energy, E_b, over the channel's noise, N_0. As an example, a HIPERLAN type D channel [17] was considered, with uncorrelated Rayleigh fading for each path and user; similar results were observed for other severely time-dispersive channels with rich multipath propagation. Data blocks have $M = 256$ uncoded QPSK symbols, where each block occupies a $4\mu s$ time slot. Each MT's transmission is uncorrelated, i.e. with uncorrelated channel responses for each user. Walsh-Hadammard sequences were used to spread the MTs' symbols. For comparison purposes, the NDMA analytical tool from [11], [12] was used as well.

Subsection IV-A compares the performance of the proposed analytical model with simulation values; Subsection IV-B compares the performance between DS-CDMA and SC-FDE NDMA; and Subsection IV-C provides some final comments over the results.

A. Analytical DS-CDMA Performance

This section illustrates a comparison between the analytical values of the proposed model and respective simulation values. Analytical values are presented as lines, and the simulated ones as markers. Figure 1 illustrates the BER results of DS-CDMA for a single user considering the following range of spreading factors $K = [1, 2, 4]$. For the first iteration, there is a perfect match between the analytical and simulated values, though there is a slight deviation between them for succeeding iterations. It is also observed that for a successive increase of the spreading factor, the performance of DS-CDMA with iterative equalization is improved due to the redundant diversity. Figure 2 illustrates the BER results of DS-CDMA for a loaded channel where $P = K = [1, 2, 4, 8]$.

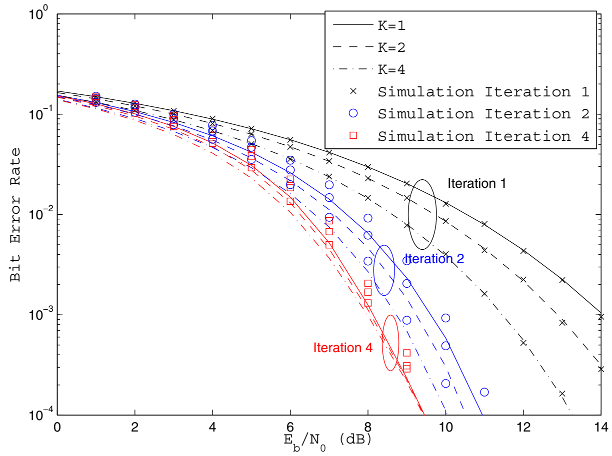

Figure 1. DS-CDMA performance for a single user considering a range $K = [1, 2, 4]$.

Once again, for the first iteration, there is a perfect match between analytical and simulated values, though degrading for increasing iterations. It is also observed that for an increasing number of MTs, P, the DS-CDMA performance is worser, but still achieving good results on successive iterations.

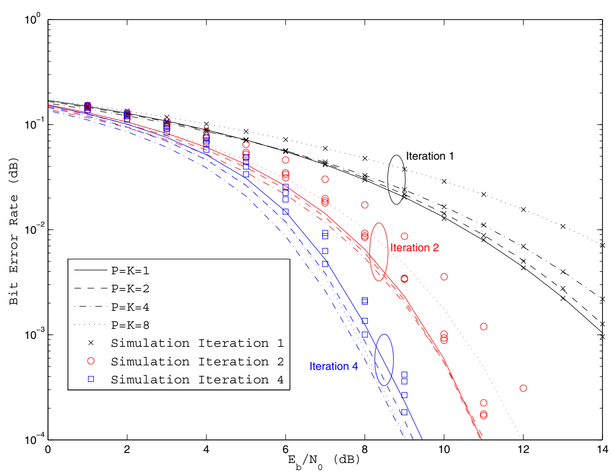

Figure 2. DS-CDMA performance for a loaded channel where $P = K = [1, 2, 4, 8]$.

Figure 3 illustrates the PER results of DS-CDMA for $P = 2$ and $K = [2, 4]$. Besides the first iteration, there is a slight difference between analytical and simulated values. As in Figure 1, it is also observed that for an increasing spreading factor, K, the DS-CDMA performance is improved.

B. DS-CDMA vs. NDMA

This section illustrates an analytical comparison between DS-CDMA and NDMA from [11], [12]. To compare both techniques, the DS-CDMA technique at the BS only requests a single transmission from P MTs with a spreading factor K, while the NDMA technique requests P transmissions without any spreading. The NDMA technique uses the Shifted Packet method from [18] to cope with channel correlation for each transmission, where each retransmitted block has a different

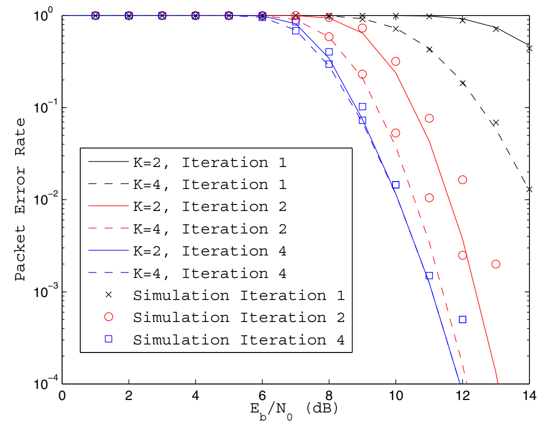

Figure 3. DS-CDMA performance for $P = 2$ and $K = [2, 4]$.

cyclic shift. For the sake of simplicity, simulation values were excluded.

Figure 4 illustrates a comparison between both techniques' BER, considering $K = 4$, up to $P = 4$ MTs and four iterations. From this figure, it is possible to observe that the DS-CDMA has a clear advantage over NDMA, though on successive iterations this advantage diminishes by a small margin.

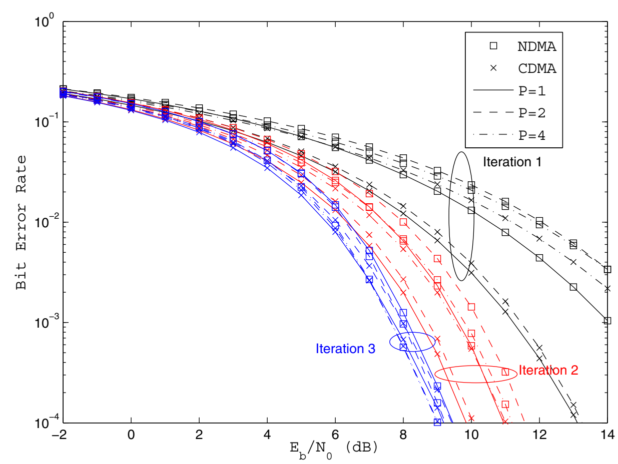

Figure 4. BER comparison between NDMA and DS-CDMA, where $K = 4$ and $P = [1, 2, 4]$ up to four iterations.

Figure 5 illustrates the BER of DS-CDMA and NDMA, assuming that the DS-CDMA's spreading factor is fully used, i.e. $K = P$. From this figure, it is possible to observe that DS-CDMA and NDMA have similar performances, though DS-CDMA has a slight advantage over NDMA.

Figure 6 illustrates a comparison between DS-CDMA and NDMA saturated throughput, where $K = 4$ and $P = [1, 2, 4]$. Observing the figure, it is possible to conclude that when DS-CDMA's channel is not fully loaded, i.e. $K > P$, it is impossible to achieve a maximum throughput of 1, while NDMA achieves this by simply requesting $L = P$ transmissions, thus illustrating the advantage of NDMA over DS-CDMA.

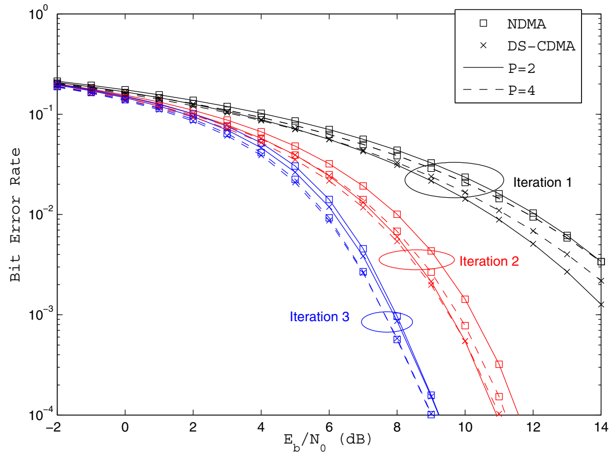

Figure 5. BER comparison between NDMA and DS-CDMA for $K = P$, where $P = [2, 4]$ up to four iterations.

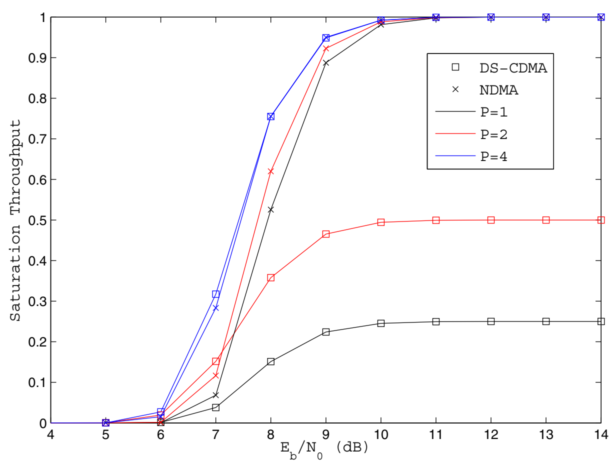

Figure 6. Saturation Throughput comparison between NDMA and DS-CDMA, where $K = 4$ and $P = [1, 2, 4]$ up to four iterations.

C. Final Comments

From the last subsection, it is possible to conclude that the DS-CDMA technique has a slight advantage over the NDMA technique in terms of packet reception, since MTs transmit K uncorrelated versions of their packets. With the IB-DFE equalization technique, the NDMA technique does achieve a similar performance when compared to the DS-CDMA technique, assuming that $K > P$, though at the cost of more iterations. Furthermore, DS-CDMA wastes much more bandwidth when compared to NDMA, assuming that $K > P$, since NDMA only requests a total of P transmissions, otherwise both perform almost the same.

V. Conclusion

A comparison between iterative frequency-domain MPR techniques for DS-CDMA and NDMA systems was performed in this paper. For this purpose, a simple and accurate analytical tool to calculate the BER and PER performances was validated with simulations. The presented results show that although the BER performance of DS-CDMA is better when the system is not fully loaded, the throughput of DS-CDMA is lower than NDMA because NDMA can be regarded as a kind of CDMA where the spreading factor is always the optimum one (i.e., it is equal to the number of users involved in the collision). For future work it is planned to extend and enhance the analytical model for upper layer protocols.

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