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RESEARCH ARTICLE

QoS-Based Resource Allocation in Multicarrier NOMA-IBFD Cellular System With Sectorization

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ABSTRACT In this study, we examine the performance of a multicell cellular system featuring an Non-orthogonal multiple access (NOMA) - In-band full duplex transmission (IBFD) enabled base station to improve spectral efficiency. The simultaneous transmission of multiple signals on the same frequency resource introduces several interferences and necessitates higher transmission powers to meet user's quality of service (QoS) requirements. To address this, we introduce a heuristic approach aimed at optimizing subcarrier and power allocation with the goal of minimizing required downlink powers while ensuring QoS for each user. We also present decodability order for downlink (DL) NOMA in the presence of uplink users. Subsequently, we extend our investigation at sector level to obtain a comprehensive understanding of network dynamics within a more confined coverage area. We use orthogonal resource allocation and half duplex scenarios as benchmarks to evaluate the performance of proposed algorithm. Numerical simulations reveal that NOMA-IBFD requires lower transmit powers to meet QoS compared to the orthogonal multiple access (OMA) system, despite having more interference terms. Our key findings emphasize that the proposed algorithm not only enables users with weaker channel conditions to meet QoS requirements but also allows users with stronger channel conditions to contribute significantly to system throughput enhancement, thereby providing enhanced energy efficiency.

INDEX TERMS Non orthogonal multiple access, in-band full duplex transmission, sectorization, subcarrier allocation, power allocation, quality of service.

I. INTRODUCTION

With the advent of next generation multiple access (NGMA) for future wireless networks, efficient solutions need to be implemented to address the diverse connectivity needs of both cellular users and wireless devices. This involves effectively managing critical application requirements, including massive connectivity, spectral efficiency, high data rates, low latency, and quality of service [1], [2]. In a multicell wireless communication system, the coverage area is divided into smaller geographical regions called cells and is typically served by a dedicated base station (BS). These BSs are interconnected and coordinated to provide QoS to the users present in the cellular system by carefully managing the limited available spectrum in the presence of severe interference components. This demands to explore, integrate and fine tune several radio access techniques to enhance data rates and improve spectral efficiency. In multicarrier multiple access systems, the available total bandwidth is divided into subcarriers and assigned to users for better spectrum utilization. Next generation wireless systems along with multicarrier multiple access technique can enhance overall system performance by exploiting diversity among users to meet various QoS requirements [3], [4], [5].

Non-orthogonal multiple access (NOMA), has been proposed for the long-term evolution advanced (LTE-A) standards [6]. It is a multiple access technique that enables simultaneous transmission or reception of several signals

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over the same frequency resource, which improves spectral efficiency and provides massive connectivity [7]. This is in contrast with the conventional orthogonal multiple access (OMA), where orthogonal resource blocks are allocated in a given direction of communication. In DL-NOMA, multiple user signals sharing the same frequency resource are multiplexed by the BS in the power domain and transmitted to all DL users. The DL user, upon receiving the superimposed signal from the BS, performs successive interference cancellation (SIC) to decode its message. Similarly, in case of uplink (UL) transmission, the BS performs the same after receiving the superimposed signal from all UL users. SIC plays a major role in separating the desired user signal by exploiting power difference in the total received signal [8], [9]. Thus, in contrast to OMA, NOMA effectively multiplexes users with diverse quality of service requirements on the same time-frequency resource, enhancing spectrum efficiency but at the expense of increased receiver complexity.

On the other hand, In-band full duplex (IBFD) system enables simultaneous transmission and reception of signals on the same frequency resource by effectively doubling the capacity of wireless system and improves spectrum efficiency [10]. However, the simultaneous UL and DL communication introduces uplink to downlink interference (UDI) at DL user and also self-interference (SI) at BS. With recent advances, the effect of SI can be suppressed significantly by deploying additional electronic circuitry at BS [11], [12], [13].

Therefore, the integration of NOMA and IBFD technologies in a multicarrier scenario holds significant promise for improving spectral efficiency and accommodate more wireless devices to connect to the BS. In the context of both single cell and multi cell environments, several related works have explored the potential benefits of combining these technologies while addressing the associated complexities, as outlined below.

A. RELATED WORKS

1) SINGLE CELL

The benefits of IBFD when integrated with NOMA heavily relies on subcarrier and power allocation. The authors in [14] consider a multi-carrier FD-NOMA system with the restriction of two user NOMA multiplexing and propose subcarrier and power allocation algorithms to maximize achievable data rates. In [15], a distributed resource allocation algorithm is proposed using matching theory for IBFD enabled NOMA system. A dynamic power allocation scheme is proposed in [16] to guarantee QoS in downlink and uplink NOMA system. Similarly, the authors in [17] propose particle swarm optimization (PSO) based, joint subcarrier and power allocation algorithm for a NOMA-IBFD system. Difference of convex programming is used in [18] to convert the problem of energy efficient resource allocation into a convex optimization problem and showed improved sum rate and energy efficiency performance than the conventional orthogonal frequency division multiple access scheme. On the other hand, the works in [19], [20], and [21] consider decoding order policies to provide QoS requirement to users in a single cell environment. However, these works were limited to either UL-NOMA or DL-NOMA. Nevertheless, several other works [22], [23], [24], [25] have been proposed to improve sum rate of the system, while these works are constrained to a single cell and cannot be directly applied to multicell cellular system due to the fact that addition of co-channel interference (CCI) resulting from the simultaneous use of the same subcarrier by BSs and uplink users in other cells.

2) MULTI CELL

Resource allocation in a multicell cellular system poses more challenges due to increased interference components, especially when NOMA and IBFD technologies are combined. Several works in the literature has addressed this problem and proposed various algorithms to improve user QoS requirements and system performance. The authors in [26] worked on cooperative and non-cooperative scheduling schemes to obtain the users for simultaneous uplink and downlink transmission with the objective of maximizing gains in IBFD based system model. In [27], both game theory and graph theory are exploited to find user grouping strategies with emphasis on QoS considerations and the primary objective is to minimize power consumption in multicell downlink NOMA system. Several other works [28], [29], [30] are carried out for multicell downlink NOMA system model. In [28], a greedy user clustering and power allocation scheme is proposed for QoS to minimize the total transmit power. The work in [29] aims at energy efficiency maximization and compared the heuristic based proposed algorithm with fractional transmit power allocation and the conventional orthogonal multiple access. In [30], optimal SIC ordering and power allocation is presented for larger number of cells and users in downlink multicell NOMA system. Nevertheless, the majority of existing studies concentrate either on full duplex or NOMA-DL, leaving a notable gap in the literature concerning the multicell NOMA-IBFD system. The authors in [31] investigate joint optimization of user association, mode selection, and power allocation in a multicell system. However, this work is constrained to operate either in full duplex (FD) or in NOMA due to severe interference. The work presented in [32] introduces a centralized multicell FD-NOMA system, with the aim of maximizing total sum rate in a single subcarrier scenario.

Moreover, to tackle the problem of interference and to provide QoS to the users, different technologies based on sectorization have been proposed [33], [34], [35]. The authors in [33] aim to maximize the energy efficiency of the entire small cells in an uplink under-laying two-tier NOMA heterogeneous network with sectorization. Further, the authors in [34] proposed multiple interference cancellation technique to improve the system performance for a NOMA based device to device (D2D) network in a tri-sectored cell. A relay based, adaptive sectorization approach is proposed in [35] and compared the energy efficiency performance with the

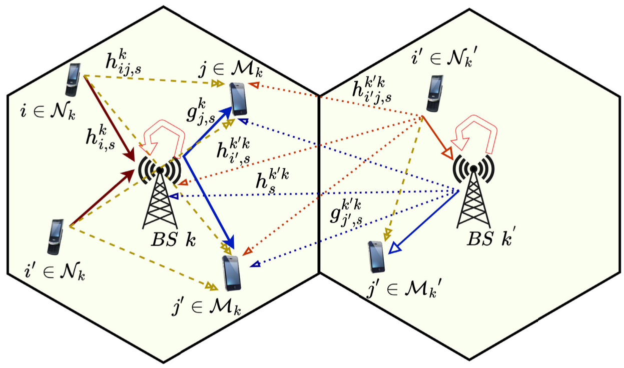

FIGURE 1. Multicell multicarrier NOMA-IBFD system model.

fixed sector approach for the downlink NOMA system. Nevertheless, these sectorization based works are confined to a single cell, emphasizing the necessity for additional research to explore their adaptability and effectiveness in a multicell environment.

B. MOTIVATION

Thus, the existing works predominantly focus on sum rate maximization, energy efficiency improvement etc., for a given fixed power budget. However, finding required DL powers to meet QoS of all users in the multicell NOMA-IBFD cellular system is crucial in the presence of severe interferences. Further, when IBFD is integrated with NOMA the simultaneous communication of uplink users will effect the QoS of downlink users and may necessitate higher power requirements to ensure the minimum required rate of transmission. Consequently, obtaining the necessary power levels to meet the QoS needs of users in a realistic wireless system is crucial for ensuring fairness among users and effectively managing interferences.

C. CONTRIBUTIONS

The works referenced above provide excellent examples of performing resource allocation in single cell or multi cell networks with objectives such as optimizing system metrics like sumrate or energy efficiency. There are several studies focused on multicarrier single cell NOMA-IBFD systems [14], [15], [16], [17], [22], [23], [24], [25], and half duplex multicell NOMA systems [27], [28], [29], [30]. Very few approaches explore single carrier multicell NOMA-IBFD for optimal power allocation [31], [32]. In contrast, this work focuses on the relatively less explored area of multicarrier multicell NOMA-IBFD cellular systems. Additionally, finding the optimal performance, such as the required powers to meet the QoS requirements for all users in a multicell cellular system, presents significant challenges due to the complexity of managing intercell interference and resource allocation across multiple cells.

Although, evolutionary algorithms based PSO approach similar to [36] can be explored, the computational complexity will explode. For instance, as noted by the authors in [14], even in single cell NOMA-IBFD systems, the complexity of resource allocation grows exponentially with the increase in number of users and subcarriers. Moreover, with the increase in problem size, the complexity of evolutionary algorithms can rise significantly due to the expansive search space. This increase in complexity can render them computationally inefficient for large-scale problems [37], [38]. Therefore, to obtain a tractable solution we propose a heuristic based subcarrier and power allocation algorithms with and without sectorization.

The main contributions of this paper are listed as follows:

- In this paper, we address the problem of minimizing transmit power required to provide QoS on transmission rates for all users in a multicell NOMA-IBFD cellular system. To the best of author's knowledge, the problem of determining the minimum required power to meet QoS for all users in multicell NOMA-IBFD cellular system remains open. Specifically, we do not impose any restrictions on the number of users to be multiplexed for NOMA either in uplink or downlink transmission for the considered system.
- We propose a heuristic algorithm for subcarrier allocation and computation of the minimum transmit powers for uplink and downlink users to ensure a minimum transmission rate for all users. This approach is applicable to both NOMA-IBFD systems and DL-NOMA alone. The power allocation scheme is obtained by setting fixed uplink powers and deriving an upper bound on the power allocation to downlink user. However, due to multi user interference introduced by NOMA, a strong user (whose signal to interference plus ratio (SINR) is higher) can perform SIC to remove the weak user message (whose SINR is lower) from the received superimposed signal. Therefore, to ensure successful SIC by BS and a strong DL user, we have derived decodability constraints for UL-NOMA and DL-NOMA respectively.
- We also propose a frequency reuse pattern with the help of 60^o sectorization to address the problem of interferences in system. In this context, the performance of proposed scheme without sectorization (i.e., at the cell level) is referred as C-NOMA-IBFD, while with sectorization (i.e., at the sector level) it is termed as S-NOMA-IBFD. Further, we benchmarked the performance of proposed scheme against orthogonal resource allocation C-OMA-IBFD and half duplex scenarios C-NOMA-DL.
- The proposed subcarrier and power allocation algorithm, provides required transmit powers to ensure a minimum transmission rate for all UL and DL users. With this algorithm, the user with poor channel condition is also guaranteed required QoS and while the user with better channel condition is used to improve total throughput of the system. Through analytical and simulation results, we demonstrate the impact of interference in NOMA-IBFD multicell cellular system.

TABLE 1. Notations used in this paper. (s indicates subcarrier).

Notation	Description
K	Number of cells in the multicell cellular system
N_k	Number of UL users in cell k
M_k	Number of DL users in cell k
S	Number of subcarriers in cell k
$h^k_{i,s}$	The channel gain from UL user i to BS in cell k
$g^k_{j,s}$	The channel gain from BS to DL user j in cell k
$h^k_{ij,s}$	The channel gain from UL user i to DL user j in same cell k
$h^{k'k}_{i',s}$	The channel gain from UL user i' in BS in cell k' to BS in cell k
$h^{k'k}_{s}$	The channel gain from BS in cell k' to BS in cell k
$h^{k'k}_{i'j,s}$	The channel gain from UL user i' in cell k' to DL user j in cell k
$g^{k'k}_{j',s}$	The channel gain from BS in cell k' to DL user j' in cell k
$p^k_{i,s}$	The transmit power of UL user i to send message to it's BS in cell k
$q^k_{j,s}$	The transmit power of the BS to send message to DL user j in cell k
$\overline{P}^k_i$	The total UL power budget available at UL user i in cell k
X^k_U	Subcarrier allocation matrix, indicating the set of UL users in cell k
X^k_D	Subcarrier allocation matrix, indicating the set of DL users in cell k

D. ORGANIZATION

The rest of the paper is organized as follows. We present the system model and formulate the problem in Section II, and define decoding orders for UL, DL NOMA in Section III. In Section IV, we propose a heuristic that computes a subcarrier allocation and power allocation. In Section V, we discuss sectorization of multicell cellular system. In Section VI, we present the results of numerical computations and finally Section VII concludes the paper.

II. SYSTEM MODEL AND PROBLEM FORMULATION

Consider a cellular system comprising K cells sharing a common spectrum for both UL and DL communication. Let $\mathcal{K} = \{1, 2, \ldots, K\}$ represent the set of cells. Each cell $k \in \mathcal{K}$ is assumed to contain N_k UL users and M_k DL users. Let $\mathcal{N}_k = \{1, 2, \ldots, N_k\}$, and $\mathcal{M}_k = \{1, 2, \ldots, M_k\}$ denote sets of UL and DL users in cell k, respectively. The total available bandwidth of W Hz is divided into S subcarriers, which are assigned to UL and DL users by their respective BSs for communication. The bandwidth of each subcarrier is W/S Hz, and let $\mathcal{S} = \{1, 2, \ldots, S\}$ represent the set of subcarriers. For a cell $k \in \mathcal{K}$, we denote the channel coefficient from UL user i to the BS over the subcarrier $s \in \mathcal{S}$ by $h^k_{i,s}$ and the same from BS to DL user j is denoted by $g^k_{j,s}$. Similarly, the transmit powers of UL user i and DL user j are denoted by $p^k_{i,s}$, $q^k_{j,s}$ respectively. Table 1 presents the complete set of variables and their notation that we use in the paper.

Further, let $x^k_{i,s}$ represent the message from UL user i and $x^k_{j,s}$ represent the message from BS to DL user j over a subcarrier s in cell k. The message is considered to be encrypted, which inherently ensures the security of the transmission [39], [40]. We assume that the mean square value of the transmitted messages to be unity, that is, $\mathbb{E}\big[|x^k_{i,s}|^2\big] = \mathbb{E}\big[|x^k_{j,s}|^2\big] = 1, \forall i, j$. Additionally, for all $k \in \mathcal{K}$, we define a $N_k \times S$ matrix X^k_U that specify a subcarrier allocation to the set of UL users, $\mathcal{N}_k$. If UL user $i \in \mathcal{N}_k$, is allocated a subcarrier $s \in \mathcal{S}$, then $X^k_U(i, s) = 1$, else $X^k_U(i, s) = 0$. Similarly, we define another matrix X^k_D, of order $M_k \times S$, to denote the subcarrier allocation to the set of DL users $\mathcal{M}_k$.

All the BSs utilize NOMA and IBFD transmissions across all subcarriers. Specifically, BS in cell $k \in \mathcal{K}$ can allocate a subcarrier $s \in \mathcal{S}$ to more than one user in either UL or DL direction, or both. Then, the received symbol at the BS is given by (1), as shown at the bottom of the page. Here, the first term is a consequence of NOMA and is the superposition

$$y^k_{B,s} = \sum_{i':X^k_U(i',s)=1} h^k_{i',s}\sqrt{p^k_{i',s}}x^k_{i',s} + \sum_{j:X^k_D(j,s)=1} \sqrt{q^k_{j,s}}x^k_{j,s} + \sum_{\substack{k'\neq k,\\ i':X^{k'}_U(i',s)=1}} h^{k'k}_{i',s}\sqrt{p^{k'}_{i',s}}x^{k'}_{i',s} + \sum_{\substack{k'\neq k,\\ j':X^{k'}_D(j',s)=1}} h^{k'k}_{s}\sqrt{q^{k'}_{j',s}}x^{k'}_{j',s} + n^k_{B,s}. \tag{1}$$

$$y^k_{j,s} = \sum_{j':X^k_D(j',s)=1} g^k_{j,s}\sqrt{q^k_{j',s}}x^k_{j',s} + \sum_{i:X^k_U(i,s)=1} h^k_{ij,s}\sqrt{p^k_{i,s}}x^k_{i,s} + \sum_{\substack{k'\neq k,\\ i':X^{k'}_U(i',s)=1}} h^{k'k}_{i'j,s}\sqrt{p^{k'}_{i',s}}x^{k'}_{i',s} + \sum_{\substack{k'\neq k,\\ j':X^{k'}_D(j',s)=1}} g^{k'k}_{j',s}\sqrt{q^{k'}_{j',s}}x^{k'}_{j',s} + n^k_{j,s}. \tag{2}$$

of the messages transmitted by the UL users in cell k that are allocated the subcarrier s. The BS decodes these messages using successive interference cancellation. The second term is the self interference at BS due to IBFD transmission over the same subcarrier. With the improvements in analog to digital converter and digital to analog converters, it is possible to achieve significant reduction in self interference through analog and digital cancellation techniques [10]. We refer the interferences that arise due to NOMA and IBFD transmission within the cell as intracell interferences. Apart from these interferences, there will be interferences at BS due to UL and DL transmissions in the neighbor cells. We refer to these interferences as intercell interferences and are given by third and fourth terms of (1). The third term in (1) is due to the UL transmissions and the fourth term is due to DL transmissions over the subcarrier s in the neighbor cells. The last term of (1), $n^k_{B,s}$ denotes the complex additive white gaussian noise (AWGN) with distribution $\mathcal{CN}(0,\ \sigma_B^2)$.

The received symbol at DL user j in cell k over subcarrier s can be written in a similar manner and is given by (2), as shown at the bottom of the previous page. Here, the first term is due to superposition coding of NOMA of DL users. The DL user j needs to decode its message using successive interference cancellation. The second term denotes interference at the DL user due to the transmission of UL users over the subcarrier s. This co-channel interference is present due to IBFD transmissions. The third term is the intercell interference due to UL transmissions in the neighbor cells over the same subcarrier. The fourth term is the interference due to DL transmissions in the neighbor cells. Finally, $n^k_{j,s}$ is the complex AWGN noise and we assume that it is distributed as $\mathcal{CN}(0,\ \sigma_j^2)$. We summarize the system model and illustrate all signal transmissions in Fig. 1. Specifically, the desired transmissions are shown with solid line and intracell transmissions with dashed line. The intercell transmissions are represented with dotted lines. Further, self interference at the BS, due to IBFD transmission is indicated with a double line.

We now compute interference powers at various receivers. For this, assume that a subcarrier $s \in \mathcal{S}$ is allocated to UL user i and DL user j in cell k. Then, we can compute the interferences at BS and DL users in cell k for a given subcarrier allocation $\{(X_U^k, X_D^k), k = 1, \ldots, K\}$. In particular, the BS k experiences interference from UL transmissions in the neighboring cells denoted by $I_B^k(s;\, UL)$. Similarly, $I_B^k(s;\, BS)$ denotes the interference due to DL transmissions from the neighboring cells. These intercell interferences are given in (3), and (4).

$$I_B^k(s;\, UL) = \sum_{k' \neq k} \sum_{i':X_U^{k'}(i',s)=1} |h^{k'k}_{i',s}|^2 p^{k'}_{i',s}. \tag{3}$$

$$I_B^k(s;\, BS) = \sum_{k' \neq k} \sum_{j':X_D^{k'}(j',s)=1} |h^{k'k}_{s}|^2 q^{k'}_{j',s}. \tag{4}$$

The BS k, has residual self interference due to DL transmissions within the cell denoted by $I_B^k(s;\, SI)$. By employing analog and digital self interference cancellation techniques, self interference can be suppressed up to the noise level [10]. The fraction of residual self interference at the BS is denoted by γ. Thus,

$$I_B^k(s;\, SI) = \gamma \sum_{j:X_D^k(j,s)=1} q^k_{j,s}. \tag{5}$$

Similarly, the DL user j experiences interference from UL transmissions in the neighboring cells denoted by $I_j^k(s;\, UL)$. The term, $I_j^k(s;\, BS)$ denotes the interference due to DL transmissions from the neighboring cells. These are given by (6), and (7).

$$I_j^k(s;\, UL) = \sum_{k' \neq k} \sum_{i':X_U^{k'}(i',s)=1} |h^{k'k}_{i'j,s}|^2 p^{k'}_{i',s}. \tag{6}$$

$$I_j^k(s;\, BS) = \sum_{k' \neq k} \sum_{j':X_D^{k'}(j',s)=1} |g^{k'k}_{j',s}|^2 q^{k'}_{j',s}. \tag{7}$$

Apart from these interferences, the DL user j, has interference due to UL to DL transmissions within the cell denoted by $I_j^k(s;\, UDI)$, which is computed as

$$I_j^k(s;\, UDI) = \sum_{i:X_U^k(i,s)=1} |h^k_{ij,s}|^2 p^k_{i,s}. \tag{8}$$

Moreover, in addition to the intracell and intercell interferences experienced by the BS and DL users, there also exists interference resulting from NOMA when signals are multiplexed over a subcarrier. The interference due to NOMA for UL user i at BS and DL user j in cell k is represented by $I_B^k(s;\, i, NOMA)$, and $I_j^k(s;\, NOMA)$ respectively. However, it is important to note that these interference terms are subject to order of decoding in SIC at the receivers, which we discuss in detail in Section III. Nevertheless, for the remainder of this section, we assume these interference terms can be computed and proceed to calculate the transmission rates for all UL and DL transmissions.

Now, to compute the SINR of UL user i and DL user j, over subcarrier s in cell k, let us denote $I_B^k(s)$ to be the total interference at BS k excluding the interference due to NOMA and it is given by

$$I_B^k(s) = I_B^k(s;\, UL) + I_B^k(s;\, BS) + I_B^k(s;\, SI). \tag{9}$$

Similarly, let $I_j^k(s)$ denote the total interference at DL user j in cell k and is given by

$$I_j^k(s) = I_j^k(s;\, UL) + I_j^k(s;\, BS) + I_j^k(s;\, UDI). \tag{10}$$

Consequently, by assuming AWGN at all receivers, the transmission rate of UL and DL transmissions in each cell can be determined using Shannon's formula. The SINR for UL user i on subcarrier s in cell k is given as

$$\Theta^k_{i,s} = \frac{|h^k_{i,s}|^2 p^k_{i,s}}{I_B^k(s) + I_B^k(s;\, i, NOMA) + \sigma_B^2}. \tag{11}$$

where, σ_B^2 is the power of the AWGN noise at the BS. Likewise, the SINR of DL user j on subcarrier s in cell k is given as

$$\Upsilon_{j,s}^k = \frac{|g_{j,s}^k|^2 q_{j,s}^k}{I_j^k(s) + I_j^k(s; NOMA) + \sigma_j^2}. \tag{12}$$

where, σ_j^2 is the power of the AWGN noise at the DL user j.

In light of the aforementioned equations, the transmission rates for UL user i and DL user j in cell k over subcarrier s are expressed, respectively by the following equations

$$R_{U,i}^k(s) = \log_2\left(1 + \Theta_{i,s}^k\right), \tag{13}$$

and

$$R_{D,j}^k(s) = \log_2\left(1 + \Upsilon_{j,s}^k\right). \tag{14}$$

Allowing for the allocation of more than one subcarrier to both UL and DL users within any cell, the overall transmission rates for UL user $i \in \mathcal{N}_k$ and DL user $j \in \mathcal{M}_k$ in cell k are given by

$$R_{U,i}^k = \sum_{s\in\mathcal{S}} X_U^k(i,s) R_{U,i}^k(s), \text{ and } R_{D,j}^k = \sum_{s\in\mathcal{S}} X_D^k(j,s) R_{D,j}^k(s).$$

Our goal is to find a subcarrier and power allocation that minimize the total transmit power at the BS, while adhering to the minimum transmission rates $\alpha_{U,i}^k$ and $\alpha_{D,j}^k$ for the UL user i and DL user j in cell k, respectively. Accordingly, the optimization problem is formulated as (15).

$$\begin{aligned}
\min_{(X_U^k, X_D^k), q_{j,s}^k} \quad & \sum_{k=1}^{K}\sum_{s=1}^{S}\sum_{j\in\mathcal{M}_k} X_D^k(j,s) q_{j,s}^k \\
\text{s.t} \quad & C1: \sum_s R_{U,i}^k(s) \geq \alpha_{U,i}^k, \quad \forall k \in \mathcal{K}, i \in \mathcal{N}_k, \\
& C2: \sum_s R_{D,j}^k(s) \geq \alpha_{D,j}^k, \quad \forall k \in \mathcal{K}, j \in \mathcal{M}_k, \\
& C3: X_U^k(i,s), X_D^k(j,s) \in \{0,1\}, \quad \forall i,j,s,k, \\
& C4: p_{i,s}^k, q_{j,s}^k \geq 0, \quad \forall i,j,s,k.
\end{aligned} \tag{15}$$

In this problem, the minimum transmission rates for both UL and DL users are enforced by constraints $C1$ and $C2$. Similarly, the constraint $C3$ highlights the discrete nature of subcarrier allocation variables which indicates subcarrier allocation to the given user, while $C4$ guarantees non-negative powers for UL and DL users. Computing the optimal solution to (15) is challenging due to the discrete nature of certain variables. Moreover, the set of potential subcarrier allocations grows exponentially with the number of subcarriers and users. Consequently, an exhaustive search for an optimal subcarrier allocation is not feasible. Therefore, we propose a heuristic that divides (15) into two problems: subcarrier allocation and power allocation. In the subsequent section, we introduce the decoding order for UL and DL NOMA and calculate the interference at UL and DL users arising from NOMA. A heuristic approach for finding a suboptimal power and subcarrier allocation is presented in Section IV.

III. DECODING ORDER FOR NOMA

The superposition coding scheme of NOMA provides multiple users to access a subcarrier for both uplink and downlink users. A NOMA receiver incorporate SIC to decode its message. In which, a receiver decodes superimposed messages of a few users while treating messages of remaining users as noise. This depends on the decodability of a receiver's message at another receiver, defining a decoding order at each receiver. Next, we discuss finding a decoding order for UL-NOMA and DL-NOMA in the following subsections.

A. UPLINK NOMA

For UL transmissions, a BS $k \in \mathcal{K}$ has the flexibility in allocating a subcarrier $s \in \mathcal{S}$ to any number of UL users in $\mathcal{N}_k$. Let $\mathcal{U}_s \subseteq \mathcal{N}_k$ be the set of UL users allocated the subcarrier s. For decoding, BS decodes the message of UL user with the highest channel gain $|h_{i,s}^k|^2$, for $i \in \mathcal{U}_s$, and by treating the messages of other users as noise. It then subtracts the decoded message from the received signal to decode the message from UL user with the second-largest channel gain. Iterating through this process, the BS decodes messages from all the UL users in $\mathcal{U}_s$. Please note that By employing this decoding method, to decode the message from the UL user with the smallest channel gain, the BS will not have interference due to NOMA.

Assuming that the UL users $i \in \mathcal{U}_s$ are indexed in decreasing order of channel gains $|h_{i,s}^k|^2$, then the NOMA interference at the BS to decode the message of UL user i is

$$I_B^k(s; i, NOMA) = \sum_{l\geq i+1} |h_{l,s}^k|^2 p_{l,s}^k. \tag{16}$$

Please note that, the transmission rate of UL user $i \in \mathcal{U}_s^k$ is given by (13). In the next subsection, we discuss the decoding order for DL-NOMA.

B. DOWNLINK NOMA

For DL transmissions, initially we fix a cell $k \in \mathcal{K}$ and a subcarrier $s \in \mathcal{S}$. Similar to the case of UL-NOMA, a BS can allocate s to a set of DL users $\mathcal{D}_s \subseteq \mathcal{M}_k$. To find a decoding order, for each DL user j, we define

$$\Gamma_{j,s}^k = \frac{|g_{j,s}^k|^2}{\sigma_j^2 + I_j^k(s)}. \tag{17}$$

Consider the set $\mathcal{D}_s^k = \{j_1, j_2, \ldots, j_D\}$ consisting ordered set of DL users in the increasing order of $\Gamma_{j,s}^k$, that is

$$\Gamma_{j_1,s}^k < \Gamma_{j_2,s}^k < \ldots < \Gamma_{j_D,s}^k. \tag{18}$$

Now, take two DL users denoted as j_l and j_m such that $l < m$. We call the user j_m stronger than j_l or j_l weaker than j_m. Through SIC, the user j_l decodes the messages of weaker users and subtracts them from the received signal. Thus, the user j_l decodes the messages of $j_1, j_2 \ldots, j_{l-1}$ in the order starting from j_1. After removing the interference from weaker users, user j_l decodes its message, by treating the messages of the stronger users as noise. Then, the NOMA interference at j_l is

$$I_{j_l}^k(s; NOMA) = |g_{j_l,s}^k|^2 \left(\sum_{d=l+1}^{D} q_{j_d,s}^k \right). \quad (19)$$

Similarly, the transmission rate of DL user j_l is given by (14), which can be expressed in terms of $\Gamma_{j_l,s}^k$ after algebraic manipulation as

$$R_{D,j_l}^k(s) = \log_2 \left(1 + \frac{\Gamma_{j_l,s}^k q_{j_l,s}^k}{1 + \Gamma_{j_l,s}^k \left(\sum_{d=l+1}^{D} q_{j_d,s}^k \right)} \right). \quad (20)$$

The following lemma shows that given (18), a DL user can decode messages of weaker DL users.

Lemma 1: Let j_l and j_m be two DL users in $\mathcal{D}_s^k$ with $l < m$. Then, j_m can decode j_l's message for any set of UL powers.

Proof: For j_l's message to be decodable at j_m, we should have

$$R_{D,j}^k(s) \leq \log_2 \left(1 + \frac{\Gamma_{j_m,s}^k q_{j,s}^k}{1 + \Gamma_{j_m,s}^k \left(\sum_{d=l+1}^{D} q_{j_d,s}^k \right)} \right). \quad (21)$$

Here, the right-hand side of (21) represents the capacity of j_l's message at user j_m. It is worth noting that while decoding the message of j_l at j_m, the NOMA interference consists of all the powers of users $j_{l+1}, \ldots, j_D$. And, the power of $j_1 \ldots, j_{l-1}$ will not contribute to interference as they have been subtracted before decoding the message of j_l. Substituting (20) in (21), and simplifying through algebraic manipulation, we get

$$\Gamma_{j_l,s}^k \leq \Gamma_{j_m,s}^k. \quad (22)$$

Therefore, this condition is satisfied, based on the hypothesis. Consequently, user j_m is capable of decoding the message from user j_l when $l < m$. □

Using the decoding orders defined for UL and DL NOMA, we propose a heuristic to solve (15) in the subsequent section.

Algorithm 1 Cell Based NOMA-IBFD Resource Allocation Algorithm

Initialize empty allocation for all cells $k = 1, 2, \ldots, K$ i.e., $X_{U,n}^k(i, s) = 0, X_{D,n}^k(j, s) = 0$, $\forall s \in \mathcal{S}, i \in \mathcal{N}_k, j \in \mathcal{M}_k$.
for $n = 1 \rightarrow$ *Max number of iterations* **do**
  Subcarrier Allocation:
  for $k = 1 \rightarrow K$ **do**
    Allocate Subcarrier in cell k:
    for $i = 1 \rightarrow N_k$ **do**
      Compute $S_u(i)$ from (23), if $R_{U,i}^k < \alpha_{U,i}^k$
    for $j = 1 \rightarrow M_k$ **do**
      Compute $S_d(j)$ from (24), if $R_{D,j}^k < \alpha_{D,j}^k$
    for $s = 1 \rightarrow S$ **do**
      • Compute $v(s; i, j)$ from (25), $v(s; j)$ from (26), and $v(s; i)$ from (27) $\forall\, i \in \mathcal{N}_k$, $j \in \mathcal{M}_k$ requesting subcarrier s.
      • Let $(\hat{i}, \hat{j}) = \arg\max_{i,j} v(s; i, j)$, $j^* = \arg\max_j v(s; j)$, $\tilde{i} = \arg\max_i v(s; i)$.
      if $v(s; \hat{i}, \hat{j}) > v(s; j^*)$ *and* $v(s; \tilde{i})$ **then**
        $X_{U,n}^k(\hat{i}, s) = 1, X_{D,n}^k(\hat{j}, s) = 1$.
      else if $v(s; j^*) > v(s; \hat{i}, \hat{j})$ *and* $v(s; \tilde{i})$ **then**
        $X_{D,n}^k(j^*, s) = 1$.
      else
        $X_{U,n}^k(\tilde{i}, s) = 1$.
    Go back to **Allocate Subcarrier** until all users are allocated a subcarrier
    Power Allocation:
    for $i = 1 \rightarrow N_k$ **do**
      $p_{i,s}^k = \bar{P}_{i_u}^k$
    for $j = 1 \rightarrow M_k$ **do**
      Compute $q_{j,s}^k$ from (29).
    Compute Rates $\forall i \in \mathcal{N}_k, \forall j \in \mathcal{M}_k$
  Stop if all UL and DL users QoS is satisfied.

IV. RESOURCE ALLOCATION IN MULTICELL WIRELESS COMMUNICATION SYSTEM

To solve problem (15), we note that the transmit power required to meet the QoS requirement depends on the interference at the corresponding receiver. Consequently, to minimize total transmit power satisfying the rate constraints requires a subcarrier allocation that minimizes the interference. Therefore, we decompose problem (15) into two subproblems: subcarrier allocation and power allocation. We iteratively determine a subcarrier allocation that multiplexes UL and DL users in a way that minimizes total intracell and intercell interferences. After obtaining a subcarrier allocation, we find a power allocation satisfying transmission rate constraints for all users in all cells. In the following subsection, we present a heuristic for subcarrier allocation.

A. SUBCARRIER ALLOCATION

We find subcarrier allocations iteratively for all cells. Let $X_{U,n}^k, X_{D,n}^k$ denote subcarrier allocations in cell k in iteration n. In each iteration, we update subcarrier allocations cell by cell starting from $k = 1$. Subcarrier allocation in cell k depends on the allocations in neighboring cells. In each iteration, we update subcarrier allocations cell by cell, starting from $k = 1$ up to $k = K$. The subcarrier allocation in cell k depends on the allocations in neighboring cells, so we must consider the current and previous allocations iteratively. Thus, $X_{U,n}^k, X_{D,n}^k$ of cell k depends on $(X_{U,n}^1, X_{D,n}^1)$, $\ldots$,

$(X_{U,n}^{k-1}, X_{D,n}^{k-1}), (X_{U,n-1}^{k+1}, X_{D,n-1}^{k+1}), \ldots, (X_{U,n-1}^{K}, X_{D,n-1}^{K})$. For $n = 1$, we initialize subcarrier allocations for each cell to be empty, i.e., $X_U^k(i,s) = 0, X_D^k(j,s) = 0$, for all $k = 1, 2, \ldots, K$, $i \in \mathcal{N}_k, j \in \mathcal{M}_k$, and $s \in \mathcal{S}$. Subsequently we update the subcarrier allocation only if QoS is satisfied for the user.

After initializing the subcarrier allocation, each UL user and DL user requests BS for a subcarrier. First, to find a subcarrier allocation in cell k, each UL user $i \in \mathcal{N}_k$ finds a subcarrier, $S_u(i)$, that maximizes the ratio of its channel gain to interference from all neighboring cells, given by

$$S_u(i) = \arg\max_{s \in \mathcal{S}} \frac{|h_{i,s}^k|^2}{\sigma_B^2 + I_B^k(s; BS) + I_B^k(s; UL)}. \tag{23}$$

Similarly, each DL user $j \in \mathcal{M}_k$ finds a subcarrier, $S_d(j)$ given by

$$S_d(j) = \arg\max_{s \in \mathcal{S}} \frac{|g_{j,s}^k|^2}{\sigma_j^2 + I_j^k(s; BS) + I_j^k(s; UL) + I_j^k(s; UDG)}. \tag{24}$$

Note that the term, $I_j^k(s; UDG) = \sum_{i=1}^{N_k} X_{U,n}^k(i,s)|h_{ij,s}^k|^2$ represents UL to DL channel gains in the present cell subcarrier allocation, and it is required to consider intracell interference.

Now, the UL user i and DL user j requests their BS for the subcarrier $S_u(i)$ and $S_d(j)$ respectively for data transmission. The BS in cell k, after receiving requests from the UL and DL users, allocates subcarriers by considering the intracell and intercell interferences. For all UL users $i \in \mathcal{N}_k$ and DL users $j \in \mathcal{M}_k$ requesting for subcarrier s, the BS computes

$$v(s; i, j) = \frac{|h_{i,s}^k|^2 |g_{j,s}^k|^2}{|h_{ij,s}^k|^2}, \tag{25}$$

$$v(s; j) = |g_{j,s}^k|^2, \tag{26}$$

$$v(s; i) = |h_{i,s}^k|^2. \tag{27}$$

Then, the BS allocates, the subcarrier s to both UL, DL users or UL user alone or DL user alone based on the maximum value among (25), (26), and (27). To guarantee minimum transmission rate for all users, a subcarrier should be allocated to all users. Hence, this procedure is repeated until each user is allocated a subcarrier. Thus, the BS allocates a subcarrier to at most one user in a given direction, hence there may be either UL or DL users that are not allocated any subcarrier. To guarantee minimum transmission rate for all users, a subcarrier should be allocated to all users. Therefore, this procedure repeats until each user is allocated a subcarrier. For minimizing interference at users, we allocate only one subcarrier to each user. For this, a user, either UL or DL, stops requesting the BS for a subcarrier if it has been allocated one subcarrier.

The subcarier allocation can be summarized as follows: The subcarrier allocation process is carried out iteratively for all cells. In each iteration, subcarriers are allocated cell by cell, from the first cell to the last. Initially, all subcarrier allocations are set to zero. For each cell in each iteration, the algorithm determines the best subcarriers for UL and DL users by considering the ratio of channel gain to interference. The BS in each cell then evaluates subcarrier requests from users and allocates subcarriers, aiming to minimize required transmission powers by reducing interference. This iterative process continues until each user is assigned at least one subcarrier and ensures minimum rate requirements are met. In the next subsection, we present computation of powers for a given subcarrier allocation.

B. POWER ALLOCATION

Given a subcarrier allocation $\{(X_U^k, X_D^k), k = 1, \ldots, K\}$, we now compute the transmit power for both UL and DL users. Let a subcarrier be assigned to UL users $\{i_1, \ldots, i_l \in \mathcal{M}_k\}$ and DL users $\{j_1, \ldots, j_m \in \mathcal{N}_k\}$. To compute the transmit power of the BS to DL users, we assume DL users are in the increasing order of $\Gamma_{j,s}^k$. Thus, user j_1 is the weakest, and j_m is the strongest. For $1 \leq v \leq m$, the rate of j_v is given by

$$R_{D,j_v}^k(s) = \log_2\left(1 + \frac{|g_{j_v,s}^k|^2 q_{j_v,s}^k}{\sigma_{j_v}^2 + I_{j_v}^k(s) + |g_{j_v,s}^k|^2 \sum_{d=v+1}^{m} q_{j_d,s}^k}\right). \tag{28}$$

Please note that, the term $I_{j_v}^k(s)$ is the intercell and intracell interference defined in (10). Therefore, for a minimum transmission rate of α_{D,j_v}^k for DL user j_v, we require

$$\frac{|g_{j_v,s}^k|^2 q_{j_v,s}^k}{\sigma_{j_v}^2 + I_{j_v}^k(s) + |g_{j_v,s}^k|^2 \sum_{d=v+1}^{m} q_{j_d,s}^k} \geq 2^{\alpha_{D,j_v}^k} - 1.$$

This implies,

$$q_{j_v,s}^k \geq (2^{\alpha_{D,j_v}^k} - 1)\left(\frac{\sigma_{j_v}^2 + I_{j_v}^k(s)}{|g_{j_v,s}^k|^2} + \sum_{d=v+1}^{m} q_{j_d,s}^k\right). \tag{29}$$

To minimize total DL power, we choose $q_{j_v,s}^k$ in (29) with equality. Given the interference, $I_{j_v}^k(s)$, we can compute DL powers $q_{j_v,s}^k$ for all $v = 1, \ldots, m$, starting from the strongest DL user $v = m$. Notably, for $v = m$, there is no interference due to NOMA, and the second term in (29) vanishes for $q_{j_m,s}^k$. UL user transmit powers can be computed similarly to guarantee minimum rate constraints for UL users. However, UL power $p_{i_u,s}^k$, $u = 1, \ldots, l$ depends on BS transmit powers. To remove interdependence of $p_{i_u,s}^k$ on $q_{j_v,s}^k$ and vice versa, we fix a sufficiently large transmit power $\bar{P}_{i_u}^k$ so that UL transmission rate R_{U,i_u}^k is greater than α_{U,i_u}^k. The subcarrier and power allocation for NOMA-IBFD multicell system is summarized in Algorithm 1.

Please note that, after power allocation in cell $k = K$, users in cells $k = 1, \ldots, K-1$ may experience much higher interference than used to compute the powers in their respective cells. Consequently, the minimum rate constraints may be violated. In order to avoid this problem, each user estimates that the actual interference is higher than the current interference by β percentage (typically set to 0.10, representing a 10% increase) and compute the required power to meet QoS constraint.

Thus, the power allocation process follows the subcarrier allocation. For DL users, power is allocated starting with the weakest user, ensuring that each user's minimum rate requirement is met. The power for each user is adjusted based on the interference from other users and the channel gain. For UL users, a sufficiently large transmit power is initially set to guarantee the minimum transmission rate. However, after the initial power allocation, users in earlier cells may experience increased interference, so their power levels are recalculated to ensure that the QoS requirements are still met. This iterative process continues until both UL and DL users in all cells meet their QoS. Next, we present sectorization approach and discuss its effects on system performance.

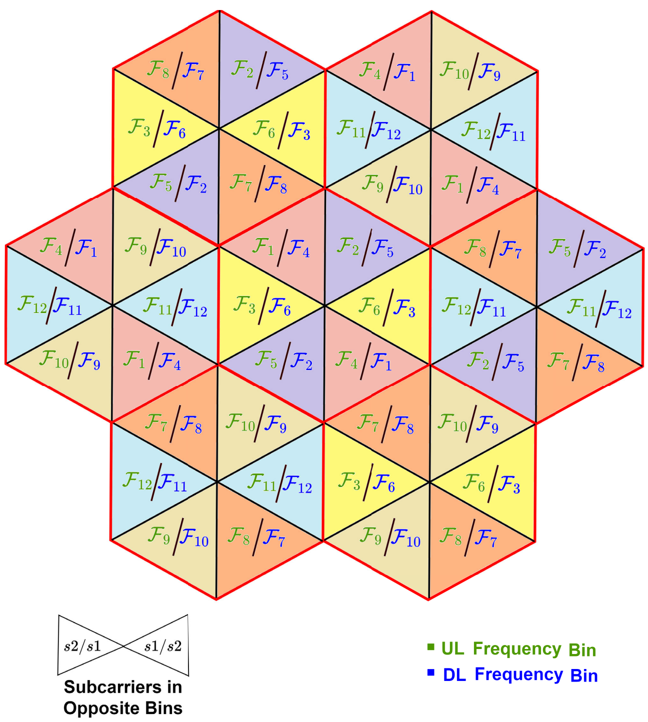

FIGURE 2. Sectorization in multicell cellular system.

V. MULTICELL NOMA-IBFD USING SECTORIZATION

Using the principles of sectorization and frequency reuse, we can effectively mitigate intracell and intercell interference. This involves partitioning a cell into multiple sectors, each assigned a specific set of subcarriers for both uplink and downlink transmission. Typically, 60° or 120° sectorizations are employed for frequency reuse, where the same set of subcarriers can be reused in the sectors of neighboring cells to alleviate interference effects. In our case, we adopt a 60° sectorization with six sectors per cell and define a frequency bin, $\mathcal{F}$, as a subset of $\mathcal{S}$.[1] In addition, we refine the organization of our subcarriers by dividing them into specific frequency bins denoted as $\mathcal{F}_1$, $\mathcal{F}_2$, and so forth, up to $\mathcal{F}_{12}$. Each of these bins represents a distinct frequency range within the overall set $\mathcal{S}$. It is important to note that we assume $\mathcal{S}$ has multiples of twelve subcarriers, allowing us to divide them into twelve nonempty disjoint frequency bins.

We introduce a frequency reuse strategy to minimize both intercell and intracell interferences while emphasizing enhanced QoS. The topology for frequency reuse is illustrated in Fig. 2, where each sector is assigned a frequency bin, and users transmit messages using subcarriers from the designated frequency bin. Notably, a sector may contain both UL and DL users. To mitigate intracell interference, two frequency bins are allocated for UL and DL transmissions in sectors opposite to each other, as shown in Fig. 2. This approach effectively increases the distance between UL and DL users, thereby reducing intracell interference. The use of the same color in Fig. 2 indicates sectors that share frequency bins.

We also aim to minimize intercell interferences at BSs and DL users in all cells. For this purpose, we propose a frequency reuse pattern across cells, as shown in Fig. 2. The objective of this pattern is to increase the distance between users using the same set of subcarriers for UL and DL transmission. Further, this approach will increase the path loss between a UL user in cell k and a DL user in cell $k' \neq k$, consequently reducing intercell interference. In the proposed pattern, the distance between a BS and an UL user utilizing the same subcarrier in the neighboring cell is also substantial thereby mitigating intercell interference at the BS through increased path loss.

Algorithm 2 Sector Based NOMA-IBFD Resource Allocation Algorithm

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Initialize empty allocation for all cells $k = 1, 2, \ldots, K$ i.e, $X^k_{U,n}(i, s) = 0$, $X^k_{D,n}(j, s) = 0$, $\forall s \in S, i \in \mathcal{N}_k, j \in \mathcal{M}_k$.

for $n = 1 \rightarrow$ *Max number of iterations* **do**

  for $k = 1 \rightarrow K$ **do**

   • Find possible UL and DL users on all sectors based on frequency bins.

   • Perform **Allocate Subcarrier** and then **Power Allocation** as per **Algorithm 1** for all possible UL and DL users.

   • Compute Rates $\forall i \in \mathcal{N}_k, \forall j \in \mathcal{M}_k$

  Stop if all UL and DL users QoS is satisfied.

---

[1] The proposed frequency bin pattern can be generalized and extended to higher order sectorization and other network layouts. However, to balance the trade-off between complexity and performance we employ 60° sectorization.

After sectorizing the multicell cellular system, we initialize subcarrier allocations for each cell to be empty, i.e., $X_U^k(i,s) = 0, X_D^k(j,s) = 0$, for all $k = 1, 2, \ldots, K$, $i \in \mathcal{N}_k, j \in \mathcal{M}_k$, and $s \in \mathcal{S}$. Next, given a cell $k \in \mathcal{K}$, we find all possible UL and DL users in opposite sectors that uses same set of subcarriers. This can be accomplished with the help of frequency bins, where each bin consists of distinct set of subcarriers within the overall set $\mathcal{S}$. Then, we proceed with subcarrier allocation until all users in cell k are allocated a subcarrier and perform power allocation as described in Section IV-B. It is worth noting that, compared to cell based resource allocation, each sector has fewer number of subcarriers, which could result in performance degradation compared to the cell. The sector based, subcarrier and power allocation for NOMA-IBFD multicell system is summarized in Algorithm 2.

A. COMPUTATIONAL COMPLEXITY

The computational complexity of the proposed resource allocation algorithms can be analyzed as follows: consider an equal number of UL and DL users present in a given cell k to be $N_k = M_k = N$. Then, for a cell based or sector based resource allocation algorithm, the number of operations required to obtain a subcarrier allocation for all UL and DL users is $O(2K^2N^2 + 7KNS)$. Next, we consider the power allocation. The computational overhead for UL users' power allocation can be neglected, as it is assumed they transmit with maximum power. However, the computational cost for the DL users' power allocation is $O(KNS)$. Thus, the overall computational complexity of proposed resource allocation algorithms is $O(2K^2N^2 + 8KNS)$.

Further, the resource allocation approach presented in [14] for a single cell NOMA-IBFD system has a complexity of $O(N^S)$. Using exhaustive search, to find a subcarrier allocation that minimizes transmit power requires exploring $(2^{(N_k+M_k)}-1)^{S^K}$ combinations. Therefore, compared with the exponential complexity associated with exhaustive search, the proposed approaches has much lower complexity.

Please note that the number of operations required per iteration with and without sectorization is same. However, the sector based algorithm requires more iterations to converge due to the limited availability of subcarriers at the sector level. We present numerical results in the next section.

VI. NUMERICAL RESULTS

We implement the proposed algorithms for a 7-cell cellular system with wraparound to conform with practical scenarios [41]. In which, we consider a hexagonal cellular network with a radius of 300 meters, ensuring a minimum separation of 30 meters between a BS and a user. The carrier frequency is 2.1 GHz and bandwidth of each subcarrier is $B = 180$ kHz. The power spectral density of AWGN noise is $N_0 = -174$ dBm and the noise variance at a receiver is BN_0. We assume that self interference at BS can be cancelled by a factor of 110 dB. All the UL users transmit with a power of 24 dBm. The channels were generated in accordance with Hata propagation model for urban environments [42]. A summary of the simulation parameters is presented in Table 2.

TABLE 2. Simulation Parameters.

Parameter	Value
Cell type	Macrocell
Cellular layout	7 cells, each with 6 sectors
The radius of a cell	300 meters
BS height	30 meters
UL, DL user height	1.5 meters
Carrier frequency	2.1 GHz
Subcarrier bandwidth	180 kHz
SI cancellation constant, γ	-110 dB
Total UL user power budget	24 dBm
Min. rate of transmission, $\alpha_{U,i}^k = \alpha_{D,j}^k$	2 bps/Hz
Noise power at the receivers, N_o	-174 dBm

We consider a non-uniform minimum rate constraints for the UL and DL users. The minimum guaranteed rate of UL and DL users, $\alpha_{U,i}^k$ and $\alpha_{D,j}^k$, are chosen proportionally to the channel gain between the user and the corresponding BS. As a result, the cell edge users may have a lower QoS constraint. We demonstrate the performance of algorithms for proposed system without sectorization (C-NOMA-IBFD) and with sectorization (S-NOMA-IBFD). The proposed NOMA-IBFD system is benchmarked [2] with traditional OMA system with IBFD (C-OMA-IBFD), in which a subcarrier is allocated to at most one user in any direction. We also compare the proposed system with NOMA in DL transmission alone (C-NOMA-DL), in which UL users are not present. We used MATLAB for simulations and the results were averaged over 1000 fading channel realizations.

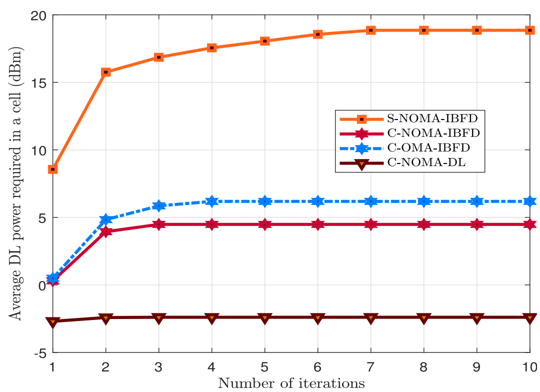

FIGURE 3. Convergence performance of the proposed resource allocation algorithms.

[2]The simulation comparison with the works in [31] and [32] is not possible due to differences in objective functions, algorithm designs and system scenarios. While these works focus on improving multicell system performance for a fixed power budget, our focus is on finding the minimum required power budget to meet the QoS requirements of all users.

TABLE 3. Performance comparison of proposed algorithms with benchmarks for $S = 36$ subcarriers and $N_k = M_k = 10$ users.

S-NOMA-IBFD			C-NOMA-IBFD			C-OMA-IBFD			C-NOMA-DL		
Iter-ation No.	DL Power Required (dBm)	QoS Satisfaction Rate (%)	Iter-ation No.	DL Power Required (dBm)	QoS Satisfaction Rate (%)	Iter-ation No.	DL Power Required (dBm)	QoS Satisfaction Rate (%)	Iter-ation No.	DL Power Required (dBm)	QoS Satisfaction Rate (%)
1	8.55	52.85	1	-0.453	47.15	1	0.493	54.28	1	-2.697	97.14
2	15.75	95.71	2	3.625	84.29	2	4.833	81.42	2	-2.417	98.57
3	16.85	95.71	3	4.087	98.57	3	5.853	98.57	3	-2.397	100.00
4	17.52	97.14	4	4.331	100.00	4	6.183	100.00	-	-2.397	100.00
5	18.05	98.57	-	4.331	100.00	-	6.183	100.00	-	-2.397	100.00
6	18.55	98.57	-	4.331	100.00	-	6.183	100.00	-	-2.397	100.00
7	18.85	100.00	-	4.331	100.00	-	6.183	100.00	-	-2.397	100.00

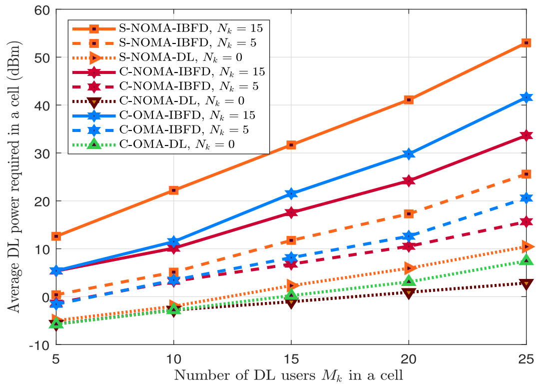

FIGURE 4. Comparison of DL power required for cell based and sector based algorithms by varying number of DL users in each cell.

Now, we demonstrate the performance of the proposed algorithm in terms of convergence in Fig. 3. For this, we consider an equal number of UL and DL users i.e., $N_k = M_k = 10$ and set the number of subcarriers to $S = 36$. Within each iteration, the algorithm checks whether the QoS requirements of all UL and DL users are satisfied. If they are met, the algorithm stops and outputs the final allocation of subcarriers and powers for each cell. In Fig. 3, we can observe that the proposed algorithms are converging in less number of iterations, and the convergence speed of proposed C-NOMA-IBFD is similar to that of C-OMA-IBFD, despite having more interference terms. Sectorization requires more iterations as the algorithm needs to run for each sector, and convergence criterion should be met for all sectors. This leads to a longer convergence for S-NOMA-IBFD. Further, C-NOMA-DL requires fewer iterations due to the reduced number of interfering links experienced by downlink users in half duplex operation. In Table 3, we compare the performance of proposed algorithms with benchmarks in terms of required DL power and QoS satisfaction rate of DL users over the iterations. The proposed C-NOMA-IBFD requires less transmission power compared to the traditional C-OMA-IBFD algorithm to provide QoS satisfaction for all users. The higher transmission power required for S-NOMA-IBFD is due to the limited available subcarriers at sector level. The half duplex C-NOMA-DL requires less transmission powers due to the reduced interference from UL users. Please note that, the dash (-) in the table indicates that no further iterations are needed once all users' QoS requirements are satisfied.

In Fig. 4, we compare the average DL power required to meet the QoS for different number of UL users, $N_k = 0, 5,$ and 15. For this, we have chosen $S = 36$. The transmit power of 24 dBm for UL users is large enough to achieve a minimum transmission rate of 2 bps/Hz. We take note of the following observations. First, we can observe a significant increase in the power requirements of the base stations for C-OMA-IBFD compared to C-NOMA-IBFD. This is due to the advantage of NOMA multiplexing of multiple users on the same subcarrier, in contrast to OMA. In general, multiple UL and DL users may have their best channels over a subcarrier. In the case of IBFD, only one user in a direction gets the best channel allocated. Hence, the remaining users may be allocated a poor channel depending on the number of users and subcarriers in the system. But, in the case of NOMA-IBFD, the UL and DL users may be allocated to their best subcarrier. This results in lower transmit power to meet the requirement. Second, a higher margin between OMA and NOMA schemes can be observed with a large number of users due to the competition among them for allocation of resources. This observation holds true for both half duplex and full duplex scenarios. Third, due to the absence of intracell interference components, the power required for HD transmission is less compared to FD. Thus, unlike OMA, which is restricted to one user per subcarrier, NOMA efficiently explores the diversity among available resources and offers significant low powers. Further, we observe a significant increase in power requirements for sectorization (S-NOMA-IBFD). The noticeable gap between sector based and cell based resource allocation is attributed to the limited availability of resources at the sector level. That is, when subcarrier allocation is done without sectorization, all subcarriers have been considered for allocation to a user. But with sectorization, only the subcarriers in that sector are considered for allocation.

Similar inferences can be drawn from Fig. 5, which shows the minimum power requirements by varying QoS for various UL and DL user settings with $S = 60$ subcarriers. As the QoS increases, the required DL power also increases. This results in higher power requirements to satisfy the minimum

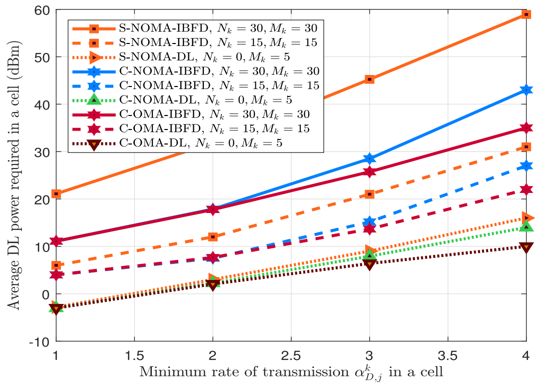

FIGURE 5. Comparison of DL power required for cell based and sector based algorithms by varying required minimum rates in each cell.

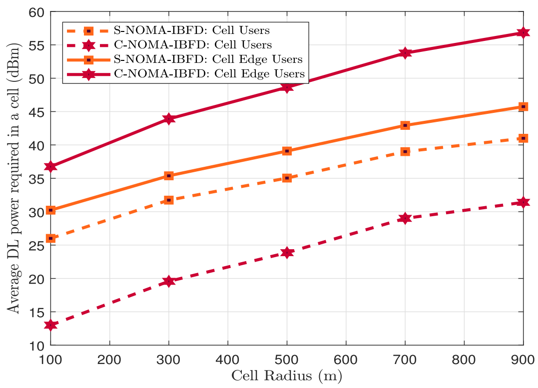

FIGURE 6. Comparison of DL power required for cell users and cell edge users by varying the cell radius.

transmission rates for all users in the cellular system. Please note that in sector based algorithm, all the users within a sector need to be served using the limited available subcarriers. As a result, a user may not always receive the best possible channel, especially if that channel is in another sector. This increases required DL power in sector based algorithm compared to cell based algorithm.

To further examine this, we analyze the performance of proposed algorithms under two scenarios with an increased cell radius, as shown in Fig. 6. The required powers are observed for $N_k = M_k = 15$ and subcarriers $S = 36$. First, we find the required DL powers for users within the cell, referred to as cell users and observe the effects of cell based and sector based algorithms. Next, we investigate system performance with cell edge users only. In this scenario, we assume that all users are positioned near the cell edges, specifically within the outer 20% of the cell radius. We observe that although the required powers increases with an increase in cell radius, the sector based approach performs better than the cell based approach for cell edge users. As the cell radius increases, the users are scattered across the cell and hence distance from the BS increases. Consequently, the minimum DL power to meet QoS also increases for both cell based and sector based algorithms. When it comes to cell edge users only, the sectorization manages the interferences effectively, as a result the minimum DL power required to meet QoS is lower for sector based resource allocation algorithm compared to the cell based algorithm.

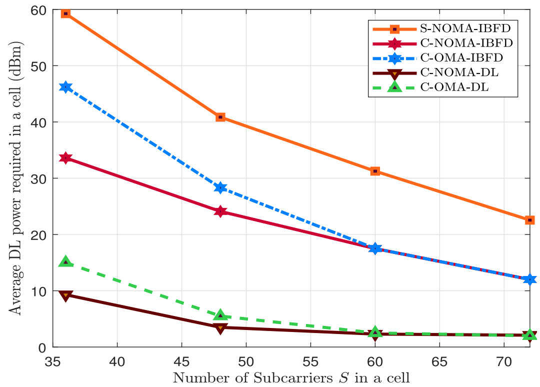

FIGURE 7. Comparison of DL power required for cell based and sector based algorithms by varying number of subcarriers in each cell.

In Fig. 7, we observe the average DL power required for a BS to meet QoS by varying the number of subcarriers with $N_k = M_k = 30$. Here, we observe that the total DL power required decreases as the number of subcarriers increases. This is due to the fact that, with increased availability of subcarriers, users are provided with a broader selection of options to access resources, consequently minimizing interference. However, the performance gap between cell based and sector based schemes is primarily attributed to resource scarcity at the sector level. Additionally, with appropriate bin mapping which diversifies the availability of subcarriers in sectors, we can further reduce the required powers by effectively mitigating interferences. This is due to the fact that the best subcarrier for a user may be located in a bin allocated to a different sector. We illustrate this in Fig. 8 to demonstrate the performance of S-NOMA-IBFD with random bin mappings by varying subcarriers. Moreover, by following an appropriate arrangement of frequency bins from the defined sets $\mathcal{F}_1, \mathcal{F}2, \ldots, \mathcal{F}12$ in each sector and then efficiently mapping the subcarriers to these frequency bins ensures a diverse distribution of subcarriers and potentially lead to performance improvement with sectorization. However, it is important to note that this introduces another optimization challenge, and thus, we consider it for future work.

The sum rate performance of the multicell system for proposed scenarios is shown in Fig. 9 for $N_k = 10$ and $S = 36$. NOMA based schemes achieves higher sum rates than OMA by multiplexing more users on the same subcarrier through exploiting users with the best channels. However, with sectorization the sumrate is reduced due to limited availability of subcarriers at the sector level. Additionally, the performance gain of FD over HD can be clearly observed, which is due to the efficient spectrum utilization achieved by combining NOMA and IBFD technologies.

The energy efficiency of cell based and sector based algorithms is demonstrated in Fig. 10 for $N_k = 10$ and

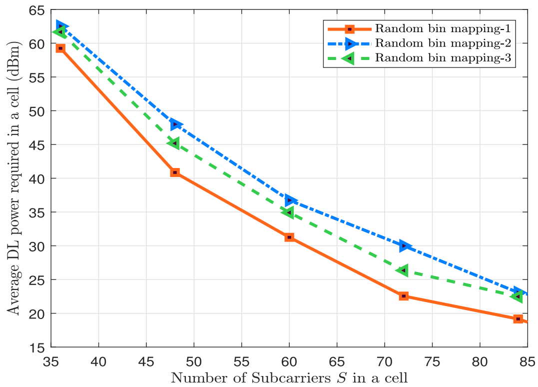

FIGURE 8. Comparison of DL power required for S-NOMA-IBFD with random bin mapping by varying number of subcarriers in each cell.

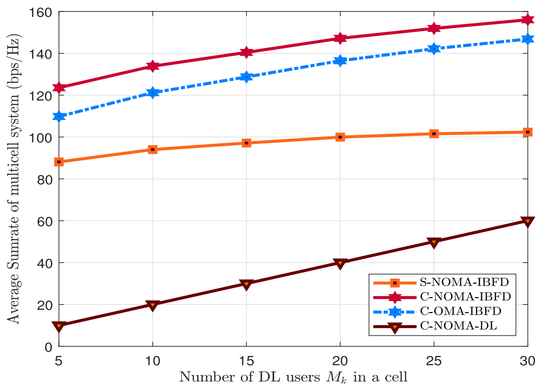

FIGURE 9. Comparison of Sumrate performance in each cell for cell based and sector based algorithms by varying number of DL users in each cell.

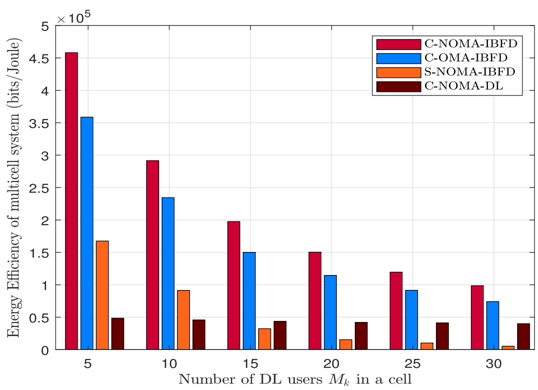

FIGURE 10. Comparison of energy efficiency of cell based and sector based algorithms by varying number of DL users in each cell for cell users.

$S = 72$ by varying number of DL users in each cell. Energy efficiency is computed as the ratio of the total sum rate to the total transmitted power per utilized subcarriers [29]. We make the following observations from Fig. 10. First, it can be observed that C-NOMA-IBFD performs better than C-OMA-IBFD due to the fact that NOMA explores subcarrier diversity and provides better sumrates. However, as the number of users increases, the complexity of decoding and power allocation in NOMA also increases. Second, the

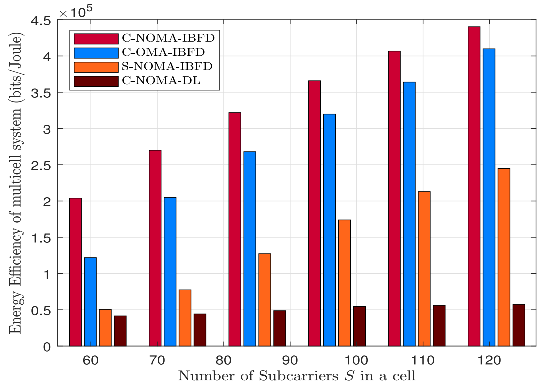

FIGURE 11. Comparison of energy efficiency of cell based and sector based algorithms by varying number of subcarriers in each cell for cell users.

performance S-NOMA-IBFD is less due to limited resource availability in the confined area. Hence, starting from number of DL users $M_k = 15$ with available subcarriers $S = 12$ at sector level, the performance of sectorization degrades compared to HD at cell level as shown in Fig. 10. But, as the number of subcarriers increases, the user can be provided with the opportunity to select the best subcarrier, enabling better energy efficient transmission. This can be observed in Fig. 11, by varying the number of subcarriers in a cell, for $N_k = M_k = 10$. Here, it is evident that the improvement in energy efficiency enhancement of C-NOMA-DL is limited due to the fixed resource allocation, while an increase in the number of subcarriers results in enhanced energy efficiency for the full duplex systems.

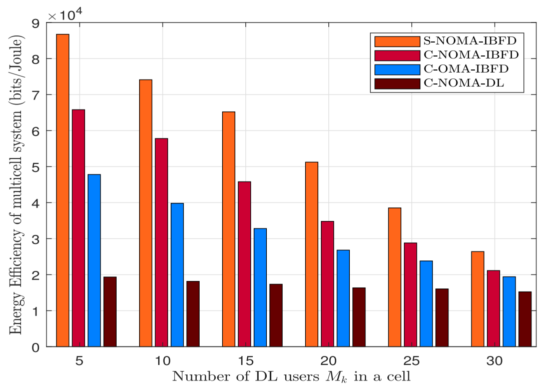

FIGURE 12. Comparison of energy efficiency of cell based and sector based algorithms by varying number of DL users in each cell for cell edge users.

Further, the energy efficiency performance of cell based and sector based algorithms for cell edge users is plotted in Fig. 12 for $N_k = 10$ and $S = 72$ by varying the number of DL users in each cell. In particular, it can be observed that although the S-NOMA-IBFD algorithm necessitates higher transmission powers due to limited subcarrier availability at sector lever, it's energy efficiency is higher than that of cell based approaches for cell edge users. This is due to the fact that, the proposed frequency bin arrangement in Section V,

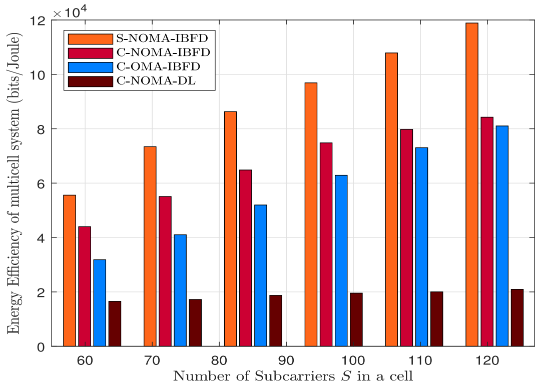

FIGURE 13. Comparison of energy efficiency of cell based and sector based algorithms by varying number of subcarriers in each cell for cell edge users.

effectively mitigates intracell, intercell interferences. Additionally, the difference in performance between C-NOMA-IBFD and C-OMA-IBFD is due to better spectrum utilization of NOMA compared with OMA by accommodating multiple users on the same subcarrier. Similar conclusions can be drawn from Fig. 13 for $N_k = M_k = 10$. As the number of subcarriers increases, sectorization allows for more effective subcarrier utilization by offering minimized transmission powers and results in higher energy efficiency for cell edge users.

A. DISCUSSION AND PRACTICAL IMPLICATIONS

The proposed subcarrier and power allocation algorithms for the NOMA-IBFD approach are designed to minimize the transmission power required to meet the QoS requirements for all users in a multicell cellular system. In modern 5G/6G architectures, where BSs are interconnected via a centralized Cloud Radio Access Network (C-RAN), our method facilitates coordinated subcarrier and power allocation across the network. This coordination allows each BS to accurately determine the required downlink power while considering interference from neighboring cells. These algorithms can be implemented either centrally in the cloud or distributed across BSs, provided there is knowledge of the subcarrier and power allocations of neighboring BSs. Additionally, our proposed sectorization techniques offer significant benefits in densely populated urban areas, where maximizing spectrum efficiency is critical. Our bin mapping and frequency allocation methods help reduce both intracell and intercell interference, thereby enhancing overall system performance. However, sectorized environments also introduce challenges, such as managing the limited subcarrier availability to prevent increased interference and necessitates careful resource allocation strategies.

B. LIMITATIONS

The limitations and trade-offs of the proposed work can be summarized as follows.

- Computational Trade-offs: In our approach, heuristic-based algorithms are employed. Unlike traditional optimization algorithms, which aim to find a local optimal solution but often face prohibitively high computational costs, especially in complex NOMA-IBFD systems, our heuristics offer a practical alternative.
- Resource Trade-offs: In sectorized environments, efficient mapping of subcarriers to the frequency bins is challenging. The best subcarrier for a users in a sector could be in a bin allocated to some other sector. This may affect the minimum transmission power required.

C. FUTURE SCOPE

The future scope includes several potential areas for further investigation.

- Advanced Algorithm Development: Develop more advanced algorithms that can balance computational efficiency with the need for optimal or near-optimal solutions in multicell NOMA-IBFD cellular systems.
- Enhanced Sectorization Techniques: Explore improved sectorization methods that can better manage subcarrier availability and reduce interference to further enhance QoS satisfaction rates. This could involve more sophisticated bin mapping and frequency allocation strategies to enhance system performance in densely populated urban areas.
- Alternate Approaches: To address the problem of subcarrier and power allocation in a multicell NOMA-IBFD enabled cellular system, several alternate approaches can be considered. Optimization-based methods, such as convex optimization and mixed-integer linear programming (MILP), offer precise solutions but may face scalability issues. Heuristic and meta-heuristic algorithms, such as genetic algorithms, particle swarm optimization provides practical solutions by exploring the solution space efficiently at the cost of increased computations. Finally, machine learning techniques, like deep learning and reinforcement learning (RL), can dynamically adapt to changing network conditions and predict resource allocations with reduced computational complexity.

VII. CONCLUSION

In this paper, we have investigated a multicell NOMA-IBFD enabled cellular system with a focus on providing QoS for all users while minimizing required downlink user powers in the network. The system model is developed using the concept of cell wrapping to align with practical scenarios. To ensure the minimum rate requirement for each user, a subcarrier and power allocation algorithm is proposed. Initially, we implemented the resource allocation algorithm at cell level and subsequently at sector level to address the capacity requirements of users within a specific cell area. Further, we examined the maximum power required by a DL user to fulfill the QoS requirements. Notably, sectorization which is a special case of multicell system, necessitates higher power levels due to limited resources within a confined coverage area. We also explored the potential improvement in sectorization through the optimization of random bin arrangement. However, we regard this extension as a subject for future work. Simulation results demonstrate that by multiplexing more number of users on each subcarrier, the proposed system provides enhancement in energy efficiency, through efficient utilization of multiuser diversity. Finally, we conclude that through the proposed algorithm, the user with a weak channel condition can also meet the QoS requirement, while the user with a strong channel condition enables to increase the sum throughput of the system.

REFERENCES

[1] L. Dai, B. Wang, Z. Ding, Z. Wang, S. Chen, and L. Hanzo, "A survey of non-orthogonal multiple access for 5G," *IEEE Commun. Surveys Tuts.*, vol. 20, no. 3, pp. 2294–2323, 3rd Quart., 2018.

[2] W. Chen, X. Lin, J. Lee, A. Toskala, S. Sun, C. F. Chiasserini, and L. Liu, "5G-advanced toward 6G: Past, present, and future," *IEEE J. Sel. Areas Commun.*, vol. 41, no. 6, pp. 1592–1619, Jun. 2023.

[3] Z. Ding, X. Lei, G. K. Karagiannidis, R. Schober, J. Yuan, and V. K. Bhargava, "A survey on non-orthogonal multiple access for 5G networks: Research challenges and future trends," *IEEE J. Sel. Areas Commun.*, vol. 35, no. 10, pp. 2181–2195, Oct. 2017.

[4] B. Makki, K. Chitti, A. Behravan, and M.-S. Alouini, "A survey of NOMA: Current status and open research challenges," *IEEE Open J. Commun. Soc.*, vol. 1, pp. 179–189, 2020.

[5] A. F. M. S. Shah, A. N. Qasim, M. A. Karabulut, H. Ilhan, and Md. B. Islam, "Survey and performance evaluation of multiple access schemes for next-generation wireless communication systems," *IEEE Access*, vol. 9, pp. 113428–113442, 2021.

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

[7] L. Salaün, M. Coupechoux, and C. S. Chen, "Joint subcarrier and power allocation in NOMA: Optimal and approximate algorithms," *IEEE Trans. Signal Process.*, vol. 68, pp. 2215–2230, 2020.

[8] Z. Ding, R. Schober, and H. V. Poor, "Unveiling the importance of SIC in NOMA systems—Part II: New results and future directions," *IEEE Commun. Lett.*, vol. 24, no. 11, pp. 2378–2382, Nov. 2020.

[9] M. S. Ali, H. Tabassum, and E. Hossain, "Dynamic user clustering and power allocation for uplink and downlink non-orthogonal multiple access (NOMA) systems," *IEEE Access*, vol. 4, pp. 6325–6343, 2016.

[10] A. Sabharwal, P. Schniter, D. Guo, D. W. Bliss, S. Rangarajan, and R. Wichman, "In-band full-duplex wireless: Challenges and opportunities," *IEEE J. Sel. Areas Commun.*, vol. 32, no. 9, pp. 1637–1652, Sep. 2014.

[11] S. Hong, J. Brand, J. I. Choi, M. Jain, J. Mehlman, S. Katti, and P. Levis, "Applications of self-interference cancellation in 5G and beyond," *IEEE Commun. Mag.*, vol. 52, no. 2, pp. 114–121, Feb. 2014.

[12] Z. Zhang, K. Long, A. V. Vasilakos, and L. Hanzo, "Full-duplex wireless communications: Challenges, solutions, and future research directions," *Proc. IEEE*, vol. 104, no. 7, pp. 1369–1409, Jul. 2016.

[13] M. S. Sim, M. Chung, D. Kim, J. Chung, D. K. Kim, and C.-B. Chae, "Nonlinear self-interference cancellation for full-duplex radios: From link-level and system-level performance perspectives," *IEEE Commun. Mag.*, vol. 55, no. 9, pp. 158–167, Sep. 2017.

[14] Y. Sun, D. W. K. Ng, Z. Ding, and R. Schober, "Optimal joint power and subcarrier allocation for full-duplex multicarrier non-orthogonal multiple access systems," *IEEE Trans. Commun.*, vol. 65, no. 3, pp. 1077–1091, Mar. 2017.

[15] R. Tang, H. Qu, J. Zhao, J. Cheng, and Z. Cao, "Distributed resource allocation for IBFD-enabled NOMA systems," *IEEE Commun. Lett.*, vol. 22, no. 11, pp. 2318–2321, Nov. 2018.

[16] Z. Yang, Z. Ding, P. Fan, and N. Al-Dhahir, "A general power allocation scheme to guarantee quality of service in downlink and uplink NOMA systems," *IEEE Trans. Wireless Commun.*, vol. 15, no. 11, pp. 7244–7257, Nov. 2016.

[17] S. K. Vankayala and S. Yoon, "Joint subcarrier and power allocation for multi-carrier NOMA-IBFD wireless communication system," in *Proc. IEEE 33rd Annu. Int. Symp. Pers., Indoor Mobile Radio Commun. (PIMRC)*, Sep. 2022, pp. 1000–1005.

[18] F. Fang, H. Zhang, J. Cheng, and V. C. M. Leung, "Energy-efficient resource allocation for downlink non-orthogonal multiple access network," *IEEE Trans. Commun.*, vol. 64, no. 9, pp. 3722–3732, Sep. 2016.

[19] Z. Wei, D. W. K. Ng, and J. Yuan, "Power-efficient resource allocation for MC-NOMA with statistical channel state information," in *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, 2016, pp. 1–7.

[20] Z. Yang, W. Xu, C. Pan, Y. Pan, and M. Chen, "On the optimality of power allocation for NOMA downlinks with individual QoS constraints," *IEEE Commun. Lett.*, vol. 21, no. 7, pp. 1649–1652, Jul. 2017.

[21] I. Azam, M. B. Shahab, and S. Y. Shin, "Energy-efficient pairing and power allocation for NOMA UAV network under QoS constraints," *IEEE Internet Things J.*, vol. 9, no. 24, pp. 25011–25026, Dec. 2022.

[22] Z. Ding, P. Fan, and H. V. Poor, "On the coexistence between full-duplex and NOMA," *IEEE Wireless Commun. Lett.*, vol. 7, no. 5, pp. 692–695, Oct. 2018.

[23] K. Singh, K. Wang, S. Biswas, Z. Ding, F. A. Khan, and T. Ratnarajah, "Resource optimization in full duplex non-orthogonal multiple access systems," *IEEE Trans. Wireless Commun.*, vol. 18, no. 9, pp. 4312–4325, Sep. 2019.

[24] H. V. Nguyen, V.-D. Nguyen, O. A. Dobre, D. N. Nguyen, E. Dutkiewicz, and O.-S. Shin, "Joint power control and user association for NOMA-based full-duplex systems," *IEEE Trans. Commun.*, vol. 67, no. 11, pp. 8037–8055, Nov. 2019.

[25] A. Abrardo, M. Moretti, and F. Saggese, "Power and subcarrier allocation in 5G NOMA-FD systems," *IEEE Trans. Wireless Commun.*, vol. 19, no. 12, pp. 8246–8260, Dec. 2020.

[26] R. Agrawal and S. Kalyanasundaram, "Scheduling and power control for in-band full duplex communications," in *Proc. IEEE Globecom Workshops (GC Wkshps)*, Dec. 2017, pp. 1–7.

[27] F. Guo, H. Lu, X. Jiang, M. Zhang, J. Wu, and C. W. Chen, "QoS-aware user grouping strategy for downlink multi-cell NOMA systems," *IEEE Trans. Wireless Commun.*, vol. 20, no. 12, pp. 7871–7887, Dec. 2021.

[28] D. Ni, L. Hao, Q. T. Tran, and X. Qian, "Transmit power minimization for downlink multi-cell multi-carrier NOMA networks," *IEEE Commun. Lett.*, vol. 22, no. 12, pp. 2459–2462, Dec. 2018.

[29] A. B. M. Adam, X. Wan, and Z. Wang, "Energy efficiency maximization in downlink multi-cell multi-carrier NOMA networks with hardware impairments," *IEEE Access*, vol. 8, pp. 210054–210065, 2020.

[30] S. Rezvani, E. A. Jorswieck, N. M. Yamchi, and M. R. Javan, "Optimal SIC ordering and power allocation in downlink multi-cell NOMA systems," *IEEE Trans. Wireless Commun.*, vol. 21, no. 6, pp. 3553–3569, Jun. 2022.

[31] M. S. Elbamby, M. Bennis, W. Saad, M. Debbah, and M. Latva-Aho, "Resource optimization and power allocation in in-band full duplex-enabled non-orthogonal multiple access networks," *IEEE J. Sel. Areas Commun.*, vol. 35, no. 12, pp. 2860–2873, Dec. 2017.

[32] G. Liu, X. Chen, Z. Ma, X. Zhang, M. Xiao, and P. Fan, "Full-duplex and C-RAN based multi-cell non-orthogonal multiple access over 5G wireless networks," in *Proc. IEEE Int. Conf. Commun. (ICC)*, May 2019, pp. 1–7.

[33] L. Wang, W. Tang, T. Qi, J. Cui, and B. Zheng, "Energy efficient resource allocation in NOMA-sectored heterogeneous network," in *Proc. Int. Conf. Wireless Commun. Signal Process. (WCSP)*, 2020, pp. 120–125.

[34] P. Gandotra, R. K. Jha, and S. Jain, "Green NOMA with multiple interference cancellation (MIC) using sector-based resource allocation," *IEEE Trans. Netw. Service Manage.*, vol. 15, no. 3, pp. 1006–1017, Sep. 2018.

[35] P. Jain and A. Gupta, "Energy-efficient adaptive sectorization for 5G green wireless communication systems," *IEEE Syst. J.*, vol. 14, no. 2, pp. 2382–2391, Jun. 2020.

[36] C. A. M. de Pinho and F. R. M. Lima, "Rate maximization with QoS guarantees in IRS-assisted WPCN-NOMA systems," in *Proc. Workshop Commun. Netw. Power Syst. (WCNPS)*, Nov. 2022, pp. 1–6.

[37] E. Björnson, "Optimal resource allocation in coordinated multi-cell systems," *Found. Trends Commun. Inf. Theory*, vol. 9, nos. 2–3, pp. 383–466, 2012.

[38] S. Boyd and L. Vandenberghe, *Convex Optimization*. Cambridge, U.K.: Cambridge Univ. Press, 2004.

[39] S. Pakravan, J.-Y. Chouinard, X. Li, M. Zeng, W. Hao, Q.-V. Pham, and O. A. Dobre, ‘‘Physical layer security for NOMA systems: Requirements, issues, and recommendations,’’ *IEEE Internet Things J.*, vol. 10, no. 24, pp. 21721–21737, Dec. 2023.

[40] X. Cao, B. Yang, K. Wang, X. Li, Z. Yu, C. Yuen, Y. Zhang, and Z. Han, ‘‘AI-empowered multiple access for 6G: A survey of spectrum sensing, protocol designs, and optimizations,’’ 2024, *arXiv:2406.13335*.

[41] R. S. Panwar and K. M. Sivalingam, ‘‘Implementation of wrap around mechanism for system level simulation of LTE cellular networks in NS3,’’ in *Proc. IEEE 18th Int. Symp. World Wireless, Mobile Multimedia Netw. (WoWMoM)*, Jun. 2017, pp. 1–9.

[42] M. Hata, ‘‘Empirical formula for propagation loss in land mobile radio services,’’ *IEEE Trans. Veh. Technol.*, vol. VT-29, no. 3, pp. 317–325, Aug. 1980.

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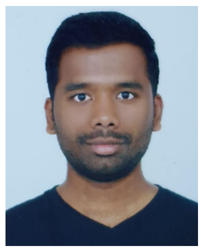

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