

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

KALAPRAVEEN BAGADI<sup>1</sup>, RAVIKUMAR C. V.<sup>1</sup>, K. SATHISH<sup>1</sup>,  
 MOHAMMAD ALIBAKHSHIKENARI<sup>2</sup>, (Member, IEEE),  
 BAL S. VIRDEE<sup>3</sup>, (Senior Member, IEEE), LIDA KOUHALVANDI<sup>4</sup>, (Member, IEEE),  
 KAREN N. OLAN-NUÑEZ<sup>5</sup>, (Student Member, IEEE), GIOVANNI PAU<sup>6</sup>, (Member, IEEE),  
 CHAN HWANG SEE<sup>7</sup>, (Senior Member, IEEE), IYAD DAYOUB<sup>8,9,10</sup>, (Senior Member, IEEE),  
 PATRIZIA LIVRERI<sup>11</sup>, (Member, IEEE), SONIA AÏSSA<sup>12</sup>, (Fellow, IEEE),  
 FRANCISCO FALCONE<sup>13,14</sup>, (Senior Member, IEEE),  
 AND ERNESTO LIMITI<sup>15</sup>, (Senior Member, IEEE)

<sup>1</sup>Vellore Institute of Technology, Vellore, Tamilnadu 632014, India

<sup>2</sup>Department of Signal Theory and Communications, Universidad Carlos III de Madrid, Leganés, 28911 Madrid, Spain

<sup>3</sup>Center for Communications Technology, School of Computing and Digital Media, London Metropolitan University, N7 8DB London, U.K.

<sup>4</sup>Department of Electrical and Electronics Engineering, Dogus University, 34775 Istanbul, Turkey

<sup>5</sup>Electronics Department, Instituto Nacional de Astrofísica, Óptica y Electrónica (INAOE), Tonantzintla, Puebla 72840, Mexico

<sup>6</sup>Faculty of Engineering and Architecture, Kore University of Enna, 94100 Enna, Italy

<sup>7</sup>School of Engineering and the Built Environment, Edinburgh Napier University, EH10 5DT Edinburgh, U.K.

<sup>8</sup>CNRS, Université Polytechnique Hauts-de-France, ISEN, University of Lille, 8520 Centrale Lille, France

<sup>9</sup>Institut d'Électronique de Microélectronique et de Nanotechnologie (IEMN), F-59313 Valenciennes, France

<sup>10</sup>INSA Hauts de France, F-59313 Valenciennes, France

<sup>11</sup>Department of Engineering, University of Palermo, 90133 Palermo, Italy

<sup>12</sup>Institut National de la Recherche Scientifique (INRS), Montreal, QC H5A 1K6, Canada

<sup>13</sup>Department of Electric, Electronic and Communication Engineering and the Institute of Smart Cities, Public University of Navarre, 31006 Pamplona, Spain

<sup>14</sup>School of Engineering and Sciences, Tecnológico de Monterrey, Monterrey 64849, Mexico

<sup>15</sup>Electronic Engineering Department, University of Rome "Tor Vergata", 00133 Rome, Italy

Corresponding authors: Ravikumar C. V. (cvrkvit@gmail.com), Mohammad Alibakhshikenari (mohammad.alibakhshikenari@uc3m.es), and Francisco Falcone (francisco.falcone@unavarra.es)

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 Skłodowska-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 (MCI/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  $\alpha$  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  $\alpha^{\text{th}}$  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

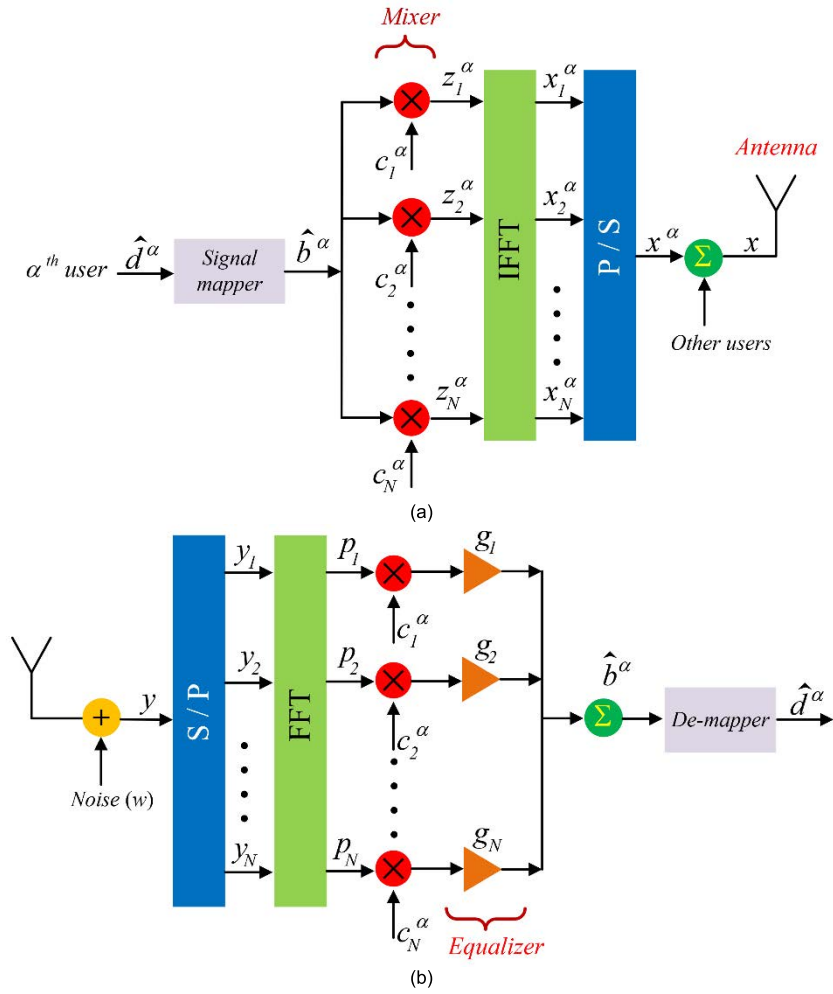


FIGURE 1. Block diagram of MC-CDMA system, (a) Transmitter, and (b) Receiver.

time slot  $m$  can be represented by:

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

where,

- $m, n = 1, 2, \dots, N$
- $b^\alpha \in \{\pm 1\}$  is the data symbol of user  $\alpha$ ,
- $c_n^\alpha \in \{\pm 1\}$  is the  $n^{\text{th}}$  chip of the  $\alpha^{\text{th}}$  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  $y$  received can be represented by:

$$y = NL(\mathbf{h} \otimes \mathbf{x}) + \mathbf{w} \quad (2)$$

The baseband signal received is the function of the nonlinearity (NL) effects introduced in the channel and the convolution

of the channel impulse response  $\mathbf{h}$ . In addition, the received signal will inevitably pick up additive white Gaussian noise (AWGN) denoted by  $\mathbf{w}$  in the transmission environment, that has zero mean and single-sided power spectral density. The serial data received  $\mathbf{x} = [x_1, x_2, \dots, x_N]^T$  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  $n^{\text{th}}$  sub-carrier is given by:

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

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

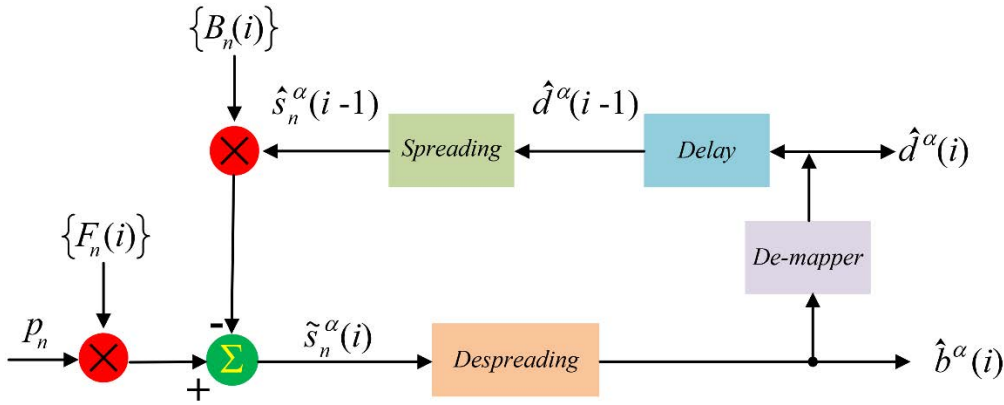


FIGURE 2. IB-DFE receiver for MC-CDMA systems.

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  $\mathbf{p}$  by applying weight vector  $\mathbf{G}_{mmse}$  and the chip code matrix  $\mathbf{C}$  of dimension  $[N \times \alpha]$ . The transmitting signal vector  $\hat{\mathbf{b}}$  of  $\alpha$  users is given by [19]:

$$\hat{\mathbf{b}} = (\mathbf{G}_{mmse}\mathbf{C})^T \mathbf{p} \tag{4}$$

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

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

where,  $\mathbf{I}_N$  is  $N$ -dimensional identity matrix, the superscript  $H$  represents Hermitian transpose, and  $\mathbf{H} = \text{diag} [H_1, H_2, \dots, H_n]$  is a  $[N \times N]$  diagonal matrix, where  $H_n$ ,  $n = 1, 2, \dots, N$ , is the frequency domain channel gain of  $n^{\text{th}}$  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  $\alpha$  are the modulation order and user count, respectively. In fact, ML calculates the Euclidean distance between the actual received signal vector  $\mathbf{p}$  and the probable transmit vector that is  $\mathbf{b} \in \mathbf{B}$ . Here,  $\mathbf{B}$  is a  $(\alpha \times 2^{m\alpha})$ -dimensional vector containing the  $i^{\text{th}}$  possible transmit vector in the  $i^{\text{th}}$  column, where  $i = 1, 2, \dots, 2^{m\alpha}$ . The shortest possible Euclidean distance by the transmit signal vector is given by:

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

where  $\hat{\mathbf{p}} = \mathbf{HCA}\mathbf{b}$ . 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  $\alpha^{\text{th}}$  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]:

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

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

where,

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

$$\sigma = E [z_n^\alpha(i-1)z_n^{\alpha*}] / E [ |z_n^\alpha|^2 ] \tag{11}$$

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

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

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

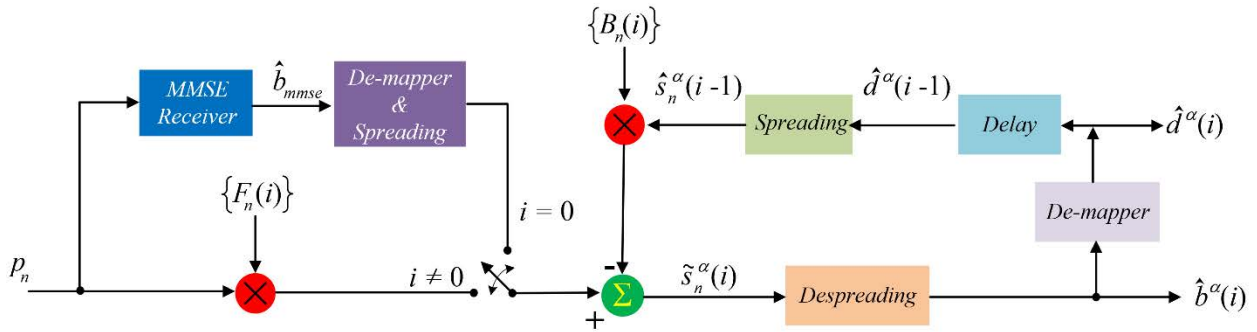


FIGURE 3. Modified IB-DFE receiver for MC-CDMA systems.

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:

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

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]:

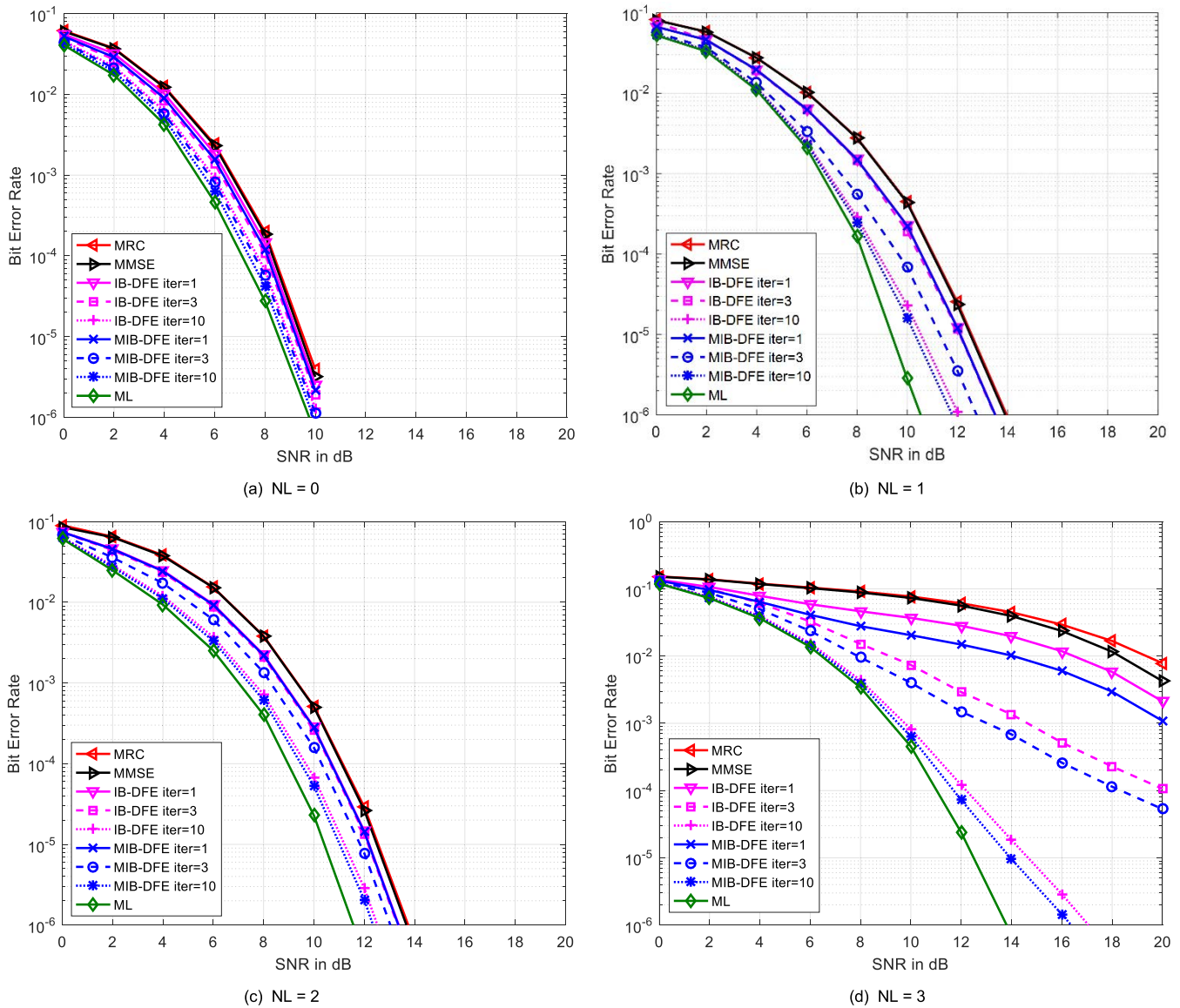
- NL = 0 :  $b = a$  (14a)
- NL = 1 :  $b = \tanh(a)$  (14b)
- NL = 2 :  $b = a + 0.2a^2 - 0.1a^3$  (14c)
- NL = 3 :  $b = a + 0.2a^2 - 0.1a^3 + 0.5\cos(\pi a)$  (14d)

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
<b>SUI – 1 Channel Parameters [29]</b>	
Delay ( $\mu$ s)	[0.9, 0.4, 0]
Doppler spread (Hz)	0.5
Average path gain (dB)	[-20, -15, 0]



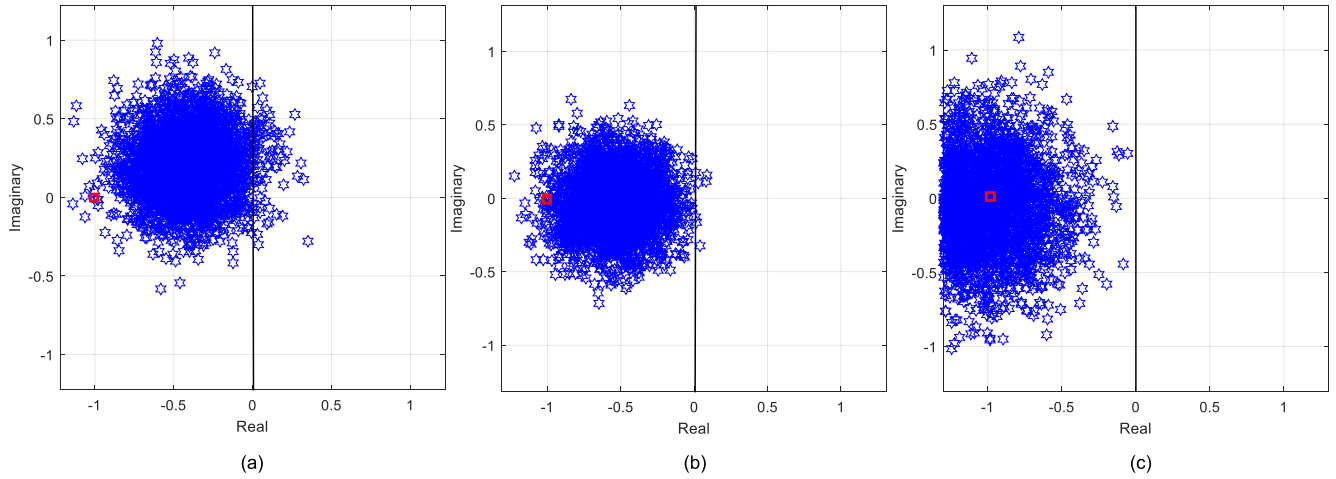
**FIGURE 4.** Mean BER of all users using different receivers in the MC-CDMA system for various non-linearity conditions, (a) NL = 0, (b) NL = 1, (c) NL = 2, and (d) NL = 3. BER curves are for MRC (maximum ratio combining), MMSE (minimum mean square error), IB-DFE (iterative block decision feedback),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

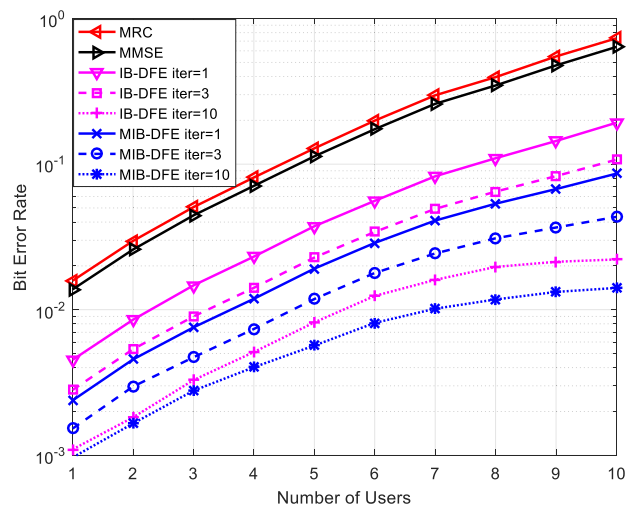
**TABLE 2.** Complexity comparison of MC-CDMA receivers.

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

Computational complexity of the proposed MIB-DFE receiver is compared with other MC-CDMA receivers



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

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	BER	BER	BER
		MRC	MMSE	IB-DFE	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.

## REFERENCES

- [1] J. Wittman, "Categorization of multiple-access/random-access modulation techniques," *IEEE Trans. Commun. Technol.*, vol. COM-15, no. 5, pp. 724–725, Oct. 1967.
- [2] A. Cohen, J. Heller, and A. Viterbi, "A new coding technique for asynchronous multiple access communication," *IEEE Trans. Commun. Technol.*, vol. COM-19, no. 5, pp. 849–855, Oct. 1971.
- [3] T. Healy, "Coding and decoding for code division multiple user communication systems," *IEEE Trans. Commun.*, vol. COM-33, no. 4, pp. 310–316, Apr. 1985.
- [4] K. P. Bagadi and S. Das, "Neural network-based multiuser detection for SDMA-OFDM system over IEEE 802.11n indoor wireless local area network channel models," *Int. J. Electron.*, vol. 100, no. 10, pp. 1332–1347, Oct. 2013.
- [5] K. P. Bagadi and S. Das, "Multiuser detection in SDMA-OFDM wireless communication system using complex multilayer perceptron neural network," *Wireless Pers. Commun.*, vol. 77, no. 1, pp. 21–39, Jul. 2014.
- [6] K. Praveen Bagadi and S. Das, "Efficient complex radial basis function model for multiuser detection in a space division multiple access/multiple input multiple-output-orthogonal frequency division multiplexing system," *IET Commun.*, vol. 7, no. 13, pp. 1394–1404, Sep. 2013.
- [7] Y. Wu and W. Y. Zou, "Orthogonal frequency division multiplexing: A multi-carrier modulation scheme," *IEEE Trans. Consum. Electron.*, vol. 41, no. 3, pp. 392–399, Aug. 1995.
- [8] K. P. Bagadi and S. Das, "Minimum symbol error rate multiuser detection using an effective invasive weed optimization for MIMO/SDMA-OFDM system," *Int. J. Commun. Syst.*, vol. 27, no. 12, pp. 3837–3854, Dec. 2014.
- [9] K. P. Bagadi, V. Annepu, and S. Das, "Recent trends in multiuser detection techniques for SDMA-OFDM communication system," *Phys. Commun.*, vol. 20, pp. 93–108, Sep. 2016.
- [10] Y. Shen and Y. Xu, "Multiple-access interference and multipath influence mitigation for multicarrier code-division multiple-access signals," *IEEE Access*, vol. 8, pp. 3408–3415, 2020.
- [11] A. S. Ling and L. B. Milstein, "The effects of spatial diversity and imperfect channel estimation on wideband MC-DS-SS and MC-CDMA," *IEEE Trans. Commun.*, vol. 57, no. 10, pp. 2988–3000, Oct. 2009.
- [12] S. Gamal, M. Rihan, S. Hussin, A. Zaghoul, and A. A. Salem, "Multiple access in cognitive radio networks: From orthogonal and non-orthogonal to rate-splitting," *IEEE Access*, vol. 9, pp. 95569–95584, 2021.
- [13] J.-P.-M. G. Linnartz, R. Hekmat, and R.-J. Venema, "Near-far effects in land mobile random access networks with narrow-band Rayleigh fading channels," *IEEE Trans. Veh. Technol.*, vol. 41, no. 1, pp. 77–90, Feb. 1992.
- [14] A. Samad and S. Majhi, "A near-optimal and low-complex joint multiuser detection for QCSS-MC-CDMA system," *IEEE Syst. J.*, vol. 15, no. 2, pp. 1594–1603, Jun. 2021.
- [15] M. Kulhandjian, H. Kulhandjian, C. D'Amours, H. Yanikomeroglu, D. A. Pados, and G. Khachatryan, "Low-complexity decoder for overloaded uniquely decodable synchronous CDMA," *IEEE Access*, vol. 10, pp. 46255–46275, 2022.
- [16] Z. Li and M. Latva-Aho, "Error probability of interleaved MC-CDMA systems with MRC receiver and correlated Nakagami-m fading channels," *IEEE Trans. Commun.*, vol. 53, no. 6, pp. 919–923, Jun. 2005.
- [17] Q. Shi and M. Latva-Aho, "Accurate bit-error rate evaluation for synchronous MC-CDMA over Nakagami-m-fading channels using moment generating functions," *IEEE Trans. Wireless Commun.*, vol. 4, no. 2, pp. 422–433, Mar. 2005.
- [18] H. Cheng and S. C. Chan, "Blind linear MMSE Receivers for MC-CDMA Systems," *IEEE Trans. Circuits Syst. I, Reg. Papers*, vol. 54, no. 2, pp. 367–376, Feb. 2007.
- [19] W. T. Tung and J. Wang, "MMSE receiver for multicarrier CDMA overlay in ultra-wide-band communications," *IEEE Trans. Veh. Technol.*, vol. 54, no. 2, pp. 603–614, Mar. 2005.
- [20] N. Kabaoglu, "SAGE based suboptimal receiver for downlink MC-CDMA systems," *IEEE Commun. Lett.*, vol. 15, no. 12, pp. 1381–1383, Dec. 2011.
- [21] Y. Yan and M. Ma, "Novel frequency-domain oversampling receiver for CP MC-CDMA systems," *IEEE Commun. Lett.*, vol. 19, no. 4, pp. 661–664, Apr. 2015.
- [22] N. Souto, R. Dinis, A. Correia, and C. Reis, "Interference-aware iterative block decision feedback equalizer for single-carrier transmission," *IEEE Trans. Veh. Technol.*, vol. 64, no. 7, pp. 3316–3321, Jul. 2015.
- [23] X. Ouyang, G. Talli, M. Power, and P. D. Townsend, "Iterative block decision feedback equalization for IM/DD-based OCDM to compensate chromatic-dispersion-induced power fading," *J. Lightw. Technol.*, vol. 37, no. 17, pp. 4349–4358, Sep. 1, 2019.



- [24] T. Kebede, Y. Wondie, J. Steinbrunn, H. B. Kassa, and K. T. Kornegay, "Multi-carrier waveforms and multiple access strategies in wireless networks: Performance, applications, and challenges," *IEEE Access*, vol. 10, pp. 21120–21140, 2022.
- [25] R. Dinis, P. Silva, and A. Gusmao, "An iterative frequency-domain decision-feedback receiver for MC-CDMA schemes," in *Proc. IEEE 61st Veh. Technol. Conf.*, May 2005, pp. 271–275.
- [26] C. V. R. Kumar and K. P. Bagadi, "MC-CDMA receiver design using recurrent neural networks for eliminating multiple access interference and nonlinear distortion," *Int. J. Commun. Syst.*, vol. 30, no. 16, p. e3328, May 2017.
- [27] C. V. R. Kumar and K. P. Bagadi, "Design of MC-CDMA receiver using radial basis function network to mitigate multiple access interference and nonlinear distortion," *Neural Comput. Appl.*, vol. 31, no. S2, pp. 1263–1273, Feb. 2019.
- [28] J. C. Patra, R. N. Pal, R. Baliarsingh, and G. Panda, "Nonlinear channel equalization for QAM signal constellation using artificial neural networks," *IEEE Trans. Syst., Man, B Cybernetics*, vol. 29, no. 2, pp. 262–271, Apr. 1999.
- [29] A. Mahmood, S. Khan, S. Hussain, and M. Zeeshan, "Performance analysis of multi-user downlink PD-NOMA under SUI fading channel models," *IEEE Access*, vol. 9, pp. 52851–52859, 2021.



**KALAPRAVEEN BAGADI** received the B.E. degree in electronics and communication engineering from Andhra University, India, in 2006, the M.Tech. degree in electronic systems and communication from the National Institute of Technology, Rourkela, India, in 2009, and the Ph.D. degree in wireless communication from the Department of Electrical Engineering, National Institute of technology. He is currently working as an Associate Professor Senior with the School of Electronics Engineering (SENSE), VIT Vellore, India. He has published several research articles in various Journals. He has also published over 50 research papers in refereed international journals and conferences. His research interest include SDMA, MIMO, OFDM, wireless communication, and artificial intelligence. He has finished six Ph.D. thesis and currently guiding two Ph.D. scholars. He is also a Reviewer of the journals like *Wireless Personal Communications*, *IET Communications*, *Telecommunication Systems*. His work has been cited more than 500 times at Google Scholar.



**RAVIKUMAR C. V.** received the M.Tech. degree in digital electronics and communication system from Jawaharlal Nehru Technology University, Anantapur, in 2009, and the Ph.D. degree in communication networks from VIT Vellore, India, in 2018. He is currently working as an Assistant Professor SG with the Department of Embedded Technology, School of Electronics Engineering, Institute of Vellore Institute of Technology. His current research interests include communication networks, machine learning, deep learning, wireless sensor networks, and information security.



**K. SATHISH** received the master's degree in communication systems from Jawaharlal Nehru Technology University, Anantapur, India, in 2017. He is currently a Research Scholar with the School of Electronics Engineering, Vellore Institute of Technology, Vellore, Tamil Nadu, India. His research interests include underwater wireless sensor networks, 5G communications, machine learning, and artificial intelligence.



**MOHAMMAD ALIBAKHSHIKENARI** (Member, IEEE) was born in Mazandaran, Iran, in February 1988. He received the Ph.D. degree (Hons.) with European Label in electronics engineering from the University of Rome "Tor Vergata", Italy, in February 2020. He was the Ph.D. Visiting Researcher at the Chalmers University of Technology, Sweden, in 2018. His training during the Ph.D. included a research stage in the Swedish Company Gap Waves AB. He is currently with the Department of Signal Theory and Communications, Universidad Carlos III de Madrid (uc3m), Spain, as a Principal Investigator of the CONEX-Plus Talent Training Program and Marie Skłodowska-Curie Actions. He was also a Lecturer of electromagnetic fields at the Electromagnetic Laboratory, Department of Signal Theory and Communications, for academic year, 2021-2022. He received the "Teaching Excellent Acknowledgement" Certificate for the course of electromagnetic fields from the Vice-Rector of studies at uc3m. His research interests include electromagnetic systems, antennas and wave-propagations, metamaterials and metasurfaces, synthetic aperture radars (SAR), multiple input–multiple output (MIMO) systems, RFID tag antennas, substrate integrated waveguides (SIWs), impedance matching circuits, microwave components, millimeter-waves and terahertz integrated circuits, gap waveguide technology, beamforming matrix, and reconfigurable intelligent surfaces (RIS). He was a recipient of the three years Research Grant Funded by Universidad Carlos III de Madrid and the European Union's Horizon 2020 Research and Innovation Program under the Marie Skłodowska-Curie Grant started, in July 2021, the two years research grant funded by the University of Rome "Tor Vergata" started, in November 2019, and the three years Ph.D. Scholarship funded by the University of Rome "Tor Vergata" started, in November 2016. His research article entitled "High-Gain Metasurface in Polyimide On-Chip Antenna Based on CRLH-TL for Sub Terahertz Integrated Circuits" published in Scientific Reports. His research article was awarded as the Best Month Paper at the University of Bradford, U.K., in April 2020. He received the two Young Engineer Awards of the 47th and 48th European Microwave Conference, Nuremberg, Germany, in 2017, and in Madrid, Spain, in 2018, respectively. He is serving as an Associate Editor for *Radio Science*, *IET Journal of Engineering*, and *International Journal of Antennas and Propagation*. He also acts as a referee in several highly reputed journals and international conferences.



**BAL S. VIRDEE** (Senior Member, IEEE) received the B.Sc. Eng. degree from the University of Leeds, U.K., and the Ph.D. degree from the University of London, U.K. He has worked in industry for various high-tech companies including Philips, as a Research; a Development Engineer at Teledyne Defence and Space; a Future Products Developer in RF/Microwave Communications. He has taught in several academic institutions in the U.K. He is currently a Senior Professor of communications technology and the Director at the Center for Communications Technology, School of Computing and Digital Media, London Metropolitan University. He has supervised and examined numerous Ph.D. students. He has published extensively research papers at international conferences and peer-reviewed journals. His research interest includes wireless communications systems. He is a Chair and an Executive Member at the Institution of Engineering and Technology's (IET) Technical and the Professional Network Committee on RF/Microwave-Technology. He is a Chartered Engineer (C.Eng.), Fellow of the IET.



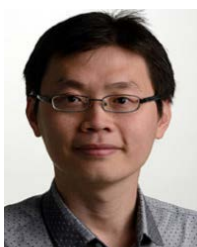
**LIDA KOUHALVANDI** (Member, IEEE) received the B.Sc. degree in electronics engineering from the Azad University of Tabriz, Tabriz, Iran, in 2011, the M.Sc. and Ph.D. (Hons.) degrees in electronics engineering from Istanbul Technical University, Istanbul, Turkey, in 2015 and 2021, respectively. She joined the Department of Electrical and Electronics Engineering, Dogus University, as an Assistant Professor, in October 2021. In recognition of her research, she received the Doctoral Fellowship at the Department of Electronics and Telecommunications, Politecnico di Torino, Turin, Italy, from 2019 to 2020, where she joined as a Research Fellowship, from February 2021 to July 2021. She also has experience in computer-aided designs and optimization algorithms through machine learning. Her research interests include radio frequency and analog engineer are power amplifier, antenna, analog designs, and implantable medical devices. She received the Best Paper Award from EExPolytech-2021: Electrical Engineering and Photonics Conference, in 2021. Her Ph.D. thesis accepted for the presentation at the Ph.D. Forum of the 2021 IEEE/ACM Design Automation Conference (DAC 2021) in San Francisco, USA. From the 30th IEEE Conference on Signal Processing and Communications Applications, she received another Best Paper Award, in 2022. She received the 2022 Mojgan Daneshmand Grant from the IEEE Antennas and Propagation Society (AP-S), organized by the IEEE AP-S Young Professionals. Additionally, her Ph.D. thesis was awarded by Istanbul Technical University as the 'Outstanding Ph.D. Thesis' and the Turkish Electronics Industrialists Association (TESID) as the 'Best Innovation and Creativity Ph.D. Thesis' in 2022.



**KAREN N. OLAN-NUÑEZ** (Student Member, IEEE) received the B.S. degree in electronic engineering from the Technological Institute of Minatitlan, Veracruz, México, in 2017, and the M.Sc. degree from the INAOE, in 2019, where she is currently pursuing the Ph.D. degree in electronics. Her current research interests include the design and modeling of on-chip antennas, metamaterial-based antennas, reconfigurable antennas, absorbers, and devices for high frequency applications.



**GIOVANNI PAU** (Member, IEEE) received the bachelor's degree in telematic engineering from the University of Catania, Italy, and the master's degree (*cum laude*) in telematic engineering and the Ph.D. degree from the Kore University of Enna, Italy. He is currently an Associate Professor with the Faculty of Engineering and Architecture, Kore University of Enna. He is a author/coauthor of more than 80 refereed papers published in journals and conference proceedings. His research interests include wireless sensor networks, fuzzy logic controllers, intelligent transportation systems, the Internet of Things, smart homes, and network security. He has been involved in several international conferences as a session co-chair and a technical program committee member. He serves/served as a leading Guest Editor in special issues of several international journals. He is the Editorial Board Member as Associate Editor of several journals, such as IEEE ACCESS, *Wireless Networks* (Springer), *EURASIP Journal on Wireless Communications and Networking* (Springer), *Wireless Communications and Mobile Computing* (Hindawi), *Sensors* (MDPI), and *Future Internet* (MDPI)



**CHAN HWANG SEE** (Senior Member, IEEE) received the B.Eng. degree (Hons.) in electronic, telecommunication and computer engineering and the Ph.D. degree from the University of Bradford, U.K., in 2002 and 2007, respectively. He is an Associate Professor with the School of Computing, Engineering and the Built Environment, Edinburgh Napier University, U.K. Previously, he was the Head of electrical engineering and Mathematics. Prior to this, he was a Senior

Lecturer (Programme Leader) in electrical and electronic engineering, at the School of Engineering, University of Bolton, U.K. Before this, he was a Senior Research Fellow at the Antennas and Applied Electromagnetics Research Group, University of Bradford. His research interests include wireless sensor network system design, computational electromagnetism, antennas, microwave circuits, wireless power transfer, and acoustic sensor design. He has published over 100 peer-reviewed journal articles in these research areas. He is a coauthor for one book and three book chapters. He was a recipient of two Young Scientist Awards from the International Union of Radio Science (URSI) and Asia-Pacific Radio Science Conference (AP-RASC), in 2008 and 2010, respectively. He was Awarded the Certificate of Excellence for his successful Knowledge Transfer Partnership (KTP) with Yorkshire Water on the design and implementation of a wireless sensor system for sewerage infrastructure monitoring, in 2009. He is a Chartered Engineer, a fellow of the Institution of Engineering and Technology, the Higher Education Academy, a full member of the EPSRC Review College. He is an Associate Editor of IEEE Access and the Editor of *Journal of Electronics and Electrical Engineering*, *Scientific Reports*, *PeerJ Computer Science*, *PLOS One* and *Wireless Power Transfer* Journals.



**IYAD DAYOUB** (Senior Member, IEEE) received the B.Eng. degree in telecommunications and electronics, Syria, in 1993, the M.A.Sc. degree in electrical engineering from the National Polytechnic Institute of Lorraine (INPL), and the Ph.D. degree from the University of Valenciennes and the Institute of Electronics, Microelectronics and Nanotechnology (IEMN), in 2001. He has worked as a System Engineer with Siemens, Middle East; and a Researcher with Alcatel Business Systems, Alcatel, Colombes, Paris. He is currently a Professor of communications engineering. His current research activities at IEMN, Université Polytechnique Hauts-de-France (UPHF) and INSA H-d-F are focused on wireless communications, high-speed communications, cognitive radio, and hybrid radio-optic technologies. He was an Adjunct Professor with Concordia University, Montreal, from 2010 to 2014. He is a member of several international conference advisory committees, technical program committees, and organization committees, such as VTC, GLOBECOM, ICC, PIMRC, and WWC. He was a member of the National Council of Universities (CNU), France, from 2007 to 2014, in the area of electrical engineering, electronics, photonics, and systems.



**PATRIZIA LIVRERI** (Member, IEEE) received the Laurea degree (Hons.) in electronics engineering, and the Ph.D. degree in electronics and communications engineering from the University of Palermo, Italy, in 1986 and 1992, respectively. She is an Associate Professor with the Department of Engineering, University of Palermo, and a Visiting Professor with the San Diego State University. From 1993 to 1994, she was a Researcher at the National Council for Researches, CNR, Rome, Italy. Since 1995, she has been serving as the Scientific Director for the 'Microwave Instruments and Measurements Laboratory' of the Engineering Department with the University of Palermo. In 2020, she also joined the CNIT National Laboratory for Radar and Surveillance Systems RaSS, Pisa. She is the Principal Investigator of the "Microwave Quantum Radar" project, funded by the Ministry of Defense, in 2021. She is the Supervisor of many funded project and the author of over 250 published papers. Her research interests include microwave and millimeter vacuum high power (TWT, Klystron) and solid-state power amplifiers for radar applications; high power microwave source (virtual cathode oscillator and magnetically insulated transmission line oscillator); microwave and optical antennas; radar; and microwave quantum radar.



**SONIA AÏSSA** (Fellow, IEEE) received the Ph.D. degree in electrical and computer engineering from McGill University, Montreal, QC, Canada, in 1998. Since then, she has been with the Institut National de la Recherche Scientifique-Energy, Materials and Telecommunications Center (INRS-EMT), University of Quebec, Montreal, QC, Canada, where she is currently a Full Professor. From 1996 to 1997, she was a Researcher with the Department of Electronics and Communications, Kyoto University, and the Wireless Systems Laboratories, NTT, Japan. From 1998 to 2000, she was a Research Associate at INRS-EMT. From 2000 to 2002, she was an Assistant Professor and the Principal Investigator in the major program of personal and mobile communications at the Canadian Institute for Telecommunications Research, leading research in radio resource management for wireless networks. From 2004 to 2007, she was an Adjunct Professor with Concordia University, Canada. She was a Visiting Invited Professor at Kyoto University, Japan, in 2006, and Universiti Sains Malaysia, in 2015. Her research interests include modeling, design, and performance analysis of wireless communication systems and networks. She is a Fellow of the Canadian Academy of Engineering. She received the several awards include the NSERC University Faculty Award, in 1999; the Quebec Government FRQNT Strategic Faculty Fellowship, in 2001–2006; the INRS-EMT Performance Award multiple times since 2004, for outstanding achievements in research, teaching and service; and the Technical Community Service Award from the FRQNT Centre for Advanced Systems and Technologies in Communications, 2007. She is a co-recipient of five IEEE Best Paper Awards and of the 2012 IEICE Best Paper Award; and a recipient of NSERC Discovery Accelerator Supplement Award. She was the Founding Chair of the IEEE Women in Engineering Affinity Group in Montreal, from 2004 to 2007; the TPC Symposium Chair or Co-Chair at IEEE ICC '06 '09 '11 '12; a Program Co-Chair at IEEE WCNC 2007; a TPC Co-Chair of IEEE VTC-Spring 2013; a TPC Symposia Chair of IEEE Globecom 2014; a TPC Vice-Chair of IEEE Globecom 2018; and serves as a TPC Chair for IEEE ICC 2021. Her main editorial activities include: the Editor, IEEE TRANSACTIONS ON WIRELESS COMMUNICATIONS, from 2004 to 2012; an Associate Editor and a Technical Editor, *IEEE Communications Magazine*, from 2004 to 2015; Technical Editor, *IEEE Wireless Communications* magazine, from 2006 to 2010; and an Associate Editor, *Wiley Security and Communication Networks Journal*, from 2007 to 2012. She currently serves as an Area Editor for the IEEE TRANSACTIONS ON WIRELESS COMMUNICATIONS. She served as Distinguished Lecturer of the IEEE Communications Society and a member of its Board of Governors, in 2013–2016 and 2014–2016, respectively.



**FRANCISCO FALCONE** (Senior Member, IEEE) received the degree in telecommunication engineering and the Ph.D. degree in communication engineering from the Universidad Pública de Navarra (UPNA), Spain, in 1999 and 2005, respectively. From February 1999 to April 2000, he was the Microwave Commissioning Engineer at Siemens-Italtel, deploying microwave access systems. From May 2000 to December 2008, he was a Radio Access Engineer at Telefónica Móviles, performing radio network planning and optimization tasks in mobile network deployment. From January 2009 to May 2009, as a co-founding member, he has been the Director of Tafco Metawireless, a spin-off company from UPNA. In parallel, he is an Assistant Lecturer with the Electrical and Electronic Engineering Department, UPNA, from February 2003 to May 2009. In June 2009, he becomes an Associate Professor with the EE Department, being the Department Head, from January 2012 to July 2018. From January 2018 to May 2018, he was a Visiting Professor with the Kuwait College of Science and Technology, Kuwait. He is also affiliated with the Institute for Smart Cities (ISC), UPNA, which hosts around 140 researchers. He is currently acting as the Head of the ICT Section. He has over 500 contributions in indexed international journals, book chapters, and conference contributions.

His research interests include computational electromagnetics applied to the analysis of complex electromagnetic scenarios, with a focus on the analysis, design, and implementation of heterogeneous wireless networks to enable context-aware environments. He has been awarded the CST 2003 and CST 2005 Best Paper Award, the Ph.D. Award from the Colegio Oficial de Ingenieros de Telecomunicación (COIT), in 2006, the Doctoral Award UPNA, in 2010, the 1st Juan Gomez Peñalver Research Award from the Royal Academy of Engineering of Spain, in 2010, the XII Talgo Innovation Award 2012, the IEEE 2014 Best Paper Award, in 2014, the ECSA-3 Best Paper Award, in 2016, and the ECSA-4 Best Paper Award, in 2017.



**ERNESTO LIMITI** (Senior Member, IEEE) is a Full Professor of electronics at the Engineering Faculty of the University of Roma Tor Vergata, since 2002, where he was a teaching assistant, in 1991, and an Associate Professor, in 1998. He represents the University of Roma Tor Vergata in the governing body of the MECSA (Microwave Engineering Center for Space Applications), an inter-university center among several Italian Universities. He has been elected to represent the Industrial Engineering Sector in the Academic Senate of the University for the period 2007–2010 and 2010–2013. He is currently the President of the Consortium “Advanced Research and Engineering for Space”, ARES, formed between the University and two companies. Further, he is also the President of the Laurea and Laurea Magistrale degrees in electronic engineering at the University of Roma Tor Vergata. His research activity is focused on three main lines, all of them belonging to the microwave and millimetre-wave electronics research area. The first one is related to characterisation and modeling for active and passive microwave and millimetre-wave devices. Regarding active devices, the research line is oriented to the small-signal, noise, and large signal modeling. Regarding passive devices, equivalent-circuit models have been developed for interacting discontinuities in microstrip, for typical MMIC passive components (MIM capacitors) and to waveguide/coplanar waveguide transitions analysis and design. For active devices, new methodologies have been developed for the noise characterisation and the subsequent modeling, and equivalent-circuit modeling strategies have been implemented both for small and large-signal operating regimes for GaAs, GaN, SiC, Si, and InP MESFET/HEMT devices. The second line is related to design methodologies and characterisation methods for low noise circuits. The main focus is on cryogenic amplifiers and devices. Collaborations are currently ongoing with the major radioastronomy institutes all around Europe within the frame of FP6 and FP7 programmes (RadioNet). Finally, the third line is in the analysis methods for nonlinear microwave circuits. In this line, novel analysis methods (Spectral Balance) are developed, together with the stability analysis of the solutions making use of traditional (harmonic balance) approaches. The above research lines have produced more than 250 publications on refereed international journals and presentations within international conferences. He is a member of the committee of the Ph.D. program in telecommunications and microelectronics at the University of Roma Tor Vergata, tutoring an average of four Ph.D. candidates per year. He acts as a referee of international journals of the *Microwave and Millimetre Wave Electronics* sector and the steering committee of international conferences and workshops. He is actively involved in research activities with many research groups, both European and Italian. He is in tight collaborations with high-tech Italian (Selex-SI, Thales Alenia Space, Rheinmetall, Elettronica S.p.A., Space Engineering) and foreign (OMMIC, Siemens, UMS) companies. He contributed, as a researcher and/or as unit responsible, to several National (PRIN MIUR, Madess CNR, Agenzia Spaziale Italiana) and international (ESPRIT COSMIC, Manpower, Edge, Special Action MEPI, ESA, EUROPA, Korrigan, RadioNet FP6 and FP7) projects. Regarding teaching activities, he teaches, over his institutional duties in the frame of the Corso di Laurea Magistrale in Ingegneria Elettronica, “Elettronica per lo Spazio” within the master’s course in Sistemi Avanzati di Comunicazione e Navigazione Satellitare.

• • •