Performance Analysis of MIMO Wavelet Packet Multicarrier Multicode CDMA System with Antenna Selection

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Abstract. *Performance of Multicarrier Multicode Code-Division Multiple Access (MC/MCD-CDMA) systems can be improved significantly by using Wavelet Packets (WPs) as subcarriers instead of a sinusoidal function. This is because WPs have much lower sidelobes and negligible sidelobe energy leakage compared to sinusoidal carriers; this property significantly decreases the intercarrier interference and improves the system performance. Further improvement can be achieved by utilizing multiple antennas at transmitter and receiver to construct a Multiple-Input Multiple-Output (MIMO) system. Channel hardening is the main drawback of MIMO systems. Antenna selection can be employed to reduce this problem. In this paper, we use the antenna selection in MIMO WP-MC/MCD-CDMA system. These combinations of antenna selection, MIMO, and WP in MC/MCD-CDMA improve the system performance significantly and reduce the channel hardening. The performance of the system is tested according to the outage probability and bit error rate. Two MIMO schemes on Nakagami-m fading channel are considered, which are: selective transmit /selective receive and selective transmit /maximum ratio combining receive. The study includes the effects antennas' number, fading parameter-m, number of users, and the threshold signal to interferences plus noise ratio. The performance of the system is compared to that of MC/MCD-CDMA based on a sinusoidal carrier. The results reveal that: by increasing antennas' number, the system performance is improved significantly, and MC/MCD-CDMA system based on WPs carriers outperforms MC/MCD-CDMA system based on a sinusoidal carrier.*

Keywords

Diversity, MIMO, Nakagami channel, wavelet packets.

1. Introduction

Multicarrier/Multicode-Code Division Multiple-Access (MC/MCD-CDMA) communication systems [1], [2] and [3], have many attractive characteristics such as:

- Using MC provides high immunity against Intersymbol Interference (ISI). This interference results when the channel delay spread exceeds the symbol duration [4]. Also, MC can suppress the effect of the narrow-band jammer [5] and [6] by increasing the signal bandwidth.
- By MCD scheme, the number of carriers can be decreased; as a result, the Intercarrier Interference (ICI) will be reduced, and the spreading gain will be increased. Also, multirate services can be achieved by using MCD [7].

MC/MCD-CDMA system performance can be enhanced significantly by using Wavelet Packets (WPs) as subcarrier instead of sinusoidal carriers [8], [9], [10], [11], [12], [13], and [14]. This can be related to the lower sidelobes and negligible sidelobe energy leakage of WPs compared to sinusoidal carriers. This property can further decrease the ICI and multiple-access interference. Another advantage of WPs is that: there is no need for frequency/time guard between different user signals because WPs are naturally orthogonal and well localized in time and frequency domain.

To further reduce the effect of multipath fading and improve system performance, antenna diversity technique can be used. In diversity schemes, the received signal via several paths, carrying the same information, are combined to improve system performance. In [8], [10], [11], [13], and [14] three schemes of diversity combining techniques were considered, namely Selection Diversity (SC), Equal Gain Combining (EGC) and Maximal Ratio Combining (MRC). It is observed that the MRC outperform the other two diversity combining methods.

A Multiple-Input Multiple-Output (MIMO) system, which uses multiple antennas for transmitting and receiving, offers advantages over Single-Input Single-Output (SISO) system because diversity can be used at both transmitter and receiver [15], [16] and [17]. The MIMO systems are classified into closed-loop systems or open-loop systems according to the Channel State Information (CSI). In the closed-loop system, CSI is available at the transmitter while in open-loop systems it is not. In the closed-loop MIMO multi user system, antenna Selection (SC) at the transmitter can be employed to reduce channel hardening and enhance the system performance.

The analysis of antenna selection at transmitter with maximal-ratio combining at the receiver (SC-TX/MRC-RX) is discussed in [18], [19], [20], [21], [22], [23] and [24]. In [18], average outage capacity of multiuser MIMO-SC-TX/MRC-RX system is derived. The author demonstrates the effects of MIMO configuration, number of users, and multiuser diversity on the outage capacity performance. The framework analysis of Multiuser Diversity (MUD) gain in selection antenna MIMO system over flat-fading Ralyleight channel is developed in [19]. Only point-to-point communication links are considered in this paper. As an extension of [19], the authors in [20] focus on the performance analysis SC-TX/MRC-RX system in point-to-multipoint communications.

Over flat-fading Ralyleight channel, the author in [21] demonstrates the analysis of average Bit Error Rate (BER) performance for multiuser MIMO-SC-TX/MRC-RX. Two scenarios were considered which are:

- Heterogeneous: independent non-identical distributed Signal to Noise Ratio (SNR).
- Homogeneous: independent identical distributed SNR.

The analysis of the impact of feedback delay between the transmission selection parameters and the transmission time on multi user system employing orthogonal space-time block coding with rate-adaptive modulation and user selection scheme is presented in [22]. The authors analyze the BER, average spectral density, and bit error outage probability in heterogeneous time-varying MIMO Ralyleight fading channel.

In [23], the authors derived the BER and the outage Probability (P_{out}) for binary phase shift keying of the SC-TX/MRC-RX system in Rayleigh fading channels. By analysis and simulation the authors prove that the SC-TX/MRC-RX system significantly outperforms the space-time block coding, which has the same diversity order and the same number of receiver antennas. The authors in [24] perform the analysis of Symbol Error Probability (SEP) of several constellations for perfect CSI feedbacks. In their analysis, they showed that the antenna diversity improves the system performance but the feedback delay degrades significantly in the SEP of SC-TX/MRC-RX scheme. In [25], expressions of P_{out} and BER on a flat-fading Rayleigh channel for some MIMO systems with MUD were presented. The authors use the uniform power allocation procedure at the transmitter and assume that the CSI of each user is known to the scheduler at the base station.

The Nakagami-m distribution is known to span via its parameter m a wide range of multipath fading. This includes one-sided Gaussian model ($m = 0.5$), the Rayleigh model ($m = 1$) and Ricean model ($m = 3$) [26]. In [27], the author investigates the performance analysis of SC-TX/MRC-RX MIMO system on Nakagami-m fading channel. The exact closed form expression for the SNR and BER are derived by obtaining statistics as such as Cumulative Distribution Function (CDF), the Probability Density Function (PDF) and the Moment Generating Function (MGF). The letter in [28] focuses on the study of the diversity advantage of using MIMO antennas by determining the PDF of single and MIMO channel by which the statistical characteristics of MIMO systems can be described. By Monte Carlo simulations, the author finds formulas that define the channel gain and the diversity order of single and multiuser MIMO systems. Also, by using a Chi-square goodness-of-fit test, the author proves that the distribution of the channel gain can be approximated by a Nakagami-m distribution. Unified simple formulas of BER and P_{out} for some multiuser MIMO systems, such as SC-TX/SC-RX, SC-TX/MRC-RX, and space-time block coding systems, on Nakagami-m channels, are presented in [29]. The performance limits of massive MIMO systems under practical antenna selection algorithms are investigated in [30]. In this system, the transmitter selects a subset of the available antennas with the strongest channel gains. They show that with only 30 % of antennas being active, more than 90 % of the ergodic rate obtained by full antenna selection, can be achieved. The analytical expression for the number of selected antennas that can maximize energy efficiency is also derived. In [31], the authors investigate the MIMO techniques in a vehicle-to-vehicle communication system. The performance of SC-TX/MRC-RX and SC-TX/SC-RX schemes was analyzed over n*Rayleigh fading channels; "n*Rayleigh can be defined as a product of n independent Rayleigh random variables connected via narrow pipes". The authors derive a closed-form expression for the outage probability and the amount of fading. Their numerical results show that SC-TX/MRC-RX outperforms SC-TX/SC-RX, but its performance is limited as n increases. Using Cumulative Density Function (cdf) an exact closed-form expression for the Symbol Error Rate (SER) of SC-TX/MRC-RX with relay and user selection for MIMO system over non-identical Nakagami fading channels is derived in [32]. They show that the SER is improved by multi-relay diversity, multi-user diversity and the sum of non-identical fading parameters for different transmit antennas, relays, and destinations. In [33], Signal Space Diversity (SSD) is employed into a MIMO system with MRC and transmit antenna selection. The system performance with Phase-Shift Keying (PSK) modulation is investigated under a slow flat Rayleigh fading channel with the correlated receive antennas. The exact closed-form expression for pairwise error probability is derived using the realistic exponential correlation model. It is shown that the error performance of the system can be improved with almost no extra complexity or cost.

Many research papers combine both technologies of MIMO and wavelet. In [34] to improve the quality of the transmitted image in the MIMO system, adaptive compression techniques based on wavelet transform in a MIMO communication system is proposed. Wavelet compression is used in [35] to reduce CSI feedback data size in MIMO system. In [36], [37], [38], [39] and [40], the authors studied the performance of MIMO-Orthogonal Frequency Division Multiplexing (OFDM) based on wavelet instead of Fast Fourier Transform (FFT) by using Space-Time Block Code (STBC) under different channel conditions. All these studies demonstrated that using wavelet in MIMO-OFDM system instead of FFT will improve the BER performance. The authors in [41] compare the BER performance of STBC-framelet OFDM system using M-PSK and M-QAM modulation techniques with various number of constellation points. The framelets eliminate a portion of the constraints of wavelets such as shift-sensitivity, poor directionality, and lack of phase information. In [42], the author proposes a Discrete Wavelet (DWT)-Joint Antenna Selection (JAS) system to mitigate the performance loss due to antenna selections in MIMO systems. Extensive simulations demonstrated that the DWT-JAS improves the capacity in the presence of correlation at the transmitter and the receiver.

In our previous work [8], [9] and [10], we propsed MC/MCD-CDMA system that uses a WP as a subcarrier to reduce ICI and multiple-access interference. The system performance is tested using the signal to interference plus noise ratio in [8] and [9]. To further improve the system performance diversity is used in [8] and [10], the system performance is tesed using BER and P_{out} performances with and without diversity. The effects of wavelet family type, wavelet filter length, diversity type, diversity order, multipath intensity profile, and Nakagami parametrs are investigated. The authors in [11], [13] and [14], use interference suppression filter at the receiver to mitigate the effect of narrow-band jammer interference and thus improve the system performance. In [12] and [14] to accommodate information sources with different data rates, we propose the use of MCD scheme for multirate services.

In this paper, which is an extension of [8], [9], [10], [11], [12], [13], and [14], we employ multiple antennae at the transmitter and receiver of the WP-MC/MCD-CDMA system. Instead of STBC which is used in [36], [37], [38], [39], [40], [41] and [42], in our system we use the selection diversity at the transmitter to reduce the channel hardening which is the main drawback of MIMO systems. The performance analysis of MIMO WP-MC/MCD-CDMA system in slow fading Nakagami-m channel is presented. Two schemes for MIMO system are introduced, which are: SC-TX/SC-RX and SC-TX/MRC-RX. The performances of them are investigated according to bit error rate and outage probability. The performance analysis includes the effects of antennas' number, number of users, fading parameter, and the threshold signal to interferences plus noise ratio. The performance of the MIMO-WP-MC/MCD-CDMA system is compared with the performance of Sinusoidal (SIN) based MIMO system, which is denoted by MIMO-SIN-MC/MCD-CDMA.

The organization of the paper is as follows. In Sec. 2. , we propose the transceiver system of MIMO-WP-MC/MCD-CDMA. Signal to interference plus noise ratio is illustrated in Sec. 3. In Sec. 4. and Sec. 5. , respectively, the BER and P_{out} for SC-TX/SC-RX and SC-TX/MRC-RX systems are given. Specific numerical results of the system BER and P_{out} performances are presented in Sec. 6. At last, in Sec. 7. , the conclusions are given.

2. System Model and Description

In this study, the channel of the system under consideration consists of N_t transmission antennas and N_r reception antennas and characterized by a $N_r \times N_t$ matrix given by:

$$\mathbf{H}_k = \begin{bmatrix} h_k^{11} & h_k^{12} & \dots & h_k^{1N_t} \\ h_k^{21} & h_k^{22} & \dots & h_k^{2N_t} \\ \vdots & \vdots & \dots & \vdots \\ h_k^{N_r1} & h_k^{N_r2} & \dots & h_k^{N_rN_t} \end{bmatrix} = \\ = \left[\begin{array}{cccc} \mathbf{h}_1^k & \mathbf{h}_2^k & \dots & \mathbf{h}_{N_t}^k \end{array}\right]. \quad (1)$$

The channel is assumed to be slowly fading Nakagami channel [26], and its elements are independent and identically distributed $(i.i.d.)$ complex Gaussian random variable with $\mu = 0$ and $\sigma^2 = 1$. The impulse responses from each ξ^{th} transmit antenna to each χ^{th} receive antenna can be written as:

$$h_k^{\chi\xi}(t) = \sum_{l=0}^{L-1} h_k^{\chi\xi}(l)\delta(t - lT_c), \quad (2)$$

where L is the number of propagation paths and $h_k^{\chi\xi}(l)$ is the parameter of the l^{th} path which depends on the gain, phase and time delay of the path between the ξ^{th} transmit antenna and χ^{th} receive antenna. Each user can transmit using only one antenna, the optimal antenna, and its signal is received by N_r antennas.

The transceiver for the system under consideration is shown in Fig. 1. Each of the transmitter and receiver consists of two parts, which are the multicoding part and the spreading/WPs part. The data for k^{th} user:

$$d_k(t) = d_k^I(t) - jd_k^Q(t) = \sum_{i=-\infty}^{\infty} d_k^i \Pi_{\frac{T}{JV}}\left(t - i\frac{T}{JV}\right), \quad (3)$$

is a random complex sequence, where T is the bit duration, J is the total number of multicode sub-streams, V is the total number of the WPs super-streams and Π_x represents a rectangular pulse with duration x. At the multicode part of the transmitter, the k^{th} user data is Serial-to-Parallel (S/P) converted to generate the J sub-streams, which then coded by an orthogonal signal:

$$a_j(t) = \sum_{i=0}^{N_c-1} a_j^i \Pi_{T_c}(t - iT_c), \quad (4)$$

to reduce the interference between the sub-streams themselves. At last, the codded sub-streams are added before being transmitted to the spreading/WPs part. At the spreading/WPs part of the transmitter, the output signal of the coding part is S/P converted into V super-streams. These super-streams are spread by the Pseudo-Noise (PN) sequence:

$$c_k(t) = \sum_{i=0}^{N_n-1} c_k^i \Pi_{T_n}(t - iT_n), \quad (5)$$

modulated by the wavelet packet $wp_v(t)$, added, and finally modulated by a sinusoidal carrier, $\exp(j\omega_0 t)$. Note that:

- the orthogonal signal, $a_j(t)$, has length $= N_c$ and chip duration $= T_c = \dfrac{T}{HN_c}$,
- the PN sequence, $c_k(t)$, has a chip duration $= T_n$ and length $= N_n = \dfrac{T}{T_n}$,
- $wp_v(t) = \sqrt{\dfrac{N}{T_n}} \sum_i p_v\left(\dfrac{N \cdot t}{T_n} - iT_n\right)$ is the v^{th} WP. The wavelet function $p_v(\bullet)$ has a support length $= N$ and is defined recursively by a pair of quadrature mirror lowpass filter $h_0(k)$ and highpass filter $h_1(k)$ [8],
- a_j^i and $c_k^i \cdot \in \{\pm 1\}$ are the i^{th} bits with probabilities $P(1) = P(-1) = 0.5$.

Assuming identical power, P, for all users and the ξ^{th} antenna is the optimal antenna for k^{th} user, the transmitted signal for the k^{th} user using the ξ^{th} antenna is given by:

$$s_k^{\xi}(t) = \sqrt{2P} \sum_{v=1}^{V} \sum_{j=1}^{J} \mathrm{Re}[d_{kjv}^{\xi}(t) a_j(t) \cdot \\ \cdot c_k(t) wp_v(t) \exp(j\omega_0 t)], \quad (6)$$

where $d_{kjv}^{\xi}(t)$ is the data symbol on the ξ^{th} transmitted antenna of k^{th} user, j^{th} sub-stream, v^{th} super-stream and with a duration $= T$. The above signal, $s_k^{\xi}(t)$, is detected by the receiver after passing through a noisy channel. The received signals on the χ^{th} receiver antenna for the k^{th} user is given by:

$$r_k^{\chi} = \sum_{\xi=1}^{N_t} h_k^{\chi\xi}(t) * s_k^{\xi}(t) + n^{\chi}(t), \quad (7)$$

where $n^{\chi}(t)$ is a zero-mean Additive White Gaussian Noise (AWGN). The total received signal for k^{th} user can be represented in vector form as follows:

$$\mathbf{r}_k = \mathbf{h}_k^{\xi} * s_k^{\xi} + \mathbf{n}_k, \quad (8)$$

where $\mathbf{r}_k = [r_k^1, r_k^2, \dots, r_k^{N_r}]^T$ is the received signal vector and $\mathbf{n}_k = [n_k^1, n_k^2, \dots, n_k^{N_r}]^T$ is the noise vector.

In this paper, two MIMO system will be considered:

- SC-TX/SC-RX Scheme

In this scheme, at any bit duration, each user can choose the link with the highest Signal to Interference plus Noise Ratio (SINR γ_k) from the $N_r N_t$ possible

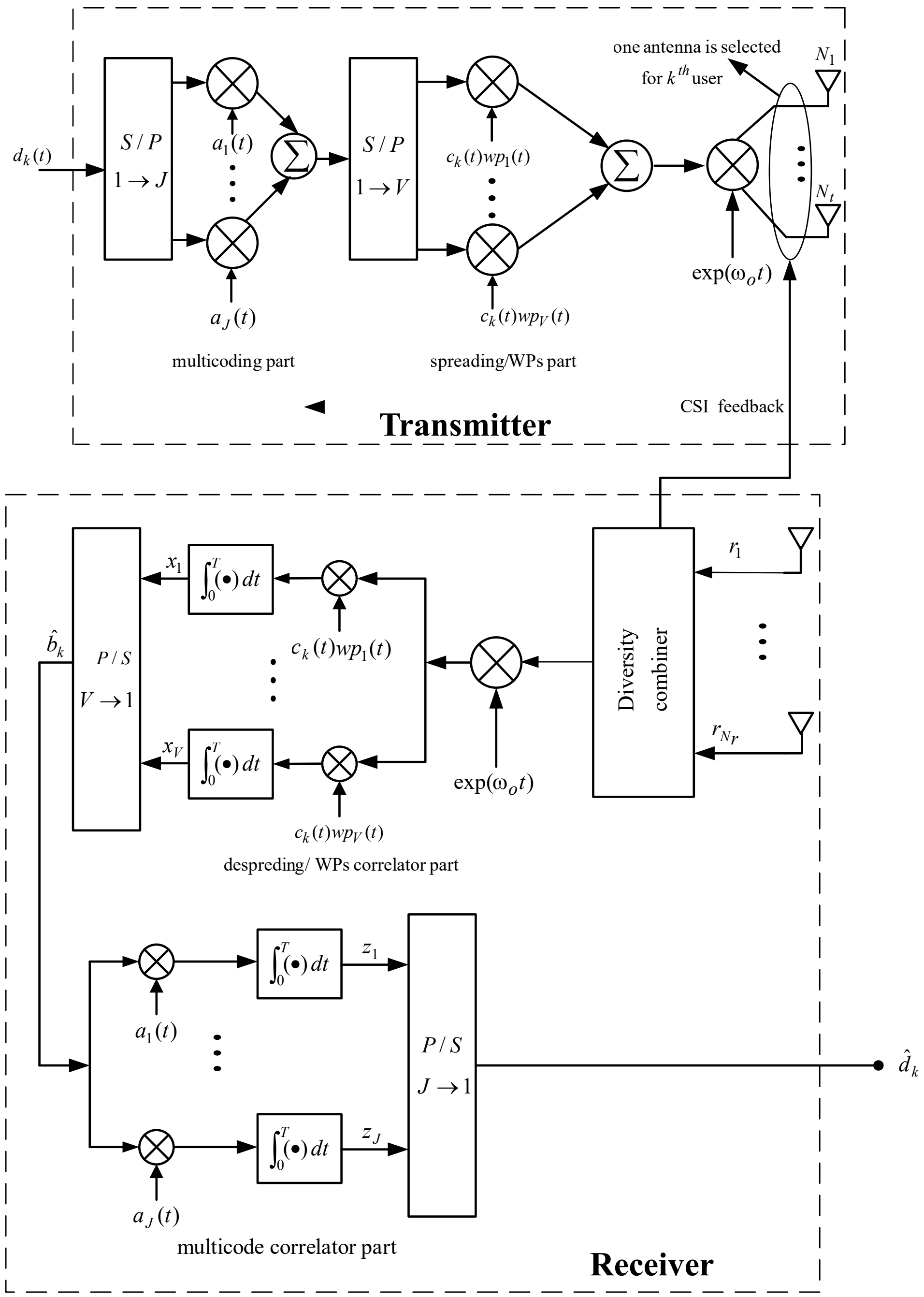

Fig. 1: Transceiver for MIMO WP-MC/MCD-CDMA system.

antenna combinations. Thus, at any bit duration, the rule for signal detection from the χ^{th} optimal transmit antenna of the k^{th} user is: $k^* = \max_{N_r} |k_k^{\chi\xi}|$. Accordingly, the effective SINR $\gamma_k$at the receiver antenna combiner output for k^{th} user is:

$$\gamma^{SC/SC} = \max \begin{bmatrix} \gamma_k^{11} & \gamma_k^{12} & \dots & \gamma_k^{1N_t} \\ \gamma_k^{21} & \gamma_k^{22} & \dots & \gamma_k^{2N_t} \\ \vdots & \vdots & \dots & \vdots \\ \gamma_k^{N_r 1} & \gamma_k^{N_r 2} & \dots & \gamma_k^{N_r N_t} \end{bmatrix}, \tag{9}$$

where $\gamma_k^{\chi\xi} = \overline{\gamma}|h_k^{\chi\xi}|^2$ and $\overline{\gamma}$ is the average SINR for each user.

- SC-TX/MRC-RX Scheme

In this scheme, the effective SINR γ_k at the receiver antenna combiner output for the k^{th} user at any bit duration with respect to the ξ^{th} transmit antenna is given by:

$$\gamma^{SC/MRC} = \sum_{\chi=1}^{N_r} \gamma_k^{\chi\xi} = \overline{\gamma} \sum_{\chi=1}^{N_r} |h_k^{\chi\xi}|^2. \tag{10}$$

The outputs of the combiner are demodulated using a locally generated carrier.

Then, at the dispreading WPs correlator part of the receiver, each k^{th} user received signal from the desired $N_r N_t$ possible antenna combinations, $r^{\chi\xi}$, is depressed and demodulated by $c_k(t)$, and $wp_v(t)$, respectively. The signal after being correlated over a period T is Parallel-to-Serial (P/S) converted to recover the superstream. If the first user is our reference user also the first path, and the first WP is our path and WP references, respectively, then the output of the first correlator, first P/S converter in this part of the receiver, x_1, is given by [8] as follows:

$$\begin{aligned} x_1 = \int_0^T r_k^{\chi\xi}(t)c_1(t)wp_1(t)[\cos(\omega_0 t) - j\sin(\omega_0 t)]dt = \\ = x_{DS}^1(t) + x_{MPI}^1(t) + x_{CDI}^1(t) + \\ + x_{WPI}^1(t) + x_{MUI}^1(t) + \hat{n}^1(t), \end{aligned} \tag{11}$$

where:

- x_{DS}^1 is the desired user signal,
- x_{MPI}^1, x_{CDI}^1, x_{WPI}^1, and x_{MUI}^1 are the multipath interference, the multicode interference, the wavelet packets interference and the multiuser interference, respectively, due to users other than the desired user at the desired $N_r N_t$ possible antenna combinations,
- $\hat{n}$ is the correlated AWGN.

The outputs of the other correlators in the WP part are given by:

$$\begin{aligned} x_v = x_{MPI}^v(t) + x_{CDI}^v(t) + x_{WPI}^v(t) + \\ + x_{MUI}^v(t) + \hat{n}^v(t), \quad v = 2, \ldots, V. \end{aligned} \tag{12}$$

The output signal of the first P/S converter in WPs part for reference user is given by:

$$\begin{aligned} \hat{b} = x_{DS}^1 + \sum_{v=1}^{V} [x_{MPI}^v + x_{CDI}^v + \\ + x_{WPI}^v + x_{MUI}^v + \hat{n}^v]. \end{aligned} \tag{13}$$

At the multicode correlator part, the second part of the receiver, the P/S converter output signals are despread by the user code a_j and correlated over a period T to recover the substreams of user' signal. The output signal for the reference user of the first correlator, z_1, is given by:

$$\begin{aligned} z_1 = \int_0^T \hat{b} \cdot a_1(t)dt = \\ = z_{DS}^1 + z_{MPI}^1 + z_{CDI}^1 + z_{WPI}^1 + z_{MUI}^1 + \tilde{n}^1. \end{aligned} \tag{14}$$

The outputs of the correlators for the all J substreams are P/S converted to recover the data signal, $\hat{d}_k(t)$.

3. Signal-to-Interference Plus Noise Ratio

Two methods will be used to test the system performance: the average bit error rate and the outage probability. The two performances depend on the instantaneous signal to interference plus noise ratio (SINR γ), which depends on the desired user signal power, the variances for the interferences and noise variance. The desired power signal, the interferences, and the noise terms consist of two parts, the inphase part and the quadrature part [8]. In this paper and without loss of generality, the inphase part was considered.

The desired inphase signal power (S), is the power of the signal for the first user, of the first wavelet packet which propagates via the first path for the desired $\chi\xi$ antenna combination. This power is given by [8]:

$$S = [z_{DS}^1]^2 = \frac{P(N_n T)^2}{2}|h_{11}^{\chi\xi}|^2. \tag{15}$$

The interference variance consists of four variances, which are:

- $\sigma_{MPI}^2 = var[z_{MPI}^1]$: multipath interference variance due to paths other than the desired path,
- $\sigma_{MCDI}^2 = var[z_{MCDI}^1]$: multicode interference variance,
- $\sigma_{WPI}^2 = var[z_{WPI}^1]$: wavelet packets interference variance,
- $\sigma_{MUI}^2 = var[z_{MUI}^1]$: multiuser interference variance.

To calculate the above variances for BPSK modulation, it is assumed that all the interference and the noise terms are Gaussian zero-mean independent random variables. Invoking the results in [8], the total interference variance, σ_{TI}^2, can be shown to be equal to:

$$\begin{aligned} \sigma_{TI}^2 = \sigma_{MPI}^2 + \sigma_{MCDI}^2 + \sigma_{WPI}^2 + \sigma_{MUI}^2 = \\ = \frac{P(N_n T)^2}{2} MI, \end{aligned} \tag{16}$$

and MI is given by:

$$\begin{aligned} MI = \frac{\Omega}{12 T_n (N_n V)^2} \cdot \\ \cdot \left[\frac{QK}{J} \sum_{v=1}^{V} \sum_{v'=1}^{V} \psi_{v'v} - \frac{1}{J^2} \sum_{v'=1}^{V} \psi_{v'1} \right], \end{aligned} \tag{17}$$

where:

- $\psi_{v'v} = \int_0^{T_n} \left\{ (r_{v'v}(\rho))^2 + (\hat{r}_{v'v}(\rho))^2 \right\} dp$, $0 < \rho < T_n$, with $r_{v'v}(\rho) = \int_0^{\rho} w_v(t) w_v'(t) dt$

and $r_{v'v}(\rho) = \int_0^{\rho} w_v(t) w_v'(t)dt$ being the partial cross-correlation functions between WPs [8],

- $\Omega = var[h_{k1}^{\chi\xi}]$ and Q is the variance of Multipath Intensity Profile (MIP).

In this paper, the uniform MIP will be used. In this MIP, all multipath components amplitude levels are the same $= h_{k1}^{\chi\xi}$. Thus:

$$\begin{aligned}\Omega Q = var\left[\sum_{l=1}^{L} h_{kl}^{\chi\xi}\right] = \sum_{l=1}^{L} var\left[h_{kl}^{\chi\xi}\right] = \\ = var\left[h_{k1}^{\chi\xi}\right]\sum_{l=1}^{L} 1 = \Omega L.\end{aligned} \tag{18}$$

The noise variance is given by [8]:

$$\begin{aligned}\sigma_n^2 = \frac{P(N_n T)^2}{2}\left[\frac{V\Omega}{N_n\left(\frac{E_s}{N_0}\right)}\right] = \\ = \frac{P(N_n T)^2}{2} NI,\end{aligned} \tag{19}$$

where $\frac{N_0}{2}$ is the double-sided power spectral density for the AWGN, $E_s = 2P\Omega T$ is the mean received symbol energy. Using Eq. (15), Eq. (17), and Eq. (19), the instantaneous SINR, γ, can be written as:

$$\begin{aligned}\gamma = \frac{S}{\sigma_{TI}^2 + \sigma_n^2} = |h_{1l}^{\chi\xi}|^2[MI + NI]^{-1} = \\ = |h_{1l}^{\chi\xi}|^2\overline{\gamma}.\end{aligned} \tag{20}$$

4. Average Bit Error Rate

The BER, $\overline{P}_e$, is obtained by averaging the instantaneous $P_e(\gamma)$, over the channel fading functions. That is:

$$\overline{P}_e = \int_0^{\infty} f_{\gamma_{\max}}(\gamma) P_e(\gamma) d\gamma, \tag{21}$$

where:

- $P_e(\gamma) = Q\sqrt{2\gamma}$, where $Q(\bullet)$ is the Gaussian Q function,
- $f_{\gamma}(\gamma)$ is the probability density function of γ. This function depends on channel gain distribution, which is assumed to be Nakagami in this paper, and also on the MIMO scheme that is used.

Based on [29], the $\overline{P}_e^{\,SC-TX}_{\,SC-RX}$ and $\overline{P}_e^{\,SC-TX}_{\,MRC-RX}$ are given by Eq. (22) and Eq. (23), respectively.

$$\overline{P}_e^{\,SC-TX}_{\,SC-RX} = B_1\left(m, \frac{m}{\overline{\gamma}}, KN_tN_r\right), \tag{22}$$

$$\overline{P}_e^{\,SC-TX}_{\,MRC-RX} = B_1\left(mN_r, \frac{m}{\overline{\gamma}}, KN_t\right), \tag{23}$$

where $m \geq \frac{1}{2}$ is the Nakagami number and $B_1(a,b,c)$ is given by [26]:

$$\begin{aligned}B_1(a,b,c) = \frac{1}{2\sqrt{\pi}}\cdot \\ \cdot\sum_{n=0}^{\infty}\frac{a_n b^{ac+n}\Gamma(ac+n+0.5)}{(1+bc)^{ac+n+0.5}}; \quad \text{real } a \geq \frac{1}{2},\end{aligned} \tag{24}$$

with $a_0 = \left[\frac{1}{\Gamma(a+1)}\right]^c$, and:

$$a_n = \frac{1}{n}\sum_{j=1}^{n}\frac{\Gamma(a+1)[j(c+1)-n]}{\Gamma(a+1+j)} a_{n-j}; \quad n \geq 1. \tag{25}$$

Note that $\Gamma(\bullet)$denotes the gamma function [43].

5. Outage Probability

The P_{out} is the probability that the channel capacity, C, fall below specific threshold capacity, C_{th} [18]:

$$P_{out} = P(C < C_{th}). \tag{26}$$

The channel capacity is given by [18]:

$$C = \log_2(1 + \gamma_{\max}) \text{ bits} \cdot s^{-1} \cdot \text{Hz}^{-1}. \tag{27}$$

From Eq. (26) and Eq. (27) we get:

$$P_{out} = P(C < C_{th}) = P(\gamma_{\max} < [2^{C_{th}} - 1] = \gamma_{th}). \tag{28}$$

According to Eq. (26), we can define P_{out} as the probability that $\gamma_{\max}$ falls below a certain threshold SINR, γ_{th}. Thus:

$$P_{out} = Pr(\gamma < \gamma_{th}) = \int_0^{\gamma_{th}} f_{\gamma_{\max}}(\gamma) d\gamma. \tag{29}$$

Invoke the result in [29], the $P_{out}{}^{SC-TX}_{SC-RX}$ and $P_{out}{}^{SC-TX}_{MRC-RX}$ are given as follows:

$$P_{out}{}^{SC-TX}_{SC-RX} = \left[\frac{\tilde{G}\left(m, \frac{m\gamma_{th}}{\overline{\gamma}}\right)}{\Gamma(m)}\right]^{\frac{KN_t}{N_r}}, \tag{30}$$

$$P_{out}{}^{SC-TX}_{MRC-RX} = \left[\frac{\tilde{G}\left(mN_r, \frac{m\gamma_{th}}{\overline{\gamma}}\right)}{\Gamma(mN_r)}\right]^{KN_t}, \tag{31}$$

where $\tilde{G}(\bullet,\bullet)$ is the incomplete gamma function [43].

6. Results and Discussions

Using the above analytical results, the BER and P_{out} performances for the system were evaluated. The results are based on the numerical evaluation of Eq. (22), Eq. (23), Eq. (30), and Eq. (31) using MATLAB packages.

The performance of the system is tested for different combinations of N_r and N_t. Also, the effects of the number of users, Nakagami parameter, and threshold values are tested. The performance of the system is compared to that of MC/MCD-CDMA based on a sinusoidal carrier. Unless otherwise stated, the numerical results were produced using:

- *Daubechies* wavelet packets with order 3 (*db3*),
- Number of substreams $J = 4$,
- Number of superstream $V = 3$,
- $\Omega = 10$ dB, $L = 3$ and Nakagami-m parameter $= 2$,
- Processing gain length $N_n = 32$ with chip duration $T_n = 10^{-6}$ s,
- The threshold of SINR γ_{th} (dB),
- The number of users $K = 2$.

Note: in the following Figs.; SCξ/SCχ and SCξ/MRCχ mean that: the number of antennas at the transmitter is "ξ" and the number of antennas at the receiver is "χ".

6.1. Effect of Number of Antennas on BER and Outage Probability

Figure 2 and Fig. 3 illustrate, respectively, the BER and P_{out} performances versus E_s/N_0 for SC-TX/SC-RX and SC-TX/MRC-RX using different numbers of N_t and N_r combinations. From those two figures, it is clear that for the same number of antennas, the SC-TX/MRC-RX scheme outperforms the SC-TX/SC-RX scheme. These results are expected since the MRC is the optimum combination diversity. Also, for the two schemes, the performance improved as the total number of antenna increases. For the SC/MRC systems with a fixed total number of antennas at transmitter and receiver, the diversity gain decreases as the number of receiver antennas increases. For example, SC2/MRC3 scheme outperforms SC3/MRC2. In all diversity techniques, this is a typical diminishing effect. This confirms the observations in [18], [27] and [28].

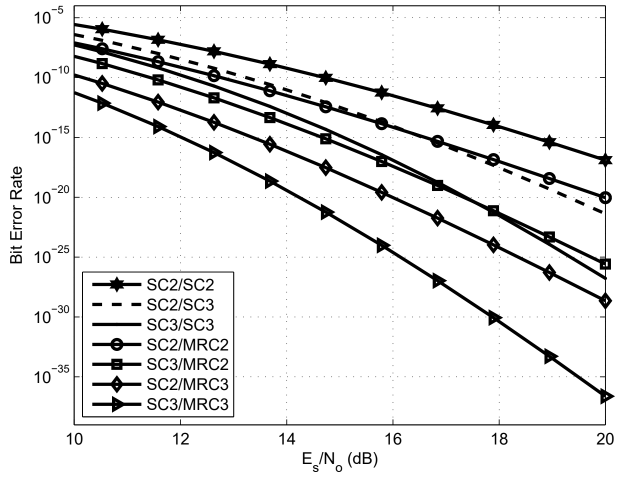

Fig. 2: BER performance versus E_s/N_0 for SC-TX/SC-RX and SC-TX/MRC-RX with different number of N_t and N_r combinations.

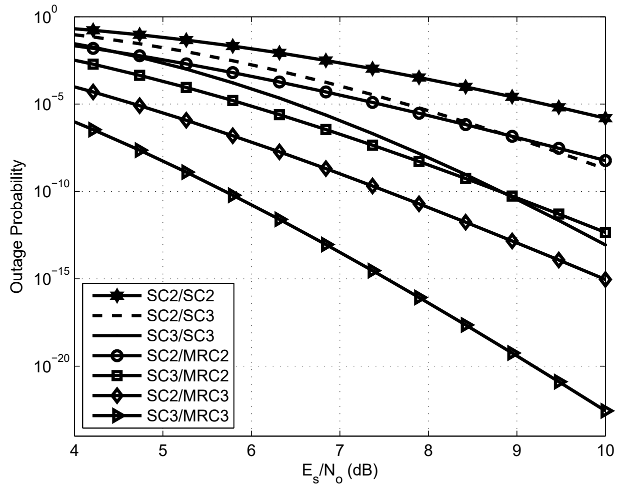

Fig. 3: P_{out} performance versus E_s/N_0 for SC-TX/SC-RX and SC-TX/MRC-RX with different numbers of N_t and N_r combinations

6.2. Effect of Number of Users on BER

For SC-TX/MRC-RX scheme with $E_s/N_0 = 16$ dB, $m = 1$ and using four different N_t and N_r combinations, Fig. 4 illustrates the effect of the number of users (K) on BER performance. It is clear from the figure that: the higher the number of users, the better the system performance. This is the inherent benefit of the multiuser system, which indicates that we can use multiuser diversity in a multi-user system. These results are identical to those found in [19] and [29]. Also, as in Fig. 2 and Fig. 3, as the number of antennas increased, the system performance improved.

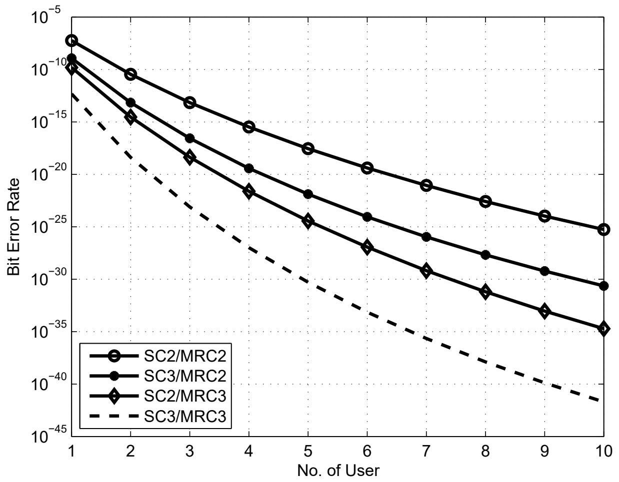

Fig. 4: Effect of the number of users on BER performance.

6.3. Effect of Nakagami-m Parameter on BER

Figure 5 shows the effect of Nakagami-m parameter on BER performance. The SC-TX/SC-RX scheme is used with $E_s/N_0 = 16$ dB and different $(N_t\ N_r)$ combinations. From the figure we can notice that: increasing m parameter and the total antennas' number improves the BER. This is expected since the higher value of m means less fading and better performance. For the antennas' number, this confirms the results in Fig. 2, Fig. 3, and Fig. 4.

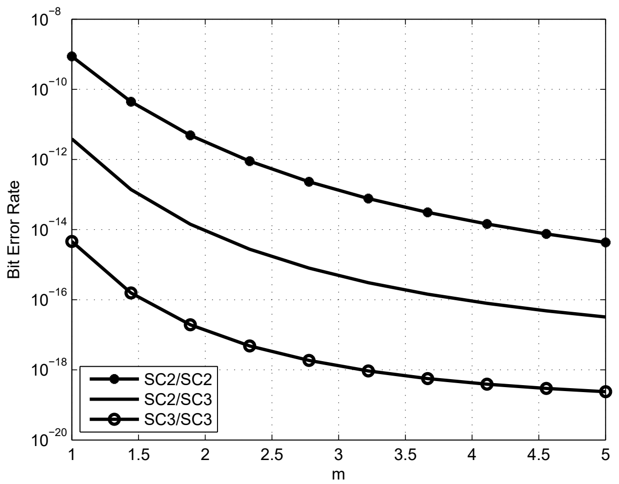

Fig. 5: Effect of Nakagami-m parameter on the BER performance.

6.4. Effect of the Threshold Value on P_{out}

Figure 6 illustrates P_{out} versus γ_{th} for the SC/SC and SC/MRC schemes using $E_s/N_0 = 6$ dB. As expected, SC/MRC scheme has better performance than the SC/SC scheme. Also, as the total number of antennas increases, the performance gets better. From the figure we can notice that: increasing γ_{th} degraded the system performance which is expected since by increasing γ_{th} there is a chance that the channel capacity may go below the required threshold level.

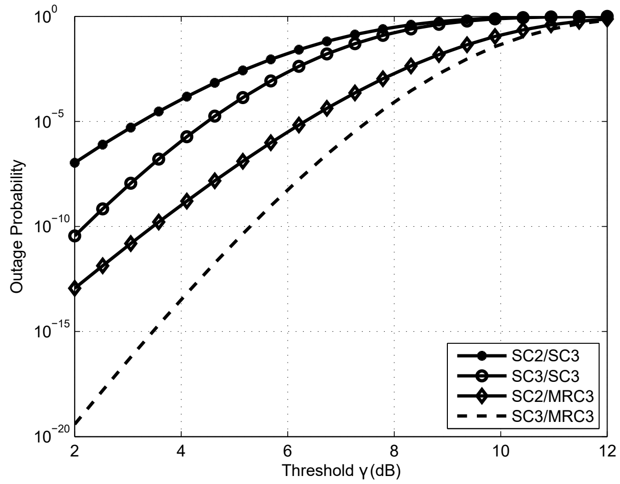

Fig. 6: P_{out} versus γ_{th} for SC-TX/SC-RX and SC-TX/MRC-RX schemes.

6.5. Performance Comparison

Figure 7 and Fig. 8 show BER and P_{out} performances, respectively, for two MIMO systems, which are MIMO-WP-MC/MCD-CDMA, our system, and MIMO-SIN-MC/MCD CDMA system. From these two figures, it can be noted that for $E_s/N_0 = 8$ dB the MC/MCD CDMA system outperforms our system slightly. But as E_s/N_0 increases, our system outperforms the other system and the difference between the two systems performance increases as E_s/N_0 increases.

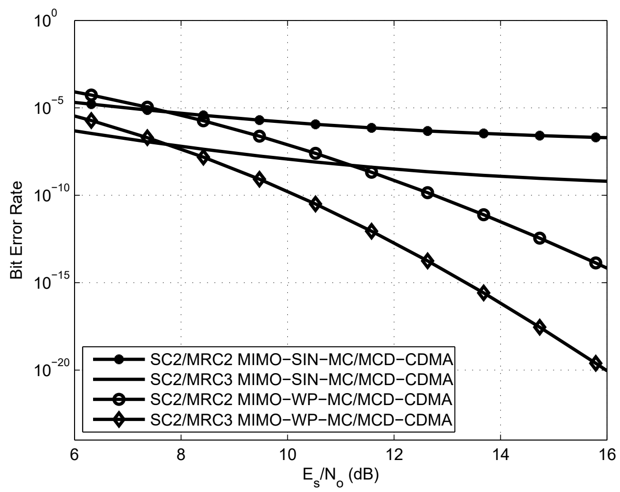

Fig. 7: BER performance for two MIMO systems.

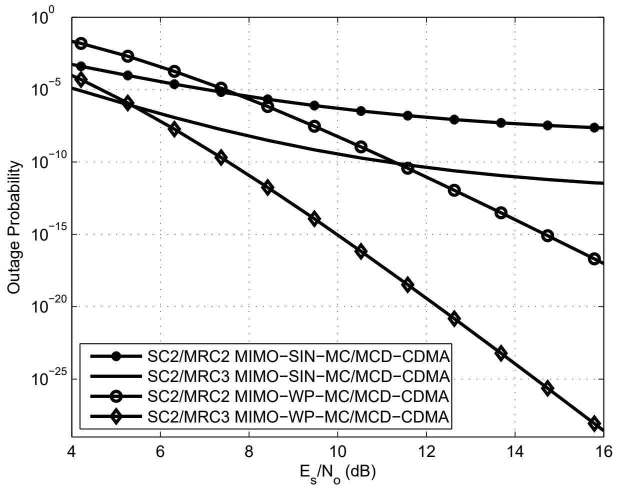

Fig. 8: P_{out} performance for two MIMO systems.

7. Conclusion

The two performances BER and P_{out} for MIMO WP-MC/MCD-CDMA system have been investigated. The results obtained in this paper are consistent with other published results. It has been shown that the system performance is improved by increasing the number of antennas. This is because, for any MIMO system, the diversity order depends on the total number of antennas. Also, the results show that for the same number of antennas, the SC-TX/MRC-RX scheme always outperform the SC-TX/SC-RX system. The performance of our system is compared with the performance of MIMO MC/MCD-CDMA system. For $E_s/N_0 = 8$ dB the MIMO-MC/MCD-CDMA outperforms our system, but the difference in their performance is marginal. As the E_s/N_0 increases, our system outperforms the other system, and the differences between the two performances increases as E_s/N_0 increases.

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