IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received 10 September 2022, accepted 28 September 2022, date of publication 3 October 2022, date of current version 10 October 2022.

Digital Object Identifier 10.1109/ACCESS.2022.3211392

RESEARCH ARTICLE

Detection of Signals in MC–CDMA Using a Novel Iterative Block Decision Feedback Equalizer

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Dr. Mohammad Alibakhshikenari acknowledges support from the CONEX-Plus programme funded by Universidad Carlos III de Madrid and the European Union's Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie grant agreement No. 801538. Also, this work was supported by Project RTI2018-095499-B-C31, funded by the Ministerio de Ciencia, Innovación y Universidades, Gobierno de España (MCIU/AEI/FEDER, UE).

ABSTRACT This paper presents a technique to mitigate multiple access interference (MAI) in multicarrier code division multiple access (MC-CDMA) wireless communications systems. Although under normal circumstances the MC-CDMA system can achieve high spectral efficiency and resistance towards inter symbol interference (ISI) however when exposed to substantial nonlinear distortion the issue of MAI manifests. Such distortion results when the power amplifiers are driven into saturation or when the transmit signal experiences extreme adverse channel conditions. The proposed technique uses a modified iterative block decision feedback equalizer (IB-DFE) that uses a minimal mean square error (MMSE) receiver in the feed-forward path to nullify the residual interference from the IB-DFE receiver. The received signal is re-filtered in an iterative process to significantly improve the MC-CDMA system's performance. The effectiveness of the proposed modified IB-DFE technique in MC-CDMA systems has been analysed under various harsh nonlinear conditions, and the results of this analysis presented here confirm the effectiveness of the proposed technique to outperform conventional methodologies in terms of the bit error rate (BER) and lesser computational complexity.

INDEX TERMS CDMA, OFDM, MAI, MMSE, IB-DFE, maximum likelihood (ML).

The associate editor coordinating the review of this manuscript and approving it for publication was Chengpeng Hao.

I. INTRODUCTION

Multiple access schemes such as frequency division multiple access (FDMA), time division multiple access (TDMA), code division multiple access (CDMA), and space division multiple access (SDMA) are used in modern wireless mobile communication systems enabling many users to simultaneously share the available radio spectrum resource more efficiently [1]. In FDMA the available bandwidth is divided up into numerous narrow bands to permit concurrent transmission of data over several communication channels. TDMA allows multiple users to share the same frequency channel by dividing the signal into different time slots. CDMA allows users to simultaneously share the same channel by assigning a unique user-specific spreading code to distinguish users from each other [2], [3]. In this respect, SDMA is akin to CDMA in that it allows for many users to simultaneously access a single frequency band. Like CDMA's spreading code, the channel impulse response is used in SDMA to identify individual users [4], [5], [6]. Conversely, the orthogonal frequency division multiplexing (OFDM) combines modulation and multiplexing into a single technology [7]. It prevents inter-symbol interference (ISI) by splitting serial data into numerous orthogonal narrow band streams [8], [9]. In direct sequence code division multiple access (DS-CDMA) different users can transmit data using the same bandwidth. As a result, DS-CDMA can provide greater spectral efficiency.

Of course, each system has its own merits, so combining the multiple access schemes is likely to yield the best performance in terms of improve security, data transmission rate and to minimize ISI. This is achieved in multi-carrier code division multiple access (MC-CDMA) by combining CDMA and OFDM [10], [11]. The MC-CDMA receiver uses the available data at the receiver's end, the spread codes from all users, and a channel estimate to differentiate the data of all users. However, when one user is in the vicinity of another user, MC-CDMA can be liable to multiple access interference (MAI) which can have an adverse impact on system's overall performance [12]. To circumvent MAI a receiver must be able to detect individual users. MC-CDMA receiver detects information of all users using the received signal, user-specific spreading codes and estimated channel state information. Unfortunately, the detection becomes very challenging as MAI amplifies with increase in user numbers.

Wireless communicational systems are subject to nonlinear distortions mainly attributed to driving the transmit signal through saturated power amplifiers and severe environmental fading. Hence a lot of work done has been done on the design of MC-CDMA receivers over the years [13], [14], [15]. This includes the development of the maximum ratio combining (MRC) receiver; however, this technology is ineffectual at correcting channel induced phase distortions [16]. The development of the equal gain combining (EGC) receiver has been shown to rectify channel distortions however it cannot correct the distortion due to signal fading [17]. The receiver based on the minimum mean square error (MMSE) is effective at detecting the transmitted signal by considering noise variance and channel covariance; however, it fails to overcome nonlinear distortion in the channel [18], [19]. By contrast, the maximum likelihood (ML) receiver provides the best solution so far. The only drawback with ML is its exhaustive search strategy which curtails its use in real-time systems [14]. Hence, interest has shifted towards suboptimal receiver designs considering the performance and complexity trade-off. This has resulted in the use of space-alternating generalized expectation maximization (SAGE) receiver [20] and frequency domain receiver [21] in MC-CDMA systems. Among the various suboptimal receivers, the block decision feedback equalizer (IB-DFE) receiver is proposed for single carrier transmission. This correlates the interference in the receiving antennas to minimize the mean squared error (MSE) of the detected symbols [22], [23]. However, under severe channel and nonlinear conditions the IB-DFE receiver yields residual MAI.

In this paper the IB-DFE receiver in MC-CDMA system is modified by including a feed-forward path with MMSE receiver. The results presented here demonstrate the proposed innovation to significantly minimize the error variance by nullifying residual MAI even in very adverse nonlinear conditions. The modified IB-DFE, denoted hereon as MIB-DFE, is shown to provide greater reliability in terms of BER over the conventional IB-DFE receiver. The proposed MIB-DFE receiver is compared to the MRC, MMSE, and optimal ML with respect to performance and computational complexity. It is shown that the proposed MIB-DFE receiver can achieve performance near to that of optimal receivers among multiple suboptimal receivers. Since MIB-DFE receiver in MC-CDMA can more accurately detect transmitted signals in harsh nonlinear environments, the adoption of this technology will greatly enhance the capabilities of existing (5G) and future (6G) wireless mobile communication systems.

This paper's structure is as follows: Section II presents the transmitter and receiver models of MC-CDMA. The conventional receiver designs are discussed in Section III. For nonlinear MC-CDMA, the proposed MIB-DFE receiver is described in Section IV. Section V is devoted to simulation analysis, and the work is concluded in Section VI.

II. MC-CDMA TRANSMITTER AND RECEIVER

Because orthogonal matrix operation is applied to the user bits the MC-CDMA system is commonly referred to as CDMA-OFDM. The schematic block diagrams of transmitter and receiver of the MC-CDMA system are shown in Fig. 1. The system accommodates α simultaneous users and each user's data bits are first mapped to higher-order signal before it's modulated with unique spreading codes of length N using a mixer. The spreading code of each user are orthogonal to each other and are mutually exclusive [24]. Spreading code is applied to the data of the α^{th} user before carrying out the inverse fast Fourier transform (IFFT). The parallel outputs from the IFFT block are converted into a serial stream which is then combined with the other users' data streams before transmission. The baseband transmitted signal vector in a

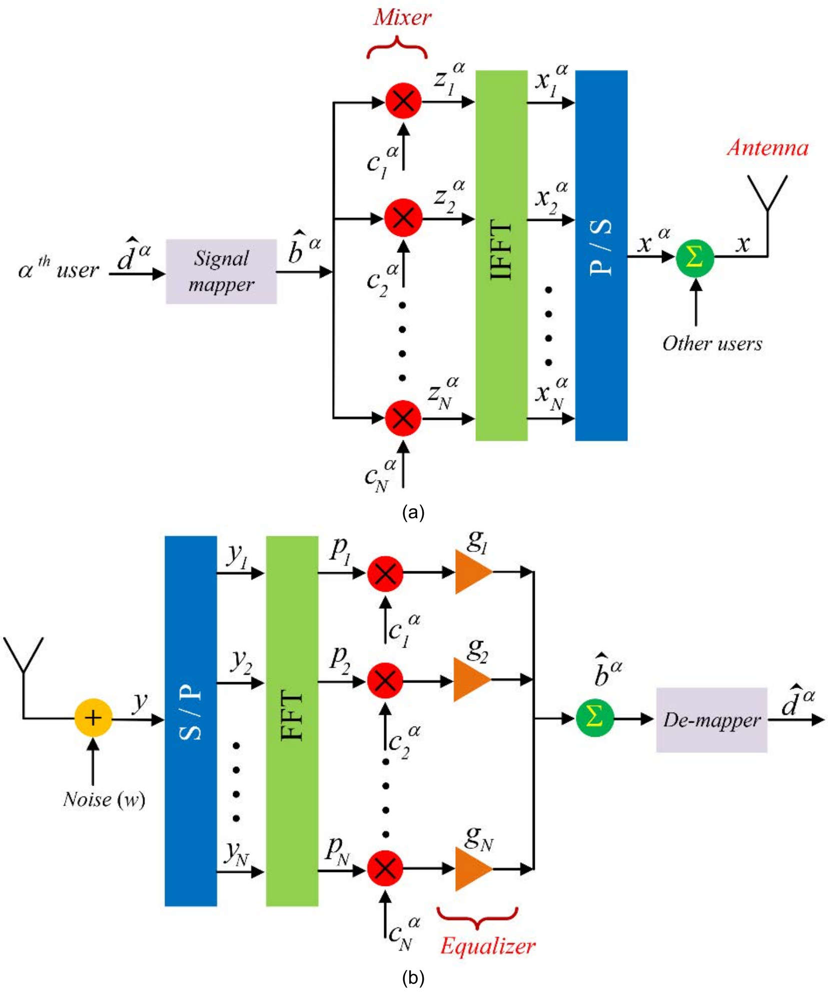

FIGURE 1. Block diagram of MC-CDMA system, (a) Transmitter, and (b) Receiver.

time slot m can be represented by:

$$x_m = \sum_{\alpha=1}^{\mathrm{A}} \sum_{n=1}^{N} b^{\alpha} c_n^{\alpha} \left(\frac{E_b}{N}\right)^{0.5} e^{j2\pi nm/N} \tag{1}$$

where,

$m, n = 1, 2, \ldots, N$	
$b^{\alpha} \in \{\pm 1\}$	is the data symbol of user α,
$c_n^{\alpha} \in \{\pm 1\}$	is the n^{th} chip of the α^{th} user's spreading code,
E_b	is the energy per binary symbol before spreading and is the same for each user, and
N	is the length of spreading sequence.

At the MC-CDMA receiver the discrete baseband signal vector $\boldsymbol{y}$ received can be represented by:

$$\boldsymbol{y} = \mathrm{NL}\left(\boldsymbol{h} \otimes \boldsymbol{x}\right) + \boldsymbol{w} \tag{2}$$

The baseband signal received is the function of the nonlinearity (NL) effects introduced in the channel and the convolution of the channel impulse response $\boldsymbol{h}$. In addition, the received signal will inevitably pick up additive white Gaussian noise (AWGN) denoted by $\boldsymbol{w}$ in the transmission environment, that has zero mean and single-sided power spectral density. The serial data received $\boldsymbol{x} = [x_1, x_2, \ldots, x_N]^T$ is first converted into parallel format before Fast Fourier transform (FFT) is applied. Here FFT is used as OFDM demodulator. The received symbol p_n of n^{th} sub-carrier is given by:

$$p_n = \sum_{m=1}^{M} y_m e^{-j2\pi nm/N}, \quad n = 1, 2, \ldots, N \tag{3}$$

A correlator is used to identify each user as each user has a unique spreading code. In the next two sections the received MC-CDMA signal is examined using a conventional receiver and nonlinear detectors.

III. CONVENTIONAL MC-CDMA RECEIVERS

In this section traditional detectors like MRC, MMSE and nonlinear detectors like ML are examined for MC-CDMA application. In each case the receiver identifies the signal of

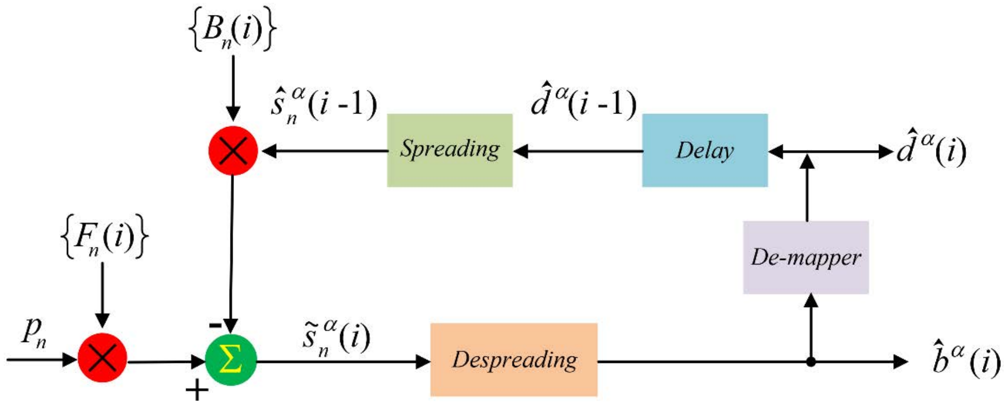

FIGURE 2. IB-DFE receiver for MC-CDMA systems.

each user by their unique spreading code. Signal detection is facilitated by applying equalizing gain g_N, as shown in Fig. 1.

A. MINIMUM MEAN SQUARE ERROR RECEIVER

MMSE can estimate the mean square error from the received signals $\boldsymbol{p}$ by applying weight vector $\boldsymbol{G}_{mmse}$ and the chip code matrix $\boldsymbol{C}$ of dimension $[N \times \alpha]$. The transmitting signal vector $\widehat{\boldsymbol{b}}$ of α users is given by [19]:

$$\widehat{\boldsymbol{b}} = (\boldsymbol{G_{mmse}C})^{\boldsymbol{T}}\,\boldsymbol{p} \tag{4}$$

where, $\boldsymbol{G}_{mmse}$ is a $[N \times N]$ diagonal matrix of equalized weights. This weight vector is obtained by minimizing the MSE, i.e., MSE $= E\left[\left|\widehat{\boldsymbol{b}} - \boldsymbol{b}\right|^2\right]$, so:

$$\boldsymbol{G}_{mmse} = (\boldsymbol{H}^H\boldsymbol{H} + 2\sigma_n^2\boldsymbol{I}_N)^{-1}\boldsymbol{H}^H \tag{5}$$

where, $\boldsymbol{I}_N$ is N-dimensional identity matrix, the superscript H represents Hermitian transpose, and $\boldsymbol{H} = diag\ [H_1, H_2, \ldots, H_n]$ is a $[N \times N]$ diagonal matrix, where H_n, $n = 1, 2, \ldots, N$, is the frequency domain channel gain of n^{th} sub-carrier.

B. MAXIMUM LIKELIHOOD RECEIVER

The maximum likelihood detector uses maximum a posteriori criterion to find the most probable transmission vector assuming all users' transmit data have equal probability [14]. ML carries out $2^{m\alpha}$ metric calculations at any given time to analyze the actual transmitted signal vector, where parameters m and α are the modulation order and user count, respectively. In fact, ML calculates the Euclidean distance between the actual received signal vector $\boldsymbol{p}$ and the probable transmit vector that is $\boldsymbol{b} \in \boldsymbol{B}$. Here, $\boldsymbol{B}$ is a $(\alpha \times 2^{m\alpha})$-dimensional vector containing the i^{th} possible transmit vector in the i^{th} column, where $i = 1, 2, \ldots, 2^{m\alpha}$. The shortest possible Euclidean distance by the transmit signal vector is given by:

$$\widehat{\boldsymbol{b}} = arg\left\{\min_{b \in B} ||\boldsymbol{p} - \widehat{\boldsymbol{p}}||^2\right\} \tag{6}$$

where $\widehat{\boldsymbol{p}} = \boldsymbol{HCAb}$. The layout of the ML detector can be determined from (6). The computational complexity of (6) grows exponentially with increase in the modulation order and user number. It is possible to limit ML to lower-order systems to prevent an exhaustive search.

C. ITERATIVE BLOCK–DECISION FEEDBACK EQUALIZER RECEIVER

The iterative IB-DFE signal detector employs feed-forward and feedback routes for equalization and the cancellation of residual interference respectively. As a result, the iterative receiver outperforms non-iterative receivers. Low complex turbo receiver is another name for the IB-DFE [22], [23]. The IB-DFE receiver in Fig. 2 is used to detect the α^{th} user in the MC-CDMA system. The equalized sample of each iteration is represented by:

$$\tilde{z}_n^{\alpha}(i) = F_n(i)p_n - B_n(i)\hat{z}_n^{\alpha}(i-1) \tag{7}$$

where the feed-forward and feedback receiver weights are $F_n(i)$ and $B_n(i)$, respectively. The overall signal-to-noise ratio (SNR) of the equalized samples are optimized by using these weights. The feedback and feed-forward weights are given by [25]:

$$B_n(i) = [F_n(i)H_n - \gamma(i)\,]\,\sigma \tag{8}$$

$$F_n\,(i) = SNR \cdot H_n^* \Big/ \left[1 + SNR \cdot \left(1 - \sigma^2\right)|H_n|^2\right] \tag{9}$$

where,

$$\gamma(i) = \frac{1}{N}\sum\nolimits_{n=1}^{N} F_n\,(i)\,H_n \tag{10}$$

$$\sigma = E\left[\hat{z}_n^{\alpha}(i-1)z_n^{\alpha *}\right] \Big/ E\left[\left|z_n^{\alpha}\right|^2\right] \tag{11}$$

Reliability coefficient is represented by (11). The correlation coefficient is zero in the first iteration ($i = 0$) because z_n^{α} is an unknown quantity. Under this condition $B_n(0) = 0$, then

$$F_n(0) = SNR \cdot H_n^* \Big/ 1 + SNR \cdot |H_n|^2 \tag{12}$$

Based on the knowledge about the previous data symbol, the feedback signal in an IB-DFE receiver can reduce the residual interference of applying the feed-forward

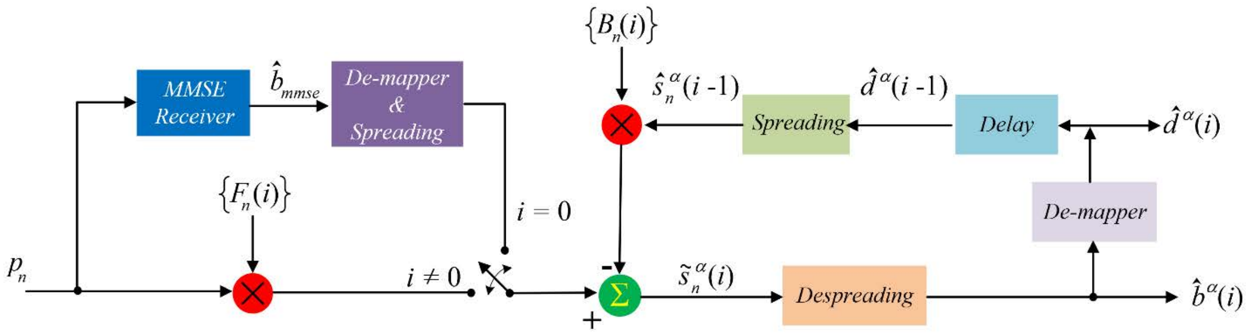

FIGURE 3. Modified IB-DFE receiver for MC-CDMA systems.

weights [22], [23]. The IB-DFE receiver however has limitations of accurately computing the magnitudes of the reliability factor and average symbol. These parameters are needed in feedback path and channel decoder.

IV. PROPOSED MODIFIED ITERATIVE BLOCK–DECISION FEEDBACK EQUALIZER RECEIVER

The performance of IB-DFE in MC-CDMA is poor at mitigating MAI especially under nonlinear channel conditions. This is due to poor selection of initial feed-forward weight, $F_n(0)$ in (13). Another major issue in the IB-DFE receiver is the effect of error propagation. The consequence of the large number of contiguous errors can significantly affect the system's BER performance.

To circumvent this issue in this paper we have modified the block decision feedback equalizer, as shown in Fig. 3, where the received signal is split between the MMSE receiver and feed-forward mixer paths and their outputs are fed into the IB-DFE receiver via the switch. Since the MMSE receiver already mitigates significant MAI, the residual interference is nullified through feed-forward and feedback filters. The initial feed-forward weights are used in the iteration to tune the MMSE receiver. The results presented in a later section confirm the proposed technique performs significantly better than the conventional IB-DFE receiver. The input vector applied to the modified IB-DFE receiver is represented by:

$$\tilde{z}_n^{\alpha}(i) = \begin{cases} Demapper(\hat{b}_{mmse}), & if\ i = 0 \\ F_n(i)p_n - B_n(i)\tilde{z}_n^{\alpha}(i-1), & if\ i \neq 0 \end{cases} \tag{13}$$

The Demapper applies appropriate demodulation schemes of digital modulated signal such as binary phase shift keying (BPSK), 4 quadrature amplitude modulation (4–QAM) and so on.

V. SIMULATION ANALYSIS

This section compares the receiver performance of the proposed MIB-DFE receiver with the conventional IB-DFE, MRC, MMSE and ML receivers. These detectors are studied in terms of both BER execution and computational complexity analysis. The results shown here are based on 1000 (N_F) information frames, each of which contains 3000 (M) information symbols [26], [27]. Table 1 outlines the remaining simulation parameters. Between channel 'a' and channel 'b' three distinct nonlinear properties are added from [28]:

$$\text{NL} = 0 : b = a \tag{14a}$$
$$\text{NL} = 1 : b = \tanh(a) \tag{14b}$$
$$\text{NL} = 2 : b = a + 0.2a^2 - -0.1a^3 \tag{14c}$$
$$\text{NL} = 3 : b = a + 0.2a^2 - -0.1a^3 + 0.5\cos(\pi a) \tag{14d}$$

where NL $= 0$ refers to a linear MC-CDMA model, while NL $= 1$ denotes a nonlinear model that may be caused by saturated power amplifiers in the system. Arbitrary nonlinear models are denoted by NL $= 2$ and NL $= 3$.

Different levels of nonlinear distortion and SNR values affect the average bit error rate (BER) of MC-CDMA systems. The computed average BER for MRC, MMSE, IB-DFE and MIB-DFE receivers are compared with the ideal ML in Fig. 4. The graphs show that although linear receivers such as MRC and MMSE work reasonably well under linear and mildly nonlinear conditions like NL $= 0$, NL $= 1$,

TABLE 1. Model attributes.

Parameter	Description
Length of the chip (N)	16
Spreading code type	Walsh
Users (K)	4
Sub-carriers	16
Modulation Type	BPSK, 4 QAM
Data symbols per frame (M)	3000
Frame data (N_F)	1000
Deployed medium	SUI, Rayleigh
Number of iterations in IB-DFE (I)	10
Number of iterations in MIB-DFE (I)	10
SUI – 1 Channel Parameters [29]	
Delay (μs)	[0.9, 0.4, 0]
Doppler spread (Hz)	0.5
Average path gain (dB)	[–20, –15, 0]

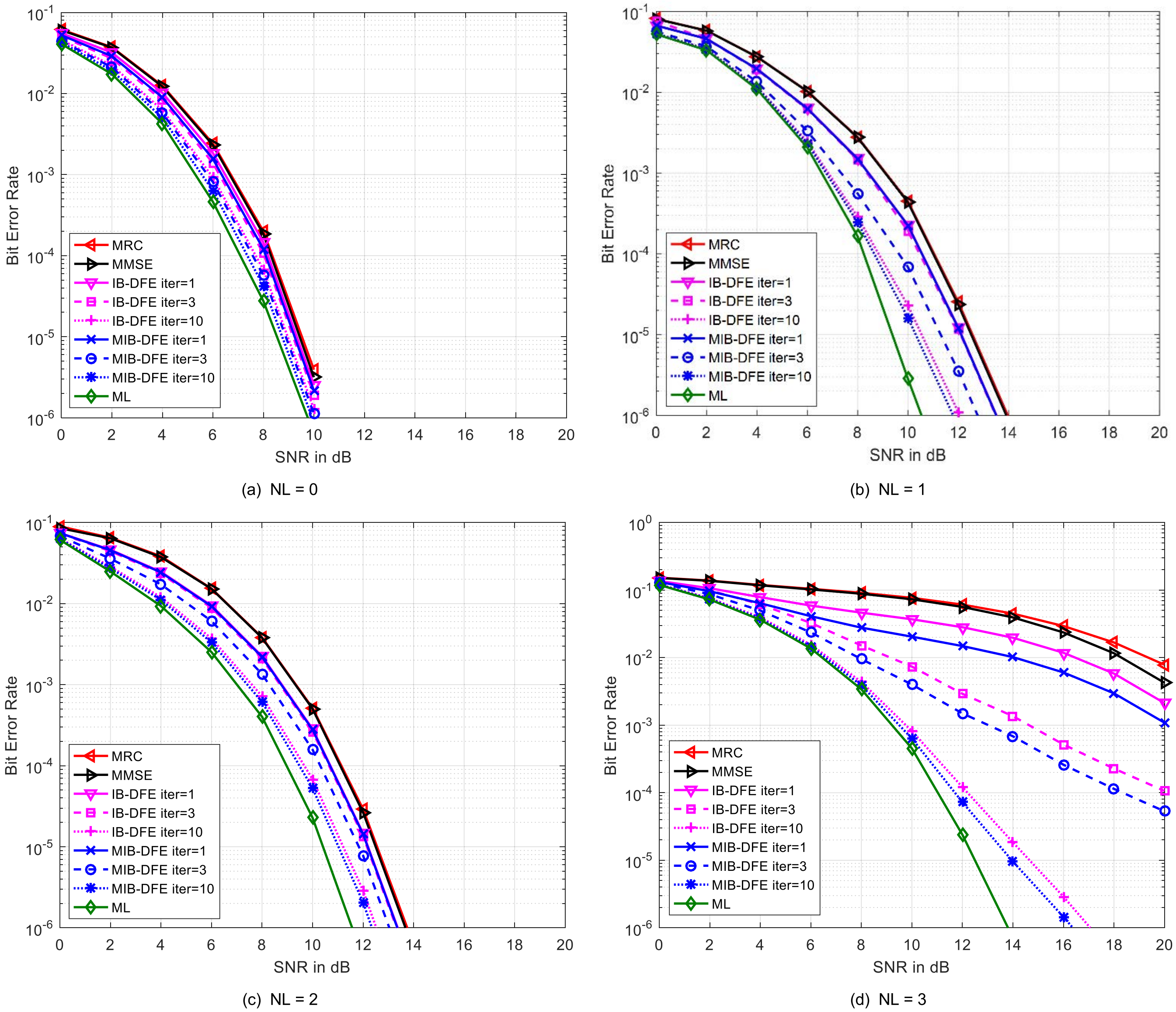

FIGURE 4. **Mean BER of all users using different receivers in the MC-CDMA system for various non–linearity conditions, (a) NL = 0, (b) NL = 1, (c) NL = 2, and (d) NL = 3. BER curves are for MRC (maximum ratio combining), MMSE (minimum mean square error), IB-DFE (iterative block decision feedback), MIB-DFE (modified iterative block decision feedback), and ML (maximum likelihood).**

and NL = 2, however under severe nonlinear conditions (NL = 3) they suffer a considerable performance loss, as shown in Fig. 4(d). This indicates that when MC-CDMA systems experience substantial nonlinear distortion, the linear detectors fail to attenuate these aberrations and leave residual interference. However, this is not the case with the proposed MIB-DFE receiver. Compared to IB-DFE the proposed MIB-DFE receiver cancels most significant interference in its first iteration through MMSE receiver.

It is also observed from the graphs in Fig. 4 that the performances of IB-DFE and MIB-DFE receivers relies on the number of iterations. In fact, interference cancellation is deeper with greater number of iterations. The graphs show that the BER performance of the receivers improves significantly for 10 iteration passes compared to 1 and 3. For example, Fig. 4(d) shows that to achieve a bit error rate floor of 10^{-6} with 10 iteration passes the SNR of 13.8 dB is required for ML receiver, 16.3 dB for MIB-DFE receiver, and 17 dB for IB-DFE receiver. On the other hand, the linear receivers such as the MRC and MMSE need sufficiently larger SNR values to satisfy the same bit error rate.

The constellation plots of the estimated signals detected using MMSE, IB-DFE and MIB-DFE receivers under severe nonlinear distortion (NL = 3) are shown in Fig. 5. These plots are for user-1 transmitting "−1" symbols in an entire data frame at a SNR of 10 dB while the MC-CDMA system simultaneously communicates with other users. In this figure, the left side of center line is the decision region of the

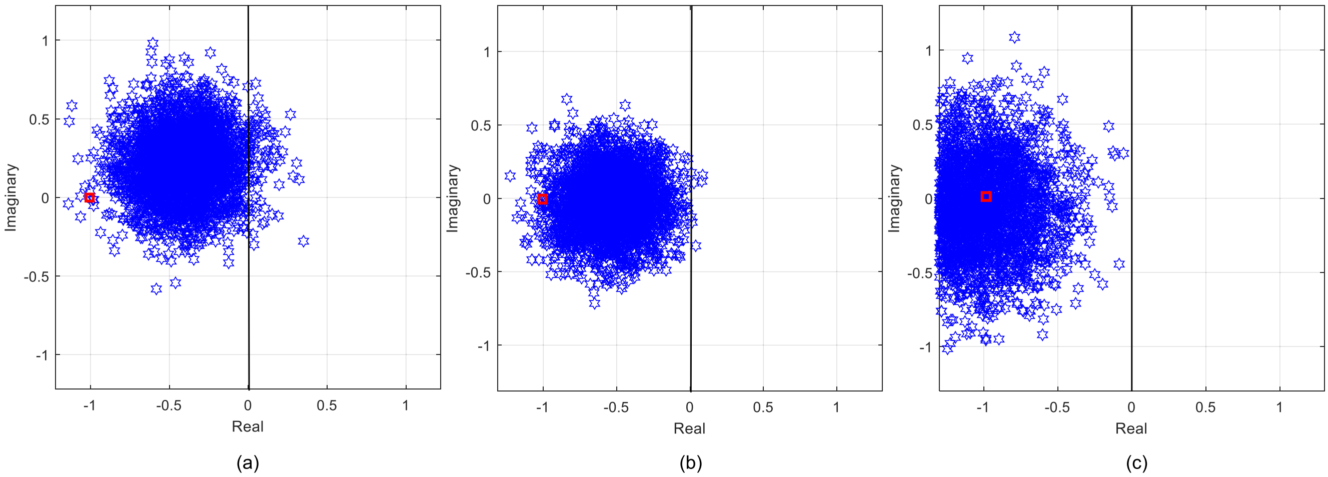

FIGURE 5. Constellation plots of a nonlinear MC-CDMA system at SNR of 10 dB when user-1 transmits '−1' symbols that are detected using: (a) MMSE receiver, (b) IB-DFE receiver, and (c) MIB-DFE receiver.

TABLE 2. Complexity comparison of MC-CDMA receivers.

Receiver	Functionality	Computational Complexity	Total Complexity	Percentage of ML
MMSE	Product	$(K + M + 2N + 1).N^2$	777×10^3	2.68
	Summation	$(K + M + N^2).(N - 1) + N^3$	529×10^3	2.03
IB–DFE	Product	$(9N + 2).I.K.M$	1752×10^4	26.84
	Summation	$(5N - 2).I.K.M$	936×10^4	20.33
MIB–DFE	Product	$(9N + 2)\ I.K.M + N^2.(K + M + 2N + 1)$	1830×10^4	28.03
	Summation	$(5N - 2)\ I.K.M + (K + M + N^2).(N - 1) + N^3$	989×10^4	21.49
ML	Product	$2^{mK}\ M.N.(N \times K + K^2 + K + 1)$	6528×10^4	100.00
	Summation	$2^{mK}\ M.\ [NK\ (N + K - 1) - 1]$	4603×10^4	100.00

symbol "−1". The diagram shows the MMSE receiver's output symbols are spread out across the entire signal space and some of them even are on the wrong side of the decision line. This is because the MMSE receiver cannot automatically correct for the distortions that occur in the output signals. Signals are picked up by the nonlinear IB-DFE receiver that eliminates most of the residual interference. It is evident that the proposed MIB-DFE receiver eliminates all the interference.

The BER performance of the proposed MIB-DFE receiver is compared with MRC, MMSE and IB-DFE receivers with increasing user numbers in Fig. 6. The results are computed for SNR of 5 dB and for NL = 3 show that as the number of users increase MAI becomes progressively severe in the various multiple access systems. The consequence of this is degradation in the BER of the system. However, unlike MRC and MMSE receivers the receivers based on IB-DFE and MIB-DFE topologies are efficient in significantly mitigating MAI through their feedback path. It is evident from Fig. 6 that the proposed MIB-DFE receiver outperformance other receivers.

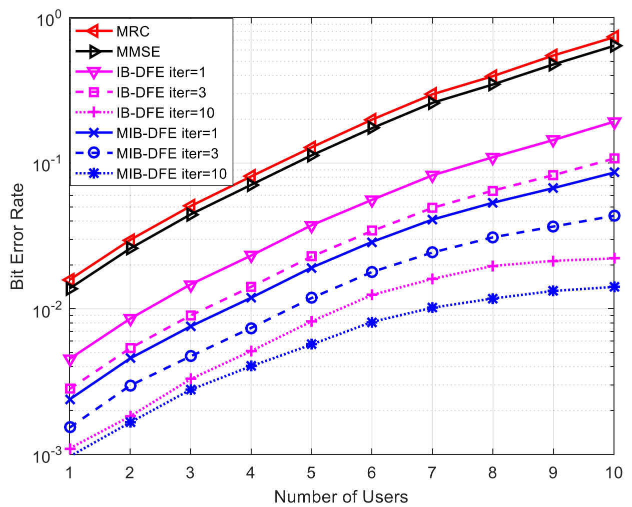

FIGURE 6. BER performances of MRC, MMSE and IB-DFE as a function of number of users.

Computational complexity of the proposed MIB-DFE receiver is compared with other MC-CDMA receivers in Table 2. The parameters used in the analysis are given in Table 1. Although the ML receiver outperforms other MC-CDMA receivers however its computational complexity

TABLE 3. Bit rate error of various MC-CDMA receivers for SNR of 12 decibels.

Modulation	Channel	BER MRC	BER MMSE	BER IB-DFE	BER MIB-DFE
BPSK	SUI	$10^{-2.1}$	$10^{-1.6}$	$10^{-2.8}$	$10^{-2.74}$
4 QAM	Rayleigh Flat Fading	$10^{-2.2}$	$10^{-1.5}$	$10^{-2.6}$	$10^{-2.53}$

is extremely high in terms of product and summation operations. In fact, the ML receiver's computational cost grows exponentially by a factor of $2^{m\alpha}$ with each additional user and each modulation order. For this reason, the usage of ML receiver in practice is non-viable. The table shows both MIB-DFE and IB-DFE receivers provide a suitable solution over ML as they are computationally less demanding.

Table 3 show the bit error rate for the various MC-CDMA receivers for SNR of 12 dB and operating under BPSK and 4-QAM modulation schemes and under SUI and Rayleigh flat fading channel conditions. The results show the proposed MIB-DFE receiver provides comparable BER to IB-DFE.

VI. CONCLUSION

The modification of IB-DFE in MC-CDMA receiver is shown to mitigate nonlinear signal distortion arising from the channel environment and/or by driving the transmit power amplifier into saturation. The proposed MIB-DFE receiver was stress tested under severe nonlinear conditions and its performance compared with other conventional receivers. The results presented confirm the MC-CDMA system with the proposed MIB-DFE receiver exhibits significantly better BER than MC-CDMA receivers based on MRC, MMSE, and IB-DFE. Moreover, conventional receivers have a higher error floor than the proposed receiver showing that the MC-CDMA system will experience significant non-linear distortions. Under such conditions, these receivers cannot handle unpredictable amplitude and phase changes in the received signal. Also, although ML receiver provides the best bit error rate than other receivers however with increasing number of users and modulation order, the computational complexity of ML receiver increases exponentially, thus making it unviable for real-time practical applications. However, the proposed MIB-DFE receiver is computationally less demanding and a viable solution for next generation MC-CDMA systems.

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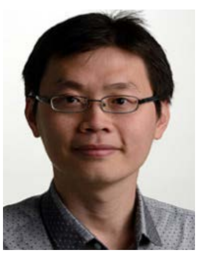

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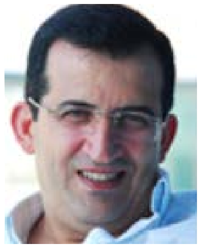

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