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Performance Analysis of Uplink Cognitive Radio Transmission based on Overloaded MC-DS-CDMA

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** Regular Paper*

***Abstract*:** This paper reports a cognitive radio network architecture based on overloaded multicarrier direct sequence code division multiple access (O-MC-DS-CDMA). The O-MC-DS-CDMA technique combines CDMA with a multicarrier modulation technique to overcome the channel fading effects. In this technique, secondary users are enabled to share the available bandwidth with the existing primary users. Two sets of orthogonal Gold codes are used to support the primary and secondary users simultaneously. The orthogonality between the spreading codes is lost due to the non-zero cross correlation between the codes and the timing synchronization error in the uplink transmission, which causes interference between primary and secondary users. This paper proposes two modified hybrid parallel/successive interference cancellation techniques for primary and secondary user base station receivers with multiple antennas to suppress the interference among users. Interference among the same group of users is cancelled by parallel interference cancellation and the interference among groups is cancelled using successive interference cancellation. The simulation results confirmed that the proposed modified interference cancellation techniques show better BER performance over conventional interference cancellation techniques.

***Keywords*:** Cognitive radio, Overloaded MC-DS-CDMA, Orthogonal gold codes, Hybrid interference cancellation

1. Introduction

The spectrum requirements for wireless multimedia applications have increased exponentially, leading to spectrum scarcity. On the other hand, recent studies have shown that most of the licensed spectrum is underutilized. Cognitive radio (CR) has been proposed to bridge the gap between the spectrum scarcity and underutilization of the available spectrum [1]. The concept of CR enables the coexistence of legacy systems and new users, called primary users (PU) and secondary users (SU), respectively, through dynamic spectrum access [2, 3]. CR systems can be divided into three types: interweave, underlay and overlay CRs. In the interweave type CR systems, the secondary devices sense the environment to detect the presence of the primary user's signal and transmit opportunistically only when there is no primary user transmission. In underlay CR systems, secondary users are allowed to communicate along with primary users provided the interference created in the primary system is below a predefined threshold. In the underlay CR systems, secondary users detect the presence of primary users and control their transmission power accordingly. Beamforming, MIMO and spread spectrum techniques are generally used to control the interference to primary users. Finally, in overlay systems, the secondary user assists the primary user's transmission by a relay operation along with its own data transmission. The secondary user is assumed to have a-priori knowledge of the primary user's message and the Channel State Information (CSI). The secondary user retransmits the primary user's signal along with its own data signal. In the presence of a relay operation, there is an increase in the Signal to Noise Ratio (SNR) at the primary user's receiver but the interference caused by the secondary user's data signal will decrease the SNR of the primary user. Therefore, there is an equal increase and decrease in the SNR of the primary user. Hence, the performance of the primary user is not

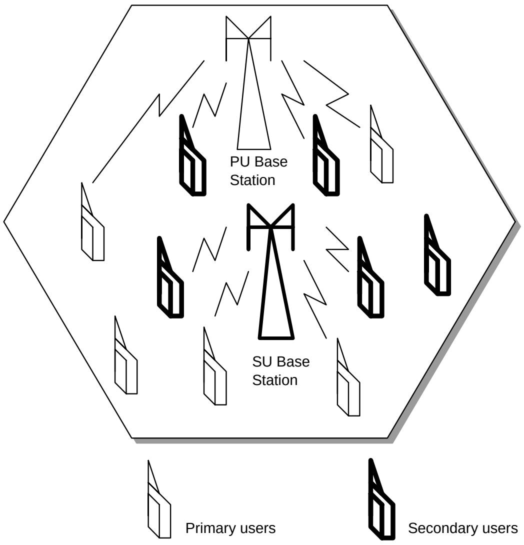

Fig. 1. Proposed overloaded MC-DS-CDMA based CR system.

degraded. At the same time, the secondary user's receiver benefits from the data signal transmitted by the secondary user's transmitter.

In this study, the underlay CR system based on overloaded multicarrier direct sequence code-division multiple access (O-MC-DS-CDMA) was considered. In the spread spectrum system, the power level of the wide band signal of the secondary user is controlled to cause acceptable interference to the primary users. In a CDMA system, the maximum number of orthogonal users supported is equal to the spreading factor N of the code. An overloaded CDMA system is used to allow efficient use of the available spectrum and support a larger number of users. Therefore, an overloaded CDMA is quite suitable for CR systems where secondary users can share the fixed bandwidth of the primary users. A range of techniques have been proposed in literature to support an additional number of users, among which the most efficient techniques use multiple sets of orthogonal codes. Fig. 1 shows the proposed CR network based on an overloaded MC-DS-CDMA system. In this network, there are N primary users and M secondary users. The PUs are allocated with the orthogonal codes from set 1 and the SUs are allocated with orthogonal codes from set 2. Therefore, $K = N + M$ users are supported by the proposed overloaded MC-DS-CDMA system. Both the PU base station and SU base station are assumed to be co-located at the center of the cell.

Section 2 reviews previous studies on overloaded CDMA systems, underlay CR transmission techniques and interference cancellation techniques. Section 3 describes the system model based on O-MC-DS-CDMA. Section 4 provides the theoretical BER expression for the proposed system. Section 5 presents the simulation results and a comparison with conventional interference cancellation techniques. The conclusions and future work are summarized in section 6.

2. Related Work

DS-CDMA technique is generally used in underlay CR systems. In DS-CDMA, the data rate and power level are controlled based on the spectrum availability and interference constraint on the primary user. In underlay CR systems, the secondary users utilize the spectrum of the primary user, provided the interference caused by the secondary users is less than the maximum interference limit that is tolerable by the primary users. A range of spectrum sharing approaches for CDMA-based CR systems have been proposed [4-15]. In [4, 5], the authors proposed an interference-minimizing code assignment strategy for secondary users in CDMA underlay CR networks. The interference caused from the existing primary and secondary users was minimized by decreasing the mean square cross-correlations between the candidate codes and received signal. The authors reported that the proposed code-assignment strategy exhibits significant performance gains over a random code-assignment strategy. In [6], the authors examined the relationship among the interference threshold settings, the transmission rate of secondary links and the transmission power of the primary links in a CDMA-based underlay cognitive wireless network. Given the interference threshold, the maximum achievable rate for secondary links is determined by formulating an optimization problem.

In [7], the authors proposed a two-phase channel and power allocation scheme that improves the total number of subscribers that can be served simultaneously by the CR base stations. The channels and power are allocated to base stations such that the total coverage is maximized while keeping the interference experienced by each primary user below a prescribed limit. The authors of [8] proposed two adaptive spectrum sharing schemes, i.e., intrusive and non-intrusive spectrum sharing, for CDMA-based cognitive medium access control (MAC) in uplink communications over the CR networks. The secondary users can switch adaptively between the schemes based on channel utilization, traffic load and interference power constraints of the primary users. The secondary users can transmit either in underlay mode or in interweave mode based on the availability of the primary users.

An iterative least square based primary user identification algorithm for detecting the signature codes utilized by the primary users in a CDMA network was proposed [9]. Based on the availability of the code channels, secondary users are allocated channels and power simultaneously. The advantage of the proposed method is that it does not require prior knowledge of the primary CDMA network. The design of channel-aware access control (CAAC) algorithms to protect the primary user transmission in CR networks was examined [10]. In their proposed algorithm, the access probabilities of the secondary users were adjusted according to the channel-state information and measured interference temperature. They reported the convergence and effectiveness of the distributed CAAC algorithms. Dashti and Azmi [11] examined the joint power and rate allocation strategies for CDMA-based underlay CR networks with heterogeneous traffic. In their contribution, a combination of streaming and elastic traffic was considered and a cross-layer resource allocation was proposed. The Max-min and proportional fairness (PF) approaches were compared for the optimization problem, and it was shown that PF outperforms the max-min approach under both homogenous and heterogeneous traffic conditions.

Two joint admission and power control (JAPC) algorithms, i.e., minimal revenue efficiency removal (JAPC-MRER) and minimal signal strength removal algorithm (JAPC-MSSRA) in the presence and absence of log-normal shadowing were investigated [12]. The authors examined the combined effect of path loss and log-normal shadowing on the total secondary revenue and blocking probability and compared the performance of the two algorithms for shadowing and non-shadowing cases. A new CR network model was proposed based on CDMA and the performance of secondary users and primary users were evaluated in terms of the outage probability, blocking probability, BER, and average data rate of secondary users [13]. The authors have also proposed two new spectrum sensing schemes based on the interference limit and compared their performance with the existing adaptive spectrum sensing scheme.

The performance of CDMA-based CR networks in the presence of receiver beamforming at the base stations for uplink communication was investigated [14]. Using simulations, the authors showed that beamforming results in significant performance improvements in terms of the probability of outage. In [15], a modified greedy algorithm was proposed to vary the number of activated secondary users based on the pre-determined interference threshold, in a DS-CDMA-based CR network. Using the simulation results it was shown that the proposed CR system exhibits acceptable BER performance at a low SNR level compared to a conventional CDMA system without a Greedy algorithm. On the other hand, to the best of the authors' knowledge, there are no reports of overloaded CDMA based CR networks. Therefore, this paper proposes a novel scheme of an overloaded MC-DS-CDMA-based CR network. Multicarrier modulation (MCM) schemes are used to overcome the intersymbol interference (ISI) in multipath fading channel conditions by converting a high-rate data stream into multiple low-rate data streams. Thus, the MC-DS-CDMA technique is suitable for high data rate CR transmission over frequency selective fading channels.

A variety of overloading schemes have been proposed [16-21]. In one study [16], two sets of orthogonal codes were generated using Walsh-Hadamard (WH) codes and the codes were orthogonal within the sets. In this scheme, the same WH code set was scrambled with a set specific scrambling sequence (s-O/O). An iterative multistage detection was suggested to mitigate the interference between the two sets of users. An overloading scheme using a set of orthogonal Gold codes was proposed [17]. The same authors evaluated the BER performance using orthogonal Gold code (OG/OG) sets with an iterative multistage detector (IMSD) based on soft decision interference cancellation (SDIC) [18]. An assortment of receiver structures for overloaded CDMA systems were also proposed [19-21].

In an overloaded system, the signature sequences are not perfectly orthogonal. A non-zero cross correlation exists between the spreading sequences, which leads to multiple access interference (MAI). In an overloaded system, a conventional matched filter receiver results in poor BER performance because the matched filter cannot overcome the MAI. Therefore, multiuser detection (MUD) techniques are used to mitigate the MAI. Several interference cancellation (IC) techniques for CDMA systems to mitigate MAI have been proposed [22-40]. Parallel Interference Cancellation (PIC) and Successive Interference Cancellation (SIC) are the most widely used interference cancellation techniques. PIC and SIC techniques are more suitable for overloaded systems because they have good complexity-performance trade-off compared to other MUD techniques, such as decorrelator, minimum mean squared error (MMSE) detector and maximum likelihood (ML) detector.

The PIC receiver estimates and cancels out all the MAI for each user in parallel [22-26]. In SIC, each user's signal is estimated and is again respread using the user's spreading code. The respreaded signal is subtracted from the received signal before decoding the next user's signal. Therefore, the interference is cancelled out successively in every iteration [27-31]. Hybrid Interference Cancellation (HIC) is a combination of SIC and PIC schemes. SIC shows optimal performance and is more reliable than PIC. On the other hand, the computational time is large for SIC because the number of iterations to cancel out the MAI is directly proportional to the number of users. PIC is faster than SIC but the receiver is quite complex. HIC combines the advantages of both schemes [32-35]. Group-wise Successive Interference Cancellation (GSIC) is also a combination of PIC and SIC. GSIC is generally applied to multi-rate transmission systems [36-39].

A hybrid interference cancellation (HIC) technique employing both parallel and successive interference cancellation was proposed for the overloaded CDMA system under imperfect synchronization conditions [40]. The timing offset error causes severe interference among users. Interference among the same group of users and among groups is cancelled out using parallel interference cancellation and successive interference cancellation, respectively. The proposed HIC was shown to efficiently mitigate the multiuser interference (MUI).

These interference cancellation receivers [19-40] use only one receiver antenna. In the proposed modified interference cancellation techniques, multiple receiver antennas are considered to achieve antenna diversity gain. Using multiple receiver antennas, the BER performance of the proposed system is improved significantly compared to other conventional single antenna receivers. In addition, the power levels of the users are assumed to be equal [19-40]. In the proposed work, different power levels are assumed for the two sets of users. The primary users are considered to have more transmission power than secondary users to reduce the interference caused by the secondary users on the primary users. Underloaded CDMA systems have been considered, where the number of users is less than or equal to the spreading factor of the code [22-39]. In the proposed work, overloaded CDMA system is considered, where the number of users is greater than the spreading factor of the code. In most existing receiver structures, synchronous transmission of different users is considered, whereas in the proposed work, synchronization error between the users is also considered. In a previous study [40], the AWGN channel model was considered, whereas the proposed work considered the Rayleigh fading channel model. The BER performance of the proposed interference cancellation receivers were also compared with other conventional techniques, such as the Matched filter, PIC [22] and SIC [31].

3. System model

In the MC-DS-CDMA technique, the transmitter spreads the serial to parallel converted data streams in the time domain, using a spreading code. In this study, an overloaded MC-DS-CDMA system with N number of primary users and M number of secondary users was analyzed. Therefore, the total number of users was $K=M+N$. The number of PUs was assumed to be greater than or equal to the number of SUs. Let N be the spreading code length. Two sets of orthogonal Gold codes are used, one for PUs and another for SUs.

Fig. 2 shows the proposed overloaded MC-DS-CDMA transmitter model. At the transmitter, the data bit stream is modulated by binary phase shift keying (BPSK) modulation and the stream of data symbols s_i is converted from serial to U parallel sub streams. The symbols in each substream are spread using orthogonal Gold code sequence C_k of the k^{th} user with a spreading factor of N. As a result, each symbol of the k^{th} user is changed into the chip stream $\{d_{k,u}(i),\ i=0,1,\ldots,\ N-1;\ u=1,2,\ldots,\ U\}$. Finally, the inverse fast Fourier transform (IFFT) is performed to carry out multicarrier modulation. The output signal of the IFFT block is transmitted after adding a cyclic prefix, whose length is greater than the maximum delay spread of the channel.

The channel is assumed to be a frequency selective Rayleigh fading channel and the coefficients are constant for a time period of $U.T_b$, where T_b is the symbol period. For more than one receiver antenna, h^{v}_{u,k_u} denotes the channel between the K_u^{th} user's transmitter antenna and the v^{th} receiver antenna. The coefficients, $\{\left|h^{v}_{u,k_u}\right|,\ v = 1,\ 2,\ \cdots,\ V;\ u = 1,\ 2;\ K_1 = 1,\ 2,\ \cdots N$ and $K_2 = 1,\ 2,\ \cdots M\}$, are independent and identically distributed (i.i.d.) random variables obeying the Rayleigh distribution. The phases $\{\psi^{v}_{u,k_u},\ v = 1,\ 2,\ \cdots,\ V;\ u = 1,\ 2;\ K_1 = 1, 2,\ \cdots N$ and $1,\ 2,\ \cdots M\}$ are introduced by the fading channels and are distributed uniformly in the interval $[0,\ 2\pi)$.

Fig. 3 shows the proposed overloaded MC-DS-CDMA receiver model with two antennas. At the receiver side, the cyclic prefix is first removed and the symbols are converted serial to parallel to perform fast Fourier transform (FFT). FFT converts the convolution operation between the channel coefficients and the transmitted symbols to simple multiplication. Interference cancellation is then performed at each subchannel using modified hybrid interference cancellation (m-HIC1/ m-HIC2) techniques. The signals at the output of the FFT blocks of the two receiver antennas are used to negate the interference. After interference cancellation, the estimated symbols are parallel to serial converted, to obtain the stream of symbols, s_i'.

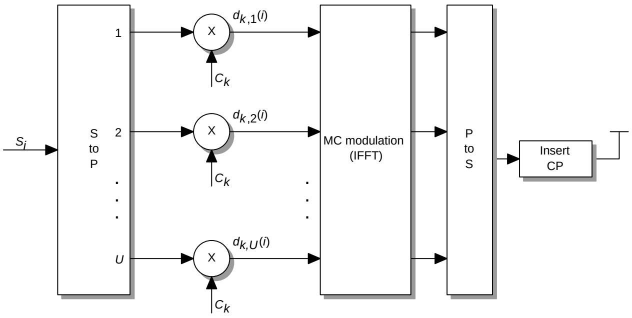

Fig. 2. Proposed overloaded MC-DS-CDMA transmitter.

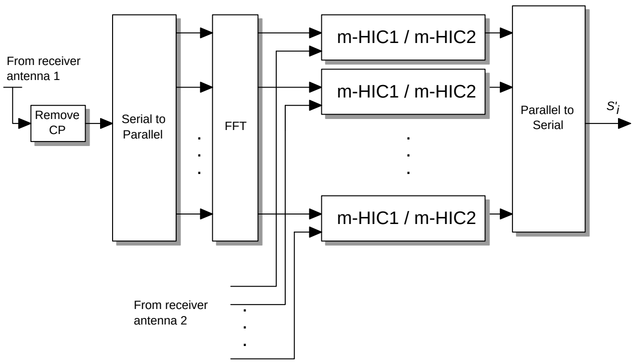

Fig. 3. Proposed overloaded MC-DS-CDMA base station receiver with two antennas.

3.1 Type 1- modified Hybrid Interference Cancellation (m-HIC1)

Fig. 4 shows the block diagram of the proposed type 1-modified hybrid interference cancellation technique for an O-MC-DS-CDMA receiver with V antennas. The signal received at each of the receiver antenna is demodulated using FFT and given to the interference cancellation block at each subchannel. The signals are first despreaded using a matched filter (MF). The soft output of the matched filter corresponding to the l^{th} transmitted symbol, s^{l}_{u,K_u}, $u \in \{1,\ 2\}$, $K_1 \in \{1,\ 2...N\}$ and $K_2 \in \{1,\ 2...M\}$, is corrupted by MAI from the same set of users and other set of users due to timing synchronization error and the non-zero cross correlation between the spreading sequences. The PIC is used to cancel out the interference caused by the same set of users. The interference caused by another set of users is cancelled out successively using SIC. After cancelling out the interference, the soft outputs of V arms are given to a maximal ratio combiner (MRC). The output of the MRC is thresholded (Th) to provide an estimate of the transmitted symbol, s^{l}_{u,K_u}. In the regenerator block (Reg), the estimated symbols are again multiplied with the cross

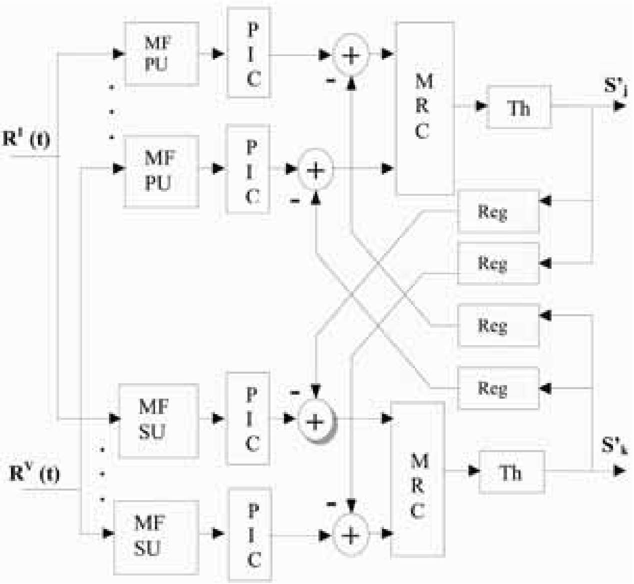

Fig. 4. Proposed type 1- modified Hybrid Interference Cancellation technique.

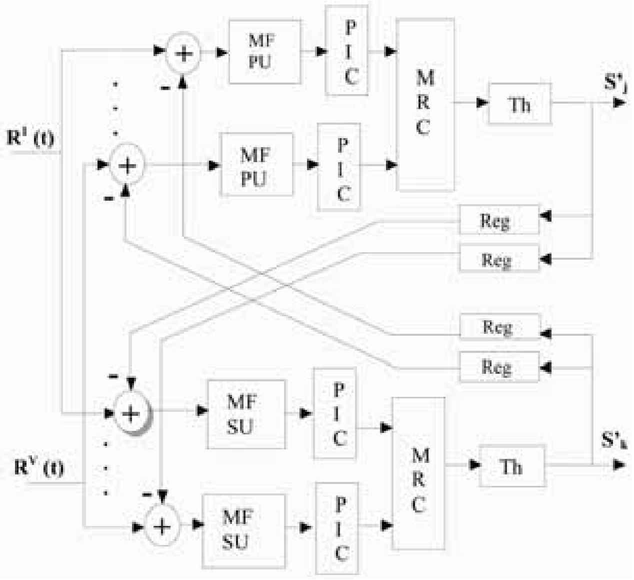

Fig. 5. Proposed type 2- modified Hybrid Interference Cancellation technique.

correlation value and channel gain corresponding to the particular antenna (v). The regenerated signal is cancelled out from the PIC's output of the other set of users. During the first iteration, the signal of the PUs is regenerated and cancelled from PIC output of the SU. Therefore, in this type of receiver, PIC is performed only once, followed by iterative SIC and MRC combining.

3.2 Type 2- modified Hybrid Interference Cancellation (m-HIC2)

Fig. 5 shows a block diagram of the proposed type 2- modified hybrid interference cancellation technique for an O-MC-DS-CDMA receiver with V antennas. The technique is similar to that shown in Fig. 4 except that in m-HIC2, SIC is performed prior to PIC. Estimates of the transmitted symbols, s^l_{u,K_u}, of other set users, obtained from the previous iteration, are used to regenerate the transmitted signals of the users and are first cancelled out from the received composite signal before performing matched filtering. Therefore, in the soft output of the matched filter, MAI due to the other set users is reduced and then supplied to the PIC stages to cancel out the MAI due to the same set of users. After cancelling out the interference, the soft outputs of the V arms are given to an MRC combiner and its output is thresholded (Th) to provide an estimate of the transmitted symbol. During the first iteration, the data for the PU is estimated and respread to cancel out the signal of the PUs from the received signal before estimating the data of the SUs. Therefore, in this type of receiver, the SIC and PIC stages are repeated during every iteration and the delay in estimating the symbols is higher in m-HIC2 compared to m-HIC1.

4. Bit error rate performance

This section reports the theoretical BER expression for the proposed O-MC-DS-CDMA system for the M-ary PSK modulation scheme. Let $\Theta = \sum_{v=1}^{V} \left| h^v_{u,k_u} \right|^2$ be the random variable that follows the χ^2 distribution with a degree of freedom, 2V. The closed-form of the BER for M-ary PSK modulation [41] is given by:

$$P_b = \frac{2}{log_2 M}\left(\frac{1-\mu}{2}\right)^V \sum_{i=0}^{V-1}\binom{V+i-1}{i}\left(\frac{1+\mu}{2}\right)^i \quad (1)$$

where $\mu = \sqrt{\bar{\gamma}_s \sin^2\frac{\pi}{M} \Big/ \left(1+\bar{\gamma}_s \sin^2\frac{\pi}{M}\right)}$ and $\bar{\gamma}_s = E_s\Omega / N_0$.

The BER P_b for BPSK is given by the following:

$$P_b = \left(\frac{1-\mu}{2}\right)^V \sum_{i=0}^{V-1}\binom{V+i-1}{i}\left(\frac{1+\mu}{2}\right)^i \quad (2)$$

where $\mu = \sqrt{\bar{\gamma}_b / (1+\bar{\gamma}_b)}$, $\bar{\gamma}_b = E_b\Omega / N_0$ and $\Omega = \mathrm{E}[(h_{u,k_u})^2]$.

E_s and E_b are the symbol energy and bit energy at the transmitter, respectively. The above expression gives the probability of error without interference. With MAI, the probability of error can be obtained by adding the variance of the residual MAI with that of AWGN in $\bar{\gamma}_b$ and $\bar{\gamma}_s$.

5. Results and Discussions

MATLAB simulations are used to compare the performance of the proposed modified interference cancellation techniques in suppressing the MAI caused by

Table 1. Description of some parameters relevant in the simulation.

Parameters	Specifications
Transmission mode	Uplink
Modulation	BPSK
Spreading factor	64
Number of subcarriers	64
Power of SUs	Less than or Equal to the Power of PUs
Number of transmitter antennas	1
Number of receiver antennas	2
Number of taps in the channel	4
Assumptions	Timing synchronization error exists among the users
Number of Symbols	1000
Spreading codes	Orthogonal Gold codes
Number of PIC stages	2
Number of iterations of SIC	2

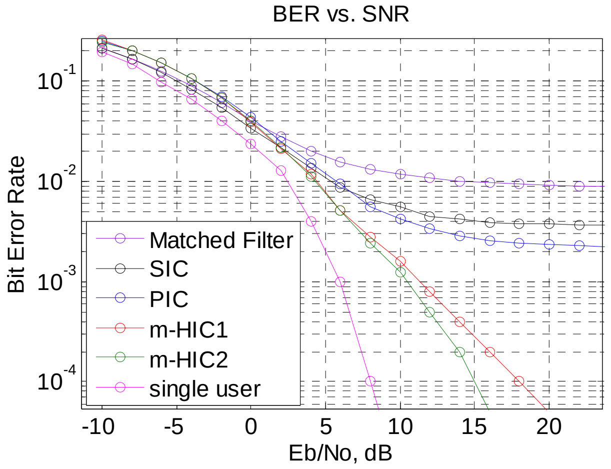

Fig. 6. BER performance for SU data in the proposed system with 20 PUs and 20 SUs of the same power.

timing synchronization error and non-zero cross correlation between the spreading codes. Table 1 lists the system parameters used for the simulation. A perfect channel estimation is assumed at the receiver.

Fig. 6 shows the BER performance of MF, PIC, SIC, m-HIC1, and m-HIC2 receivers for a SU data over the Rayleigh fading channel with the number of PUs and SUs set to $N = 20$ and $M = 20$, respectively. Fig. 7 shows the BER performance of various receivers for SU data over the Rayleigh fading channel with the number of PUs and SUs set to $N = 30$ and $M = 20$, respectively. Fig. 8 shows the BER performance of various receivers for a SU data over Rayleigh fading channel with the number of PUs and SUs set to $N = 40$ and $M = 20$, respectively, in an O-MC-DS-CDMA system. The transmitted power of the SUs was assumed to be equal to that of PUs. As shown in Figs. 6-8, m-HIC2 outperformed the other interference cancellation receivers in suppressing the MAI, which results in better BER performance. The m-HIC2 receiver exhibited better performance because during each iteration, PIC is performed to cancel out the interference caused by the same set of users after cancelling out the interference due to the other set of users. On the other hand, in m-HIC1, PIC is performed only during the first iteration and the interference caused by the other set of users affect the performance of the PIC. Because the computational complexity of m-HIC2 is higher than that of m-HIC1, the receiver introduces an additional delay in detecting the data compared to m-HIC1. Moreover, if the number of iterations is increased, the delay will be increased further but the BER performance can be improved. There is always trade-off between the BER performance and the delay constraints.

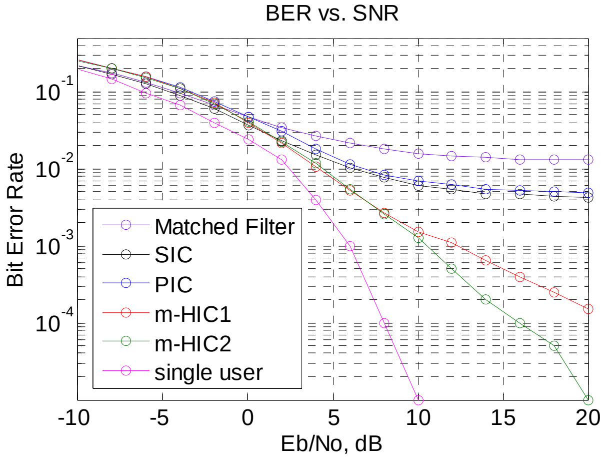

Fig. 7. BER performance for SU data in the proposed system with 30 PUs and 20 SUs of the same power.

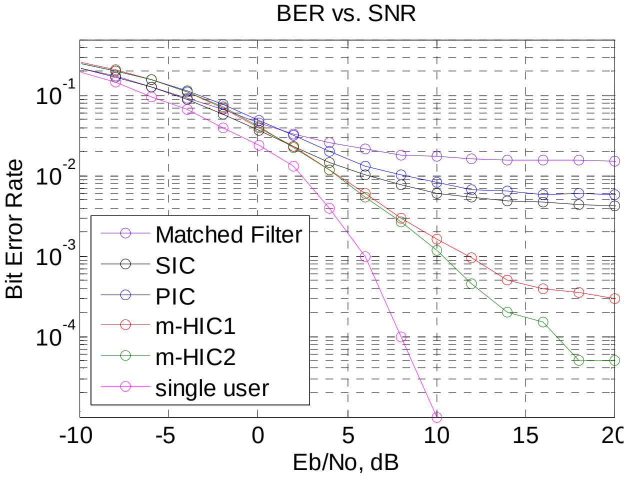

Fig. 8. BER performance for a SU data in the proposed system with 40 PUs and 20 SUs of the same power.

The BER performance of the receivers were analyzed for PU data over the Rayleigh fading channel. Fig. 9

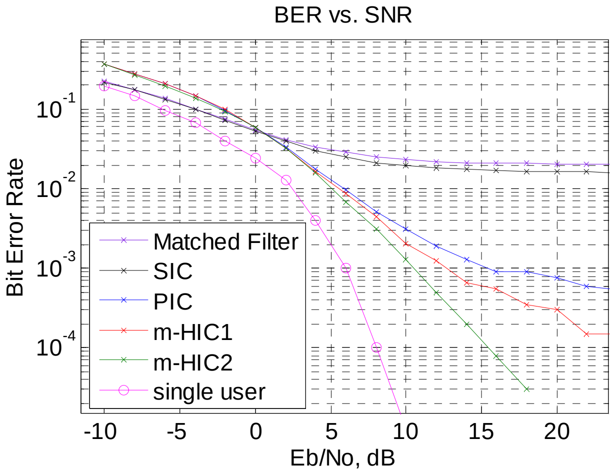

Fig. 9. BER performance for PU data in the proposed system with 20 PUs and 10 SUs of the same power.

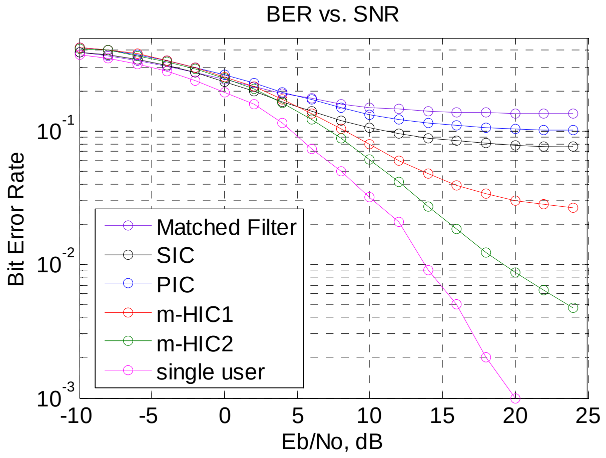

Fig. 11. BER performance for a SU data in the proposed system with the 40 PUs and 20 SUs of different power.

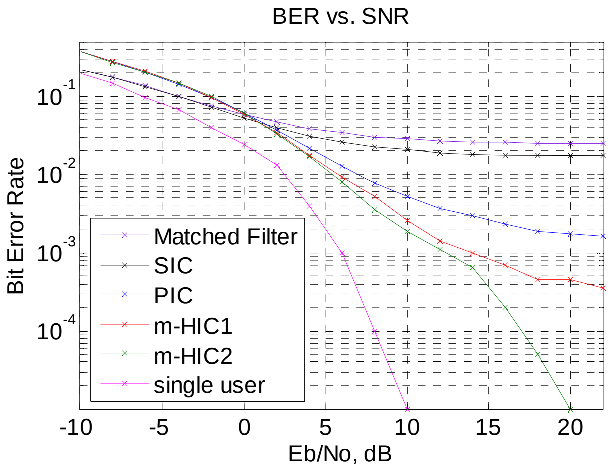

Fig. 10. BER performance for a PU data in the proposed system with 20 PUs and 20 SUs of the same power.

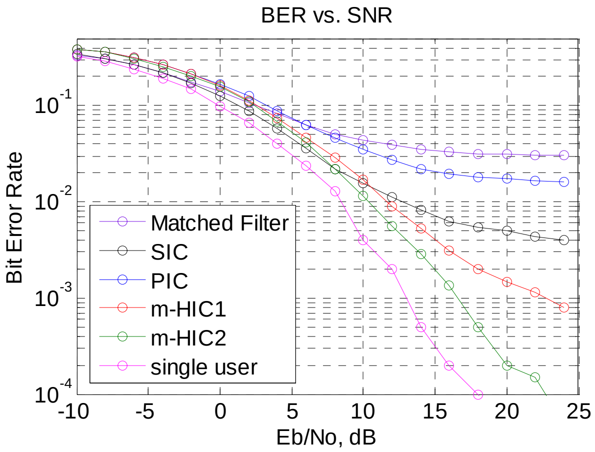

Fig. 12. BER performance for a SU data in the proposed system with 20 PUs and 20 SUs of different power.

presents the BER performance of various receivers for PU data in an O-MC-DS-CDMA system with the number of PUs and SUs set to N = 20 and M = 10, respectively. Adding more secondary users to the overloaded MC-DS-CDMA system results in more interference to the primary users, and the interference can be suppressed effectively using a m-HIC2 receiver. Fig. 10 shows the BER performance of various receivers for PU data in an O-MC-DS-CDMA system with N = 20 and M = 20. The transmitted power of SUs was assumed to be equal to that of PUs. As shown in Figs. 9 and 10, m-HIC2 outperformed the other interference cancellation receivers in suppressing the MAI and results in better BER performance. To improve the BER performance of PUs further, the power level of the SUs was reduced. On the other hand, a decrease in the power level of the SUs will affect their BER performance.

The performance of the receivers was analyzed further for SU data while considering different power levels for the PUs and SUs. Fig. 11 shows the BER performance of the various receivers for SU data with the number of PUs and SUs set to N = 40 and M = 20, respectively. Similarly, Fig. 12 shows the BER performance of various receivers for SU data over a Rayleigh fading channel with the number of PUs and SUs set to N = 20 and M = 20, respectively. The transmitted power of the SU was assumed to be one quarter of the power of PU. As shown in Figs. 11 and 12, m-HIC2 outperforms the other interference cancellation receivers in suppressing the MAI, resulting in better BER performance. The performance gain in m-HIC2 was because during the first iteration, PIC was performed for the PUs and the interference due to the PUs was cancelled out from the received signal before performing the PIC for SUs, thereby improving the performance of the PIC.

Fig. 13 presents the BER performance of the proposed receiver with m-HIC2 technique for a SU data. The number of users was assumed to be N = 40 and M = 20. The power level of the SU (P2) was varied in steps with respect to the power level of the PUs (P1). From the figure,

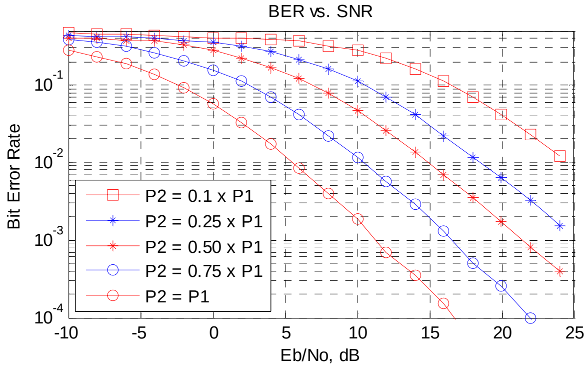

Fig. 13. BER performance for a SU of the O-MC-DS-CDMA system with 40 PUs and 20 SUs of variable power.

it is clear that as the power level increases, the BER performance of SU improves. On the other hand, the increase in the power level of the SU causes more interference to the PUs. Therefore, the power level of the SU is controlled to cause minimal interference to the PUs.

6. Conclusions and Future work

In this study, the BER performance of the proposed CR network architecture based on overloaded MC-DS-CDMA was analyzed. The performance of two modified hybrid parallel/successive interference cancellation techniques was compared for receivers with multiple antennas to suppress the interference among the users. The simulation results showed that for both primary and secondary user base stations, the proposed type 2- modified hybrid interference cancellation receiver outperformed the type 1-modified hybrid interference cancellation technique and other conventional techniques by effectively suppressing the interference among the users. The number of receiver antennas can be increased to improve the BER performance of the proposed receivers. Therefore, both primary and secondary users can achieve better quality of service with the m-HIC2 receivers. Future work should analyze the performance of the overloaded MC-DS-CDMA based CR downlink transmission and in multiple input multiple output (MIMO) scenarios. In addition, the proposed receivers can be implemented using FPGA, and the performance metrics, such as the delay, area and power consumption, should be analyzed.

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