Cooperative Dual-Mode OFDM Index Modulation based Downlink Multi-User NOMA System

Sandhya Soni*, Rahul Makkar†*, Divyang Rawal*, Gurinder Singh*, Vivek Ashok Bohara‡ and Zilong Liu§
*Electronics and Communication Engg., The LNMIIT, Jaipur, Rajasthan, India.
†Electronics and Communication Engg., Indian Institute of Information Technology (IIIT), Kota, Rajasthan, India
‡Electronics and Communication Engg., Indian Institute of Information Technology (IIIT), Delhi, India.
§School of CSEE, University of Essex, Wivenhoe Park, Colchester, CO4 3SQ, United Kingdom.
Email: 18pec002@lnmiit.ac.in, rahul.ece@iiitkota.ac.in, divyang.rawal@lnmiit.ac.in,
gurinder.singh@lnmiit.ac.in, vivek.b@iiitd.ac.in and zilong.liu@essex.ac.uk

***Abstract*—To fulfil the demand for high energy and spectral efficiency (SE) while serving multiple users concurrently for next-generation 6G systems, both non-orthogonal multiple access (NOMA) and orthogonal frequency division multiplexing (OFDM) aided index modulation (IM) endorse the requirements. NOMA serves several users concurrently while sharing the frequency and time resources. In addition, the single-mode OFDM-IM system improves the SE by broadcasting the additional bits of active subcarrier selection. Meanwhile, dual-mode OFDM-IM relatively enhances the SE via transmitting different constellation sets over a subblock OFDM vector. Furthermore, broadcasting the baseband NOMA symbols over a dual-mode OFDM-IM scheme improves the SE compared to the conventional IM schemes. This paper describes a dual-mode aided cooperative relaying OFDM-IM-based downlink hybrid NOMA system serving multiple users simultaneously. The Monte Carlo simulation results demonstrate that the bit error rate (BER) performance of the proposed system accessed using the maximum likelihood (ML) detector for different modulation schemes is significantly better as compared to the existing cooperative relaying OFDM-IM-aided NOMA systems, including single-mode and hybrid systems.**

***Index Terms*—6G, dual-mode index modulation, spectral efficiency, non-orthogonal multiple access, orthogonal frequency division multiplexing, bit error rate.**

I. Introduction

The sixth-generation (6G) networks are expected to provide substantial breakthroughs beyond the previous five generations in terms of a number of key performance indicators, such as user-experienced date-rates, reliability, latency, connection density, spectrum efficiency, energy efficiency, etc. [1]. In fact, 6G networks are anticipated to support up to 10 million devices per square kilometre while maintaining the trade-off between the number of served users and spectral efficiency (SE) [2]. Orthogonal multiple access (OMA) schemes can hardly concur with the linear relation between the above-mentioned parameters.

Unlike OMA techniques that employ orthogonal resource distribution, non-orthogonal multiple access (NOMA) allocates resources to different users in a non-orthogonal way to improve the system throughput [3], [4]. Besides, index modulation (IM) emerges in recent years due to many promising properties, such as high energy efficiency, high SE, and low detection complexity, which fulfil the above requirements [5]. OFDM-IM transmits the information bits as modulated symbols through the fixed and selected active subcarriers (chosen using a lookup table or combinatorial method) in each subblock of OFDM. Only the active subcarriers send the modulated information data, while the inactive subcarriers are idle.

A. Related Works

The performances of OMA and NOMA systems in terms of bit error rate (BER), outage probability, sumrate, with or without OFDM-IM have been extensively studied [6]–[9]. Kara *et al.* [6] studied the performance analysis of a two-user NOMA system in the presence of successive interference cancellation (SIC) errors. The error probability of OFDM-IM for non-cooperative system considering imperfect channel state information (CSI) is presented in [7]. In addition, Arslan *et al.* [8] derived the average pairwise error probability for OFDM-IM integrated with the power-domain (PD) downlink two-user NOMA non-cooperative system over fading channels.

Further, [9] derived the BER for three-node OFDM-IM with the cooperative NOMA system (termed CIM-OFDM-NOMA) using maximum likelihood (ML) and low-complexity greedy detectors. In contrast, authors in [10] integrated the code-domain (CD) and PD NOMA schemes and showed the sum rate of the intended users. In addition, [11] explored the hybrid NOMA for highlighting the PD and the sparse code multiple access system, comparing the coded and uncoded error rate performance.

On the other side, to overcome the scarcity of SE in OFDM-IM system, [12]–[17] presented the dual-mode transmission while utilizing the vacant subcarriers. Mao *et al.* proposed in [12] the concept of dual-mode IM-based OFDM, where all the OFDM subcarriers transmit the information data bits modulated by two different constellation alphabets and showed the BER performance using ML and low-complexity based log-likelihood ratio detectors. Further, they proposed the idea of generalized dual-mode OFDM-IM in [13], where the number of subcarriers modulated with the same constellation mode is adjustable according to user requirements. In addition, the inherent merits of the cooperative system integrated with OFDM-IM offer reliable performance and extended coverage for long-haul communication [14], [15]. A dual-mode OFDM-IM is proposed to enhance the SE [16] by utilizing all subcarriers with distinct modulation orders corresponding to the two selection indices. Similarly, [17] extended the work for dual-mode OFDM-IM with a two-user NOMA system.

B. Motivation and Contributions

Most of the existing studies have investigated the performance of the dual-mode OFDM-IM and cooperative OFDM-IM-aided hybrid downlink (three-user) NOMA systems independently. In [18], the BER performance of the cooperative relaying single-mode OFDM-IM-aided downlink hybrid NOMA three-user system has been evaluated using ML detector over various modulation schemes and distinct power levels. To the authors' best knowledge, no prior research has explored the cooperative dual-mode OFDM-IM-aided downlink hybrid NOMA systems. Motivated by the practical importance of such a system for next-generation communication systems, we examine the performance of the cooperative OFDM-IM integrated with a downlink hybrid NOMA system supporting five users. Specifically, the key contributions of this paper can be summarized as:

- The performance of a cooperative dual-mode OFDM-IM-aided downlink multi-user hybrid NOMA (incorporating CD and PD) system is presented.
- The Monte-Carlo simulations of BER over signal-to-noise ratio (SNR) are shown for the proposed cooperative dual-mode OFDM-IM-aided five-user hybrid NOMA system using ML detection over different modulation schemes. In addition, the results of BPSK and QPSK modulations are compared with existing cooperative and non-cooperative OFDM-IM modes (single and dual) with a multi-user NOMA system.
- Furthermore, Monte-Carlo simulations are also obtained for the BER performance with PD NOMA users' power fraction coefficient (PFC), and results are compared with prior schemes.
- Moreover, the performance of the proposed framework has been compared in terms of SE against cooperative OFDM-IM single-mode and dual-mode hybrid NOMA systems.

The remainder of the paper has been structured as follows: Section II presents the cooperative relaying OFDM-IM-aided multi-user hybrid NOMA system model. Section III presents the ML detection of intended users in the broadcast and cooperation phase. Results are discussed in Section IV, and the concluding remarks are provided in Section V.

II. System Model

A half-duplex cooperative dual-mode OFDM-IM-aided downlink hybrid NOMA system has been illustrated in Fig. 1. It consists of a BS and five NOMA users, i.e., user A in the PD[†] and the remaining four users in the PD in two independent clusters analogous to the conventional two-user downlink NOMA system [6] assuming a single antenna at each node. These PD NOMA near user (NU) and far user (FU) are designated by B_1 and B_2, respectively, irrespective of the different cluster co-location. *Note that the NU is regarded as a cell-centre user, whereas the FU is designated as a cell-edge user.*

[†]This paper uses the PD for index bits transmission as it uses Gaussian random codes and further re-transmitted to the NOMA end users for estimating their information in cooperative phase [15], [18].

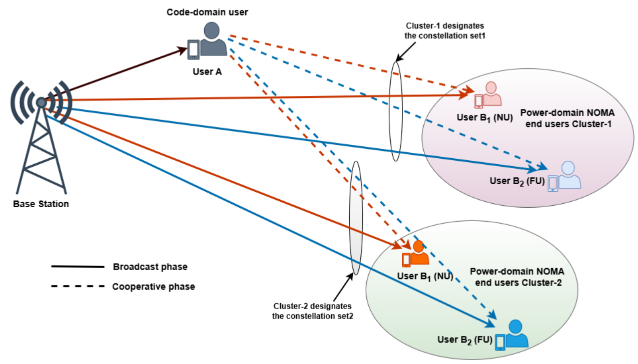

Fig. 1. An illustration of cooperative dual-mode OFDM-IM assisted downlink Multi-user hybrid (code and power domain) NOMA system

All users' modulated information is broadcasted via dual-mode OFDM-IM-aided vector as per active subcarrier selection. For the dual mode case, two different constellation alphabets $\{\mathcal{S}_1, \mathcal{S}_2\}$ are considered, as shown in Fig. 2. For a BPSK modulation scheme, $\mathcal{S}_1 \in \exp(\iota\theta)$ and $\mathcal{S}_2 \in \exp(\iota\phi)$, where $\theta \in \{0, \pi\}$ and $\phi = (2p+1)\frac{\pi}{2}\ \forall\ p \in \{0,1\}$. Similarly, for QPSK modulation scheme, $\mathcal{S}_1 \in \exp(\iota\theta)$ and $\mathcal{S}_2 \in \exp(\iota\phi)$, where $\theta = (2p+1)\frac{\pi}{4}\ \forall\ p \in \{0,1,2,3\}$ and $\phi = \left(\frac{p\pi}{2}\right)\ \forall\ p \in \{0,1,2,3\}$ for generalized p.

These constellation alphabets are arranged in the OFDM subblock vector for the dual-mode scenario [17] using a lookup table or combinatorial method (utilizing Lexicographically ordered sequence) based index selection criteria [5]. The cooperative relaying technique has intrinsic advantages, since index bits are decoded at user A in PD mode and subsequently re-transmitted to the other NOMA end users in PD mode[§]. Further, BS broadcasts the superposition coded (SC) signal by a weighted linear combination of PD users $\mathrm{B}_u \forall\ u = 1, 2$, i.e. u^{th} PD NOMA user, consisting of information using different modulations. A statistical CSI at the BS is considered to allocate the user's power. Thus, the transmitted SC signal x_{sc} at the BS for users B_u is given as [6], [18]

$$\mathrm{x}_{\text{sc}} = \sqrt{\psi}\,\mathrm{m}_1 + \sqrt{(1-\psi)}\,\mathrm{m}_2, \tag{1}$$

where m_1, m_2 are modulated symbols $\in$ {BPSK, QPSK} with the transmitting power ψ and $(1-\psi)$ corresponding to the NU and FU user, respectively.

[§]Without loss of generality, BPSK modulation has been chosen in the entire paper and simulations for user A. In contrast, a different modulation scheme {BPSK, QPSK} is used for PD NOMA users.

Referring to Fig. 2, the solid squares represent the dual-mode BPSK constellation alphabets, while dotted squares represent the dual-mode constellation alphabets for the QPSK modulation scheme.

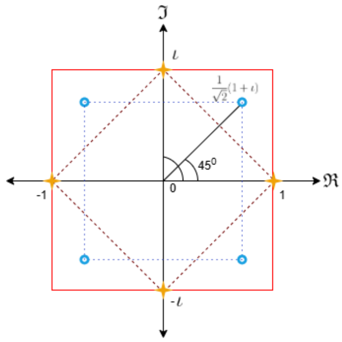

Fig. 2. Generalized Constellation mapper of dual-mode transmission for BPSK and QPSK modulation scheme

TABLE I
LOOKUP TABLE FOR MAPPING THE SUBCARRIERS PER SUBBLOCK OF DUAL-MODE OFDM-IM-AIDED NOMA SCHEME

Index bits	**Indices for $\mathcal{I}_1$**	**Indices for $\mathcal{I}_2$**	**Subblocks**
[0,0]	[1,2]	[3,4]	$\left[\mathbb{X}_{s_1}^{(1)}, \mathbb{X}_{s_1}^{(2)}, \mathbb{X}_{s_2}^{(3)}, \mathbb{X}_{s_2}^{(4)}\right]$
[0,1]	[2,3]	[1,4]	$\left[\mathbb{X}_{s_2}^{(1)}, \mathbb{X}_{s_1}^{(2)}, \mathbb{X}_{s_1}^{(3)}, \mathbb{X}_{s_2}^{(4)}\right]$
[1,0]	[3,4]	[1,2]	$\left[\mathbb{X}_{s_2}^{(1)}, \mathbb{X}_{s_2}^{(2)}, \mathbb{X}_{s_1}^{(3)}, \mathbb{X}_{s_1}^{(4)}\right]$
[1,1]	[1,4]	[2,3]	$\left[\mathbb{X}_{s_1}^{(1)}, \mathbb{X}_{s_2}^{(2)}, \mathbb{X}_{s_2}^{(3)}, \mathbb{X}_{s_1}^{(4)}\right]$

III. DUAL-MODE AIDED OFDM-IM NOMA DETECTION STRATEGY

This section covers the detection approach of a cooperative relaying dual-mode OFDM-IM-aided hybrid downlink NOMA system using ML detection with perfect CSI. The detection of users A and PD user B_u is described in the following subsections. In addition, the SE gain for the proposed system compared to other IM schemes is also shown.

A. Broadcast Phase

BS first transmits the SC symbol to user A and user B_u processed by $\mathbf{N}_{\text{FFT}} \times 1$ OFDM-IM vector with a total of N_b information bits in the broadcast phase. Later, this OFDM block is divided into independent and identical N_g subblocks, each containing $b = N_b/N_g$ bits and independently applying the IM process within $n = \mathbf{N}_{\text{FFT}}/N_g$ subcarriers. For each subblock, the total $b = b_1 + b_2$ bits are provided, where $b_1 = \left\lfloor \log_2 \binom{n}{k} \right\rfloor$ bits are used to determine k active subcarriers out of n, while $b_2 = k \sum_{u=1}^{2} \log_2(\mathrm{M}_u)$ bits are mapped to transmit SC constellations to u^{th} PD NOMA user, carried by k selected subcarriers [8], [17]¶.

The symbol vector of length $\mathbf{N}_{\text{FFT}}$ is divided into N_g subblocks of size n for each intended user. The SC modulated symbol is transmitted to k randomly activated subcarriers out of n with $n > k > 0$ for the constellation set $\mathcal{S}_1$, and the remaining $n-k$ subcarriers are mapped with the constellation set $\mathcal{S}_2$ [12], [17]. Based on the lookup method, the constellation mapping for all the subcarriers in each subgroup is given in Table I. The active indices vector $\mathcal{I}$ for SC transmission of α^{th} subblock, where $\alpha \in 1, \ldots, N_g$, the SC symbol vector carrying b_2 bits is represented by‡

$$\mathbf{x}_{\text{SC}}^{(\alpha)}(\lambda) = \left[x_{\text{SC}}^{(\alpha)}(1), \ldots, x_{\text{SC}}^{(\alpha)}(k)\right]^{\text{T}}, \tag{2}$$

where $\mathbf{x}_{\text{SC}}^{(\alpha)}(\cdot) \in \mathbb{X}$ with $\lambda = \{1, \ldots, n\}$ and represents a set of complex SC symbols [18] and mentioned in Table II for BPSK-BPSK modulation pair. *Likewise, the QPSK-QPSK modulation pair constellations are obtained using $\{\mathcal{S}_1, \mathcal{S}_2\}$ alphabets in* (1).

TABLE II
SC CONSTELLATIONS FOR POWER-DOMAIN USERS

Modulation Pair	Constellation Set	Bits Mapped	SC Symbol
BPSK-BPSK	$\mathcal{S}_1$	$[0,0]$	$-\sqrt{\psi} - \sqrt{(1-\psi)}$
		$[0,1]$	$-\sqrt{\psi} + \sqrt{(1-\psi)}$
		$[1,0]$	$\sqrt{\psi} - \sqrt{(1-\psi)}$
		$[1,1]$	$\sqrt{\psi} + \sqrt{(1-\psi)}$
	$\mathcal{S}_2$	$[0,0]$	$-\sqrt{\psi}\iota - \sqrt{(1-\psi)}\iota$
		$[0,1]$	$-\sqrt{\psi}\iota + \sqrt{(1-\psi)}\iota$
		$[1,0]$	$\sqrt{\psi}\iota - \sqrt{(1-\psi)}\iota$
		$[1,1]$	$\sqrt{\psi}\iota + \sqrt{(1-\psi)}\iota$

Furthermore, concatenated subblocks form an OFDM vector $\mathbf{X}_{\text{SC}}$ of length $\mathbf{N}_{\text{FFT}}$, and, conventional steps of inverse FFT, cyclic prefix (CP), and parallel-to-serial conversion are performed. At the receiver, the frequency-domain α^{th} subblock's received signals at user A and B_u are expressed as follows.

$$y = \sqrt{P_1}\, h\, \mathbf{X}_{\text{SC}} + w, \tag{3}$$

where P_1 is the total transmitting power at the BS, $\mathbf{X}_{\text{SC}} = \text{diag}(\mathbf{x}_{\text{SC}})$. h and w are the channel coefficients and additive white Gaussian noise (AWGN) vectors $\sim \mathcal{CN}(0, \sigma_n^2)$ associated with the links BS $\rightarrow$ A and BS $\rightarrow$ B_u, respectively, in the broadcast phase and the detection of active indices at user A using (3) is evaluated as follows

$$\widetilde{\mathcal{I}} = \arg\max_{\mathcal{I}} \left\| y_{\text{A}} - h_{\text{A}}\, \mathbf{X}_{\text{SC}} \right\|^2. \tag{4}$$

On the other side, in cooperative phase, the detection of user B_1 is carried out in presence of SIC errors [6] as user B_2's power is more dominating than B_1's for $\psi < 0.5$ using (1) and expressed as

$$\hat{\mathbf{x}}_{\mathrm{B}_1} = \arg\max_{(\widetilde{\mathcal{I}},\ \mathbf{x}_{\text{SC}})} \left\| (y_{\text{A}} - h_{\mathrm{B}_1}\, \hat{\mathbf{x}}_{\text{SIC}}) - h_{\mathrm{B}_1}\, \mathbf{X}_{\text{SC}} \right\|^2, \tag{5}$$

¶Refer to the [8], [9], [17] for the explicit description of the subblocks, and bits splitting procedure for the OFDM-IM scheme.

‡Note that the equations are designated for the α^{th}, $\forall\ \alpha = 1, \ldots, N_g$ subblock notations throughout the paper.

Throughout the paper, the channel gains of intended users are considered inversely proportional to the proximity using the law of generality and modelled as independent and identically distributed complex Gaussian random variables with distributions $\sim \mathcal{CN}(0, \sigma_l^2)$, where l indicates the link established between any two nodes, i.e. BS to the intended users in broadcast phase and CD-aided user A to PD-aided users in cooperative phase.

TABLE III
COMPARATIVE ANALYSIS OF SE (ξ) FOR PROPOSED DUAL-MODE OFDM-IM (4,2) HYBRID NOMA OVER THE EXISTING SYSTEMS

System	User's A Modulation	Modulation pair of user B_u	b_1	b_2	ξ
CIM-OFDM-NOMA (two-user) SM [15]	BPSK	QPSK	64	128	1.334
CIM-OFDM-NOMA (three-user) SM [18]		BPSK-BPSK		128	1.334
		QPSK-BPSK		192	1.778
DM-OFDM-IM NOMA (two-user) [17]		BPSK-BPSK		256	2.223
		QPSK-QPSK		576	4
Proposed System (five-user)		BPSK-BPSK		576	4
		QPSK-QPSK		1088	7.556

where $\hat{\mathbf{x}}_{\text{SIC}}$ is the estimate of user B_2 info at user B_1 and detection of user B_2 is evaluated referring (3) as

$$\hat{\mathbf{x}}_{\mathrm{B}_2} = \underset{\mathcal{I},\ \mathbf{x}_{\text{SC}}}{\arg\max} \left\| y_{\mathrm{A}} - h_{\mathrm{B}_2} \mathbf{X}_{\text{SC}} \right\|^2 . \tag{6}$$

B. Cooperative Phase

Based on the IM information associated with the user A and the two different received signals at user B_u, the joint ML detector estimates for k active subcarriers out of n are evaluated referring (3). The farthest PD NOMA user (B_2) receives more power based on proximity, which considers B_1's info as interference. Thus, ML detection is given as

$$\left(\widehat{\mathcal{I}},\ \widehat{\mathbf{x}}_{\mathrm{B}_2}\right) = \sum_{m=\{\mathrm{B}_2, \mathrm{AB}_2\}} \underset{\widetilde{\mathcal{I}},\ \hat{\mathbf{x}}_{\mathrm{B}_2}}{\arg\max} \left\| y_m - h_m \mathbf{X}_{\text{SC}} \right\|^2 , \tag{7}$$

where y_{AB_2} is the received signal at the user B_2 from the user A in cooperation phase and given as

$$y_{\mathrm{AB}_2} = \sqrt{P_2}\, z_{\mathrm{AB}_2} \hat{\mathbf{X}}_{\text{SC}} + w_{\mathrm{AB}_2}, \tag{8}$$

where $\hat{\mathbf{X}}_{\text{SC}}$ is the diagonal matrix of SC symbol for α^{th} sub-block at user A over estimated index bits, P_2 is the transmitting power at user A. Similarly, the detection of user B_1 is carried out in presence of SIC errors with similar detection procedure as provided in Section III-A.

C. SE gain of OFDM-IM system

User A and user B_u for the considered cooperative OFDM-IM-aided hybrid downlink NOMA system are served by the b_1 and b_2 bits, respectively. Hence, the proposed system's overall SE gain (ξ) is enhanced and given by $\xi = \frac{N_g\left(\left\lfloor \log_2 \binom{n}{k} \right\rfloor + k \sum_{u=1}^{2} \log_2 (\sum \mathrm{M}_u | \mathcal{S})\right)}{\mathbf{N}_{\text{FFT}} + \mathrm{L}_{\text{CP}}}$, where $\mathbf{N}_{\text{FFT}}$ and L_{CP} is the length of OFDM vector and CP, respectively. Here, ξ is compared for the proposed system and with the prior co-operative and non-cooperative NOMA-IM schemes including single and dual-mode as mentioned in Table III for distinct modulation schemes, $\mathbf{N}_{\text{FFT}} = 128$ and $\mathrm{L}_{\text{CP}} = 32$ [15], [18] §.

IV. SIMULATION RESULTS AND DISCUSSION

This section presents the numerical simulation results of the average BER for the proposed cooperative dual mode OFDM-IM-aided multi-user (for five users) hybrid downlink NOMA system. It possesses an advantageous amalgamation of both the CD and PD NOMA systems. For simulations, each subcarrier is assumed to be independent frequency-selective Rayleigh faded with perfect CSI known to all users. In addition, the channel variance for the links involved in the broadcast phase $\mathbb{E}\left\{|h_{\text{BS}\to\text{A}}|^2\right\} = \mathbb{E}\left\{|h_{\text{BS}\to\text{NU}_u}|^2\right\} = 1$, $\mathbb{E}\left\{|h_{\text{BS}\to\text{FU}_u}|^2\right\} = 0.5$ and in the cooperative phase $\mathbb{E}\left\{|h_{\text{A}\to\text{NU}_u}|^2\right\} = 1$, $\mathbb{E}\left\{|h_{\text{A}\to\text{FU}_u}|^2\right\} = 0.5$ for $u = \{1, 2\}$ are assumed depending on the vicinity of the BS. Further, the PFC (ψ) is chosen to be < 0.5 due to users' proximity and OFDM-IM mapping, n = 4 and k = 2 are chosen for simulations. In addition, L_{taps} = 3 multipath channel taps are considered along with L_{CP} = 32 and $\mathbf{N}_{\text{FFT}} = 128$.

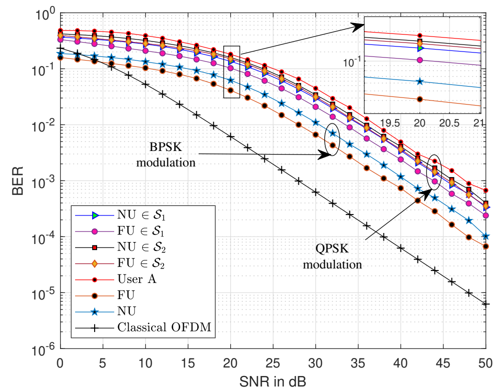

Fig. 3. BER performance of proposed dual-mode OFDM-IM-aided multi-user NOMA system for various modulation schemes

Fig. 3 presents the BER performance of the discussed cooperative OFDM-IM-aided five-user hybrid NOMA system considering CD-aided user A and PD-aided user B_u. The results are simulated for BPSK and QPSK modulation schemes for all the PD-aided NOMA end users, while for the CD-aided user, BPSK is assumed only. Further, the power level at the BS and the user A is assumed to be unity for simulations. For BPSK modulated users, the constellation alphabet magnitude is the same for $\{-1, 1,\}$ and $\{-\iota, \iota\}$ in the dual-mode representation, thus, only NU and FU results are presented irrespective of four PD-aided users. It is noted that the BER for the QPSK modulated users is worse than the BPSK modulated users due to a significant erroneous probability of QPSK-QPSK modulation pair (similar constellation of 16QAM) instead of BPSK-BPSK modulation pair (similar constellation of 4PAM). At an error floor of 10^{-3}, a gain of 6 dB is achieved while altering the modulation scheme from QPSK to BPSK.

In addition, Fig. 4 describes the comparison of the proposed dual-mode cooperative OFDM-IM-aided multi-user NOMA system along with the prior dual-mode OFDM-IM NOMA two-user scheme [17] and single-mode OFDM-IM hybrid NOMA three users [18]. The result shows the trade-off between the number of users and reliability. It is noted that the two-user NOMA scheme performs better than the multi-user NOMA scheme, irrespective of IM modes and occurs due to

§ Note that in Fig. 4 and Fig. 5, single-mode and dual-mode are designated by SM and DM, respectively.

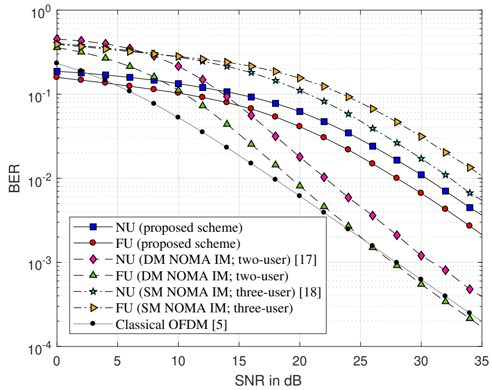

Fig. 4. A comparison of BER performance of proposed cooperative dual-mode OFDM-IM-aided multi-user NOMA system with prior IM scheme

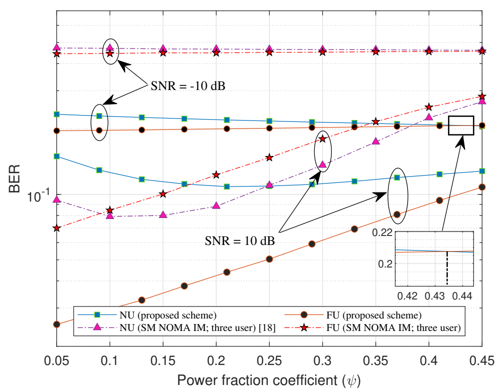

Fig. 5. Comparison of BER performance for the cooperative dual-mode OFDM-IM-aided hybrid NOMA system over PFC at distinct transmit SNR

the severe SIC propagation while estimating the near users. On the other side, it is also observed that dual-mode IM performs better than a single-mode IM system. Although the proposed scheme does not cross the classical OFDM curve [5], it has better SE gain, as mentioned in Table III.

Similarly, Fig. 5 shows the BER of each user at $\{-10, 10\}$ dB transmit SNR to examine the efficacy of PFC (ψ) on the performance of the proposed cooperative dual-mode OFDM-IM-aided multi-user hybrid NOMA system and compared with the prior SM NOMA-IM three users system [18]. It can be observed that the proposed system has better BER performance in comparison to the SM NOMA-IM three-user system because it broadcasts the SC symbol at each subcarrier rather than transmitting zeros, as in the SM NOMA-IM case. Furthermore, in the confined range, the proposed system is unable to attain the ideal PFC in the SM NOMA-IM scenario. It happens due to the serving multi-user resulting in severe SIC propagation. Meanwhile, at -10 dB SNR, the proposed system is obtaining the crossing point near $\psi = 0.435$.

V. Conclusion

This paper presented the cooperative OFDM-IM-aided hybrid five-user NOMA system's BER performance for $\{$BPSK, QPSK$\}$ modulation schemes. The proposed framework highlights the intrinsic benefits of cooperative relaying and the amalgamation of code domain and power domain NOMA scheme to improve the SE and support massive connectivity. The BER results are simulated over ML detection, and SE gain is also compared to the traditional two and three-user cooperative and non-cooperative NOMA-IM systems. In contrast to the single-mode IM scheme, the proposed system shows the trade-off between SE and reliability while supporting multiple users. Further, the impact of ψ over the BER performance is also compared, and it is evident that the proposed system offers a better approach in achieving the optimal PFC value.

References

[1] F. Fang, Y. Liu, H. S. Dhillon, Y. Wu, Z. Ding, and E. Basar, "Guest editorial: Next generation multiple access for 6G," *IEEE Netw.*, vol. 37, no. 1, pp. 8–9, 2023.

[2] J. Li, S. Dang, M. Wen, Q. Li, Y. Chen, Y. Huang, and W. Shang, "Index modulation multiple access for 6G communications: Principles, applications, and challenges," *IEEE Netw.*, vol. 37, no. 1, pp. 52–60, 2023.

[3] Y. Saito, Y. Kishiyama, A. Benjebbour, T. Nakamura, A. Li, and K. Higuchi, "Non-orthogonal multiple access (NOMA) for cellular future radio access," in *2013 IEEE 77th Veh. Technol. Conf. (VTC Spring)*, pp. 1–5, 2013.

[4] Z. Ding, R. Schober, and H. V. Poor, "A general MIMO framework for NOMA downlink and uplink transmission based on signal alignment," *IEEE Trans. Wirel. Commun.*, vol. 15, no. 6, pp. 4438–4454, 2016.

[5] E. Basar, U. Aygolu, E. Panayırcı, and H. V. Poor, "Orthogonal frequency division multiplexing with index modulation," *IEEE Trans. Signal Process.*, vol. 61, no. 22, pp. 5536–5549, Nov. 2013.

[6] F. Kara and H. Kaya, "BER performances of downlink and uplink NOMA in the presence of SIC errors over fading channels," *IET Commun.*, vol. 12, no. 15, pp. 1834–1844, 2018.

[7] T. Van Luong and Y. Ko, "A tight bound on BER of MCIK-OFDM with greedy detection and imperfect CSI," *IEEE Commun. Lett.*, vol. 21, no. 12, pp. 2594–2597, 2017.

[8] E. Arslan, A. T. Dogukan, and E. Basar, "Index modulation-based flexible non-orthogonal multiple access," *IEEE Wirel. Commun. Lett.*, vol. 9, no. 11, pp. 1942–1946, 2020.

[9] X. Chen, M. Wen, and S. Dang, "On the performance of cooperative OFDM-NOMA system with index modulation," *IEEE Wirel. Commun. Lett.*, vol. 9, no. 9, pp. 1346–1350, 2020.

[10] N. M. Balasubramanya, A. Gupta, and M. Sellathurai, "Combining code-domain and power-domain NOMA for supporting higher number of users," in *IEEE Global Commun. Conf. (GLOBECOM)*, pp. 1–6, 2018.

[11] K. Deka and S. Sharma, "Hybrid NOMA for future radio access: Design, potentials and limitations," *Wirel. Pers. Commun.*, pp. 1–16, Apr. 2022.

[12] T. Mao, Z. Wang, Q. Wang, S. Chen, and L. Hanzo, "Dual-mode index modulation aided OFDM," *IEEE Access*, vol. 5, pp. 50–60, 2017.

[13] T. Mao, Q. Wang, and Z. Wang, "Generalized dual-mode index modulation aided OFDM," *IEEE Commun. Lett.*, vol. 21, no. 4, pp. 761–764, 2017.

[14] M. Wen, X. Chen, Q. Li, E. Basar, Y.-C. Wu, and W. Zhang, "Index modulation aided subcarrier mapping for dual-hop OFDM relaying," *IEEE Trans. Commun.*, vol. 67, no. 9, pp. 6012–6024, Sept. 2019.

[15] X. Chen, M. Wen, and S. Dang, "On the performance of cooperative OFDM-NOMA system with index modulation," *IEEE Wireless Commun. Lett.*, vol. 9, no. 9, pp. 1346–1350, Sept. 2020.

[16] S. Jacob, N. T. Lakshmi, and A. Chockalingam, "Dual-mode index modulation schemes for CPSC-MIMO systems," in *2018 IEEE 88th Veh. Technol. Conf. (VTC-Fall)*, pp. 1–5, 2018.

[17] M. Jain, R. Makkar, D. Rawal, and R. Gangopadhyay, "Dual-mode index modulation based OFDM system over NOMA networks," *Physical Commun.*, vol. 47, p. 101395, Aug. 2021.

[18] R. Makkar, M. Jain, D. Rawal, N. Sharma, and V. K. Chakka, "On performance of cooperative OFDM index modulation aided hybrid NOMA system," in *2024 IEEE 99th Veh. Technol. Conf. (VTC2024-Spring)*, pp. 1–5, 2024.