IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received February 19, 2020, accepted March 9, 2020, date of publication March 23, 2020, date of current version April 7, 2020.

Digital Object Identifier 10.1109/ACCESS.2020.2982677

User Selection and Resource Allocation Algorithms for Multicarrier NOMA Systems on Downlink Beamforming

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This work was supported in part by the Ministry of Science and Technology, Taiwan, under Grant MOST 107-2218-E-007-044 and Grant MOST 108-2218-E-007-036, and in part by the MediaTek Inc., Hsinchu, Taiwan.

ABSTRACT In this paper, we propose user grouping, subcarrier allocation, and bit allocation schemes in multicarrier nonorthogonal multiple access (NOMA) systems on downlink beamforming to reduce the total transmit power while considering the data-rate and the error-rate constraints of practical modulation types. Power control is also considered. In this system, each subcarrier can be assigned to multiple users for data transmission. Each subcarrier is allocated to a cluster that contains groups of two users for data transmission. A subset of subcarriers is assigned to the same cluster for sharing. The system is based on orthogonal frequency division multiple access (OFDMA), in which a primary user (PU) is more important than a secondary user, and we ensure that all assigned subcarriers transmit data to the PU in the system. In the proposed schemes, the user-grouping operation is performed first and the subcarrier allocation along with the bit loading and power assignment are performed subsequently based on the user-grouping results. The simulation results obtained using the proposed schemes in conjunction with the nonorthogonal multiple access to allocate bits, subcarriers, and transmit power show that the proposed schemes outperform the conventional OFDMA system in terms of transmit power.

INDEX TERMS 5G cellular, nonorthogonal multiple access (NOMA), orthogonal frequency division multiple access (OFDMA), successive interference cancellation (SIC), resource allocation, zero-forcing beamforming.

I. INTRODUCTION

In the light of recent technological advances, nonorthogonal multiple access (NOMA) is considered a promising technology for fifth-generation (5G) multiple access and beyond [1]–[4]. To satisfy the increasing requirements of mobile Internet and the Internet of Things (IoT), improving the sum capacity or reducing the required transmit power is a challenge associated with NOMA in 5G [5], [6]. Orthogonal frequency-division multiple access (OFDMA) has been adopted as the main technology for 4G multiple access [7], [8]. Given that a NOMA scheme comprises many signals of different users in a cell and these signals are multiplexed in the power domain at the transmitter side [4], the multiuser signals are separated by executing successive interference cancellation (SIC) and the beamforming vector (BF) at the receiver side [9], [10]. Thus, we consider the aggregated scenarios of OFDMA-based NOMA systems on downlink beamforming to enhance system performance in terms of transmit power.

Different aspects of the problems associated with NOMA-based systems have been studied thus far [11]–[31]. In [11], admission control was investigated, along with resource allocation during uplink, by recasting the problem as the maximum independent set problem, and an efficient algorithm was proposed. The coverage region of downlink NOMA was discussed in [12]. The resource allocation problems associated with NOMA systems have attracted considerable attention in recent years. The theoretically achievable rates are usually utilized in discussions of these problems. In [13], a joint power and channel allocation scheme was proposed, in which the achievable rate was used in the formulated optimization problem and an algorithmic framework combining Lagrangian duality and dynamic programming

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

was developed to solve the problem. Moreover, the optimal bounds of the global bounds were provided for comparison. In [14], a relay network with amplify-and-forward was considered for subchannel and power allocation. When the sum rate is maximized, fairness is reduced. Therefore, several studies have considered fairness-related problems [15], [16]. Quality of service (QoS) is an important factor governing wireless services in NOMA systems. In [17], an optimization problem involving minimization of the total transmit power under a QoS with a minimum rate constraint was studied for downlink orthogonal frequency-division multiplexing (OFDM)-based NOMA systems. A resource-allocation problem was investigated for achieving an optimal tradeoff between spectral efficiency and energy efficiency by considering users' minimum rate requirements in hybrid multicarrier nonorthogonal multiple access (MC-NOMA) systems, which incorporated both NOMA and orthogonal multiple access (OMA) modes in a unified framework [18]. In [19], with a decoding order assumption, a power allocation algorithm was developed to maximize the sum rate of users subject to a minimum user rate requirement. The theoretical power allocation limits of the minimum QoS rate requirement were derived in [20]. The existence of imperfect channels in NOMA resource-allocation problems is another issue, and it has been discussed in [21], [22].

The abovementioned reports investigated single-antenna systems. The problem becomes more complex when multiple-antenna transmission is involved because of the inter-beam interference effect. An iterative waterfilling-based power allocation algorithm was proposed for downlink NOMA in single-user multiple-input multiple-output (MIMO) systems [23]. In [24], by using a singular-value-decomposition (SVD)-based interference alignment technique for downlink multiuser MIMO-NOMA systems, where users shared the same frequency channel, an optimization problem was formulated to maximize the sum rate under the total power and proportional fairness constraints. A low-complexity suboptimal solution was proposed therein. A joint beamforming and power allocation scheme for downlink NOMA multiuser MIMO networks was designed to maximize the sum rate of users with the minimum required target rates of users in another group [25]. In [26], coordinated multipoint (COMP) was considered for cell-edge users with NOMA in a single-carrier system for a power minimization problem with a rate constraint. COMP was also considered in [25]. Clustering, beamforming, and power-allocation problems associated with the solutions were discussed in [27], where the objective was to maximize the overall cell capacity. A single-frequency resource was considered in these reports. In [28], a resource-allocation problem associated with the downlink OFDM-NOMA system was investigated, wherein the problem was decomposed into two subproblems of subcarrier allocation and power allocation. The goal was to maximize the data rates with the minimum rate constraints. Beamforming is effective for increasing the information rate. A different beamforming design methodology was proposed for the application to simultaneously achieve wireless information transfer and power transfer with the aim of maximizing the achievable secrecy sum rate under the transmit power constraint and the energy harvesting constraint [32]. Physical layer security is an emerging technique, where base stations equipped with multiple antennas can steer their beamforming vectors and artificial noise is added to impair the information reception of potential eavesdroppers. In [33], a resource allocation algorithm design was investigated for such a system with a scenario of multiple-input single-output multicarrier non-orthogonal multiple access. The derived schemes provided the solutions of optimal beamforming, artificial noise design, subcarrier allocation, and power allocation for the maximization of the weighted system throughput. In [34], the authors investigated beamforming design for cooperative secure transmission in cognitive two-way relay networks. With the objective of maximizing the secrecy sum rate for primary transmitters, the proposed algorithms were developed for the joint solutions of the beamforming matrix for the primary transmitters' signals, the beamforming vector for the cognitive receiver's signal, and the artificial noise's beamforming matrix under the quality of service constraint at the cognitive receiver and the transmit power constraint at the cognitive transmitter. In the system considered in this study, beamforming is used to suppress interference among users, such that the transmit power is reduced to satisfy a few QoS constraints.

The main novelty and contribution of the paper is as follows. Usually, system capacity maximization is considered in NOMA transmission. To our knowledge, the resource allocation problem with rate and error-rate constraints considering the aggregation of multiuser, multicarrier, NOMA, and downlink beamforming in systems has not been investigated thus far. Specifically, in addition to the data-rate constraint, the QoS of the required error rate is considered, and a subset of the subcarriers is allocated to the same group of users. Practical modulation types are considered, such as binary phase shift keying (BPSK), quadrature phase shift keying (QPSK), and 16-quadrature amplitude modulation (16-QAM), instead of considering the theoretical capacity expressions. The problem to be solved is complex, and there is no report of an investigation of such systems. To reduce the required transmit power in the resource-allocation problem with subcarrier allocation in the scenario under consideration, we adapt the schemes proposed in [29] and [30] for application to our system and propose a subcarrier allocation scheme for OFDMA-based NOMA systems to minimize the total required transmit power. The number of users within the coverage radius of a base station (BS) is usually larger than the number of users that can be served by the BS [27], [31]. Thus, we investigate the user selection problem and design resource-allocation algorithms for downlink beamforming in OFDMA-based NOMA systems. In the developed algorithms, the user-grouping operation is performed first, followed by subcarrier allocation along with bit loading and power assignment under the constraints of the required data rate and error rate based on the user-grouping results.

A summary of the symbols used in the paper along with their explanations is as follows.

Notation	Description
K	Total number of users in a cell
M	Total number of transmitted antennas
N, n	Total number of subcarriers, index of a subcarrier
G, g	Total number of user groups, index of a group
C	Total number of clusters
p, p'	Index of a primary user, index of a primary user who is allocated bits adaptively
s	Index of a secondary user
S_c	Number of subcarriers assigned to the *c-th* cluster
$\tilde{r}^p_{n,c}$	Number of bits allocated to primary users in the *c-th* cluster on the *n-th* subcarrier, summation over G groups
$r^p_{n,c,g}$	Number of bits allocated to primary user in the *g-th* group within the *c-th* cluster on the *n-th* subcarrier
$r^{p'}_{n,c,g}$, $r^s_{n,c,g}$	Numbers of bits allocated to primary and secondary users in the *g-th* group within the *c-th* cluster on the *n-th* subcarrier
R_C, R_c	Data rates of total clusters, *c-th* cluster (in bits per OFDM symbol)
$f^{(\cdot)}_{c,g}$	Required received signal power to interference and noise power ratio in a particular modulation mode and at a data error rate
$\mathrm{P}^p_{n,c,g}$, $\mathrm{P}^{p'}_{n,c,g}$, $\mathrm{P}^s_{n,c,g}\mathrm{P}_{n,c,g}$	Transmit power required for a particular BER at $r^p_{n,c,g}$, $r^{p'}_{n,c,g}$ and $r^s_{n,c,g}$, respectively; total power transmitted to users in the g-th group in the c-th cluster on the n-th subcarrier
$\tilde{\mathbf{P}}_{n,c}$, $\tilde{\mathbf{P}}^O_{n,c}$, $\tilde{\mathbf{P}}^N_{n,c}$	Required transmit power, required transmit power in the OMA mode, and required transmit power with NOMA allocation for the *c-th* cluster on the *n-th* subcarrier

The remainder of this paper is organized as follows. In Section II, the system model and problem formulation are discussed. In Section III, the proposed user selection algorithm and the subcarrier allocation scheme for NOMA are developed. Complexity analysis is presented in Section IV. In Section V, the simulation results obtained using the proposed system and a conventional OFDMA system are presented and compared. Finally, in Section VI, we present conclusions of this study.

II. SYSTEM MODEL AND PROBLEM FORMULATION

The system consists of a single base station (BS) that is equipped with M antennas, and each receiver is equipped with one antenna. There are two types of users in a cell, namely primary users (PUs) and secondary users (SUs). The BS can simultaneously transmit G beams to facilitate multiuser downlink transmission, and each beam serves one user group. Notably, a maximum of two users can be multiplexed over a channel from the practical implementation viewpoint [35]. By considering the complexity and performance on the mobile side, two users per group would be suitable for NOMA transmission on the downlink. Given that each group can serve more than one user, we assume that each group contains two users, including a PU and a SU.

The frequency resource is divided into N subcarriers, and each subcarrier is assumed to serve a cluster with G groups ($M \geq G$) of PUs and SUs. With M antenna elements, M orthogonal beams can be formed, and $G = M$ groups can be employed per cluster in the proposed scheme. The system assigns a subset of the N subcarriers to be shared by this one cluster with the G groups. C is the number of clusters served by the system. One cluster may be viewed as one allocation unit after the user-grouping operation. The total number of users in a cell is K, and thus, $2G$ out of K users are selected into G groups in a cluster. Fig. 1 illustrates the MIMO-NOMA system for downlink beamforming with M antennas in the c-th cluster on the n-th subcarrier.

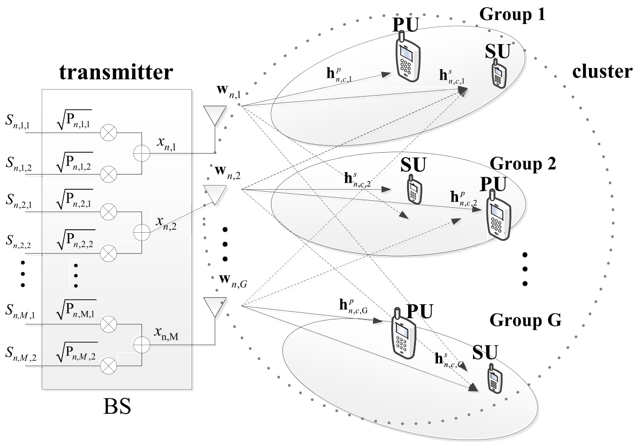

FIGURE 1. MIMO-NOMA system for downlink beamforming with M antennas in the c-th cluster on the n-th subcarrier. $c = 1, \ldots, C$, and $n = 1, \ldots, N$.f.

Two operational scenarios could be considered in the multicarrier MIMO-NOMA system, namely the multiple-user orthogonal multiple access (MU-OMA) mode and the NOMA mode. In the developed algorithms, relevant mathematical expressions are required for both operational scenarios, and the corresponding discussions are as follows. In the first scenario, a subcarrier is allocated to a cluster that contains only G Pus, and it is equivalent to the MU-OMA mode. In the second scenario, if a subcarrier is allocated to a cluster that contains G groups of both PUs and SUs simultaneously, the system is operated in the NOMA mode, and each group of PUs and SUs suffers from intergroup interference and interuser interference owing to the nonorthogonal property in the same subcarrier transmission. The interference effect can be mitigated if the designed algorithm considers the correlations and gains of users' channels while selecting the users from K users. Moreover, the user with a higher channel gain is categorized as the strong user and the other with a lower channel gain is categorized as the weak users across PU and SU in a group. Zeroforcing beamforming (ZFBF) and SIC are performed to eliminate interferences from other groups and the weak user in the same group, respectively. One study [36] investigated the user selection problem along with power control by using ZFBF and SIC for downlink NOMA transmission, where the criterion of capacity maximization and a scenario involving a single carrier were considered. In this study, a multicarrier scenario with the data rate requirement constraint and the QoS of the required error rate associated with practical modulation types such as QPSK and 16 QAM is considered instead.

Time-division duplexing (TDD) is assumed, so the BS estimates the instantaneous channel information of all users in a cell from the uplink transmission, adapts the subcarrier, and then transmits bit assignments along with power control in the downlink transmission through NOMA allocation algorithms. Perfect channel estimation is assumed in the development. Owing to the duality of the downlink and uplink channels, downlink beamforming weight vectors can be calculated based on the channel estimation results of uplink transmission. With the assumption of perfect channel estimation, as in other works on solving resource-allocation type problems, because of the orthogonality resulting from the use of ZFBF, the strong users would not face interferences from other groups in the same cluster. For a particular user requiring the SIC operation, the user's downlink channel is estimated at the receiver and the estimated channel is employed to process SIC for the user.

As mentioned before, we assume the presence of N subcarriers and C clusters. Each cluster contains G groups of PUs and SUs ($G = M$). The parameter $r^p_{n,c,g}$ denotes the number of bits assigned to the PU for transmission over the *n-th* subcarrier in the *g-th* group of the *c-th* cluster, which corresponds to a modulation mode for transmission, for example, BPSK, QPSK, 16-QAM, or 64-QAM, in these cases: $r^p_{n,c,g} \in \{0,\ 1, 2, 4, 6\}$. The parameters of the signal-to-interference-plus-noise ratio (SINR) associated with the QoS of the specified error rate are required and predetermined for the proposed scheme.

The subcarriers allocated to the *c-th* cluster have the following relationship:

$$S_c \leq N, \quad \sum_{c=1}^{C} S_c = N \tag{1}$$

where S_c is the number of subcarriers assigned to the *c-th* cluster and can be determined adaptively during execution of the proposed algorithm. Based on (1), the following conditions are discussed for a subcarrier in a cluster with G groups. The power of each user in each group is allocated. By summing the required transmit power for each cluster over all G groups of users on different subcarriers, $\tilde{\mathbf{P}}_{n,c}$ is denoted as the overall required transmit power of the *c-th* cluster on the *n-th* subcarrier, where the symbol '$\sim$' denotes summation over groups in a cluster and is used in the following discussion. Then, the two different power assignment conditions of the MU-OMA mode and the NOMA mode are considered. In terms of the first condition, $\tilde{\mathbf{P}}^O_{n,c}$ is the required transmit power in the MU-OMA mode, and only G PUs in the *c-th* cluster on the *n-th* subcarrier transmit data. The related expressions are discussed in subsection A. In terms of the second condition, $\tilde{\mathbf{P}}^N_{n,c}$ is the required transmit power in the NOMA mode, which includes both G groups of PUs and SUs for transmission in the *c-th* cluster on the *n-th* subcarrier, and the related expressions are discussed in subsection B.

A. ALLOCATION WITH THE MU-OMA MODE

Under the MU-OMA operational condition, the data rate of the *c-th* cluster of PUs (in bits per OFDM symbol) is a predetermined system parameter that can be expressed as follows:

$$\sum_{n=1}^{N} \tilde{r}^p_{n,c} = R_c \tag{2}$$

where $\tilde{r}^p_{n,c}$ is the number of bits allocated to the PUs in the *c-th* cluster on the *n-th* subcarrier. It is also the data rate summed over the groups of the *c-th* cluster on the *n-th* subcarrier as $\tilde{r}^p_{n,c} = \sum_{g=1}^{G} r^p_{n,c,g}$.

Then, the transmit signal $x^p_{n,c,g}$, which consists of power $\mathrm{P}^p_{n,c,g}$ and modulated signal $S(r^p_{n,c,g})$ of the PUs in the *g-th* group of the *c–th* cluster on the *n-th* subcarrier, can be expressed as follows:

$$x^p_{n,c,g} = \sqrt{\mathrm{P}^p_{n,c,g}}\, S(r^p_{n,c,g}) \tag{3}$$

where $\mathrm{P}^p_{n,c,g}$ is the required transmit power assigned to the PU on the *n-th* subcarrier in the *g-th* group of the *c-th* cluster for a specific error rate (e.g., bit error rate [BER]) in the $r^p_{n,c,g}$ mode as one of the modulation modes, for example, QPSK, 16-QAM, or 64-QAM.

Thus, the signal received by the PU on the *n-th* subcarrier in the *g-th* group of the *c-th* cluster can be expressed as follows:

$$y^p_{n,c,g} = \mathbf{h}^p_{n,c,g} \sum_{g'=1}^{M} \mathbf{w}^p_{n,c,g'} x^p_{n,c,g'} + n^p_{n,c,g} \tag{4}$$

where $\mathbf{h}^p_{n,c,g}$ and $\mathbf{w}^p_{n,c,g}$ denote the $1 \times M$ channel vector of the PU on the *n-th* subcarrier in the *g-th* group of the *c-th* cluster and the associated $M \times 1$ BF vector, which is generated based on the PUs' channels satisfying the following ZFBF equation:

$$\frac{\mathbf{h}^p_{n,c,g}}{||\mathbf{h}^p_{n,c,g}||} \mathbf{w}^p_{n,c,g'} = \left\{ \begin{matrix} 1, \, for \; g' = g \\ 0, \, for \; g' \neq g \end{matrix} \right\} \tag{5}$$

where $1 \leq g, g' \leq G$. This means that no intergroup interference signals exist among groups in the same cluster when the n-th subcarrier is used. $n^p_{n,c,g}$ is identically independently distributed (i.i.d.) additive white complex Gaussian noise (AWGN) with zero mean and variance of σ^2_N.

The BF vectors are constructed based on the channel gains of the PUs: $\mathbf{H}^O_{n,c} = [\mathbf{h}^p_{n,c,1}{}^T \mathbf{h}^p_{n,c,g}{}^T \ldots \mathbf{h}^p_{n,c,G}{}^T]^T$; $(\cdot)^T$ denotes the transpose of a matrix.

$$\begin{aligned} \mathbf{W}^O_{n,c} &= [\mathbf{w}^p_{n,c,1} \mathbf{w}^p_{n,c,g} \ldots \mathbf{w}^p_{n,c,G}] \\ &= (\mathbf{H}^O_{n,c})^{\dagger} = (\mathbf{H}^O_{n,c})^H ((\mathbf{H}^O_{n,c})(\mathbf{H}^O_{n,c})^H)^{-1} \end{aligned} \tag{6}$$

where $(\cdot)^{\dagger}$ denotes the pseudoinverse of a matrix, and $(\cdot)^H$ denotes the Hermitian transpose. Based on Eqs. (3) and (5), we can rewrite eq. (4) as

$$y^p_{n,c,g} = \mathbf{h}^p_{n,c,g} \mathbf{w}^p_{n,c,g} (\sqrt{\mathrm{P}^p_{n,c,g}} S(r^p_{n,c,g})) + n^p_{n,c,g}. \tag{7}$$

The required SINR $f_{c.g}(\cdot)$ of the PU as the modulation switching level at a particular BER is a function of the $r^p_{n,c,g}$ modulation mode. For the case of the PU on the *n-th* subcarrier in the *g-th* group of the *c-th* cluster, $f_{c,g}(r^p_{n,c,g})$ can be expressed as

$$SINR^p_{n,c,g} \equiv f_{c,g}(r^p_{n,c,g}) = \frac{|\mathbf{h}^p_{n,c,g} \mathbf{w}^p_{n,c,g}|^2 \mathrm{P}^p_{n,c,g}}{\sigma^2_N}. \tag{8}$$

It follows that the required transmit power for the particular BER in the $r^p_{n,c,g}$ modulation mode can be given as

$$\mathrm{P}^p_{n,c,g} = \frac{f_{c,g}(r^p_{n,c,g}) \sigma^2_N}{|\mathbf{h}^p_{n,c,g} \mathbf{w}^p_{n,c,g}|^2}. \tag{9}$$

The required overall transmit power allocated to the *c-th* cluster of all PUs on the *n-th* subcarrier with the MU-OMA operational condition can be expressed as

$$\tilde{\mathbf{P}}^O_{n,c} = \sum_{g=1}^{G} \mathrm{P}^p_{n,c,g}. \tag{10}$$

B. ALLOCATION IN THE NOMA MODE

When the system is operated in the NOMA mode, the data rate of the *c-th* cluster with data transmission of both PU and SU (in bits per OFDM symbol) can be expressed as

$$\sum_{n=1}^{N} \sum_{g=1}^{G} (r^{p\prime}_{n,c,g} + r^s_{n,c,g}) = \mathrm{R}_c \tag{11}$$

$$\text{subject to } \tilde{r}^{p'}_{n,c} + \tilde{r}^s_{n,c} = \tilde{r}^p_{n,c} \tag{12}$$

where $r^{p'}_{n,c,g}$ and $r^s_{n,c,g}$ are the numbers of bits allocated to the PU and the SUs on the *n-th* subcarrier in the *g-th* group of the *c-th* cluster, respectively. $\tilde{r}^{p'}_{n,c}$ and $\tilde{r}^s_{n,c}$ are obtained by summing the data rates over all G groups of the *c-th* cluster on the *n-th* subcarrier.

The signals received by the PU and the SUs on the *n-th* subcarrier in the *g-th* group of the *c-th* cluster can be expressed as follows, respectively:

$$\begin{aligned} y^{p'}_{n,c,g} &= \mathbf{h}^{p'}_{n,c,g} \mathbf{w}_{n,c,g} (x^{p'}_{n,c,g} + x^s_{n,c,g}) \\ &\quad + \mathbf{h}^{p'}_{n,c,g} \sum_{k=1,k\neq g}^{M} \mathbf{w}_{n,c,k} (x^{p'}_{n,c,k} + x^s_{n,c,k}) + n^{p'}_{n,c,g}; \end{aligned} \tag{13}$$

$$\begin{aligned} y^s_{n,c,g} &= \mathbf{h}^s_{n,c,g} \mathbf{w}_{n,c,g} (x^{p'}_{n,c,g} + x^s_{n,c,g}) \\ &\quad + \mathbf{h}^s_{n,c,g} \sum_{k=1,k\neq g}^{M} \mathbf{w}_{n,c,k} (x^{p'}_{n,c,k} + x^s_{n,c,k}) + n^s_{n,c,g} \end{aligned} \tag{14}$$

where $x^{p'}_{n,c,g}$ and $x^s_{n,c,g}$ are the signals transmitted to the PU and SUs of the *g-th* group in the *c-th* cluster on the *n-th* subcarrier, respectively. Then, the transmit signals of both $x^{p'}_{n,c,g}$ and $x^s_{n,c,g}$ are composed of $\mathrm{P}^{p'}_{n,c,g}$, $S(r^{p'}_{n,c,g})$, $\mathrm{P}^s_{n,c,g}$, and $S(r^s_{n,c,g})$, respectively, and can be expressed as follows:

$$x^{p'}_{n,c,g} = \sqrt{\mathrm{P}^{p'}_{n,c,g}} S(r^{p'}_{n,c,g}), \quad x^s_{n,c,g} = \sqrt{\mathrm{P}^s_{n,c,g}} S(r^s_{n,c,g}) \tag{15}$$

where $\mathrm{P}^{p'}_{n,c,g}$ is the transmit power assigned for a particular BER in the $r^{p'}_{n,c,g}$ mode to the PU of the *g-th* group in the *c-th* cluster on the *n-th* subcarrier. $\mathrm{P}^s_{n,c,g}$ is the transmit power assigned at the particular BER in the $r^s_{n,c,g}$ mode to the SU of the *g-th* group in the *c-th* cluster on the *n-th* subcarrier. Meanwhile, $\mathrm{P}_{n,c,g} = \mathrm{P}^{p'}_{n,c,g} + \mathrm{P}^s_{n,c,g}$ is the total power transmitted to the users of the *g-th* group in the *c-th* cluster on the *n-th* subcarrier. Therefore, (13) and (14) can be rewritten as follows:

$$\begin{aligned} &y^{p'}_{n,c,g} \\ &= \mathbf{h}^{p'}_{n,c,g} \mathbf{w}_{n,c,g} (\sqrt{\mathrm{P}^{p'}_{n,c,g}} S(r^{p'}_{n,c,g}) + \sqrt{\mathrm{P}^s_{n,c,g}} S(r^s_{n,c,g})) \\ &\quad + \mathbf{h}^{p'}_{n,c,g} \sum_{k=1,k\neq g}^{M} \mathbf{w}_{n,c,k} (\sqrt{\mathrm{P}^{p'}_{n,c,k}} S(r^{p'}_{n,c,k}) + \sqrt{\mathrm{P}^s_{n,c,k}} S(r^s_{n,c,k})) \\ &\quad + n^{p'}_{n,c,g} \end{aligned} \tag{16}$$

and

$$\begin{aligned} & y^s_{n,c,g} \\ & = \mathbf{h}^s_{n,c,g}\mathbf{w}_{n,c,g}\left(\sqrt{\mathrm{P}^{p'}_{n,c,g}}S(r^{p'}_{n,c,g}) + \sqrt{\mathrm{P}^s_{n,c,g}}S(r^s_{n,c,g})\right) \\ & \quad + \mathbf{h}^s_{n,c,g}\sum_{k=1,k\neq g}^{M} \mathbf{w}_{n,c,k}\left(\sqrt{\mathrm{P}^{p'}_{n,c,k}}S(r^{p'}_{n,c,k}) + \sqrt{\mathrm{P}^s_{n,c,k}}S(r^s_{n,c,k})\right) \\ & \quad + n^s_{n,c,g}. \end{aligned} \tag{17}$$

Based on the signal properties of the strong and weak users in the NOMA system, the BF vectors are generated based on the strong users' channel gains and the SIC process is executed in the receivers of the strong users. Here, we consider $\left|\mathbf{h}^s_{n,c,g}\right|$ to be larger than $\left|\mathbf{h}^{p'}_{n,c,g}\right|$, for example. This implies that the SU is the strong user and the PU is the weak user on the *n-th* subcarrier in the *g-th* group of the *c-th* cluster. In the following discussion, we denote the user index of the strong user as "1" and that of the weak user as "2." It follows that the SU in the *g-th* group can eliminate the inter- and intragroup interferences via ZFBF and SIC on the *n-th* subcarrier, respectively. However, the PU would be influenced by both types of interference signals. Regarding ZFBF with M transmit antennas and G groups of PUs and SUs in the *c-th* cluster, $\mathbf{w}_{n,c,g}$ is the BF vector generated by the strong users' channels $\{\mathbf{h}^1_{n,c,g}\}$ on the *n-th* subcarrier, and it satisfies the following condition:

$$\frac{\mathbf{h}^1_{n,c,g'}}{|\mathbf{h}^1_{n,c,g'}|}\mathbf{w}_{n,c,g} = \begin{Bmatrix} 1, \mathit{for}\ g' = g \\ 0, \mathit{for}\ g' \neq g \end{Bmatrix} \tag{18}$$

where $1 \le g, g' \le G$. This means that there are no intergroup interference signals of the strong users among groups in the same cluster on the *n-th* subcarrier.

According to (16) and (17), the signals of two users in the same group are transmitted on the same subcarrier simultaneously, and thus, each user is affected by intragroup interference from the other users. The strong user in the *g-th* group is not affected by the interference signals of the other groups. However, the other user in the same *g-th* group is affected by intergroup interference because condition (18) is not satisfied. Moreover, the strong user can eliminate the intragroup interference from the weak user through the SIC process, whereas the weak user decodes the receive signal directly without performing SIC.

The BF vectors are generated based on the strong users' channel gains $\mathbf{H}^N_{n,c} = [\mathbf{h}^1_{n,c,1}{}^T\mathbf{h}^1_{n,c,g}{}^T \ldots \mathbf{h}^1_{n,c,G}{}^T]^T$, where $\mathbf{h}^1_{n,c,g}$ is the $1 \times M$ channel vector of the strong user belonging to the *g-th* group in the *c-th* cluster on the *n-th* subcarrier. These vectors can be computed as follows:

$$\begin{aligned} \mathbf{W}_{n,c} &= [\mathbf{w}_{n,c,1}\mathbf{w}_{n,c,g}\ldots\mathbf{w}_{n,c,G}] \\ &= (\mathbf{H}^N_{n,c})^{\dagger} = (\mathbf{H}^N_{n,c})^H((\mathbf{H}^N_{n,c})(\mathbf{H}^N_{n,c})^H)^{-1} \end{aligned} \tag{19}$$

where $\mathbf{w}_{n,c,g}$ is the $M \times 1$ ZFBF vector in the *g-th* group of the *c-th* cluster on the *n-th* subcarrier.

Based on the above discussion, we derive the SINR of the PU and the SUs as follows. Here, we take the SU as the strong user and the PU as the weak user on the *n-th* subcarrier in a group, for example. The required SINRs of the SU and the PU on the *n-th* subcarrier in the *g-th* group of the *c-th* cluster can be expressed as

$$\begin{aligned} & SINR^s_{n,c,g} \\ & \equiv f_{c,g}(r^s_{n,c,g}) = \frac{|\mathbf{h}^s_{n,c,g}\mathbf{w}_{n,c,g}|^2\mathrm{P}^s_{n,c,g}}{\sigma_N^2}; \end{aligned} \tag{20}$$

$$\begin{aligned} & SINR^{p'}_{n,c,g} \\ & \equiv f_{c,g}(r^{p'}_{n,c,g}) \\ & = \frac{|\mathbf{h}^{p'}_{n,c,g}\mathbf{w}_{n,c,g}|^2\mathrm{P}^{p'}_{n,c,g}}{|\mathbf{h}^{p'}_{n,c,g}\mathbf{w}_{n,c,g}|^2\mathrm{P}^s_{n,c,g} + \sum\limits_{k=1,k\neq g}^{M}|\mathbf{h}^{p'}_{n,c,g}\mathbf{w}_{n,c,k}|^2\mathrm{P}_{n,c,k} + \sigma_N^2}. \end{aligned} \tag{21}$$

Based on (20) and (21), the transmit power required for a specified BER in the $r^s_{n,c,g}$ and the $r^{p'}_{n,c,g}$ modes can be rewritten as (22) and (23), shown at the bottom of this page.

Consequently, the transmit power required for the *c-th* cluster, including G groups of the PU and the SUs on the *n-th* subcarrier with NOMA transmission, can be expressed as

$$\tilde{\mathbf{P}}^N_{n,c} = \sum_{g=1}^{G}(\mathrm{P}^s_{n,c,g} + \mathrm{P}^{p'}_{n,c,g}). \tag{24}$$

The objective function is to minimize the total required transmit power in the system. The data rates of all clusters $\{R_1, R_2, \ldots, R_C\}$ are predetermined parameters that may be set to be equal, for example. The bit error rate must also be restricted to a particular level to achieve the required service quality. By considering possible transmission modes, we denote the required transmit power on the *n-th* subcarrier in the *c-th* cluster as $\tilde{\mathbf{P}}_{n,c} = \tilde{\mathbf{P}}^z_{n,c}, z \in \{"O", "N"\}$, where "z" depends on the type of transmission mode, namely the MU-OMA and NOMA modes.

For the multiuser multicarrier NOMA system with downlink beamforming under consideration, the total required transmit power for all C clusters with allocation of

$$\mathrm{P}^s_{n,c,g} = \frac{f_{c,g}(r^s_{n,c,g})\sigma_N^2}{|\mathbf{h}^s_{n,c,g}\mathbf{w}_{n,c,g}|^2} \tag{22}$$

$$\mathrm{P}^{p'}_{n,c,g} = \frac{f_{c,g}(r^{p'}_{n,c,g})\left(|\mathbf{h}^{p'}_{n,c,g}\mathbf{w}_{n,c,g}|^2\mathrm{P}^s_{n,c,g} + \sum\limits_{k=1,k\neq g}^{M}|\mathbf{h}^{p'}_{n,c,g}\mathbf{w}_{n,c,k}|^2\mathrm{P}_{n,c,k} + \sigma_N^2\right)}{|\mathbf{h}^{p'}_{n,c,g}\mathbf{w}_{n,c,g}|^2} \tag{23}$$

N subcarriers for downlink beamforming transmission is expressed as

$$\min_{r^{p'}_{n,c,g},\, r^{s}_{n,c,g}} \sum_{n=1}^{N}\sum_{c=1}^{C} \tilde{\mathbf{P}}_{n,c} \tag{25}$$

$$\text{subject to } R_c = \sum_{n=1}^{N}\sum_{g=1}^{G} \left(r^{p'}_{n,c,g} + r^{s}_{n,c,g}\right), \quad for\ c = 1, \ldots, C; \tag{26}$$

$$r^{p'}_{n,c,g},\ r^{s}_{n,c,g} \in \{0, b_1, \ldots, b_Q\}. \tag{27}$$

The constraints are explained as follows. According to Eq. (26), the total data rate achieved using the subcarriers allocated to the *c-th* cluster, which contains G groups (in bits per OFDM symbol), is R_c. According to Eq. (27), the numbers of bits allocated to the PU and the SUs in the *g-th* group of the *c-th* cluster on the *n-th* subcarrier range from zero to b_Q depending on the modulation mode.

III. PROPOSED RESOURCE ALLOCATION SCHEMES

Referring to the processing diagram in Fig. 2, the proposed schemes are mainly composed of two parts: user grouping and radio resource allocation. The radio resource allocation part includes subcarrier allocation, bit loading, and power allocation. The details are explained as follows.

A subset of subcarriers is allocated to the cluster for sharing. The subcarriers in the subset are not contiguous and disjointed with varied channel gains. Therefore, existing single-carrier NOMA user selection algorithms along with the resource allocation can not be employed and applied straightforward. Some properties pertaining to the user selection and the resource allocation designs are notable. The power levels of intergroup and interuser interferences considerably influence the performance of the weak user in the OFDMA-NOMA system for downlink beamforming. Because the same BF vector is shared by the PU and the SUs in the same group, the channel properties of paired users, for example, channel correlation, in the user selection algorithm should be utilized. In this section, we propose user grouping, subcarrier allocation, and bit allocation schemes to reduce the total required transmit power with consideration of the QoS of the data rate and the error rate constraints.

A. USER-GROUPING ALGORITHM

An exhaustive search can be conducted to arrive at the best solution to achieve the optimum performance. However, the process would be highly computationally complex. Therefore, we propose a user-grouping algorithm for minimizing the required transmit power while reducing the computational complexity by considering the properties of channel gains among users and the relationship between two users for pairing in the same group. Two major indicators should be considered in the user grouping: users' channel gain correlation and channel gain difference between users. The algorithm is designed based on the following parameters as the indicators.

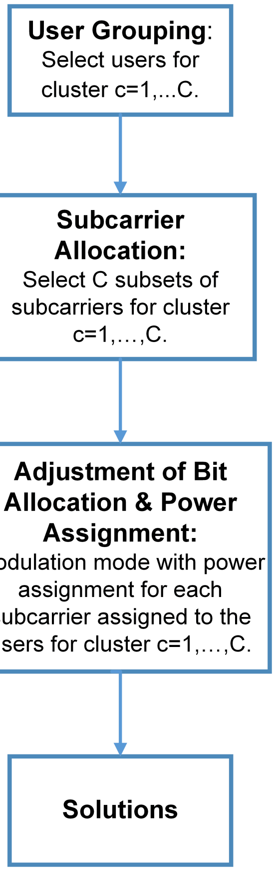

FIGURE 2. **Flowchart of proposed processing scheme.**

1) CHANNEL GAINS OF K USERS

A list $\mathcal{H}$ is constructed by sorting the channel gains of K users in descending order, and $\mathcal{U}$ is the associated user index list with respect to $\mathcal{H}$. In the list of channel gains $\mathcal{H} = \{H_{(1)}, H_{(2)}, \ldots H_{(K)}\}$, the subscript (k) denotes the user index of the channel gain at rank k, and the channel gain indicator H_k is computed by considering all channels of all subcarriers for user k as follows:

$$H_k = \sum_{n=1}^{N} ||\mathbf{h}_{n,k}||, \quad for\ k = 1, \ldots, K, \tag{28}$$

where $\mathbf{h}_{n,k}$ is the channel gain vector of user k on the n-th subcarrier.

2) CORRELATION OF USERS' CHANNEL GAINS

The channel gain correlation between two users is calculated, and the number of highly correlated subcarriers between the two users is evaluated. The channel gain correlation $Cor(i,j)_n$ and the parameter of the highly correlated times $T(i,j)$ between the *i-th* user and the *j-th* user across all subcarriers can be written, respectively, as follows:

$$Cor(i,j)_n = \begin{cases} \dfrac{|\mathbf{h}_{n,i}\mathbf{h}^{H}_{n,j}|}{|\mathbf{h}_{n,i}||\mathbf{h}_{n,j}|}, & i \neq j \\ 1, & i = j; \end{cases} \tag{29}$$

$$T(i,j) = \sum_{n=1}^{N} T(i,j)_n, \tag{30}$$

where

$$T(i,j)_n = \begin{cases} 1, & \text{if } Cor(i,j)_n \geq \rho \\ 0, & \text{otherwise.} \end{cases}$$

Eq. (30) represents the number of the highly correlated subcarriers between the *i-th* user and the *j-th* user across all subcarriers.

3) MEAN OF CHANNEL GAIN DIFFERENCES

For the other factor to be considered in the user grouping, the channel gain differences across all subcarriers should be calculated. However, the channel gain difference $D(i,j)$ is computed only for the subcarriers with the highly correlated condition between the *i-th* and the *j-th* users. The parameter related to the mean of the channel gain differences $\overline{D}(i,j)$ as an indicator for the user grouping algorithm can be expressed as

$$D(i,j) = \sum_{n \in \{T(i,j)_n = 1\}} \left(\left| \left\| \mathbf{h}_{n,i} \right\| - \left\| \mathbf{h}_{n,j} \right\| \right| \right), \tag{31}$$

$$\text{and} \quad \overline{D}(i,j) = \frac{D(i,j)}{T(i,j)}. \tag{32}$$

That is, after summing the channel gain differences for the subcarriers satisfying the highly correlated condition, the mean of the channel gain differences as the indicator $\overline{D}(i,j)$ is evaluated by dividing the aforementioned sum of channel gain differences for the subcarriers with the number of highly correlated subcarriers between users.

4) MEAN OF THE NUMBERS OF HIGHLY CORRELATED SUBCARRIERS AS THE THRESHOLD

The threshold $\overline{T}$ used in the proposed user-grouping algorithm to select a PU is obtained from the mean of the indicator given in Eq. (30) among all users, which is calculated as

$$\overline{\mathrm{T}} = \frac{1}{K^2} \sum_{i=1}^{K} \sum_{j=1}^{K} T(i,j). \tag{33}$$

In sum, to minimize the required system transmit power during user selection, the user-grouping algorithm is composed of six steps as follows:

Step 1: *Methodology for selecting a PU in a group*

Pairing users with high correlation in the same group would mitigate interference signals in the system because of the orthogonality property of the BF vectors in Eq. (18). In the list $\mathcal{H}$ of total K users, consider the *(1)*-th user with the associated channel gain indicator $H_{(1)}$ at rank 1. The maximum value of the highly correlated number of the (1)-th user is compared with the threshold computed using Eq. (33). The condition for this check can be represented as

$$\max\{T(i,j) : i = 1, i \neq j, j = 1, 2, \ldots, K\} > \overline{T}.$$

If the condition is satisfied, the user candidate is selected as the PU in a group belonging to the first cluster and is removed from the candidate list; else, the next user candidate in list $\mathcal{H}$ is evaluated as the PU in this group belonging to the first cluster.

Step 2: *Consider the selection of a PU for the next group in the cluster*

Repeat **Step 1** until all PUs of all groups in the cluster have been selected.

Step 3: *Consider the selection of a PU for the next cluster*

Repeat **Step 1-2** until all PUs of all clusters have been selected.

Step 4: *SU selection in a group*

After the PUs in all groups have been selected, these users are not considered as the SUs in each group. Referring to the list $\mathcal{H}$, the first unassigned user candidate is considered as the SU in a group.

Step 5: *Consider an SU in the next group*

After selection of the SU in Step 4, the other SU in the other group is selected based on the indicator $\overline{D}$ according to the following methodology. With the selected SU in Step 4, the corresponding list of channel gain differences in descending order is formed, which is calculated with the remaining users. The user with the minimum channel gain difference is selected as the other SU in the other group, but this user must satisfy the constraint described in [10]:

$$\begin{aligned} \varepsilon = {} & |\mathbf{h}^{s}_{n,c,g}\mathbf{w}_{n,c,g}|^2 \beta_g - \{\sqrt{(1 + |\mathbf{h}^{s}_{n,c,g}|^2 \beta_g)} - 1\} \\ & \times \{ \sum_{k=1, k \neq g}^{M} |\mathbf{h}^{\mathrm{s}}_{n,c,g}\mathbf{w}_{n,c,k}|^2 \beta_g + 1\} > 0 \end{aligned} \tag{34}$$

where β_g is the ratio of the total transmit power of the *g-th* group to the noise power in each cluster. In this process, it is assumed all groups have the same transmit power and noise density $\beta_g = \beta$ for $g \in \{1, \ldots, G\}$.

If the NOMA constraint $\varepsilon > 0$, the user candidates are suitable as SUs in the same cluster. Else, the next set of user candidates would be considered as the SUs. Step 5 stops when all SUs in the same cluster have been selected.

Step 6: *Consider SUs in the next cluster*

Repeat **Step 5** until all SUs in all clusters have been selected.

Note that fairness is not considered in the proposed algorithm, and the issue would be investigated in future studies. However, the proposed algorithm may be viewed to be performed in a priority class regarding some fairness consideration, where a user set for this service class has been obtained. Then, the proposed user-grouping algorithm is applied to all users within this priority class.

B. SUBCARRIER ALLOCATION ALGORITHM

After the users are paired as groups in each cluster, a subcarrier is used by a cluster that contains G groups of users in the system. After the application of a well-designed subcarrier allocation algorithm, a subset of subcarriers is appropriately allocated to the cluster for sharing. Such a subcarrier allocation scheme is proposed here to enhance system performance in terms of transit power subject to the constraints associated with NOMA transmission in the system. A two-phase suboptimal subcarrier allocation scheme is proposed for the system. The solution of Phase I can be improved to reduce the required transmit power by applying an iterative subcarrier refinement scheme in Phase II. The details are explained as follows.

Phase I:

Given the initialization of the subcarrier candidate index set $\mathcal{A} = \{1, 2, \ldots, N\}$ and the allocated subcarrier index set $\mathcal{B}_c = \phi$ for the *c-th* cluster, $c = 1, \ldots C$, we execute the following steps.

Step 1: *Sorting the channel gains of the primary users*

Similar to **Step 1** in the user-grouping scheme, the list $\mathcal{H}_c$ of the composite channel gains for aggregating G groups in each cluster is constructed in descending order with respect to the subcarriers as follows:

$\mathcal{H}_c = \{H_{(1),c}, \ldots, H_{(N),c}\}$, for $c = 1, \ldots, C$, and the subscript$_{(n),c}$ denotes the subcarrier index (n) at rank n in cluster c. The composite channel gain of the PUs for subcarrier n with the cluster index $c \in \{1, \ldots, C\}$ is calculated as $H_{n,c} = \sum_{g=1}^{G} ||\mathbf{h}_{n,c,g}^{p'} \mathbf{w}_{n,c,g}||$, for $n = 1, \ldots, N$.

Step 2: *Sequential subcarrier assignment to each cluster*

After construction of the subcarrier sequence for each cluster after the sorting as in the list $\mathcal{H}_c$, the first unassigned subcarrier in the ordered list of the *c-th* cluster is allocated to the *c-th* cluster and marked "assigned" if the required transmit power is the minimum among the first unassigned subcarriers of all C composite channel gains lists $\{\mathcal{H}_c\}$. A uniform bit distribution of R_c bits to the PUs is considered here for determining the power required for each cluster, and the exact modulation modes for each user in all groups will be determined eventually in Phase II. After evaluating all subcarriers in the composite channel gain lists of all clusters, the total subcarriers would be distributed to each cluster. That is, a subcarrier from the subcarrier candidate set $\mathcal{A}$ would be allocated to the clusters one after another. Then, the subcarrier is deleted from $\mathcal{A}$ and added to the allocated subcarrier index set $\mathcal{B}_c$ if the subcarrier is selected for the first unassigned element in list $\mathcal{H}_c$. This subcarrier can not be used for other clusters. The above procedure is executed repeatedly until $\mathcal{A} = \phi$ and $\{\mathcal{B}_c\}$, c = 1,.., C are formed.

Phase II:

The assignment results obtained in Phase I are considered to constitute one final solution. The following iterative subcarrier refining scheme obtained by adapting the ideas in [29], [30] to this NOMA system can be applied to further reduce the required transmit power. Note that the algorithm described in [29] has the lowest complexity in solving similarly formulated problems in OFDMA systems, and it offers the best performance among the existing suboptimal algorithms. The major processing steps are formation of the power reduction lists and execution of the iterative process, which are explained as follows.

1) SWAPPING OPERATION

We consider two assigned subcarriers and assume that the former subcarrier is allocated to the *i-th* cluster and the latter subcarrier to the *j-th* cluster. Then, the swapping operation is considered for all possible cases of swapping of two subcarriers between clusters (i, j). The best subcarrier swapping case for the cluster pair (i, j) in terms of reduced transmit power is then subjected to the swapping operation, and the reduced required transmit power is expressed as follows:

$$\mathrm{P}_{i,j} = \Delta\mathrm{P}_{i,j} + \Delta\mathrm{P}_{j,i} \tag{35}$$

where is the change in the required transmit power of the *i–th* cluster after swapping, and $\Delta\mathrm{P}_{j,i}$ is the change in the required transmit power of the *j–th* cluster. Consequently, $\{P_{i,j}\}$ denotes the transmit power reduction list of all cluster pairs (i, j) for this swapping operation.

2) REALLOCATION OPERATION

Similar to the swapping operation, for the reallocation operation, consider the subcarrier reallocated to the *j-th* cluster, which is originally assigned to the *i–th* cluster. The best case is considered for this cluster pair (i, j) reallocation operation. Thus, the power reduction $\mathrm{P}^*_{i,j}$, which represents the decrease in the required transmit power after implementation of the reallocation operation between the cluster pair (i, j) is expressed as follows:

$$\mathrm{P}^*_{i,j} = \Delta\mathrm{P}^*_{i,j} + \Delta\mathrm{P}^*_{j,i} \tag{36}$$

where $\Delta\mathrm{P}^*_{i,j}$ and $\Delta\mathrm{P}^*_{j,i}$ represent the changes of in the required transmit power for the subcarrier reallocation from the *i-th* cluster to the *j-th* cluster, respectively. $\{P^*_{i,j}\}$ denotes the transmit power reduction list of all cluster pairs (i, j) for this reallocation operation.

The power reduction lists of the swapping and the reallocation operations between the *i-th* and *j-th* clusters are merged to obtain $\{\mathrm{P}_{i,j}, \mathrm{P}^*_{i,j}\}$. The best case from either the swapping or the reallocation operation to minimize the required transmit power is selected, and then, the related parameters and the power reduction lists are recalculated and updated for the next iteration. The iterative process is stopped when the required transmit power does not decrease through either swapping or reallocating. The proposed iterative subcarrier allocation scheme comprises the procedures of **Phase I** and **Phase II**.

C. BIT ALLOCATION ALGORITHM

After subcarrier allocation, the bit allocation problem should be considered. One idea for solving this problem involves applying a R_c bit loading process on the assigned subcarriers for individual clusters, regardless of the distribution results of bits among subcarriers in the last stage. An alternative idea involves adjusting the results by considering the numbers of bits on the assigned subcarriers. By considering the complexity and the performance tradeoff, the latter idea is adopted in the proposed approach.

The subcarrier allocation process has already assigned the number of bits $\tilde{r}^{p}_{n,c}$ allocated to the PUs in the *c-th* cluster per OFDM symbol on the *n-th* subcarrier. Then, $r^{p'}_{n,c,g}$, and $r^{s}_{n,c,g} \in \{b_1, \ldots, b_Q\}$ can be redistributed into PU and SU in the *g-th* group of the *c-th* cluster on the *n-th* subcarrier, where Q is the highest modulation mode index with NOMA transmission in the system. The strong user with large channel gain would transmit greater numbers of bits than the weak user on a subcarrier in the same group within each cluster, $(r^{1}_{n,c,g} \geq r^{2}_{n,c,g})$.

To redistribute the bits assigned in the subcarrier allocation process in a cluster, many combinations and operational cases can be applied. The closed-form expressions for bit loading based on the bit-by-bit loading process are excessively complex when using the classical bit loading concept, especially when different interference effects are involved. Therefore, a lookup table method is adopted to accomplish a low-complexity bit loading task. One case associated with one transmit mode pertaining to a bit loading result is built for calculating the required transmit power. A two-antenna case is considered as an example, and the idea can be extended. A few cases in which several numbers of bits in combinations are assigned to the transmission of PU and SU on a subcarrier in one cluster per OFDM symbol are as follows.

Case 1: *One bit per cluster*

For the case of transmitting 1 bit per OFDM symbol on a subcarrier for a cluster, it is assigned to only one strong user, and the corresponding modulation mode is BPSK.

Case 2: *Two bits per cluster*

For the case of transmitting 2 bits per OFDM symbol on a subcarrier, two conditions might be encountered.

a) 2 bits are assigned to one strong user to transmit, and the modulation mode is QPSK.
b) 2 bits are equally distributed into two strong users, and the modulation mode for each user would be BSPK.

Case 3: *Four bits per cluster*

For the case of transmitting 4 bits per OFDM symbol on a subcarrier, three conditions might be encountered.

a) 4 bits are assigned to one strong user to transmit, and the modulation mode 16-QAM.
b) 4 bits are divided equally between two strong users, and the modulation mode for each user is QPSK.
c) 4 bits are divided equally into two groups as 2 bits per group. For each group, 2 bits are assigned only to the strong user with QPSK transmission, or 1 bit each is allocated to the strong and the weak users with BPSK transmission.
d) 4 bits are divided into two groups with 3 bits and 1 bit respectively. For the group assigned with 3 bits, 2 bits are assigned to the strong user, and 1 bit is assigned to the weak user.

A few other additional conditions and cases can be similarly enumerated and elaborated.

Next, the required transmission power is addressed as follows. Essentially, $\tilde{r}^{p}_{n,c}$ is redistributed into $r^{p'}_{n,c,g}$ and $r^{s}_{n,c,g}$ among G groups in cluster c. When the allocation result is mapped to NOMA transmission, two conditions related to the PU and the SU in each group appear. Regarding the first condition, we assume that the PU in the *g-th* group of the *c-th* cluster on the *n-th* subcarrier is the strong user. Then, the required transmit power for the particular BER at $r^{p'}_{n,c,g}$ and $r^{s}_{n,c,g}$ bit transmission can be written as

$$\mathrm{P}^{p'}_{n,c,g} = \frac{f_{c,g}(r^{p'}_{n,c,g})\sigma_N^2}{|\mathbf{h}^{p'}_{n,c,g}\mathbf{w}_{n,c,g}|^2}; \tag{37}$$

$$\mathrm{P}^{s}_{n,c,g} = \{f_{c,g}(r^{s}_{n,c,g})(|\mathbf{h}^{s}_{n,c,g}\mathbf{w}_{n,c,g}|^2\mathrm{P}^{p'}_{n,c,g} + \sum_{k=1,k\neq g}^{M}|\mathbf{h}^{s}_{n,c,g}\mathbf{w}_{n,c,k}|^2\mathrm{P}_{n,c,k} + \sigma_N^2)\} \Big/ |\mathbf{h}^{s}_{n,c,g}\mathbf{w}_{n,c,g}|^2 \tag{38}$$

For the other condition, if the SU of the *g-th* group in the *c-th* cluster on the *n-th* subcarrier is the strong user, Eqs. (22) and (23) can be used as the expressions of the required transmit power for the specific BER at $r^{s}_{n,c,g}$ and $r^{p'}_{n,c,g}$ bit transmission, respectively.

Based on the above discussion, we summarize the bit allocation process into two steps, as follows. For $c = 1, \ldots, C$ and the associated allocated subcarrier set $\mathcal{B}_c$ with the subcarrier index $n' = 1, \ldots, |\mathcal{B}_c|$, the following tasks are performed:

Step 1: *Check the number of bits per cluster, and determine the strong user on a per assigned subcarrier basis*

Check the number of bits allocated to the *c-th* cluster for subcarrier $n' = 1, \ldots, |\mathcal{B}_c|$ in $\mathcal{B}_c$ and $|\mathcal{B}_c| = S_c$. Determine the strong and the weak users by comparing the channel gains of the PU and the SUs on the assigned n' *-th* subcarrier in the *g-th* group of the *c-th* cluster at a time. Note that the index n' is mapped into one index n out of the total N subcarrier indexes.

Step 2: *Determine the transmit mode along with the required transmit power*

(a) According to the modulation modes on the *n-th* subcarrier in the *c-th* cluster, $\tilde{r}^{p}_{n,c}$ is the number of bits originally allocated to the *n-th* subcarrier of the *c-th* cluster in the subcarrier allocation process. The transmit power required for the particular BER at $\tilde{r}^{p}_{n,c}$ is $\tilde{\mathbf{P}}^{O}_{n,c}$ in the MU-OMA mode, and it is defined in Eq. (10).
(b) If NOMA transmission is involved, given that there are many combinations of bit allocations, the case with the minimum required transmit power satisfying the condition of Eq. (12) is selected. Therefore, the sum of both the required transmit powers $\mathrm{P}^{s}_{n,c,g}$ and $\mathrm{P}^{p'}_{n,c,g}$

on the *n-th* subcarrier across all G groups of the *c-th* cluster represent the required power $\tilde{\mathbf{P}}^{N}_{n,c}$ for NOMA transmission.

(c) The smaller of $\tilde{\mathbf{P}}^{O}_{n,c}$ and $\tilde{\mathbf{P}}^{N}_{n,c}$ is the required transmit power on the *n-th* subcarrier in the *c-th* cluster, and the associated transmit mode is employed.

IV. COMPLEXITY ANALYSIS

In this section, at first, with respect to the user grouping part, the computational complexities of the greedy search scheme and the proposed user grouping approach are compared. The system considered herein consists of C clusters, and each cluster consists of G groups with two paired users. In the greedy search approach, two users are picked, and G groups are formed for the first clusters. This process is continued until all clusters are full of users. In this manner, we have $C_2^K \times C_2^{K-1} \times \ldots C_2^{K-2(G-1)} \ldots \times C_2^{K-2(G-1)C}$ combinations from which to select users for C clusters. Where C_k^n denotes the number of k combinations from a given set of n elements. Therefore, the computational complexity of the greedy search algorithm is $O(K^{2GC})$ at least, even though the complexity of the evaluations for individual cases is neglected.

In terms of the computational complexity of the proposed user-grouping approach, the calculation complexity for all channel gain indicators is $O(MNK)$; the sorting complexity is $O(K \log K)$. The complexity of the calculation for the correlations of users' channel gains is $O(NK^2)$, and the complexity of computing the mean of channel gain differences is $O(NK^2)$. After these parameter calculations, the complexity of the selection process is approximately $O((K-1)+(K-2)+\ldots+(K-2GC)) \approx O(KGC)$. The total computational complexity of the proposed user-grouping algorithm is thus $O(MNK + 2NK^2 + K \log K + KGC) \approx O(NK^2)$, which is considerably lower than $O(K^{2GC})$.

Next, in terms of the computational complexity of the subcarrier allocation process, the complexity of computing the ZF BF weight vector is $O(CNM^3)$, the complexity of computing composite channel gains is $O(CNGM) = O(CNM^2)$. For the remainder of the proposed subcarrier allocation process in the NOMA system, referring to the analysis of [29], the computational complexity is $O(CN \log N + N^2 + NC)$. Therefore, the overall complexity of the process is $O(CNM^3 + CN \log N + N^2 + NC)$.

In terms of the complexity of the bit allocation process, each subcarrier allocated to a cluster is loaded with $(R_c C)/N = r_b$ bits on average after execution of the subcarrier allocation algorithm. The number of cases in the lookup table to be checked and evaluated would be limited and is denoted Q_{table}. The computational complexity of the r_b bit redistribution process per subcarrier and cluster is $O(\sum_{c=1}^{C} |B_c| Q_{table}) = O(NQ_{table})$. Note that the power required for each transmission case can be evaluated separately in parallel by assigning multiple processors to accelerate the computational process. The computational complexity of the proposed resource allocation algorithm is $O(CNM^3 + CN \log(N) + N^2 + NC + NQ_{table})$.

Therefore, the overall complexity of the proposed solution to the user grouping and resource allocation problem is:

$$\begin{aligned} &O(NK^2 + CNM^3 + CN \log(N) + N^2 + NC + NQ_{table}) \\ &\qquad \approx O(NK^2 + CNM^3 + N^2 + NQ_{table}). \end{aligned}$$

V. SIMULATION RESULTS

We performed simulations to demonstrate the superiority of the proposed system over conventional methods. The performances of the proposed schemes were compared with those of a conventional OFDMA system (MU-OMA). The system consisted of one BS, which was equipped with two transmit antennas, M = 2. There were four modulation modes for each user's transmission, namely BPSK, QPSK, 16-QAM, and 64-QAM. The other simulation settings were described as follows:

- Number of subcarriers $N = 48$
- Symbol rate per subcarrier: 250 k transmit symbols per second
- Frame duration: 10 ms
- Total number of users in a cell: $K = 50$
- Numbers of clusters for service $C = 3, 4, 6,$ and 8
- Total system transmission data rate: 72 Mb/s
- Switching levels: 3.31, 6.48,11.61, and 17.64 dB [37]
- Required BER: 10^{-2}
- Number of multipath components: 15; maximum multipath delay spreads: 0.64 μs; user velocity: 1 km/h (in indoor propagation environments) [38]

Note that the performance in the case of raw data transmit was considered in the discussion. The BER performance of the calculated power required for the SINR associated with BER = 0.01 can be further improved with the inclusion of channel coding or another performance improvement technique over and above the transmission. In considering the above factor, BER was set to 0.01 because it yielded a performance improvement in the transmit by employing additional communication techniques, such as coding. The proposed schemes remained feasible upon adjusting the required SINRs associated with the specified BER to calculate the required transmit power. The resulting performance trends remained similar.

Adaptive allocation was performed on a per-frame basis. Perfect channel estimation was assumed in each frame. The user correlation threshold ρ was set to 0.9. Because the total system transmission data rate was 72 Mb/s, the average number of bits for each cluster per subcarrier was 6 bits per OFDM symbol transmission. The required data rate of each cluster was assumed to be the same. In this case, a few combinations of BPSK, QPSK, 16-QAM, and 64-QAM were available for groups of users in each cluster to transmit.

In the following simulation results, a few performance aspects are inspected. The advantages of the user-grouping algorithm are demonstrated by means of a comparison with random user selection in the MU-OMA and the NOMA

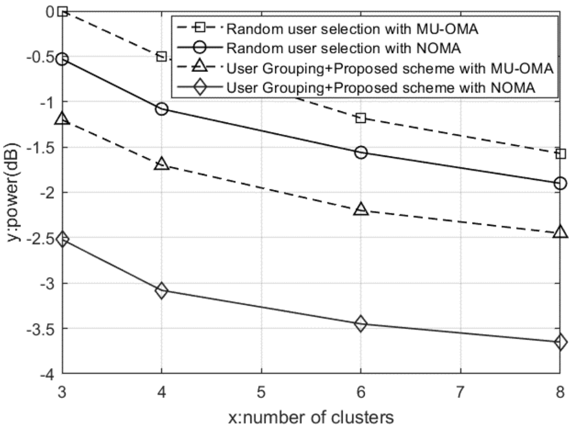

FIGURE 3. **The largest channel power difference among all selected users is 10 dB.**

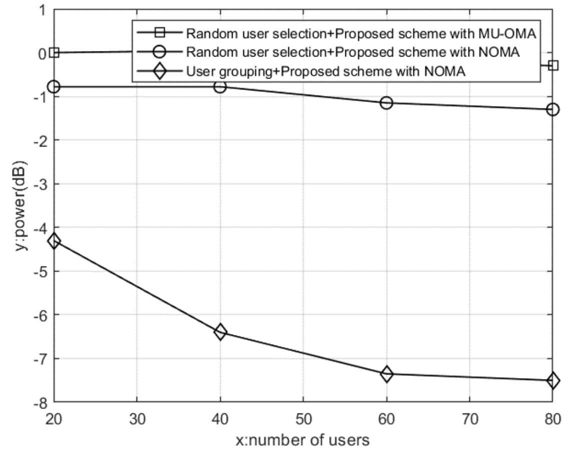

FIGURE 4. **The largest channel power difference among all users is 10 dB. C = 3.**

systems. The performance enhancement achieved by the proposed subcarrier allocation scheme, along with the bit allocation scheme, relative to that of random allocation is also discussed.

Figure 3 illustrates the total required system transmit power for different numbers of clusters in service, where the largest channel power difference among all selected users is 10 dB. The proposed subcarrier, along with the bit allocation scheme, was employed. By comparing the proposed user-grouping scheme with random user selection, we found that the former improved system performance when applied to either the MU-OMA or NOMA systems. In addition, in the NOMA system, the transmit power was reduced to an extent greater than that in case of the MU-OMA system when the proposed user-grouping scheme was employed. Note that the transmit power decreased as the number of clusters increased. This performance trend was ascribed to multiuser diversity gain. In Figs. 4 and 5, the number of the clusters for service $C = 3$ was fixed, and the total number of users for selection was varied. The largest channel power differences among users were 10 and 30 dB. The proposed allocation scheme offered the best performance. The required system transmit power decreased as the number of users increased.

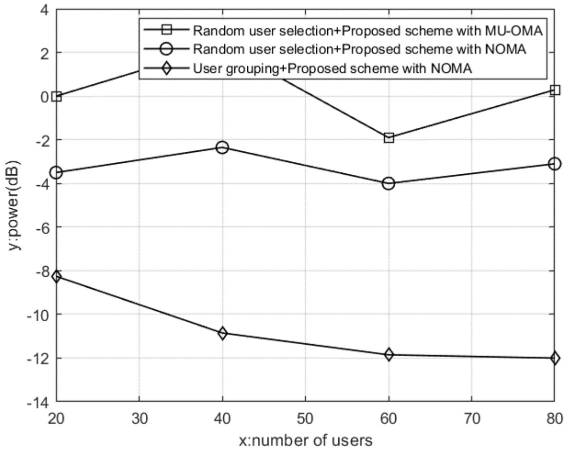

FIGURE 5. **The largest channel power difference among all users is 30 dB. C = 3.**

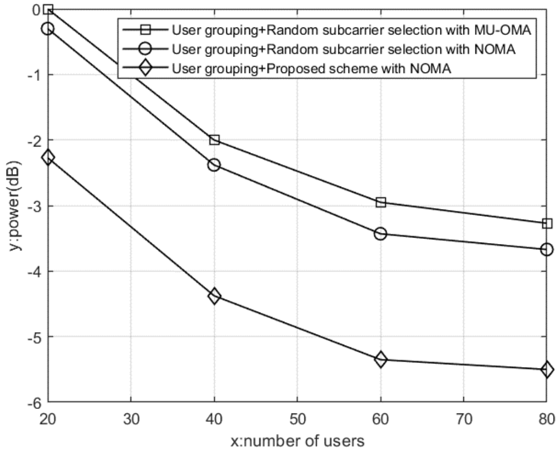

FIGURE 6. **The largest channel power difference among all users is 10 dB, C = 3.**

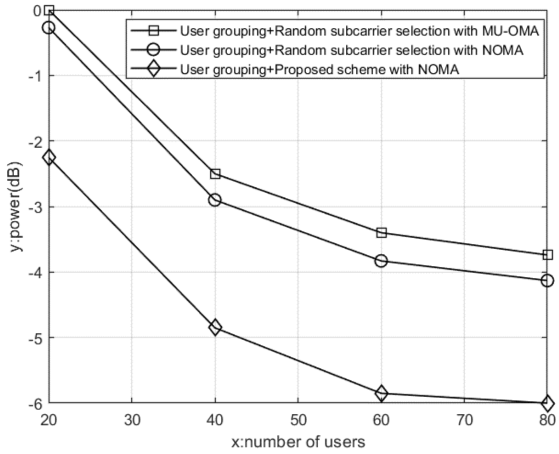

FIGURE 7. **The largest channel power difference among all users is 30 dB. C = 3.**

Figs. 6 and 7 depict the advantages of the proposed subcarrier allocation scheme relative to the random subcarrier allocation scheme used in the MU-OMA and the NOMA systems. The proposed user-grouping algorithm was employed in the proposed scheme. The number of the clusters for service

$C = 3$ was fixed, and the total number of users for selection was varied. The largest channel power differences among users were 10 and 30 dB. By implementing the proposed subcarrier allocation scheme, the required system transmit power can be reduced. It is well-known that multiuser diversity gain can be achieved by assigning subcarriers based on channel conditions for multiuser OFDM systems. The efficacy of the proposed subcarrier allocation procedures in NOMA systems can be inferred from the simulation results depicted in Figs. 6 and 7. As revealed in the simulation results, with the proposed subcarrier allocation algorithm, additional performance gain was achieved in terms of transmit power. In the scenarios under consideration, transmit power decreased by approximately 2 dB transmit when using the subcarrier assignment procedures after executing the user selection algorithm with NOMA transmission.

VI. CONCLUSION

In this paper, we proposed the user-grouping and the resource allocation algorithms to reduce the total required transmit power in multiuser multicarrier NOMA systems for downlink beamforming by considering the data-rate and error-rate constraints and practical modulation types. SIC and ZFBF were assumed in the systems. Our simulation results demonstrated the efficacy of the proposed user-grouping and resource allocation algorithms. The proposed NOMA allocation scheme outperformed the conventional MU-OMA in terms of the transmit power while fulfilling the QoS requirements.

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