Subcarrier-User Assignment in Downlink NOMA for Improving Spectral Efficiency and Fairness

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ABSTRACT Non-orthogonal multiple access (NOMA) has been recognized as an essential technology for beyond fifth-generation (beyond-5G) wireless networks to increase connectivity, spectral efficiency, cell-edge throughput, and user fairness. In this paper, we propose two subcarrier-user assignment algorithms (SUAAs) for the downlink NOMA system to enhance the spectral efficiency, the fairness, the data rate of weak users, and the outage probability. The assignment order of the first proposed SUAA is based on the worst subcarrier first (WSF) to avoid selecting a user with the worst channel gain with any subcarrier and called (WSF-SUAA). On the other hand, the second proposed SUAA is based on spectral efficiency maximization (SEM) and called (SEM-SUAA), but requires exhaustive search. The assignment process of both algorithms is based on making the channel gain of the selected paired users per subcarrier as high as possible to increase the data rate of each user. Besides, the assignment process of strong users for all subcarriers is performed before the assignment process of weak users to increase the total system sum-rate. It is exposed throughout the simulation that the two proposed SUAAs can attain significant improvement in the total spectral efficiency, weak user data rate, outage probability, and user fairness compared to the existing algorithms. While the performances of the two proposed SUAAs are convergent, the computational complexity of WSF-SUAA is significantly lower than that of SEM-SUAA and slightly higher than that of the existing algorithms.

INDEX TERMS Computational complexity, NOMA, spectral efficiency, user fairness.

I. INTRODUCTION

Due to the enormous demands of various services and fast growth of the mobile Internet and the Internet of Things (IoT) applications, the achievement of the fifth-generation (5G) and beyond-5G wireless system is expected to turn out by 2020s [1], and [2]. Non-orthogonal multiple access (NOMA) is a necessity to empower technology for beyond-5G wireless networks. NOMA related research has been investigated by both academia and industry because of its high spectral efficiency, enhanced cell-edge throughput, very low transmission latency, massive device connectivity, very high achievable data rate, ultra-high reliability, enhanced user fairness, and high energy efficiency [3]–[5]. The NOMA schemes can be categorized into two classes: power-domain NOMA (PD-NOMA) and code-domain NOMA (CD-NOMA).

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This paper concentrates on the PD-NOMA, in which various users are allocated distinct power levels according to their channel condition while appropriating the same time, frequency, and code resources at the transmitter sides. On the other hand, multiuser-detection (MUD) algorithms, such as successive-interference-cancellation (SIC) are implemented at the receiver sides to distinguish the favored signals. Also, PD-NOMA manages flexible resource allocation to enhance the performance of NOMA schemes, such as spectral efficiency (SE), energy efficiency (EE), and user fairness. On the way to demonstrate how PD-NOMA enhances user fairness, higher transmission power is allocated to the user with the bad channel state, on the other hand, lower transmission power is allocated to the user with the better channel [6]–[9].

The resource allocation problem in NOMA systems has attracted the attention of the research community in the past decade. Specifically, the problem of user pairing (UP) and power allocation (PA) based on NOMA have been adopted

in various researches [10]–[26]. Thus, in this paper, we concentrate on the UP problem and how the subcarrier selects its paired users. Particularly, two new subcarrier-user assignment algorithms (SUAAs) are introduced in this paper. Consequently, the main contributions of this paper are outlined as follows:

- Formulating the optimization problem of the subcarrier-user assignment and the power allocation in the downlink NOMA system for maximizing total system capacity and spectral efficiency.
- Proposing two new SUAAs that improve the spectral efficiency, the fairness, the data rate of weak users, and the outage probability of the considered system.
- Finally, the computational complexities of the two proposed SUAAs are investigated and compared with other existing algorithms.

The rest of the paper is organized as follows. The related works of NOMA-UP algorithms are presented in Section II. In Section III, we introduce the system model and formulate the sum-rate maximization issue mathematically. In Section IV, the two proposed subcarrier-user assignment algorithms are introduced; and their computational complexities are analyzed in Section V. In Section VI, simulation results and discussion are presented. Finally, Section VII concludes the paper.

II. RELATED WORKS

Recently, many researchers concentrated on enhancing SE, EE, and user fairness in the NOMA system through UP and PA algorithms. The random pairing in [10] is the primitive UP algorithm, in which random users are picked by the base station (BS) and are allocated randomly to free sub-channels. Although the random pairing algorithm is recognized as the lowest complexity method for UP schemes, it leads to a sub-optimal throughput because it does not take the users' channel gains into account. Thus, two UP schemes are investigated in [11], in which they greatly recognized the users' channel gains. These two UP schemes are namely, "fixed-power-allocation NOMA" (F-NOMA) and "cognitive-radio-inspired NOMA" (CR-NOMA). F-NOMA (pointed to as "conventional-user-pairing") has NOMA throughput which is higher than the orthogonal multiple-access (OMA) throughput because F-NOMA depends on pairing the user with the largest channel gain with the user of the worst channel gain. Conversely, in CR-NOMA, the quality of service (QoS) for users with the worst channel gains is warranted by pairing the user with the largest channel gain ("secondary user") with one of the second-largest channel gain ("primary user").

In [12], two UP approaches have been introduced, then, a generalized M-UP scheme is developed, to increase the capacity of almost all the users, while evading or lowering the mid-UP problem. These schemes are named "uniform channel gain difference" (UCGD) pairing and "hybrid UP". In the UCGD pairing, the great-gain users are associated with mid-gain users only, but the mid-gain users are associated

with great-gain users or low-gain users. In the hybrid UP scheme, "the conventional-user-pairing" is served for farthest edge-users with high channel gain differences, but when the channel gain difference between users begins to reduce, it changes to the UCGD pairing.

In [13] a virtual-UP is implemented to professionally appropriate the spectrum of un-paired users in NOMA systems, in which the frequency band can be participated by two far-users of comparable channel gains and a near-user. A "divide and next-largest-difference-based UP algorithm" (D-NLUPA) is introduced in [14], in which the fairness between the NOMA clusters can be achieved and the minimum sum-rate gain for each cluster is guaranteed. A joint UP and PA problem are examined in a downlink NOMA network in [15] towards optimizing the "achievable-sum-rate" (ASR) with the smallest rate restriction for each user, which is mixed-integer programming.

In [16], the enhanced low complexity radio resource allocation based on a greedy algorithm is presented for user grouping on the subcarriers. Furthermore, the work in [16] considered power allocation optimization for the sub-carriers of each user group by integrating the linear water filling with the fraction transmit power allocation (FTPA). A downlink multicarrier NOMA network is considered in [17] to jointly optimize (EE) and user fairness for subcarrier and power allocation parameters. Besides this, a novel greedy subcarrier assignment scheme that depends on the worst-user-first principle is advised with adequate complexity which is called the worst-case user first subcarrier allocation (WCUFSA) algorithm. Compared to the greedy algorithm, the WCUFSA algorithm allows the largest achievement in distributing better channel quality to allocate a subcarrier to users and avoids the assignment of the channel with low channel quality even in the end-stage.

The matching theory is employed in [18]–[23] to solve the UP problem in NOMA systems where suitable solutions can be obtained with relatively acceptable complexities. The principal concept of the matching process is that the users and subcarriers are viewed as two sets of players (proposers and selectors) to be joined with each other to maximize the total sum-rate. Each user and subcarrier select their favorite lists that should be consistent with their channel status. Then, each user (proposers) transmits a request to its most favored subcarrier. Later, this favored subcarrier (selector) owns the power to accept or decline the user's request based on the subcarrier's favorite list.

A joint subcarrier and PA problem for the downlink multi-carrier NOMA (MC-NOMA) system is studied in [25], which can reach a comparable performance to Lagrangian-duality and dynamic programming (LDDP) through designing the three-step resource allocation framework to deal with the sum-rate maximization problem. In the first step of the three-step resource allocation, the problem is relaxed by assuming each of the users can use all subcarriers simultaneously. Then, the problem converts to convex and can be solved efficiently via convex programming tools to get a
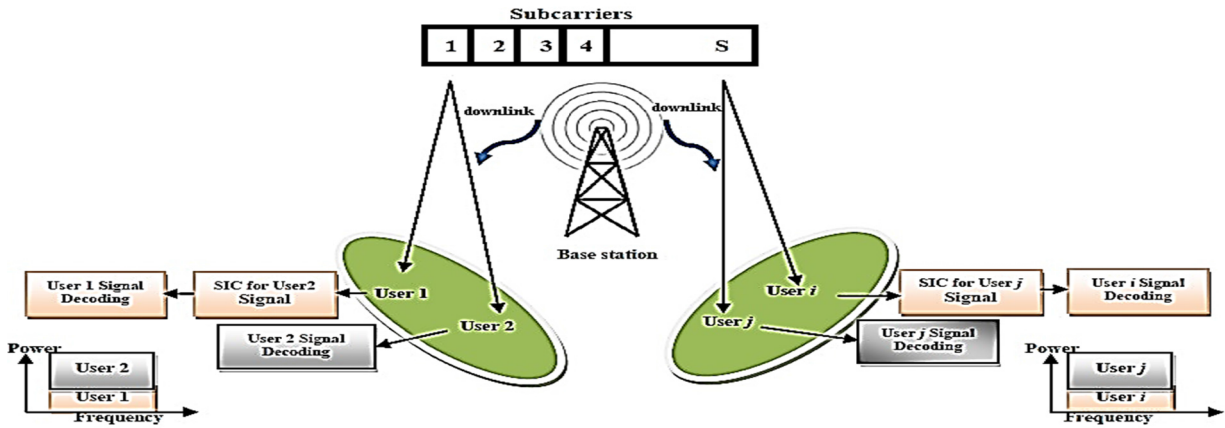
FIGURE 1. The downlink NOMA system model.

power vector for each user. In the second step, the subcarriers are allocated to users by a heuristic greedy manner with the obtained power vectors in the first step. In the third step, the proposed power control schemes used in the first step are further adjusted to optimize the final system performance.

In [26], the power consumption minimization problem for a generic multi-cell multiple input and single output NOMA (MISO-NOMA) system is studied through a joint user grouping, beamforming (BF), and power control perspective.

III. SYSTEM MODEL AND PROBLEM FORMULATION
In this section, the system model of the considered downlink NOMA systems is presented. Additionally, the problem of sum-rate maximization is formulated to improve SE and user fairness.

A. SYSTEM MODEL
A downlink NOMA system is depicted in Fig.1, where a BS concurrently sends information to a set of users expressed by $\mathbb{K} = \{1 \ldots K\}$, where K is the total number of users, which equals the cardinality of the set $\mathbb{K}$, (i.e., $= \#\mathbb{K}$, with # is the cardinality operator). The total available bandwidth B is uniformly apportioned into S subcarriers, each with bandwidth $W = \frac{B}{S}$ and the set of available subcarriers is $\mathbb{S} = \{1 \ldots S\}$, where $S = \#\mathbb{S}$ is the total number of possible subcarriers. The channel state information (CSI) is assumed to be perfectly informed to the BS. Based on the CSI of each subcarrier, the BS assigns a subset of subcarriers to a set of users and distributes various levels of power to them.

It is assumed that each subcarrier can be assigned to K_s users, where K_s is the number of multiplexed users on the subcarrier s. Consequently, the number of users is considered to be K= K_sS [15], [17], and [20].

Next, the signal sent from the BS to the K_s users paired on the subcarrier s is represented by [1], [2], and [6]–[8]:

$$x_s = \sum_{k=1}^{K_s} \sqrt{P_{s,k}} M_{s,k} \qquad (1)$$

where $P_{s,k}$ is the power allocated to user k on subcarrier s. Moreover, $M_{s,k}$ denote the message signal sent to user k on subcarrier s.

On subcarrier s, the obtained signal of user k can be expressed as in [1], [2], and [6]–[8]:

$$y_{s,k} = h_{s,k} x_s + Z_{s,k}$$
$$= \sqrt{P_{s,k}} h_{s,k} M_{s,k} + \sum_{i=1,i\neq k}^{K_s} \sqrt{P_{s,i}} h_{s,k} M_{s,i} + Z_{s,k} \qquad (2)$$

where $h_{s,k}$ is the complex channel gain from the BS to the kth user on subcarrier s, and $Z_{s,k}$ is the "complex additive white Gaussian noise" (AWGN) at user k with zero mean and variance $\sigma^2 = N_0 \frac{B}{S}$, where N_o is the noise-power-spectral-density.

To demodulate the desired signal at the receiving end, the receiver can utilize the SIC technique for signal detection, where the descending order of channel gains normalized by noise is a key factor in performing the SIC process. Let's assume that the channel gain normalized by noise for the users on the same subcarrier s are sorted in descending order as $\frac{|h_{s,1}|^2}{\sigma^2} \geq \ldots \geq \frac{|h_{s,k}|^2}{\sigma^2} \geq \ldots \geq \frac{|h_{s,K_s}|^2}{\sigma^2}$. The receiver of user K_s (i.e. user with worst channel gain on subcarrier s) can decode its signal message M_{s,K_s} directly without realizing the SIC technique and considers the signals of other users as interference. Alternatively, the receiver of user 1 (i.e. user with best channel gain on the same subcarrier s) decodes the signals messages of other users at first; and then extract them from the superimposed received signal. After that, user 1 can decode its signal $M_{s,1}$ without any interference from other users' signals.

To provide fairness and facilitate the SIC process among the paired users in NOMA, the BS will allocate more power to the low-channel-gain user, i.e. $P_{s,1} \leq \ldots \leq P_{s,k} \leq \ldots \leq P_{s,K_s}$.

Therefore, after performing the SIC process, the received signal to the interference plus noise ratio (SINR) of the user

k on subcarrier s is written as [16]–[20]:

$$SINR_{s,k} = \frac{P_{s,k} \left| h_{s,k} \right|^2}{\sum\limits_{i=1,i\neq k}^{k-1} P_{s,i} \left| h_{s,k} \right|^2 + \sigma_s^2} \tag{3}$$

Assume that the transmitted bandwidth per subcarrier is normalized to 1Hz and N_o is consistent over all subcarriers. Thus, the obtainable data rates of the kth user on the subcarrier s can be represented as follows [1], [2], and [6]–[8]:

$$R_{s,k} = \log_2 \left(1 + SINR_{s,k} \right)$$

$$= \log_2 \left(1 + \frac{P_{s,k} \left| h_{s,k} \right|^2}{\sum\limits_{i=1,i\neq k}^{k-1} P_{s,i} \left| h_{s,k} \right|^2 + N_o} \right) \tag{4}$$

Then the total system sum-rate is given by:

$$R_T = \sum_{s=1}^{S} R_s, \tag{5}$$

where, $R_s = \sum\limits_{k=1}^{K_s} R_{s,k}$ is the total sum-rate for subcarrier s.

B. PROBLEM FORMULATION

To adequately represent the pairing relation between subcarriers and users, we present a $(S \times K)$ subcarrier-user assignment matrix $Q_{S,K}$, wherein the binary element $q_{s,k}$ indicates whether subcarrier s is allocated to user k.

$$Q_{S,K} = \begin{bmatrix} q_{1,1} & \cdots & \cdots & q_{1,k} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ q_{s,1} & \cdots & \cdots & q_{s,k} \end{bmatrix} \tag{6}$$

$$q_{s,k} = \begin{cases} 1, & \text{if user } k \text{ is assigned to subcarrier } s; \\ 0, & \text{otherwise}; \end{cases} \tag{7}$$

To reduce the complexity of the SIC technique, it is recognized that each user can employ one subcarrier and only K_s users can be multiplexed over the same subcarrier. Accordingly, the number of users is thought to be K_s the number of subcarriers ($K = K_s S$).

Our goal is to maximize the total system sum-rate and to improve fairness among users. Hence, the optimization problem is formulated as follows:

Objective: $\max R_T$

Subject to

$$C_1 : \sum_{s=1}^{S} \sum_{k=1}^{K_s} P_{s,k} \leq P_t$$

$$C_2 : P_{s,k} \geq 0, \quad \forall s, k$$

$$C_3 : \sum_{k=1}^{K} q_{s,k} = K_s, \quad \forall s$$

$$C_4 : \sum_{s=1}^{S} q_{s,k} = 1, \quad \forall k$$

$$C_5 : q_{s,k} \in \{0, 1\}, \quad \forall s, k \tag{8}$$

where, P_t is the BS total available power. The constraints C_1 and C_2 ensures the power constraints for the BS and the users on each subcarrier, respectively. C_3 guarantees that each subcarrier can be used by no more than K_s users. C_4 shows that each user can obtain its data from only one subcarrier. C_5 imposes the subcarrier allocation indicator values.

IV. THE TWO PROPOSED SUBCARRIER-USER ASSIGNMENT ALGORITHMS (SUAAs)

In the procedures of the two proposed WSF-SUAA and SEM-SUAA, it is assumed that $K_s = 2$, subsequently, ($K = 2S$), to guarantee a suitable complexity of the SIC decoding technique at the user receiver.

The main objectives of the proposed WSF-SUAA and SEM-SUAA are as follows:

- Firstly, improving spectral efficiency by increasing the total system sum-rate.
- Secondly, enhancing the data rate of weak users which consequently improves the fairness among users and reduces the outage probability.

WSF-SUAA has lower computational complexity than that of SEM-SUAA since the assignment process of SEM-SUAA requires an exhaustive search for the maximization of spectral efficiency. To achieve these objectives, the following procedures are performed in the two proposed SUAA:

- The assignment of the strong users (1st paired users) for all subcarriers is firstly performed, then the assignment of the weak users (2nd paired users) for all subcarriers is performed. This procedure ensures that the subcarriers can get the strong users with the highest channel gains to increase the total system sum-rate since the sum-rate of the paired users mainly depends on the channel gain of the strong user.
- The channel gain of the assigned user whether a strong user or a weak user should be as high as possible according to the assignment process of each SUAA to increase the sum-rate of the paired users and the data rate of each user.

These procedures also guarantee that there will be a difference in channel gain between two paired users which is necessary for successful SIC.

A. THE PROPOSED WORST SUBCARRIER FIRST BASED SUBCARRIER-USER ASSIGNMENT ALGORITHM (WSF-SUAA)

The proposed WSF-SUAA depends on sorting subcarriers in ascending order according to the user with the worst channel gain of each subcarrier before assignment (i.e., pairing) process to prevent choosing a user with the worst channel gain with any subcarrier. The steps of the WSF-SUAA are described in detail as follows:

1) Given the subcarriers-users channel gain matrix, choose the user with the worst channel gain for each subcarrier (i.e., the worst channel gain in each row).
2) Order subcarriers in ascending order according to the worst user channel gain such that the assignment process starts with the subcarrier that has the lowest worst user channel gain (i.e., worst subcarrier first).
3) For each ordered subcarrier, select a strong user (1st paired user) as a user with the largest channel gain (select the highest value in each row) with removing the selected user from the next assignment process.
4) The remained unselected users will be selected as a weak user (2nd paired user) as:
   For each ordered subcarrier, select a weak user (2nd paired user) from the remained unselected users as the user with the largest channel gain (select the highest value in each row) with removing the selected user from the next assignment process.

The example displayed below uses a channel gain matrix to demonstrate the assignment process of the WSF-SUAA in detail.

Step 1 is performed as given in the matrix (M1). The selection of worst channel gain for each subcarrier is demonstrated in (M1) in which, the worst channel gain for subcarriers 1, 2, and 3 is 0.2, 0.4, and 0.1, respectively.

$$
\begin{bmatrix}
users: & 1 & 2 & 3 & 4 & 5 & 6 \\
subcarrier\,1: & 0.8 & 1.6 & 1.7 & 1.1 & 1.0 & \mathbf{0.2} \\
subcarrier\,2: & 0.7 & 0.9 & 1.5 & \mathbf{0.4} & 1.3 & 0.6 \\
subcarrier\,3: & 1.1 & 1.4 & 0.6 & 1.2 & 1.9 & \mathbf{0.1}
\end{bmatrix}
$$
(M1)

Step 2 is performed as given in (M2). The matrix (M2) displays the sorting of subcarriers (rows) from subcarrier 3 that has the worst channel gain to subcarrier 2 that has the best "worst channel gain". Thus, the assignment process starts with subcarrier 3 followed by subcarrier 1 and, lastly, subcarrier 2.

$$
\begin{bmatrix}
users: & 1 & 2 & 3 & 4 & 5 & 6 \\
subcarrier\,3: & 1.1 & 1.4 & 0.6 & 1.2 & 1.9 & \mathbf{0.1} \\
subcarrier\,1: & 0.8 & 1.6 & 1.7 & 1.1 & 1.0 & \mathbf{0.2} \\
subcarrier\,2: & 0.7 & 0.9 & 1.5 & \mathbf{0.4} & 1.3 & 0.6
\end{bmatrix}
$$
(M2)

Step 3 is performed as given in (M3). In (M3), the user that has the largest channel gain is selected as the strong user for each order subcarrier. Thus, user 5 is selected as the strong user for subcarrier 3. Then, user 3 is selected as the strong user for subcarrier 1. Finally, for subcarrier 2, user 3 is the largest channel gain, but user 3 was elected before by subcarrier 1. Therefore, a different user is explored with the next largest channel gain for subcarrier 2 which is user 5, but user 5 is selected before by subcarrier 3. Accordingly, user 2 has the next largest channel gain for subcarrier 2 and was not selected before by any subcarrier, so it can be allotted to subcarrier 2. The selected users 2, 3, and 5 are eliminated from the next selection as in M4. Also, in M4, the remained unselected

users will be selected as the weak user (the user with the largest channel gain) for each order subcarrier (i.e., Step 4). Thus, user 4 is selected as the weak user for subcarrier 3. Then, user 1 is selected as the weak user for subcarrier 1. Finally, for subcarrier 2, user 6 is selected as the weak user for it.

$$
\begin{bmatrix}
users: & 1 & 2 & 3 & 4 & 5 & 6 \\
subcarrier3: & 1.1 & 1.4 & 0.6 & 1.2 & \mathbf{1.9} & 0.1 \\
subcarrier1: & 0.8 & 1.6 & \mathbf{1.7} & 1.1 & 1.0 & 0.2 \\
subcarrier2: & 0.7 & \mathbf{0.9} & 1.5 & 0.4 & 1.3 & 0.6
\end{bmatrix}
$$
(M3)

$$
\begin{bmatrix}
users: & 1 & 2 & 3 & 4 & 5 & 6 \\
subcarrier3: & 0.0 & 0.0 & 0.0 & \mathbf{1.2} & \mathbf{1.9} & 0.0 \\
subcarrier1: & \mathbf{0.8} & 0.0 & \mathbf{1.7} & 0.0 & 0.0 & 0.0 \\
subcarrier2: & 0.0 & \mathbf{0.9} & 0.0 & 0.0 & 0.0 & \mathbf{0.6}
\end{bmatrix}
$$
(M4)

The subcarrier-user assignment matrix ($Q_{S,K}$) presented in (M5) shows that subcarrier 1 selects users {1, 3}, subcarrier 2 selects users {2, 6} and subcarrier 3 selects users {4, 5}. Algorithm 1 demonstrates the pseudo-code following the steps of the proposed WSF-SUAA.

$$
Q_{s,k} = \begin{bmatrix}
1 & 0 & 1 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 & 0 & 1 \\
0 & 0 & 0 & 1 & 1 & 0
\end{bmatrix}
$$
(M5)

Algorithm 1 Proposed WSF-SUAA

1:   *Initialization*: Construct channel gain matrix.

    $H = |h_{s,k}|^2 \,\forall s \in \mathbf{S}subcarriers\ k \in Kusers.$

2: **for** s =1 to S **do**
3:     **Select** the worst channel gain for each s subcarrier:

    $H_s^{worst} = min\,|h_{s,k}|^2\,\forall s.$

4:     **Sort** s subcarriers in ascending order according to $H_s^{\,worst}$.
5: **end for**
6: **for** Sorted s subcarrier **do**
7:     **Select** the user with ***max*** channel gain for each sorted s subcarrier (i.e. strong user):

    $H_{s-sorted}^{max} = max\,|h_{s-sorted,k}|^2\,\forall s - sorted$

8:     **Remove** the selected user from all *K-users* and don't select again by any subcarrier.
9: **end for**
10: **for** Sorted s subcarrier **do**
11:     **Select** the user with ***max*** channel gain from the remained unselected users for each sorted s subcarrier (i.e. weak user):

    $H_{s-sorted}^{max} = max\,|h_{s-sorted,remained-k}|^2\,\forall s - sorted$

12:     **Remove** the selected user from all *K-users* and don't select again by any subcarrier.
13: **end for**
14: *End of the Algorithm.*

B. THE PROPOSED SPECTRAL EFFICIENCY MAXIMIZATION BASED SUBCARRIER-USER ASSIGNMENT ALGORITHM (SEM-SUAA)

The assignment process of the proposed SEM-SUAA depends on exhaustive searching in the whole subcarrier-user matrix to maximize the spectral efficiency, and its steps can be illustrated briefly as follows:

1) Given the subcarrier-user gain matrix, find the maximum channel gain in the whole subcarrier-user channel gain matrix and select the user that has this channel gain as the strong user (1st paired user) over that subcarrier.
2) Remove the selected subcarrier-user (row-column) value in the previous step from the next selection.
3) Repeat steps 1 and 2 until each subcarrier selects its strong user.
4) The remaining unselected users in the subcarrier-unselected user channel gain matrix will be selected as a weak user (2nd paired user) as follows:
   a) Given the subcarrier-unselected user channel gain matrix, find the maximum channel gain in the whole subcarrier-unselected user channel gain matrix and select the user that has this channel gain as the weak user over that subcarrier.
   b) Remove the selected subcarrier-user (row-column) value in the previous step from the next selection.
5) Repeat steps (4.a) and (4.b) until each subcarrier selects its weak user.

The example displayed below uses a channel gain matrix to demonstrate the assignment process of the SEM-SUAA.

The matrix (M6) displays the selection of strong users (i.e., step 1 to step3). It is shown that the maximum channel gain value in the whole subcarriers-user matrix is 1.9 which belongs to user 5 over subcarrier 3. So, user 5 is selected as the strong user over subcarrier 3 and its channel gain value is removed from the subcarriers-user matrix. Then, a maximum channel gain value in the whole subcarriers-user matrix is explored again, and user 3 is selected as the strong user over subcarrier 1 and its channel gain value is removed from the subcarriers-user matrix. Finally, user 2 is selected as the strong user over subcarrier 2 and its channel gain value is removed from the subcarriers-user matrix to complete the assignment process of the strong user over each subcarrier.

$$
\begin{bmatrix}
\textbf{users}: & \textbf{1} & \textbf{2} & \textbf{3} & \textbf{4} & \textbf{5} & \textbf{6} \\
\textbf{subcarrier1}: & 0.8 & 1.6 & \underline{\textbf{1.7}} & 1.1 & 1.0 & 0.2 \\
\textbf{subcarrier2}: & 0.7 & \underline{\textbf{0.9}} & 1.5 & 0.4 & 1.3 & 0.6 \\
\textbf{subcarrier3}: & 1.1 & 1.4 & 0.6 & 1.2 & \underline{\textbf{1.9}} & 0.1
\end{bmatrix} \quad \text{(M6)}
$$

In (M7), the selected users 2, 3, and 5 are rejected from the next selection, and the assignment process of the weak user over each subcarrier is started according to step 4. The subcarrier-user assignment matrix ($Q_{S,K}$) presented in (M8) shows that subcarrier 1 selects users {1, 3}, subcarrier 2 selects users {2, 6}, and subcarrier 3 selects users {4, 5}. Algorithm 2 displays the pseudo-code following the steps of the proposed SEM-SUAA.

$$
\begin{bmatrix}
\textbf{users}: & \textbf{1} & \textbf{2} & \textbf{3} & \textbf{4} & \textbf{5} & \textbf{6} \\
\textbf{subcarrier1}: & \underline{\textbf{0.8}} & 0.0 & 0.0 & 1.1 & 0.0 & 0.2 \\
\textbf{subcarrier2}: & 0.7 & 0.0 & 0.0 & 0.4 & 0.0 & \underline{\textbf{0.6}} \\
\textbf{subcarrier3}: & 1.1 & 0.0 & 0.0 & \underline{\textbf{1.2}} & 0.0 & 0.1
\end{bmatrix} \quad \text{(M7)}
$$

$$
Q_{s,k} = \begin{bmatrix}
1 & 0 & 1 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 & 0 & 1 \\
0 & 0 & 0 & 1 & 1 & 0
\end{bmatrix} \quad \text{(M8)}
$$

From two previous examples of the two proposed SUAAs which consider a small number of subcarriers and users, it is worth mentioning that the subcarrier-user assignment matrix ($Q_{s,k}$) resulted in the allocation process of WSF-SUAA and SEM-SUAA are equal. So, it is expected that there will be no significant differences in the results of the allocation process of the two proposed SUAAs (i.e., the resulted subcarrier-user assignment matrix ($Q_{s,k}$) of the two proposed SUAAs will be slightly different) when the number of subcarriers and users increases. Thus, the performance of both of them will be convergent as will be seen in section VI. But it should be noted that the proposed SEM-SUAA needs exhaustive search and has a higher computational complexity compared to WSF-SUAA.

V. COMPUTATIONAL COMPLEXITY

In this section, the computational complexities of the two proposed SUAAs are investigated and compared with the existing algorithms such as the worst-case user first subcarrier allocation (WCUFSA), the "conventional-user-pairing", and "random pairing" algorithms. As presented in section II, the random pairing [10] needs a number of operations K operations to pick two random users for each of the S numbers of subcarriers (i.e. $\sum_{s=1}^{S} 2 = 2S = K$). For the conventional user pairing [11], it involves a number of operations $S(K-1)$ operations for searching for the user with the maximum channel gain and the user with the minimum channel gain from the available K users to be paired together for the S subcarriers (i.e. $\sum_{s=1}^{S} \frac{2(K-1)}{2} = S(K-1)$).

For the WCUFSA algorithm in [17], it needs the number of operations ($\sum_{k=1}^{K}(S-1) = K(S-1)$) operations to find a subcarrier with the minimum channel quality for each user of the K users. Then, ($2K \ln K$) operations are needed to sort the K users in ascending order. Finally, ($K(S-1)$) operations are needed to search the subcarrier with the highest channel gain for each user of the K sorted users. So the total number of operations for the WCUFSA algorithm are ($2K \ln K + 2K(S-1)$) operations.

For the proposed WSF-SUAA, the number of operations needed to find the user with the worst channel gain from accessible K users for each subcarrier of the S subcarriers are $\sum_{s=1}^{S}(K-1) = S(K-1)$ operations. Then, ($2S \ln S$) operations are needed to sort the S subcarriers. Finally, ($\sum_{s=1}^{S} \frac{(K-1)}{2} = S\frac{(K-1)}{2}$) operations are needed to find the strong user that has the maximum channel gain for the S

Algorithm 2 Proposed SEM-SUAA

1: *Initialization*: Construct channel gain matrix.

$$H = \left|h_{s,k}\right|^2 \forall s \in S \text{ subcarriers } \& \ k \in K \text{ users.}$$

2: **Select** the **strong user** as a user with **max** channel gain in all channel gain matrix:

$$H^{max} = max \left|h_{s,k}\right|^2 \forall s \& \ k.$$

3: **Remove** the selected subcarrier-user (row-column) value from the next assignment process.

4: **if** all subcarriers select its strong user **then**

5:   **Go to** the remainder subcarrier-unselected user channel gain matrix.

6:   **Select** the **weak user** as a user with *max* channel gain in all remainder channel gain matrix:

$$H^{max} = max \left|h_{s,k-remained}\right|^2 \forall \ s\& \ remained - k.$$

7:   **Remove** the selected subcarrier-user (row-column) value from the next assignment process.

8: **else**

9:   **Repeat** step 2 & step 3.

10: **end if**

11: **if** all subcarriers select its weak user **then**

12:   **End the algorithm.**

13: **Else**

14:   **Repeat** step 6 & step 7.

15: **end if**

16: *End of the Algorithm.*

---

subcarriers, and the same number of operations are needed to find the weak user for the S subcarriers with eliminating the selected user after each allocation process. Therefore, the number of operations needed to find the two paired users are $\frac{\sum_{s=1}^{S} 2}{2} (K-1) = S(K-1)$ operations, where $K = 2S$. So the total number of operations for the proposed WSF-SUAA are $(S(K-1) + 2S \ln S + S(K-1)) = 2S \ln S + (K-1)(S+S) = 2S \ln S + 2S(K-1)$ operations.

For the proposed SEM-SUAA, the required number of operations to search for the maximum channel gain in the whole subcarrier-user channel gain matrix (i.e., finding the strong user for the S subcarrier) are $\sum_{i=0}^{S-1} (S-i)(K-i) - S$. Keeping in mind that each selected value will delete the row-column values belongs to it after each allocation process. Then, this process is repeated for finding the weak user in the remained subcarrier-unselected user channel gain matrix. So, the number of operation for this step are $\sum_{i=0}^{S-1} (S-i)\left(\frac{K}{2} - i\right) - S$ operations. Therefore, the total number of operations for the proposed SEM-SUAA can be viewed as $\sum_{i=0}^{S-1} (S-i)(K-i) - S + \sum_{i=0}^{S-1} (S-i)\left(\frac{K}{2} - i\right) - S = (\sum_{i=0}^{S-1} (S-i)(\frac{3*K}{2} - 2i)) - 2S$ operations.

To justify the computational complexity equations of the two proposed SUAAs, the steps of the two previous examples of the two proposed SUAAs are analyzed, which use $K = 6$ users and $S = 3$ subcarriers.

For the example of the assignment process of the WSF-SUAA, the number of operations can be calculated as:

1) In M1, the user with the worst channel gain for each subcarrier is selected. So, for subcarrier 1, user 1 is taken as a reference number to be compared with the remainder of users. Thus, this step requires (5-operations) to complete this comparison and obtain the user with the worst channel gain. The previous operation is repeated for subcarrier 2 and subcarrier 3, so the total numbers of operations required in M1 are (5+5+5=15 operations).

2) In M2, the subcarriers are sorted in an ascending order consistent with the obtained worst channel gain in M1.
2-a) Comparison between the worst channel-gains obtained in M1 is required (3-operations).
2-b) Then, the subcarriers re-order in their new position (row), and this needs (3-operations). Accordingly, the total numbers of operations required in M2 are (6-operations).

3) In M3, each subcarrier selects one user (strong user) that has the largest channel gain in his row. So, sub-carrier 3 needs (5-operations) and subcarrier 1 needs (4-operations). Since the user selected by subcarrier 3 is eliminated from the total number of users. Similarly subcarrier 2 needs (3-operations). Therefore, the total numbers of operations required in M3 are (5+4+3=12 operations).

4) In M4, the operations that performed previously in M3 is repeated to distribute the remaining unselected users as weak users among the three subcarriers. Thus, subcarrier 3 selects one of the three remaining unselected users (i.e. 2-operations), subcarrier 1 selects one of the two remaining users (i.e. 1-operation) and finally, subcarrier 2 has to select the one remaining user (i.e. zero-operation). Accordingly, the total numbers of operations required in M4 are (2+1+0=3 operations).

Consequently, the total numbers of operations of the previous example of the WSF-SUAA are (15+6+12+3=36 operations) and this result approves the validity of the computational complexity equation of the WSF-SUAA which is $(2S \ln S + 2S(K-1) = 2*3* \ln 3 + 2*3(6-1) = 36)$.

Furthermore, the number of operations of the example of the assignment process of the SEM-SUAA can be calculated as:

1) In M6, the maximum channel gain value in the whole subcarriers-user matrix (row-column matrix) is searched and the obtained value belongs to the strong user over that subcarrier (column-row value). Thus, if the first number in the whole matrix is taken as a reference number to be compared with all remainder numbers in the matrix, the numbers of operations required to perform this step are ((3*6)−1=17 operations). Then, the selected subcarrier-user value (row-column value) in the previous step is removed from the next
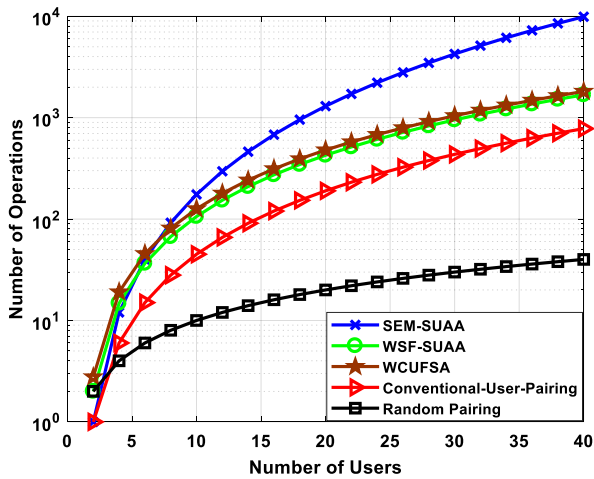
FIGURE 2. The number of operations versus the different number of users with $K = 2S$.

TABLE 1. Comparison of computational complexity.

Algorithms	NO. of Operations
Random Pairing	K
Conventional-User-Pairing	$S(K-1)$
WCUFSA	$2K \ln K + 2K(S-1)$
1st Proposed SUAA (WSF-SUAA)	$2S \ln S + 2S(K-1)$
2nd Proposed SUAA (SEM-SUAA)	$(\sum_{i=0}^{S-1}(S-i)(\frac{3*K}{2}-2i))-2S$

TABLE 2. The number of operations of the different SUAAs at a different number of users.

Number of Users	The number of operations of the different SUAAs				
	Random Pairing	Conventional-User-Pairing	WCUFSA	WSF-SUAA	SEM-SUAA
$K=4$	4	6	19	14	12
$K=8$	8	28	81	61	92
$K=16$	16	120	312	273	680
$K=32$	32	496	1181	1080	5136
$K=40$	40	780	1815	1679	9900

search and the previous operation is repeated until all subcarriers select their strong user. So, in each searching operation, both the number of rows and the number of columns are decreased by 1. Also, the searching operation in the whole matrix is repeated 3 times, as the number of subcarriers is equal to 3. Accordingly, the total numbers of operations required in M6 are ([[(3*6)−1] + [(2*5)−1] + [(1*4)−1] =29 operations).

2) In M7, the previous searching operations performed in M6 is repeated to allocate the remaining unselected users as weak users among the three subcarriers in the subcarrier-unselected user channel gain matrix. So, the total numbers of operations required in M7 are ([[(3*3)−1] + [(2*2)−1] + [(1*1)−1] =11 operations).

Consequently, the total numbers of operations of the previous example of the SEM-SUAA are (29+11 = 40 operations) and this result confirms the validity of the computational complexity equation of the SEM-SUAA which is $((\sum_{i=0}^{S-1}(S-i)(\frac{3*K}{2}-2i))-2S) = ((\sum_{i=0}^{2}(3-i)(\frac{3*6}{2}-2i))-2*3) = 40$.

Table 1 displays the total number of operations of the above-discussed SUAAs. Moreover, the number of operations versus the different number of users for the different SUAAs are displayed in Fig. 2. Also, Table 2 illustrates the number of operations of the different-discussed SUAAs at a different number of users. It is noted from fig. 2 and table 2 that the two proposed SUAAs provide a high computational complexity than the "conventional-user-pairing", and "random pairing" algorithms and the proposed SEM-SUAA gives a higher computational complexity than that of the proposed WSF-SUAA because of its exhaustive searching. Furthermore, the WCUFSA algorithm gives higher computational complexity than all algorithms when the number of users < 5. But, when the number of users > 5, the WCUFSA algorithm furnishes the computational complexity value between two proposed SUAAs.

VI. SIMULATION RESULTS

In this part, we display the simulation results to assess the performance of the two proposed SUAA schemes, specifically in comparison with the worst-case user first subcarrier allocation (WCUFSA) algorithm, the "conventional-user-pairing", "random pairing", and "orthogonal-multiple-access system" (OMA). The channel of the considered downlink NOMA system in our simulations is a multipath frequency-selective-fading channel. In the channel model, the fading parameter is a random variable and follows a Rayleigh distribution. The transmitted bandwidth per subcarrier is normalized to 1Hz.

For simplicity, the BS distributes the total transmit power uniformly between subcarriers. Then, a fixed power allocation algorithm is applied to distribute the power per subcarrier s between its paired users, therefore $P_{s,i} = 0.2P_s$ and $P_{s,j} = 0.8P_s$. In our evaluations, we performed 10000-channel realizations.

Most of the simulation results are presented versus "the signal-to-noise-ratio" (SNR) per subcarrier for $S = 16$ subcarriers and $K = 32$ users.

The Spectral efficiency (SE) versus SNR is demonstrated in Fig. 3 for $S = 16$ subcarriers and $K = 32$ users. The SE is denoted by [24] as:

$$SE = \frac{achieved\ system\ sum\ rate}{amount\ of\ used\ BW} \qquad (9)$$

Fig. 3 illustrates that the SE of all algorithms increases with the increase of the SNR. The two proposed SUAAs
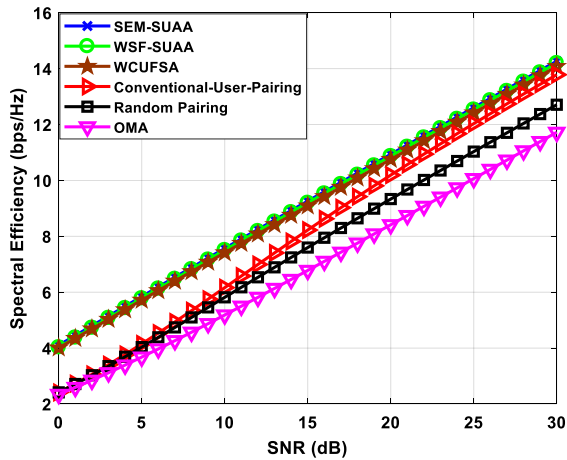
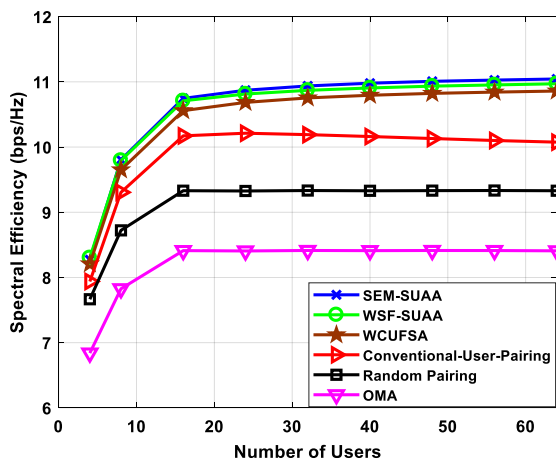**FIGURE 3.** The spectral efficiency versus SNR for $S = 16$ subcarriers and $K = 32$ users.

FIGURE 4. The spectral efficiency versus the different number of users at SNR=20dB.

TABLE 3. The percentage of increase in SE of the two proposed SUAAs with respect to other algorithms at different number of users and SNR=20dB.

Algorithms	Percentage of increase in SE of the two proposed SUAAs			
	1st Proposed SUAA (WSF-SUAA)		2nd Proposed SUAA (SEM-SUAA)	
	At K=32 users	At K=64 users	At K=32 users	At K=64 users
OMA	29.2 %	30.4 %	29.4 %	31.3 %
Random Pairing	16.4 %	17.6 %	17.1 %	18.4 %
Conventional-User-Pairing	6.7 %	8.9 %	7.3 %	9.6 %
WCUFSA	1.2 %	1.0 %	2.3 %	1.8 %
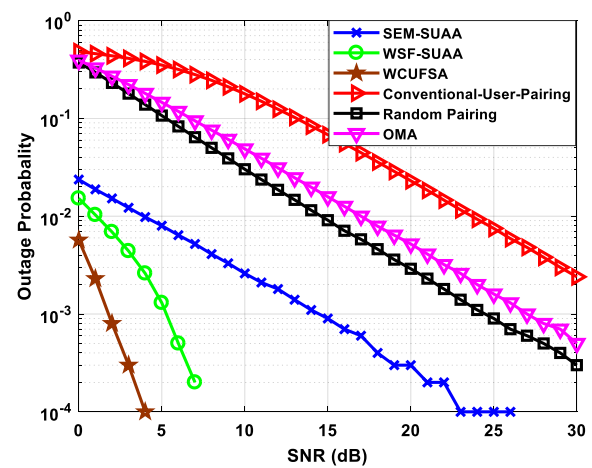
FIGURE 5. The outage probability versus SNR for $S = 16$ subcarriers and $K = 32$ users.

accommodate larger SEs than other algorithms, Because of the higher channel gain of the assigned users (strong user or weak user) which resulted from the assignment process of each one of the proposed SUAA, leading to an increase in the sum-rate of the assigned users. The SE of the two proposed SUAAs is approximately identical since the two paired users (strong user and weak user) have the same nature despite the different steps of the two proposed SUAAs.

To prove that two proposed SUAAs enhance the performance of the SE than other algorithms, Fig. 4 displays the SE versus the different number of users at SNR=20dB. The SE of the two proposed SUAAs is identical when the number of users is small but, when the number of users is increased, the SE of the proposed SEM-SUAA becomes slightly higher than that of the proposed WSF-SUAA. Because the SEM-SUAA relies on the exhaustive search for finding the user with maximum channel gain in the whole subcarrier-user matrix to maximize the spectral efficiency. On the other hand, the WSF-SUAA relies on sorting subcarriers in ascending order according to the user with the worst channel gain that is selected for each subcarrier

before the assignment process to avoid selecting a user with the worst channel gain with any subcarrier.

To illustrate that the two proposed SUAAs provide better performance in the SE than other algorithms, Table 3 shows the percentage of increase in SE of the two proposed SUAAs than other algorithms at the different number of users and SNR=20dB.

The outage probability versus SNR is investigated in Fig. 5. The outage probability is described as the probabilities that the data transmission rate of the simulated user has not arrived at the target data rate of 1bps/Hz. It is shown that the outage probabilities of the two proposed SUAAs are better than that of the existing algorithms except for the WCUFSA algorithm as they enhance the data rate of each of the paired users (strong user and weak users). The WCUFSA algorithm gives a better outage probability value than the two proposed SUAAs and this value is approximately near to the proposed WSF-SUAA as it allows the users with the worst channel quality to select their desired best subcarrier first and hence, it enhances the data rate of these poorer users. The outage
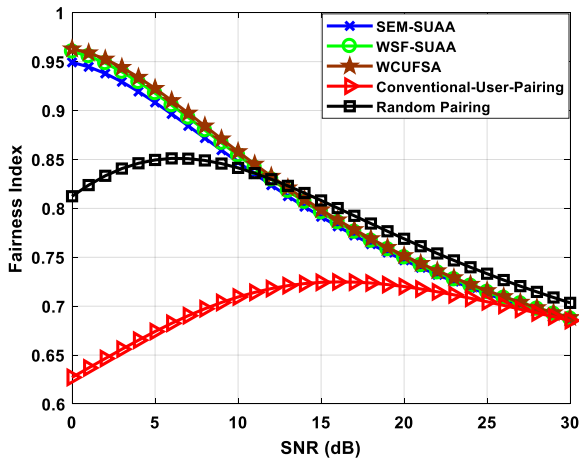
FIGURE 6. The fairness index versus SNR for $S = 16$ subcarriers and $K = 32$ users.

FIGURE 7. The average data rate per weak user versus SNR for $S = 16$ subcarriers and $K = 32$ users.

probability of the proposed WSF-SUAA is better than that of the proposed SEM-SUAA. As the assignment process of the proposed WSF-SUAA improves the opportunity of selecting the best-paired users with the high channel gains for the worst subcarriers and hence avoids the degradation of the data rates paired users for the worst subcarriers.

The fairness index versus SNR is displayed in Fig. 6 for the NOMA schemes (the two proposed SUAA schemes, WCUFSA, "conventional-user-pairing", and "random pairing"). The goal of the fairness index is to show how fairly the resources are distributed among the users in the system. The fairness index (FI) is expressed in terms of a data rate of users by [27], [28] as:

$$FI = \frac{(\sum_{k=1}^{K} R_k)^2}{K \sum_{k=1}^{K} (R_k)^2} \quad (10)$$

Fig. 6 demonstrates that the FI of the two proposed SUAAs is approximately identical to the WCUFSA algorithm because the WCUFSA algorithm also aims to enhance the data rate of the two paired users. The FI of the two proposed SUAAs is larger than that of the conventional user pairing algorithm and the random pairing algorithm when SNR < 10dB since they provide high sum-rate than other existing algorithms. When SNR > 10 dB, the random pairing algorithm provides slightly better FI compared to the two proposed SUAAs and conventional user pairing algorithms. Because there is no preference in the subcarrier-user assignment of the random pairing algorithm, and because of the random characteristics of its subcarrier-user assignment.

The average data rate per weak user versus SNR is exposed in Fig. 7 for the NOMA schemes. This figure confirms that the average data rates per weak user of two proposed SUAAs are higher than the "conventional-user-pairing", "random pairing" algorithms for SNR < 25dB. Although the steps of the two proposed SUAAs and the WCUFSA algorithm are different, they provide the same average data rate per weak user. Because the assignment process of the two proposed SUAAs and the WCUFSA algorithm is based on making
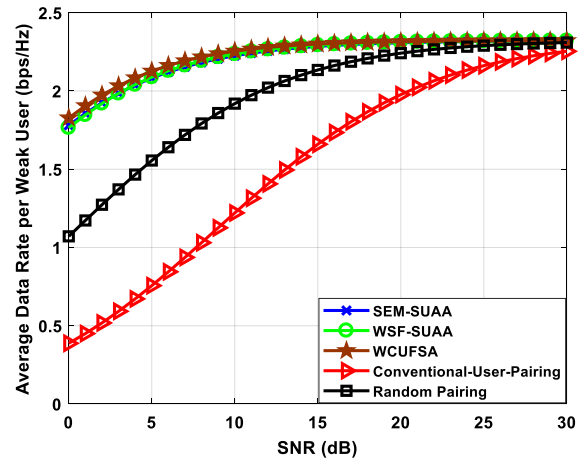
the channel gain of the two paired user (strong user and weak user) as high as possible which consequently enhance the data rate of each user and the sum-rate of the paired users. On the other hand, the "conventional-user-pairing" algorithm chooses the weak user as a user of the minimum channel gain, and the "random pairing" algorithm chooses the weak user randomly.

VII. CONCLUSION

Two new proposed algorithms for the subcarrier-user assignment in the NOMA system are investigated in this paper. The first proposed algorithm is named WSF-SUAA, and depends on arranging subcarriers in ascending order consistent with the user with the worst channel gain that is chosen for each subcarrier before the subcarrier-user assignment process to prevent choosing a user with the highest worst channel gain with any subcarrier. Conversely, the second proposed algorithm is named SEM-SUAA, and relies on exhaustive exploration to choose the paired users for each subcarrier. The assignment process of both proposed SUAA aims to make the channel gain of the selected paired user per subcarrier whether the strong user or weak user as high as possible to increase the data rate of each user. Besides the assignment of the strong users for all subcarriers is performed before the assignment of the weak users to increase the total system sum-rate. The presented simulation results demonstrate that the two proposed SUAAs outperform other existing SUAA algorithms in improving spectral efficiency and enhancing the data rate of the weak user, outage probability, and user fairness. But, the computational complexity of the proposed SEM-SUAA is higher than the proposed WSF-SUAA and other existing algorithms.

REFERENCES

[1] S. M. R. Islam, N. Avazov, O. A. Dobre, and K.-S. Kwak, "Power-domain non-orthogonal multiple access (NOMA) in 5G systems: Potentials and challenges," *IEEE Commun. Surveys Tuts.*, vol. 19, no. 2, pp. 721–742, 2nd Quart., 2017, doi: 10.1109/COMST.2016.2621116.

[2] S. M. R. Islam, M. Zeng, O. A. Dobre, and K. Kwak, *Non-Orthogonal Multiple Access (NOMA): How It Meets 5G and Beyond*. Hoboken, NJ, USA: Wiley, 2019, doi: 10.1002/9781119471509.w5GRef032.

[3] 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, doi: 10.1109/COMST.2018.2835558.

[4] M. Aldababsa, M. Toka, S. Gökçeli, G. K. Kurt, and O. Kucur, "A tutorial on nonorthogonal multiple access for 5G and beyond," *Wireless Commun. Mobile Comput.*, vol. 2018, pp. 1–24, Jun. 2018, doi: 10.1155/2018/9713450.

[5] L. Dai, B. Wang, Y. Yuan, S. Han, I. Chih-lin, and Z. Wang, "Non-orthogonal multiple access for 5G: Solutions, challenges, opportunities, and future research trends," *IEEE Commun. Mag.*, vol. 53, no. 9, pp. 74–81, Sep. 2015, doi: 10.1109/MCOM.2015.7263349.

[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, doi: 10.1109/VTCSpring.2013.6692652.

[7] K. Higuchi and A. Benjebbour, "Non-orthogonal multiple access (NOMA) with successive interference cancellation for future radio access," *IEICE Trans. Commun.*, vol. E98.B, no. 3, pp. 403–414, 2015, doi: 10.1587/transcom.E98.B.403.

[8] Z. Wei, J. Yuan, D. Ng, M. Elkashlan, and Z. Ding, "A survey of downlink non-orthogonal multiple access for 5G wireless communication networks," *ZTE Commun.*, vol. 14, no. 4, pp. 17–26, Oct. 2016.

[9] 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, doi: 10.1109/JSAC.2017.2725519.

[10] Z. Ding, P. Fan, and H. V. Poor, "User pairing in non-orthogonal multiple access downlink transmissions," in *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, Dec. 2015, pp. 1–5, doi: 10.1109/GLOCOM.2015.7417061.

[11] Z. Ding, P. Fan, and H. V. Poor, "Impact of user pairing on 5G nonorthogonal multiple-access downlink transmissions," *IEEE Trans. Veh. Technol.*, vol. 65, no. 8, pp. 6010–6023, Aug. 2016, doi: 10.1109/TVT.2015.2480766.

[12] M. B. Shahab, M. Irfan, M. F. Kader, and S. Y. Shin, "User pairing schemes for capacity maximization in non-orthogonal multiple access systems," *Wireless Commun. Mobile Comput.*, vol. 16, no. 17, pp. 2884–2894, Sep. 2016, doi: 10.1002/wcm.2736.

[13] M. B. Shahab, M. F. Kader, and S. Y. Shin, "A virtual user pairing scheme to optimally utilize the spectrum of unpaired users in non-orthogonal multiple access," *IEEE Signal Process. Lett.*, vol. 23, no. 12, pp. 1766–1770, Dec. 2016, doi: 10.1109/LSP.2016.2619371.

[14] S. M. R. Islam, M. Zeng, O. A. Dobre, and K.-S. Kwak, "Resource allocation for downlink NOMA systems: Key techniques and open issues," *IEEE Wireless Commun.*, vol. 25, no. 2, pp. 40–47, Apr. 2018, doi: 10.1109/MWC.2018.1700099.

[15] L. Zhu, J. Zhang, Z. Xiao, X. Cao, and D. O. Wu, "Optimal user pairing for downlink non-orthogonal multiple access (NOMA)," *IEEE Wireless Commun. Lett.*, vol. 8, no. 2, pp. 328–331, Apr. 2019, doi: 10.1109/LWC.2018.2853741.

[16] O. A. Saraereh, A. Alsaraira, I. Khan, and P. Uthansakul, "An efficient resource allocation algorithm for OFDM-based NOMA in 5G systems," *Electronics*, vol. 8, no. 12, p. 1399, Nov. 2019, doi: 10.3390/electronics8121399.

[17] A. J. Muhammed, Z. Ma, P. D. Diamantoulakis, L. Li, and G. K. Karagiannidis, "Energy-efficient resource allocation in multicarrier NOMA systems with fairness," *IEEE Trans. Commun.*, vol. 67, no. 12, pp. 8639–8654, Dec. 2019, doi: 10.1109/TCOMM.2019.2938963.

[18] B. Di, S. Bayat, L. Song, and Y. Li, "Radio resource allocation for downlink non-orthogonal multiple access (NOMA) networks using matching theory," in *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, Dec. 2015, pp. 1–6, doi: 10.1109/GLOCOM.2015.7417643.

[19] B. Di, L. Song, and Y. Li, "Sub-channel assignment, power allocation, and user scheduling for non-orthogonal multiple access networks," *IEEE Trans. Wireless Commun.*, vol. 15, no. 11, pp. 7686–7698, Nov. 2016, doi: 10.1109/TWC.2016.2606100.

[20] 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, doi: 10.1109/TCOMM.2016.2594759.

[21] W. Liang, Z. Ding, Y. Li, and L. Song, "User pairing for downlink non-orthogonal multiple access networks using matching algorithm," *IEEE Trans. Commun.*, vol. 65, no. 12, pp. 5319–5332, Dec. 2017, doi: 10.1109/TCOMM.2017.2744640.

[22] J. Zhu, J. Wang, Y. Huang, S. He, X. You, and L. Yang, "On optimal power allocation for downlink non-orthogonal multiple access systems," *IEEE J. Sel. Areas Commun.*, vol. 35, no. 12, pp. 2744–2757, Dec. 2017, doi: 10.1109/JSAC.2017.2725618.

[23] D. Pliatsios and P. Sarigiannidis, "Resource allocation combining heuristic matching and particle swarm optimization approaches: The case of downlink non-orthogonal multiple access," *Information*, vol. 10, no. 11, p. 336, Oct. 2019, doi: 10.3390/info10110336.

[24] M.-R. Hojeij, J. Farah, C. A. Nour, and C. Douillard, "New optimal and suboptimal resource allocation techniques for downlink non-orthogonal multiple access," *Wireless Pers. Commun.*, vol. 87, no. 3, pp. 837–867, Apr. 2016, doi: 10.1007/s11277-015-2629-2.

[25] Y. Fu, L. Salaun, C. W. Sung, and C. S. Chen, "Subcarrier and power allocation for the downlink of multicarrier NOMA systems," *IEEE Trans. Veh. Technol.*, vol. 67, no. 12, pp. 11833–11847, Dec. 2018, doi: 10.1109/TVT.2018.2875601.

[26] Y. Fu, Y. Zhang, L. Salaun, C. W. Sung, and C. S. Chen, "Zero-forcing oriented power minimization for multi-cell MISO-NOMA systems: A joint user grouping, beamforming, and power control perspective," *IEEE J. Sel. Areas Commun.*, vol. 38, no. 8, pp. 1925–1940, Aug. 2020, doi: 10.1109/JSAC.2020.3000825.

[27] R. Jain, D. M. Chiu, and WR. Hawe, "A quantitative measure of fairness and discrimination for resource allocation in shared computer systems," Eastern Res. Lab., Digit. Equip. Corp., Hudson, MA, USA, Tech. Rep., cs.NI/9809099, 1998.

[28] M. Elsherief, M. Elwekeil, and M. Abd-Elnaby, "Resource and power allocation for achieving rate fairness in D2D communications overlaying cellular networks," *Wireless Netw.*, vol. 25, no. 7, pp. 4049–4058, Oct. 2019, doi: 10.1007/s11276-018-01935-y.

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