Enhanced Resource Allocation in D2D Communications With NOMA and Unlicensed Spectrum

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***Abstract*—Device-to-device (D2D) communications with non-orthogonal multiple access (NOMA) have been proved in enhancing the network capacity and reducing the burden of the traditional cellular network. Due to reusing the same resources, underlying D2D communication may cause high interference to cellular users, and thus reducing the network throughput. To alleviate this issue, we consider moving D2D users to the unlicensed band. In this case, D2D users can reuse the resources in cellular networks or share the unlicensed band with WiFi users. However, a critical question is how to effectively perform NOMA user clustering and determine D2D pairs that should use unlicensed band and how to guarantee the quality service of users at both networks. Our objective is to maximize the network throughput by investigating a joint resource allocation problem of user clustering, power control, and D2D mode selection. Since the formulated problem is a mixed-integer non-linear programming problem, finding an optimal solution is a great challenge. To solve this problem, we propose to use a swarm intelligence approach, namely whale optimization algorithm in solving our optimization problem with an efficient solution. Through simulation results, we show that our proposed scheme attains a better performance than other alternative schemes.**

***Index Terms*—D2D Communications, LTE-U, NOMA, Resource Allocation, WiFi Spectrum, WOA.**

I. Introduction

DEVICE-to-device (D2D), non-orthogonal multiple access (NOMA), and long-term evolution in the unlicensed band (LTE-U) are envisioned as three key technologies of wireless 5G networks and beyond [1]–[3]. With the explosive growth of Internet-of-Things (IoT) devices and limited resource conditions, underlay D2D communication in a cellular network was introduced as an effective method of meeting data rate services and enhancing the performance of 4G/5G wireless systems [4], [5]. In a cellular network, data of D2D users (D2D pairs) are transferred directly in the short-range without traversing the base station (BS) by reusing the resource block with cellular users (CUs). The network throughput can be improved, and various benefits in terms of fast access communication (proximity gain), increase using spectral efficiency (reuse gain), and the gain from using only uplink or downlink resources (hop gain) can be achieved [2]. However, the interference and traffic congestion caused by D2D communication is a research challenge. To overcome this challenge, many studies have demonstrated the benefits of coordination between licensed networks (*e.g.*, LTE and 5G) and unlicensed networks (*e.g.*, wireless fidelity and WiFi). In this case, users exploit extensively the unlicensed spectrum under the licensed network infrastructure [6]–[8].

In WiFi networks, both stations and access points (APs) use the same channel access technique *i.e.*, distributed coordinate function (DCF). The DCF uses the carrier-sense multiple access with collision avoidance (CSMA/CA) mechanism, wherein nodes detect the channel is idle before beginning to transmit, thus negating the probability of a collision between WiFi users. By constraint licensed networks, users are not required to perform carrier sensing before transmission. The BS can serve multiple users simultaneously by scheduling different channel resources. Owing to the various channel access methods, D2D users may cause the degradation of the performance of WiFi networks in coexistence networks. Moreover, the number of competing users in WiFi networks always increases dramatically that also impacts to its performance. The problem to be solved is determining how to manage the coexistence and ensure fairness in spectrum sharing among WiFi users and cellular users without affecting the WiFi users' performance. Listen before talk (LBT) and duty cycle protocols were introduced to address this issue. LTE users employ the CSMA/CA mechanism for data transmission and packet collision avoidance between WiFi users in the LBT technique [9], [10]. In another sense, the duty cycle approach works on the same premise as switching on and off activation time in the time slot between LTE-U and WiFi users. The first interval of the time slot is the activated time of LTE-U users before deactivating for the remainder of the time slot. During the LTE-U off time, WiFi users resume using the unlicensed channel normally [8], [11], [12].

Moreover, with a tremendous increase in IoT connections, 5G networks and beyond are required to provide for the massive connectivity of users/devices along with high performance, low latency, low cost, and low power consumption. NOMA has introduced to tackle issues and becoming a key technique for 5G networks and beyond [13]–[18]. The basic

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concept of the NOMA technique is to allocate the same set of orthogonal resources for users [14], which is the main difference to conventional orthogonal multiple access (OMA), wherein users occupy different orthogonal resources. Far users (with weaker channel gains) are served concurrently with near users (with better channel gains) in the same subcarrier. In general, the achievable sum rate of the NOMA scheme can performance the corresponding OMA network [19], [20]. Additionally, power domain NOMA can relax the channel feedback through the received signal strength only, the exact channel state information (CSI) is not required [21]. Furthermore, the successive interference cancellation (SIC) technique is used at the receiver side that allows to eliminate the unwanted signals transmitted from other weaker users and obtain its signal from the superposition signal transmitted by the BS. The SIC decoding order is optimized based on the order of increasing normalized channel gain [22]. To evaluate the combination of NOMA with other methods, Kazmi *et al.* [23] addressed a resource allocation problem by optimizing user clustering and power control of D2D users under the NOMA scheme. They demonstrated that, if the user clustering is performed well, a better average sum rate of the network can realize than that obtained using traditional schemes.

With the aforementioned potential benefits of NOMA, D2D, and the unlicensed spectrum in a corporation system, we investigate a D2D communication network with NOMA and an unlicensed spectrum and an approach for maximizing the total data rate of users. The contributions of this study are listed below.

- First, we investigate an optimization problem by maximizing the system throughput via user clustering, power control for users, and D2D joint mode selection subject to various resource constraints and the minimum rate requirement of all users. D2D users can either work in the licensed spectrum while following the NOMA principle or share resources with WiFi users in the unlicensed mode. In the cellular network, the crossing user interference certainly occurs due to sharing resource blocks between CUs and D2D. It should be noted that it is disadvantageous when the performance of CUs is degraded owing to the interference of D2D users. To reduce or mitigate the strong D2D interference and improve the data rate of users also, these D2D users are expected to utilize the available resource of the unlicensed band using the duty cycle technique.
- The max-min problems of the wireless system consider as a mixed-integer non-linear programming (MINP) problem that is a serious challenge in finding an optimal solution. We devised an algorithm to realize an optimal solution by employing a recent swarm intelligence approach, namely the whale optimization algorithm (WOA) [24]. Mathematically, WOA is a formulation based on the social feeding behavior of humpback whales and has been effectively applied to a variety of engineering challenges. Moreover, the WOA demonstrated competitive performance in solving various wireless network optimization problems [25]. Motivated by our previous work, we employ the WOA in finding a global optimal solution for our considered problem. Moreover, binary WOA version and penalty method are introduced respectively to deal with binary variables and resource constraints that are considered in the optimization problem.
- Numerical simulations illustrate clearly that the effectiveness of our proposed scheme and its superiority over the benchmarks, including the OMA scheme, the licensed band only scheme, and the scheme wherein one subchannel is shared by two CUs only.

The remainder of the paper is organized as bellows. The previous works related to this study are introduced in Section II. Section III illustrates clearly the network model and our problem formulation. Section IV explains the fundamental WOA, binary WOA (BWOA), and constraint handling technique is introduced. We show the problem formulation in Section V. Section VI explains the popular setting parameters and numerical simulation results. Finally, in Section VII, the study's conclusion is stated.

II. Related Works

Recently, many researchers have focused on resource optimization in underlay D2D communication with the power-domain NOMA. In this context, [26], [27] proposed a new concept of a circle of many users as a D2D group in which multiple users simultaneously receive data from one transmitter. The goal is to maximize the total throughput of users under data rate requirement constraint, numerical results have shown that the proposed algorithm generally got better achievement than the conventional OMA scheme. Besides the traditional underlay and overlay D2D modes, others D2D mode selections were introduced in [28]. The interlay mode was proposed to eliminate the strong D2D users' interference to CUs and to maximize the system throughput. Zhai *et al.* [29] introduced four spectrum sharing D2D modes and solved a connectivity maximization problem under the decoding threshold constraints. In [30], the authors maximized the total data rate of D2D users with the constraint on the data rate requirement of CUs. First, power assignments for CUs on each subcarrier task are derived, and then the channel assignment problem adopts a dual-based iterative algorithm to finding an optimal solution. However, it is assumed that one subchannel is only scheduled to one D2D user at most which help reduce the high computation complexity of the objective function. To improve the spectral efficiency and system throughput, user clustering and power assignment problems were considered in [23]. With the limitation of two CUs and unlimited D2D pairs that can be scheduled on one subchannel, the proposed framework demonstrated a good performance in terms of interference protection and enhanced network connectivity. However, these studies were not focused on mitigating the D2D interference to CUs. Naturally, if the D2D interference is managed well, the system throughput is also enhanced.

In the case of traditional networks, the interference protection for CUs has been investigated, for the purpose of increasing the achievement rate of the system network. By utilizing the available unlicensed band resources, Chen and

Yu [31] developed three techniques for cellular traffic offloading in the unlicensed band through resource allocation, data offloading, and a hybrid method that guarantees the minimum rate requirement of WiFi users. A new approach for resource allocation in small cells was introduced by [32]. The objective of the study was to maximize users' sum rate by jointly resource allocation for cellular users at both the licensed and unlicensed spectrum. Besides signification gains realized by D2D communications, the investigation of new technologies such as LTE-U in D2D communication was also investigated. Liu and Ju [33] presented a novel technology to allow D2D communications to work over either the licensed or unlicensed band. The authors proposed a technique to mitigate the D2D interference to CUs and WiFi users, as a result, enhance the system throughput. In advances, they presented that the duty cycle technique outperformed the LBT access method. To improve the spectral efficiency by allowing one more than D2D users on the same subchannel and utilizing the capability of swarm intelligence in addressing network optimization problems, the authors studied the resource allocation and joint mode selection for D2D communication on licensed and unlicensed bands [34]. Through simulations, the proposed algorithm was found to significantly improve the network throughput as well as eliminate the interference to CUs caused by D2D communication.

The authors in [35] maximized the total throughput of users by investigating the spectrum access problem by allowing both CUs and D2D pairs to utilize the unlicensed band. The authors of the aforementioned studies solved problems in a traditional network where CUs use the orthogonal spectrum. In contrast to previous studies, Sun and Xu [36] approached the traffic offloading problem by employing NOMA enable D2D and unlicensed access technologies. Their objective was to maximize the total achievement rate of the D2D network while ensuring the capacity of cellular and WiFi systems. The results indicated that the proposed scheme could efficiently increase the throughput of the D2D networks.

III. System Model and Problem Formulation

A. System Model

We consider a downlink[1] single-cell NOMA network, as shown in Fig. 1, wherein the center point represents the macro BS that serves a list of CUs $\mathcal{C} = \{1, \ldots, C\}$ through $\mathcal{S} = \{1, \cdots, S\}$ subchannels. The transmitted signals from BS may have high interference to D2D users, thus we limit the scope of the paper to indoor environments and will further consider outdoor scenarios in our future work. Furthermore, the CUs share the resource with a set of D2D users $\mathcal{D} = \{1, \ldots, D\}$. In this model, the bandwidth of the subchannels is considered with the same value and is denoted by B. Moreover, W users in the WiFi network operate on the 5 GHz unlicensed spectrum. To support massive connections in network communication, we applied the power-domain NOMA technique to allow CUs to share frequency resources with D2D communication. D2D

[1]Similar to [23], [37], we also consider the downlink NOMA and investigate an interference management scheme for D2D communication with quality of service (QoS) guarantee for cellular users.

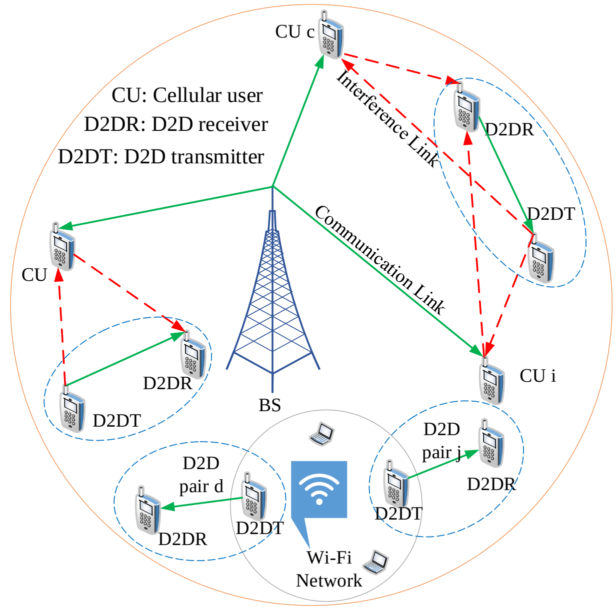

Figure 1: Illustration of a downlink NOMA-assisted D2D communication network with unlicensed spectrum.

users can operate on either licensed or unlicensed bands, as shown below. 1) In the licensed band, D2D users reuse the channel with existing CUs. In the NOMA network, receivers implement the SIC technique to decode the target signal, and the signals from D2D pairs are considered as a reference. 2) In conditions when the D2D interference has a significant impact on the CUs, these D2D pairs are forced to use the duty cycle technique to access the unlicensed band in order to mitigate or reduce interference.

1) Channel models: In the entire network, users (CUs and D2D users) are grouped into clusters. The k-th cluster is handled by the k-th subchannel ($k \leq S$) with $\mathcal{C}_k$ and $\mathcal{D}_k$ scheduled CUs and D2D users, respectively. At the receiver of the downlink, the signals are obtained at both CU c and D2D pair d at the k-th subcarrier and are written as

$$\begin{aligned} y_c^k =& \sqrt{P_{\mathrm{B}c}^k} h_{\mathrm{B}c}^k x_c^k + \sum_{i \in \mathcal{C}_k \setminus \{c\}} \sqrt{P_{\mathrm{B}i}^k} h_{\mathrm{B}c}^k x_i^k \\ &+ \sum_{d \in \mathcal{D}_k} \sqrt{P_d^k} h_{dc}^k x_d^k + z_c^k, \end{aligned} \tag{1}$$

$$\begin{aligned} y_d^k =& \sqrt{P_d^k} h_{dd}^k x_d^k + \sum_{c \in \mathcal{C}_k} \sqrt{P_{\mathrm{B}c}^k} h_{\mathrm{B}d}^k x_c^k \\ &+ \sum_{j \in \mathcal{D}_k \setminus \{d\}} \sqrt{P_j^k} h_{jd}^k x_j^k + z_d^k, \end{aligned} \tag{2}$$

where x_c and x_d indicate the received signals at CU c and D2D d user, respectively. The allocated power for cellular and D2D users are alternately with $P_{Bc}^k, P_{Bi}^k, P_d^k$, and P_j^k. h_{pq}^k indicates the channel response from transmitter p to receiver q, where B denotes the BS. $z_c^k(z_d^k) \sim \mathcal{CN}(0, \sigma^2)$ indicates the additive white Gaussian noise with noise variance σ^2. In power-domain NOMA, the user's receiving signal comprises the signal and the interference from the other users (CUs and D2D users), which is due to the sharing resource block problem. It is necessary for receivers to measure the downlink channel using reference signals and to transmit back CSI to the BS in the form of a predesigned transmission format [21].

The data rate of CU c at the k-th cluster is given as [23]

$$R_c^k = B\log_2\left(1+\frac{\delta_c^k P_{\mathrm{B}c}^k g_{\mathrm{B}c}^k}{I_c^k+I_d^k+\sigma^2}\right), \tag{3}$$

where $g_{\mathrm{B}c}^k$ denotes the channel gain of CU c, and I_c^k is the co-interference from other CUs in the cluster. Moreover, the mutual D2D interference is calculated as $I_d^k = \sum_{d\in\mathcal{D}_k}\gamma_d^k P_d^k g_{dc}^k$, with g_{dc}^k being the direct channel gain between the D2D transmitters and CU c. γ_d^k and δ_c^k denote the scheduled channel indicators. More specifically, $\delta_c^k = 1$ when channel k is arranged to user c; whereas, $\delta_c^k = 0$. Similarly, if $\gamma_d^k = 1$, the D2D user d is scheduled for cluster k, or $\gamma_d^k = 0$ otherwise. Because the SIC decoding is on the order of channel gain, with K users in the k-th cluster, the SIC descending order is sorted as follows

$$g_{\mathrm{B}1}^k \geq g_{\mathrm{B}2}^k \geq \cdots \geq g_{\mathrm{B}i}^k \geq g_{\mathrm{B}c}^k \geq \cdots \geq g_{\mathrm{B}K}^k. \tag{4}$$

Following the SIC principle, user i can correctly decode and remove the interference signal from users c if $g_{\mathrm{B}i}^k \geq g_{\mathrm{B}c}^k$. However, the signal of user i is not decoded by user c, thus it is treated as noise.

The inter-interference in the cluster can be written as

$$I_c^k = \sum\nolimits_{i\in\mathcal{C}_k|g_{\mathrm{B}i}^k\geq g_{\mathrm{B}c}^k}\delta_i^k P_{\mathrm{B}i}^k g_{\mathrm{B}c}^k, \tag{5}$$

where δ_i^k is the channel indicator. In the case that user i is grouped into one cluster with user c, $\delta_i^k = 1$, and $\delta_i^k = 0$ otherwise.

On the same k-th subcarrier, as in [23], the data rate of D2D pair d is achieved as

$$R_d^k = B\log_2\left(1+\frac{\gamma_d^k P_d^k g_{dd}^k}{I_c^k+I_d^k+\sigma^2}\right), \tag{6}$$

where g_{dd}^k represents the direct channel gain from the D2D transmitter to the D2D receiver, $I_c^k = \sum_{c\in\mathcal{C}_k}\delta_c^k P_{\mathrm{B}c}^k g_{\mathrm{B}d}^k$ is the cellular interference on subcarrier k, and $I_d^k = \sum_{j\in\mathcal{D}_k\setminus\{d\}}\gamma_j^k P_j^k g_{jd}^k$ indicates the inter-channel interference caused by other D2D users. $g_{\mathrm{B}d}^k$ and g_{jd}^k are the channel gains from BS to D2D receiver d and from other D2D transmitters j to D2D receiver d, respectively. Here, γ_j^k is the channel indicator of D2D user j that is scheduled for cluster k if $\gamma_j^k = 1$, and $\gamma_j^k = 0$ otherwise.

The total rate of the entire network system (*i.e.*, the CUs and D2D pairs) on the licensed band is given by

$$\Re = \sum_{k\in\mathcal{S}}\left(\sum_{c\in\mathcal{C}_k}R_c^k + \sum_{d\in\mathcal{D}_k}R_d^k\right). \tag{7}$$

2) Duty cycle based unlicensed mode: In our study, we intend to user duty cycle technique to allows uses utilize the available spectrum in unlicensed band. Following the method principle, WiFi users and D2D users operated alternatively at different time slots. The achievement rate of D2D user d when accessing the unlicensed band is expressed as follows

$$R_d^u = \lambda_d B^u \log_2\left(1+\frac{P_d^u g_{dd}^u}{\sigma^2}\right), \tag{8}$$

where u denotes the unlicensed band, λ_d indicates the duration of time slot occupied by D2D pair d, and B^u represents the unlicensed bandwidth. P_d^u is the allocated power, and g_{dd}^u indicates the channel response of D2D user d on the unlicensed spectrum.

3) WiFi throughput model: We assume that the WiFi network contains one AP and w competing WiFi users. The probability for the transmission data of a user at random time is τ, and the system probability in the case of at least one transmit data at any time is $P_{tr} = 1-(1-\tau)^w$ [38]. Meanwhile, the probability that there is no collision during transmission time *i.e.*, the successful transmission probability, is $P_s = \frac{w\tau(1-\tau)^{w-1}}{P_{tr}}$.

As a result, as in [38], the saturation throughput of the WiFi network depends on the number of competing users and is defined as

$$R(w) = \frac{P_{tr}P_sE(P)}{(1-P_{tr})T_e + P_{tr}P_sT_s + P_{tr}(1-P_s)T_c}, \tag{9}$$

with $E(P)$ representing the average packet size. T_e indicates the period of time slot, T_s is the total channel time in the case of successful transmission, and T_c is the duration of time slot in terms of the occurrence of collisions.

B. Problem Formulation

Our objective is to maximize the throughput of all the CUs and D2D pairs while guaranteeing the QoS requirements of users by employing user clustering, power allocation, and joint D2D mode selection in the licensed and unlicensed bands. Our optimization problem is expressed as

$$\max_{\boldsymbol{\delta},\boldsymbol{\gamma},\boldsymbol{p}} \Re \tag{10a}$$

$$\text{s.t.:}\ \sum_{k\in\mathcal{S}}\sum_{c\in\mathcal{C}_k}\delta_c^k P_{\mathrm{B}c}^k \leq P_{\mathrm{B}}^{\max}, \tag{10b}$$

$$P_{\mathrm{B}c}^k \geq 0, 0 \leq P_d^k \leq P_d^{\max}, \forall c\in\mathcal{C}_k, \forall d\in\mathcal{D}_k, \tag{10c}$$

$$R_c^k \geq R_{\min}, R_d^k \geq R_{\min}, \forall c\in\mathcal{C}_k, \forall d\in\mathcal{D}_k, \tag{10d}$$

$$\sum_{k\in\mathcal{S}}\delta_c^k \leq 1, \qquad \forall c\in\mathcal{C}_k, \tag{10e}$$

$$\sum_{k\in\mathcal{S}}\gamma_d^k + \gamma_d^u \leq 1, \qquad \forall d\in\mathcal{D}_k, \tag{10f}$$

$$\delta_c^k\in\{0,1\}, \gamma_d^k\in\{0,1\}, \gamma_d^u\in\{0,1\},$$
$$\forall c\in\mathcal{C}_k, \forall d\in\mathcal{D}_k, \tag{10g}$$

$$(1-\sum_{d=1}^{D}\gamma_d^u\lambda_d)R(W) \geq R_T, \tag{10h}$$

$$R_d^u \geq R_{\min}. \tag{10i}$$

As shown above, $\forall c\in\mathcal{C}_k, \forall d\in\mathcal{D}_k, \forall k\in\mathcal{S}$, $\boldsymbol{\delta} \triangleq \{\delta_c^k\}$ denotes the CUs scheduled channel matrix, $\boldsymbol{\gamma} \triangleq \{\gamma_d^k, \gamma_u^k\}$ is the D2D users channel assignment matrix, and $\boldsymbol{p} \triangleq \{P_{\mathrm{B}c}^k, P_d^k\}$ indicates the power assignment vector. R_T illustrates the throughput threshold of WiFi network, and $R_{\min}$ represents the target data rate requirements of users, respectively. Furthermore, γ^u is an unlicensed mode access indicator for which, if $\gamma^u = 1$, the unlicensed band allows access for the D2D user; versa vice the value is zero. Constraints (10b) and (10c), respectively, indicate that the transmitting powers are non-negative and the total power assignment of all CUs is not over the power of BS $P_{\mathrm{B}}^{\max}$; furthermore, the power value of the D2D pairs does not exceed its maximum $P_d^{\max}$. As shown in equation (10d), the rate requirement of users must be met in the licensed band. A CU is only assigned to one NOMA group (*i.e.*, one channel can serve one more than users), and D2D communication only works on either the licensed or unlicensed band (10e) and (10f), respectively. The scheduled channel indicators accept only the binary value given by (10g). In the unlicensed band, constraints (10h) and (10i) guarantee the quality for both WiFi users and D2D users.

As the optimization problem (10) is a MINP problem, it is significantly difficult to find the optimal solution. Motivated by the simplicity and efficiency.F of the WOA, we employ the WOA and introduce its binary version to address the problem under consideration [25]. The details of the original WOA and the binary version are presented in the next section.

IV. Overview of Whale Optimization Algorithm

A. Continuous Version of WOA

In recent times, besides convex optimization, game theory, and deep learning, swarm intelligence algorithms have many advantages in solving problems of wireless communications. Mirjalili *et al*. introduced a new metaheuristic optimization algorithm, called the whale optimization algorithm, which mimics the humpback whale's hunting behavior [24]. The target prey of humpback whales is krill or small fishes that are swimming near the water surface. From the surface to a depth of approximately 12 m, the whales create a distinctive bubble along with a spiral shape and swim up toward the surface following the part of the bubbles (*i.e.*, bubble-net feeding method). The hunting behavior is modeled as bellows.

1) Encircling prey: One of the possibility of humpback whales is to recognize the target position and encircle them completely. In WOA mathematical formation, the optima position is not known, and it is assumed that the current target prey, or something near to it, considers as the best candidate at each iteration. The mathematical model is given as

$$\vec{D} = |\vec{C} \cdot \vec{X}^*(t) - \vec{X}(t)|, \tag{11}$$

$$\vec{X}(t+1) = \vec{X}^*(t) - \vec{A} \cdot \vec{D}, \tag{12}$$

with t being the current iteration, $\vec{A}$ and $\vec{C}$ being coefficient vectors, and $\vec{X}^*, \vec{X}$ indicating the location of the best candidate and the current location vector, respectively. Let $\cdot$ denote an element-by-element multiplication. Consequently, the optimal value $\vec{X}^*$ will be updated to reflect a better solution at each iteration.

The hunting area is controlled by coefficient vectors which is calculated as

$$\vec{A} = 2\vec{a} \cdot \vec{r} - \vec{a}, \tag{13}$$

$$\vec{C} = 2\vec{r}. \tag{14}$$

Here, in both the exploitation and exploration phase, value of $\vec{a}$ decreases linearly from 2 to 0 over each iteration, and $\vec{r}$ is a random number in the range [0,1]. Let T be the total iterations, and at the current t iteration, a vector $\vec{a}$ is updated as $a = 2 - t\frac{2}{T}$.

2) Bubble-net attacking method: There are two main approaches to the bubble-net behavior: shrinking encircling and spiral updating position. Because the value of $\vec{a}$ reduces from 2 to 0, the value of $\vec{A}$ changes as well, and the optimal value is achieved with the shrinking encircling behavior dependent on $\vec{A}$ in (13). On setting the value of $\vec{A}$ in the range $[-1, 1]$, the next position is in the range of the best search agent position and the current agent position. The path from the position of the whale to the prey imitates the helix-shaped strategy that is formulated as a spiral equation.

$$\vec{X}(t+1) = \vec{D}_s \cdot e^{bl} \cdot \cos(2\pi l) + \vec{X}^*(t), \tag{15}$$

$$\vec{D}_s = |\vec{X}^*(t) - \vec{X}(t), \tag{16}$$

Here, $\vec{D}_s$ indicates the distance from the whale to the target, b represents the form of the logarithm spiral, and l is a random number between [-1,1].

In the simultaneous behavior, the assuming chance of choosing either the shrinking encircling mechanism or the spiral update location is 50%. The model follows a formula.

$$\vec{X}(t+1) = \begin{cases} \vec{X}^*(t) - \vec{A} \cdot \vec{D}, & \text{if } p < 0.5, \\ \vec{D}_s \cdot e^{bl} \cdot \cos(2\pi l) + \vec{X}^*(t), & \text{if } p \geq 0.5. \end{cases} \tag{17}$$

3) Search for prey: An approach of exploration phase is based on the variant of vector $\vec{A}$. In this way, the value sets $|\vec{A}| > 1$, as a result, the search agent is forced to depart from the optimal search reference. Instead of updating the location based on the best search agent, the search agent's position will be determined at random during the exploration phase. The mathematical model is written in the following way

$$\vec{D} = |\vec{C} \cdot \vec{X}_r - \vec{X}|, \tag{18}$$

$$\vec{X}(t+1) = \vec{X}_r - \vec{A} \cdot \vec{D}, \tag{19}$$

with $\vec{X}_r$ denoting a randomly chosen position vector from the current population.

In summary, the literature has shown that the WOA outperforms other meta-heuristic algorithms such as particle swarm optimization (PSO), evolution strategy (ES), ray optimization (RO), genetic algorithm (GA), and gravitational search algorithm (GSA) [24]. It is worth noting that keeping the balance between exploitation and exploration is a critical task for any metaheuristic algorithm. Exploitation and exploration are exactly described by the bubble-net attacking and search for prey strategies, respectively. Several works have looked into how the WOA can obtain the solution optimality. For instance, two strategies are provided to obtain a trade-off between exploration and exploitation phases, called Local Search Strategy and Lévy flight walks [39]. In [40], a nonlinear technique based on arcsine function is proposed to considerably enhance exploitation and exploration capabilities as well as the performance of WOA. Other variants of the WOA are introduced to devise binary WOA versions in [39], [41], to enhance the convergence speed by chaos theory in [42], and to optimize neural networks in [43]. Finally, the WOA algorithm can be used as a good global optimizer for solving

Algorithm 1 Pseudocode of the continuous WOA algorithm

Initialize the whales population $X_i (i = 1, 2, \ldots, N)$ and set the maximum number of iterations T.
Calculate the fitness value of each search agent and give out the best search agent $\vec{X}^*$.
while $t < T$ **do**
  for each search agent **do**
    Update a, A, C, l, p.
    if $p < 0.5$ **then**
      if $|A| < 1$ **then**
        Update $\vec{D}$ and $\vec{X}$ using (11) and (12), respectively.
      else
        Select a random search agent (X_r).
        Update the position of the agent according to (19).
      end if
    else
      Update the position $\vec{X}$ by (15).
    end if
  end for
  Calculate the fitness of each search agent.
  Update X^* if there is a better solution.
  $t = t + 1$.
end while
Output: the fitness value and optimal position.

many optimization problems in wireless and communication networks [25]. The pseudocode of the WOA is demonstrated in Algorithm 1.

In brief, the computational complexity of Algorithm 1 can be calculated as $\mathcal{O}(N \times D)$, where N is the number of search agents, and D is the dimension of each search agent [25], [41]. Computing the updating of the position of each search agent also requires $\mathcal{O}(N \times D)$ time. The sum of the complexity of WOA becomes $\mathcal{O}(N \times D)$ per iteration. Moreover, with the maximum iteration T, the total time is $\mathcal{O}(N \times D \times T)$.

B. Binary Version of WOA

Many optimization problems involve the use of discrete variables and have a discrete search space. This requires algorithms to be applied for binary variables in a set binary space. The authors in [25], [41] have extended the original WOA to a binary WOA. The main difference between the original WOA for continuous variables and the binary version is the position updating mechanism. The toggle value between 0 and 1 indicates the position updating. There are three major changes in the continuous WOA, which are as follows.

Firstly, in the shrinking and encircling phases, the position of the whales is changed according to

$$\vec{X}(t+1) = \begin{cases} (\vec{X}(t))^{-1}, & \text{if } p_{\text{BWOA}} < \sigma_{\text{ep}}, \\ \vec{X}(t), & \text{otherwise,} \end{cases} \tag{20}$$

where p_{BWOA} is a random value in the range [0,1], and $(\vec{X}(t))^{-1}$ is the complement of $\vec{X}$. $\sigma_{\text{ep}} = \frac{1}{1+e^{-10(\vec{A}\cdot\vec{D}-0.5)}}$ expresses the step size that evaluated according to an appropriate probability function (*i.e.*, sigmoid function), and $\vec{D}$ and $\vec{A}$ are computed using (11) and (13), respectively.

Algorithm 2 Pseudocode of BWOA algorithm

Initialize the whales population $X_i (i = 1, 2, \ldots, N)$ and set the maximum number of iterations T.
Calculate the fitness value of the search agent and identify the best search agent $\vec{X}^*$.
while $t < T$ **do**
  for each search agent **do**
    Update a, A, C, l, p.
    if $p_{\text{BWOA}} < 0.5$ **then**
      if $|A| < 1$ **then**
        Update the position using (20).
      else
        Select a random search agent (X_r).
        Update the position of the agent via (22).
      end if
    else
      Update the position using (21).
    end if
  end for
  Calculate the fitness of each search agent.
  Update X^* if there exists a better solution.
  $t = t + 1$.
end while
Output: the fitness value and optimal position.

In the bubble-net behavior, the calculated position is as follows

$$\vec{X}(t+1) = \begin{cases} (\vec{X}(t))^{-1}, & \text{if } p_{\text{BWOA}} < \sigma_{\text{sb}}, \\ \vec{X}(t), & \text{otherwise,} \end{cases} \tag{21}$$

where $\sigma_{\text{sb}} = \frac{1}{1+e^{-10(\vec{A}\cdot\vec{D}_s-0.5)}}$ is the step size, wherein $\vec{A}$ and $\vec{D}_s$ are computed using (13) and (16), respectively.

In the searching for prey phase, the modification position is updated according to

$$\vec{X}(t+1) = \begin{cases} (\vec{X}(t))^{-1}, & \text{if } p_{\text{BWOA}} < \sigma_{\text{ps}}, \\ \vec{X}(t), & \text{otherwise.} \end{cases} \tag{22}$$

Here, $\sigma_{\text{ps}} = \frac{1}{1+e^{-10(\vec{A}\cdot\vec{D}-0.5)}}$ is the step size, wherein $\vec{A}$ and $\vec{D}$ are computed using (13) and (18), respectively.

The BWOA is illustrated in Algorithm 2. In addition, the steps that comprise the BWOA are similar to those of the continuous WOA except for the method of position updating. Overall, the complexity level of the BWOA algorithm is also computed as $\mathcal{O}(N \times D \times T)$.

C. Constraint-Handling Techniques

Originally, the WOA was used for solving unconstrained optimization problems; however, general problems are constrained problems. Therefore, many constraint-handling techniques have been presented for solving constrained optimization problems. Yang *et al.* [44] introduced two categories of constraint-handling techniques: classic and recent methods.

The classic methods have been widely used in many applications, and new or recent developments have been based on the concept of the classic methods. Numerous methods are recommended, such as the penalty method, equality with tolerance, stochastic ranking, and multi-objective approach. The simplest method of these is the penalty method, which attempts to exchange a constrained optimization problems into an unconstrained problems by including its constraints in the revised object. The penalty method is presented bellow.

We consider an optimization problem that minimizes $f(\boldsymbol{x})$ with all the feasible $\boldsymbol{x}$ and, with p inequalities and m equality constraints

$$\begin{aligned} \underset{\boldsymbol{x}}{\text{minimize}} \quad & f(\boldsymbol{x}) \\ \text{s.t.:} \quad & g_i(\boldsymbol{x}) = 0,\ i = 1, \ldots, m, \\ & h_j(\boldsymbol{x}) \le 0,\ j = 1, \ldots, p. \end{aligned} \tag{23}$$

The penalty function is $\omega(x) = f(\boldsymbol{x}) + P(\boldsymbol{x})$, where $P(\boldsymbol{x})$ is the penalty term defined as

$$P(\boldsymbol{x}) = \sum_{i=1}^{m} \nu_i G_i(g_i(\boldsymbol{x})) g_i^2(\boldsymbol{x}) + \sum_{j=1}^{p} \mu_j H_j(h_j(\boldsymbol{x})) h_j^2(\boldsymbol{x}). \tag{24}$$

Here, $\nu_i \gg 1$ and $\mu_j \ge 0$ are penalty constants or penalty factors, and their values depend on the required solution quality. Moreover, for simplicity of implementation, we can use $\nu = \nu_i, \forall i$ and $\mu = \mu_j, \forall j$. $G_i(g_i(\boldsymbol{x}))$ is an index function, for which $G_i(g_i(\boldsymbol{x})) = 1$ if $g_i(\boldsymbol{x}) \ne 0$, and $G_i(g_i(\boldsymbol{x})) = 0$ if $g_i(\boldsymbol{x}) = 0$. Similarly, the index function $H_j(h_j(\boldsymbol{x})) = 0$ if $h_j(\boldsymbol{x}) \le 0$ is true, whereas $H_j = 1$ if $h_j(\boldsymbol{x}) > 0$. For the majority of applications, ν and μ range from 10^3 to 10^{15}. For our purposes, we use 10^{14} as the ν and μ values [25].

In terms of the constrained problem, the WOA algorithm becomes more complex depending on the number of equality and inequality constraints [25]. With m equality and p inequality constraints, the time complexities are $\mathcal{O}(Nm)$ and $\mathcal{O}(Np)$, respectively. The algorithm is terminated in T iterations, and the computational complexity level of the original WOA in solving unconstrained optimization problems becomes $\mathcal{O}(TN(m + p + D))$.

V. Proposed Algorithm

A. Hybrid WOA-Based Joint-Channel and Power-Allocation Algorithm for the Licensed Band

1) Fitness function: With the constraints of the licensed band from (10b) to (10g), both the continuous and binary WOA algorithms are applied to address the power control and channel assignment problems and jointly D2D mode selection. The channel and power assignment matrices $\boldsymbol{x} = (\boldsymbol{\delta}, \boldsymbol{\gamma}, \boldsymbol{p})$ indicate the position of the search agents, while users defines as a search agent. The fitness function that evaluates the output value of the algorithm is defined as

$$\begin{aligned} \omega = & -\Re(\boldsymbol{x}) + \mu \Bigg(H^p(h^p(\boldsymbol{p})) {h^p}^2(\boldsymbol{p}) \\ & + \sum_{j \in \mathcal{M}} H_j^r(h_j^r(\boldsymbol{x})) {h_j^r}^2(\boldsymbol{x}) \Bigg), \end{aligned} \tag{25}$$

where $h^p(\boldsymbol{p}) = \sum P_{\text{Bc}}^k - P_B^{\max}, \forall c \in \mathcal{C}_k, \forall k \in \mathcal{S}$. Furthermore, $\mathcal{M} = \mathcal{C} \cup \mathcal{D}$, $h_j^r(\boldsymbol{x}) = R_{\min} - R_j(\boldsymbol{x})$, and $\mu = 10^{14}$. It should be noted that the minus sign in front of the fitness function is required to transform the minimization problem into a maximization problem. The inequality functions are redefined as follows: 1) $h^p(\boldsymbol{p}) = P_B^{\max} - \sum P_{\text{Bc}}^k$ with the index function $H^p(h^p(\boldsymbol{p})) = 0$ if $P_B^{\max} \ge \sum P_{\text{Bc}}^k$, and $H^p(h^p(\boldsymbol{p})) = 1$ if $P_B^{\max} < \sum P_{\text{Bc}}^k$. 2) $h_j^r(\boldsymbol{x}) = R_j(\boldsymbol{x}) - R_{\min}$ with the index function $H_j^r(h_j^r(\boldsymbol{x})) = 0$ if $h_j^r(\boldsymbol{x}) \ge 0$, and equals 1 otherwise.

2) Binary coding variable: From the formulation problem in (10a), the channel constraints from (10e) to (10g) express the following: 1) Only one user is served by one channel; 2) Unlimited users are not required in one channel; 3) D2D users are only operated in either the licensed or unlicensed band. In the algorithm, we use a binary coding method to solve these problems. An integer k_u in the range $[1, S]$ presents the channel assignment of user $u, u \in C \cup D$. Subsequently, the presented integer channel is encoded using binary coding, which is used as the input of the BWOA algorithm. For instance, we sample that network contains eight users (seven CUs and one D2D pair), and four channels. We need 3 bits to represent the scheduled channels of users; for instance, [0 0 1] represents channel 1, and [1 0 0] represents channel 4. A binary variable of the channel allocation is illustrated in Fig. 2.

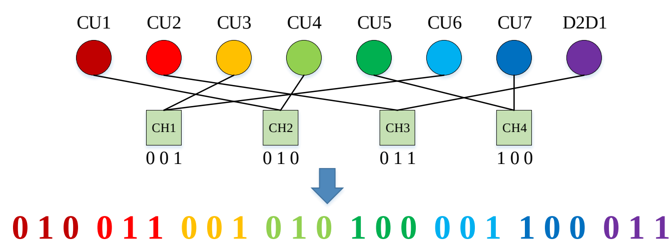

Figure 2: An example binary coding variable.

B. Duty-Cycle-Based Unlicensed Mode

Our purpose of applying the hybrid WOA is to determine the scheduled channel and power control and to detect D2D that high impact on CUs achievable rate, to mitigate or reduce the D2D interference, these D2D pairs are forced onto the WiFi network using the duty cycle method. Following this method, the D2D user d operates in the fraction λ_d of the slot time, and this is the main reason for throughput degradation in the WiFi system. The degrading throughput caused by D2D user d in the WiFi system is modeled as

$$-\lambda_d R(W),\ \forall d.$$

The obtained gain of the cellular network of D2D user d, which allows access to the unlicensed band, is given as

$$H_d = -\lambda_d R(W) - G_{d,c}^k,\ \forall d \in \mathcal{D}_k, \forall c \in \mathcal{C}_k, \forall k \in \mathcal{S}, \tag{26}$$

where $G_{d,c}^k = A_c^k - C_c^k$ presents the gap between the rate of CU c with D2D interference and without D2D interference on channel k . $A_c^k = \log_2(1 + \frac{\delta_c^k P_{Bc}^k g_{Bc}^k}{I_d^k + I_c^k + \sigma^2})$ is the actual spectral

Algorithm 3 Pseudocode of our proposed algorithm.

The hybrid WOA versions determine the set of the optimal channel and power control for users. It also determines the set of throughput losses of CUs owing to D2D communication.
Initialize $\mathcal{D} = \{1, \ldots, D\}$ and calculate $H_d = -\lambda_d R(W) - G^k_{d,c}$
while $\mathcal{D} \neq \emptyset$ **do**
    $d^* = \underset{d \in \mathcal{D}}{\operatorname{argmax}}(H_d)$
    if $H_{d^*} > 0$ and **then**
        if $\lambda_{d^*} < \lambda_{\max}$ **then**
            $\lambda_{\max} = \lambda_{\max} - \lambda_{d^*}$
            Move the D2D pair d^* to the unlicensed band.
        end if
    end if
    $\mathcal{D} = \mathcal{D} - d^*$
end while

efficiency, and $C^k_c = \log_2(1 + \frac{\delta^k_c P^k_{Bc} g^k_{Bc}}{I^k_{d'} + I^k_c + \sigma^2})$ is the spectral efficiency without the interference of the D2D d and with $I^k_{d'}$ being the interference causing by other D2D users on subcarrier k.

Our goal is to minimize the total throughput loss of CUs as well as maximizing the system throughput, the minimum resource allocation λ_d for D2D user d on the unlicensed band can be obtained using (10a) as follows

$$\lambda_d = \frac{R_{\min}}{B^u \log_2(1 + \frac{P^u_d g^u_{dd}}{\sigma^2})}.$$

In addition, the total time slots $\lambda_{\max}$ for the D2D communication that is shared by the WiFi network can be calculated using (10h) as follows

$$\lambda_{\max} = 1 - \frac{W R_T}{R(W)}. \tag{27}$$

The interference level caused by D2D users is different because of their respective location and allocated power. Therefore, to maximize gains when D2D communications exploit the unlicensed band, the D2D pair (d^*) with the highest H_d should be handled to move to the unlicensed spectrum first. If H_d is positive, it means that the WiFi users are not influenced by the D2D communication. However, if H_d is negative, the WiFi throughput is degraded caused by the strong interference of the transferred D2D pair d. Subsequently, in case $\lambda_d < \lambda_{\max}$, the D2D pair d is permitted to access the unlicensed bands; otherwise, this D2D pair should be skipped in the reuse mode. This process is performed when there is no positive H_d or the maximum time-slot occupancy $\lambda_{\max}$ is reached. The pseudocode of our proposed algorithm using the duty cycle method is explained in Alg. 3.

VI. Numerical Simulation

In this section, Monte Carlo simulations are conducted to evaluate the proposed algorithm. We assumed that the network has one central BS with 500 m radius and used the Rayleigh fading channel model. Users are distributed uniformly in coverage area, and the WiFi AP places within the network area. Users work in unlicensed spectrum by using the unlicensed 5 GHz band. The main setting parameters are presented in Table 1. The distance between the transmitter and the receiver of a D2D pair is random from 15 m to 50 m. The licensed band parameters comprise configured parameters in [37], and the unlicensed spectrum and WiFi network are obtained from [6]. In the simulation, we configure the number of channel as a half of total CUs. For evaluation, we compare our proposed algorithm with other schemes as follows

Table 1: Simulation parameters.

Parameters	Values
$P^{\max}_{\mathrm{B}}$	43 dBm
$P^{\max}_d$	23 dBm
P^u_d	20 dBm
Cell radius	500 m
B, B^u	1 MHz, 20 MHz
Total WiFi users	10
Variance noise	–140 dBm/Hz
Path loss for cellular links	128.1 + 37.6 $\log_{10}$(d[km])
Path loss for D2D links (licensed, unlicensed)	148 + 50 $\log_{10}$(d[km])
N	30
T	200
$E(P)$	8224 bits
PHY header	192 bits
MAC header	224 bits
ACK	112 bits
$CW_{\min}$	32
$CW_{\max}$	1024
SIFS	16 μs
DIFS	50 μs
RTS	160 + PHY header
CTS	112 + PHY header
ACK	112 + PHY header
Time slot	9 μs
Propagation delay	20 μs

- **NOMA-O**: This is our proposed scheme wherein unlicensed band is utilized to mitigate interference from D2D users, and we configure that one subcarrier can served multiple CUs.
- **NOMA-L**: The scheme defines that D2D users operate in the licensed band only.
- **NOMA-T**: A cellular network scheme wherein one subchannel is shared by two CUs.
- **OMA**: A conventional network scheme wherein one channel is assigned to one CU at most.

Our optimization problem is addressed by adopting hybrid WOA which has steps as follows: the binary BWOA algorithm is run first, and in each iteration, the continuous WOA is run simultaneously. The channel assignment for users initially comprises integers, random in the interval $[1, S]$. The integer values are then converted into binary variables; with each assigned channel, the continuous WOA is also utilized to find the optimal power control solution as well as obtain the best value of the fitness function. The termination criterion $|\omega(t) - \omega(t-1)| \leq 10^{-6}|$ (i.e., the difference between the fitness values of the two consecutive iterations falls below a threshold) is set up within thirty consecutive times, and the algorithms are finished.

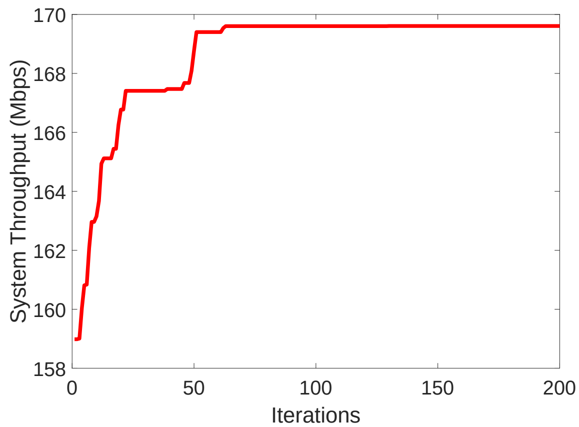

Figure 3: Convergence of WOA algorithm.

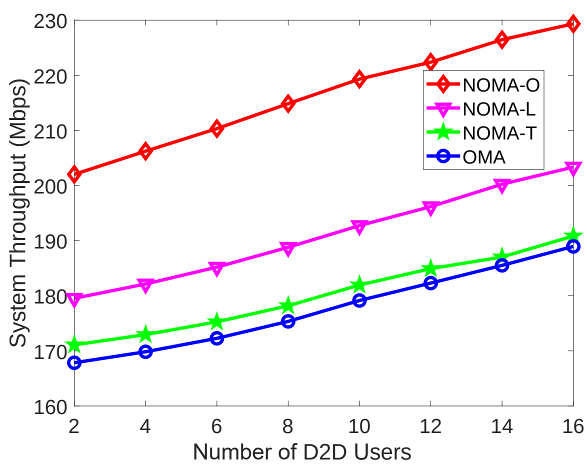

Figure 4: System throughput versus the number of D2D users ($C = 16, R_{\min} = 250$ Kbps).

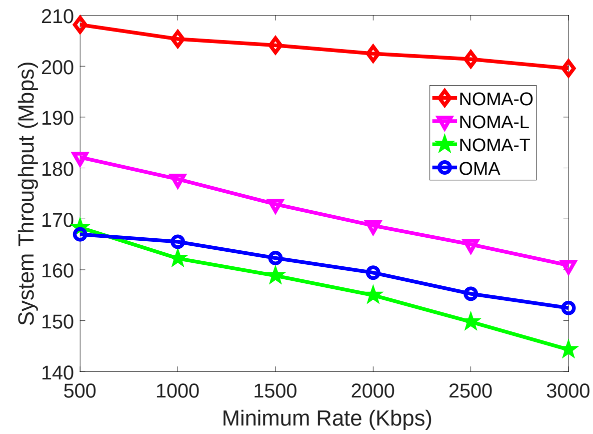

Figure 5: System throughput versus the minimum rate requirement ($C = 16, D = 10$).

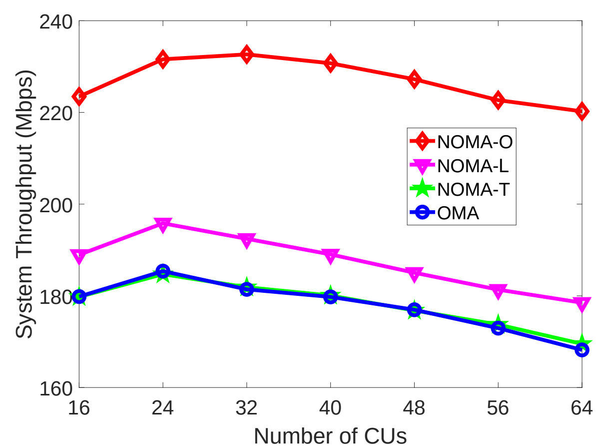

Figure 6: System throughput versus the number of CUs ($D = 10, R_{\min} = 250$ Kbps).

The numbers of CUs and D2D pairs are 16 and 10, respectively. In addition, the minimum rate requirement of users is 0.25 Mbps. Firstly, the convergence curve of the hybrid WOA algorithm in the "NOMA-L" scheme is presented in Fig. 3. It is apparent that the system throughput increases in approximately 70 iterations and converges in the remaining iterations.

We then evaluate the network capacity versus the different numbers of D2D users, and the obtained result is presented in Fig. 4. According to the figure, the total data rate of users is achieved versus the raising of D2D pairs in the system. Our proposed algorithm archives good result than the other three schemes. Using the simulation parameters and computational complexity analyses in Section IV, the computational complexity of our proposed WOA algorithm for NOMA and OMA is $\mathcal{O}(T \times N \times (26 + 208 + 27))$ and $\mathcal{O}(T \times N \times (18 + 144 + 19))$, respectively.

We investigate the impact of the different minimum target data rate of users on the system throughput, which is presented in Fig. 5. We can observe that the system output reduces slightly as the rate requirement increases. This is because a higher minimum rate requirement requires additional allocated power, which also results in an increased interference between the users. The system throughput then fails to satisfy the increased minimum rate requirement. As compared to the other three schemes, the "NOMA-O" scheme can enhance the system, and the "NOMA-T" scheme has the speed reduction higher than the "OMA" scheme.

Fig. 6 presents the system throughput with a change in the number of CUs. The figure shows that the data rate system reaches a peak and then decreases versus the increasing number of CUs. The reason is that when the number of CUs exceeds the provision possibility of the system, the throughput declines to ensure that the requirement of the minimum data rate of users is fulfilled. Moreover, the proposed "NOMA-O" scheme achieves the highest and provides a better system throughput than the three benchmarks.

Finally, we evaluate the maximum power of the BS on the network capacity in Fig. 7. We can observe that the system sum rate significantly increases under a high BS power. The "NOMA-O" scheme exhibited the most enhanced output among all the compared schemes.

VII. Conclusion

We investigated channel assignment and power allocation for CUs and D2D users as an optimization problem, and LTE-

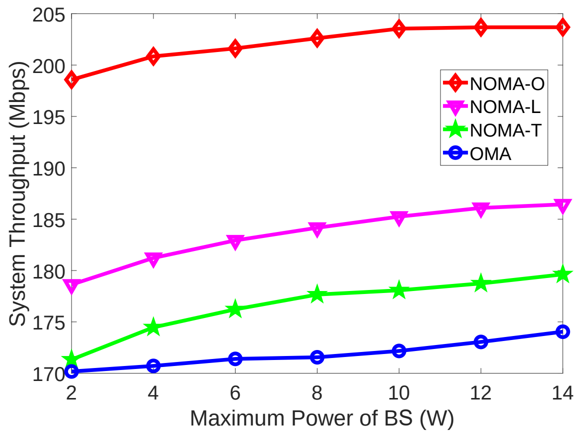

Figure 7: System throughput versus the power of the BS ($C = 16, D = 10, R_{\min} = 250$ Kbps).

U technology is also applied to improve the system throughput. To address the NP-hard problem, a meta-heuristic algorithm, hybrid WOA, is used to assign binary channels and continuous powers to users jointly. Moreover, WOA always gives out the set of disadvantage D2D pairs, and it is expected that these users will utilize available resources of the unlicensed spectrum while guaranteeing the performance of all WiFi users. Through numerical simulations, we determined that our proposed scheme converges within a reasonable amount of time. Furthermore, based on the change in the value of some parameters *e.g.*, the number of D2D pairs, the target data rate requirement of users, the number of CUs, and total power transmission of BS in the simulation results which show our proposed algorithm provided a better solution in terms of throughput compared to OMA scheme and NOMA without an unlicensed network scheme.

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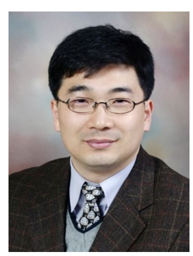

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