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Joint channel and Power Allocation for Device-to-Device Communication on Licensed and Unlicensed Band

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ABSTRACT Device-to-Device communications (D2D) are being used to improve the spectral efficiency and to reduce the load of the base station (BS) by reutilizing the licensed spectrum. However, the primary cellular users may face high interference from D2D users. There is also a scarcity of licensed spectrum due to the dense deployment of smart devices. To alleviate this problem, in this paper, we are extending the D2D users to the unlicensed band. In this scenario, the D2D users are allowed to reuse the licensed spectrum or share the unlicensed spectrum with the incumbent WiFi users. However, cellular and WiFi users experience high interference if an efficient interference management scheme is not used. In this paper, we propose a joint mode selection, channel allocation, and power control algorithm using particle swarm optimization to manage the interference and improve the overall throughput of cellular and D2D users such that the minimum data rate requirement of WiFi users is guaranteed. Through numerical simulations, we show that the proposed algorithm can significantly mitigate the interference and improve the throughput of the system.

INDEX TERMS Device-to-device communication, LTE unlicensed (LTE-U), duty-cycle, listen-before-talk, LTE and WiFi coexistence.

I. INTRODUCTION

Device-to-device (D2D) communications underlying LTE networks have been proposed as a promising approach to facilitate high data rate services in a short range and to increase the performance of LTE systems [1]–[4]. Due to the short communication range of D2D pairs, D2D communication plays a vital role in improving energy efficiency, delay, and the battery lifetime of UEs (User equipment). It also improves the throughput of the cellular network by reusing the licensed spectrum and enjoys the benefit of fast access to the radio spectrum in terms of proximity gain, reuse gain, and paring gain. However, due to the deployment of a huge number of heterogeneous Network (HetNets) [5], [6], the licensed spectrum is being easily congested with a large number of small cells and requires sophisticated intercell interference management techniques to be devised. To overcome the scarcity of licensed spectrum and to alleviate the congestion problem, operators are forced to exploit the readily available unlicensed spectrum. As a result, LTE in unlicensed spectrum (LTE-U) is initiated as part of LTE release 13 to allow users to access both the licensed and unlicensed spectrum under a unified LTE network infrastructure [7]. However, if LTE is allowed to operate directly in the same band with WiFi it will result in significant performance degradation of WiFi networks. Because, stations and access points in the WiFi network use Distributed coordination function (DCF) to access a channel. DCF uses a contention-based protocol known as carrier sense multiple access with collision avoidance (CSMA/CA), where nodes listen to the channel before transmission. But LTE users do not require carrier sensing prior to transmission. Instead, the LTE base station allocates radio communication channels to users.

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To address this coexistence issue, a number of mechanisms have been developed in the literature to modify LTE and to make a good neighbor to WiFi networks. In this regard two main protocols have been proposed, these are, listen before talk (LBT) method and duty cycle method. LBT is a mechanism by which users should assess the medium before transmitting, i.e, users adopt carrier sensing multiple access with collision avoidance to prevent the probability of collision with WiFi users [8], [9]. In the duty cycle, however, LTE-U users leave a space for WiFi users by refraining from transmission for some periods of time [10]–[13]. Liu *et al.* [14] showed that the duty cycle based unlicensed access method achieves better system throughput than LBT based access method. However, the unlicensed band is better used for short-range communications because of the following reasons: (1) since we are considering the 5 GHz frequency band, the channel fading is higher than that of the carrier frequency on the licensed spectrum. (2) In the unlicensed band, there is power limitation due to power regulations. Hence, it is better to use it for D2D communication because D2D communication happens when the transmitter and receiver are nearby. However, there are two main challenges when implementing D2D communication on the unlicensed band (D2D-U). First, the interference caused by the D2D users to both the cellular and WiFi users should be mitigated carefully. Secondly, the optimal mode should be determined, that is, whether the D2D users should share the licensed band with cellular users or Unlicensed band. To solve the above problems our main contributions in this paper include the following aspects:

1) In this paper, we propose a joint mode selection, channel allocation and power control using particle swarm optimization (PSO) to maximize the overall throughput of cellular and D2D users such that data rate requirement of WiFi users is guaranteed. In the previous studies, an arbitrary number of D2D pairs are allowed to share the same channel with one cellular user (CU). However, the mitigation of the interference caused to the cellular users is difficult, because they only considered the licensed band and there is a scarcity of spectrum in the licensed band. In our case, we solve this drawback by determining those D2D pairs that cause strong interference to the cellular user using the PSO algorithm and let them use the unlicensed band using the duty cycle method. Hence, the interference faced by the cellular users can be mitigated and the throughput of the network is also maximized.
2) Our considered optimization problem is a mixed integer nonlinear problem (MINP). In the literature, many researches have been made to solve these kinds of problems by using deterministic algorithms such as linear programing, branch-and-bound approach and dynamic programing. However, these algorithms often have prohibitive time complexity and would only be feasible for network scenarios with a small number of mobile users. As a result, NP algorithms have been studied to find near-optimal solutions to such large size NP problems. These algorithms include evolutionary algorithms (EAs) and, in particular, particle swarm optimization (PSO). PSO has attracted lots of attention in wireless communication because of its better global search ability, simplicity and efficiency in dealing with large size problems, e.g. [15]–[17]. Because of these advantages we proposed PSO algorithm to solve the optimization problem. We also designed different fitness values according to the constraints to avoid the algorithm from trapping into infeasible solutions.
3) The existing works that tried to implement D2D communication on the unlicensed band used deterministic algorithms to solve the MINP which is NP hard. However, these algorithms have prohibitive time complexity and would only be feasible for small size network scenarios. In order to overcome these drawbacks we used the PSO algorithms because with PSO algorithm it is possible to solve the large size NP hard problems with polynomial time complexity while guaranteeing the convergence.

The rest of this paper is organized as follows. The related works are introduced in Section II. The system model and problem formulation are illustrated in Section III. The PSO based joint mode selection, channel allocation and power control algorithm are presented in Section IV. Numerical results are provided in Section V and the paper is concluded in Section VI.

II. RELATED WORKS

There has been a number of works that focus on improving the capacity of the network by exploiting the unlicensed band [18]–[20]. Chen *et al.* [20] proposed three methods for delivering cellular data traffic in the unlicensed spectrum, namely resource sharing, traffic offloading and hybrid method. In [19], a practical algorithm for Integrated Femto-WiFi and Dual Band Femtocell to automatically balance their traffic in licensed and unlicensed bands, based on the real-time channel, interference and traffic conditions of both bands are described. Elsherif *et al.* [18] tried to allocate resources over both licensed and unlicensed bands with the goal of maximizing sum small cell user equipment rate while controlling inter-cell interference. Even though it has been shown that proximity gain, hop gain and reuse gain can be achieved by using D2D communication [3], there are currently few papers that deal with the application of the LTE-U in the D2D communications. Zhang *et al.* [21] proposed a sensing based protocol to enable both the LTE and D2D users to access the unlicensed band. They tried to improve the system sum rate by solving the resource allocation problem of the LTE-U and D2D pairs using many to many matching game. In that work, they considered uplink resource sharing for the D2D pairs but they do not consider the QoS requirement of the LTE-U users and the minimum rate required to coexist with WiFi users. Bairagi and Hong [22] also investigated the LTE underlaid D2D communications in the LTE-U network by taking the QoS requirement of the LTE-U users and the minimum rate requirements of wireless users. Unlike Zhang *et al.* [21] that considered only one base station (BS), these authors consider multiple small base stations coexisting in the same unlicensed band. They tried to maximize the LTE-U sum rate by using the bargaining game. They also considered the downlink sharing for the D2D users. However, it is difficult to mitigate the interference in the downlink as compared to the uplink resource sharing because the uplink resources are often underutilized. Liu *et al.* [14] propose a joint mode selection and resource allocation using the Hungarian algorithm in the licensed band and both duty cycle and LBT for the unlicensed band. By doing so they tried to maximize the throughput of cellular and WiFi users while the data rate requirement of the D2D users is attained. However, only one D2D pair is allowed to share the same channel with one CU, as a result, the spectrum is not being used efficiently.

On the other hand, there have been some studies that adopt the bio-inspired PSO algorithm to D2D underlaid cellular networks. Su *et al.* [23] proposed PSO based mode selection and resource allocation approach to maximize the overall network throughput. However, only a single D2D pair is allowed to share the same channel with one cellular user. In [24], the hybrid PSO-GA algorithm has been proposed to maximize the system throughput by allowing up to two D2D pairs to share the same channel with one cellular user. But, the powers of all mobile users are fixed. Xu *et al.* [25] proposed joint channel and power allocation based on PSO for cellular networks with D2D communications. Different from the other papers they tried to maximize the throughput of the system by allowing an arbitrary number of D2D users share the same channel with one cellular user. However, since more than one D2D pairs are allowed to reuse the same channel with one CU, it is very difficult to mitigate the interference introduced by these D2D pairs to the primary CU.

III. SYSTEM MODEL AND PROBLEM FORMULATION

A. SYSTEM MODEL

As can be seen in Fig. 1 we consider a single cell network with C cellular users (CUs) which connect to the base station (BS) and D D2D pairs that communicate directly without the help of the BS. Let $\mathcal{C}$ and $\mathcal{D}$ be the sets of CUs and D2D pairs respectively. We further assume that the user devices support the D2D communication and the LTE-U technology simultaneously. As shown in Figure 1 there is also a coexisting WiFi network with L WiFi users working on the 5 GHz unlicensed band. The D2D users can transmit data using either licensed or unlicensed band as follows:

- If a D2D user is allowed to transmit on the licensed spectrum, it will reuse the channel with the cellular user. In this case the D2D users share the uplink resources rather than the downlink resources because dealing with interference is less complex than the downlink. More than one D2D users are allowed to reuse a single channel as long as the normal operation of the cellular users is not degraded.
- When the D2D users seem to introduce strong interference to the cellular users these D2D users are forced to transmit on the unlicensed band. These D2D users access the unlicensed band using duty cycle method to avoid the interference that will be introduced to the WiFi users.

1) WIFI THROUGHPUT MODEL

The saturation system throughput of the WiFi network is related to the number of competing WiFi users. Let P_{tr} be the probability that there is at least one transmission in one-time

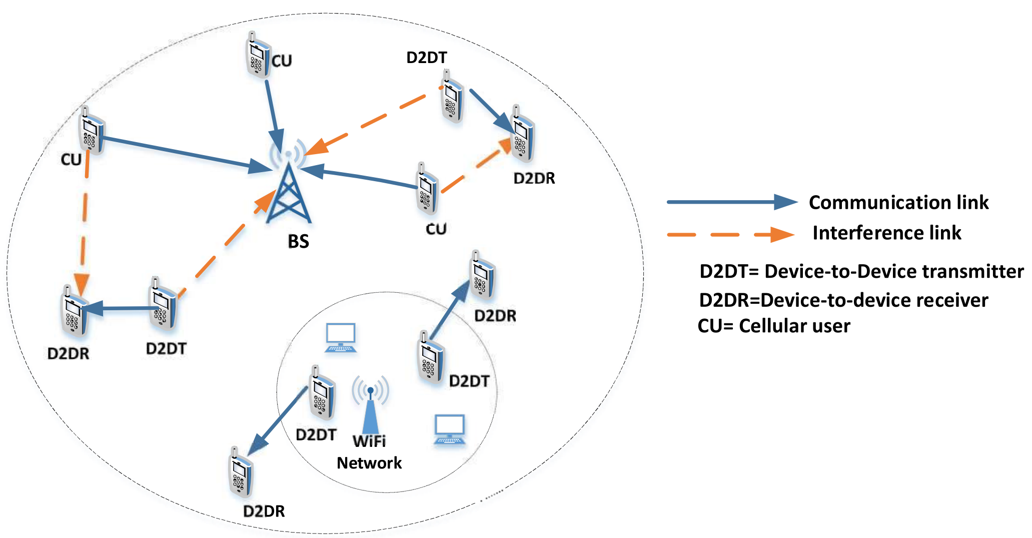

FIGURE 1. System model.

slot and there are l WiFi users competing for the channel, and each transmits with probability τ.

$$P_{tr} = 1 - (1-\tau)^l.$$

Let P_s be the probability that a transmission occurring on the channel is successful, i.e., the probability that there is no collision. P_s can be expressed as:

$$P_s = \frac{l\tau(1-\tau)^{l-1}}{P_{tr}}.$$

According to [26] the saturation throughput of the whole WiFi network is expressed as:

$$S(l) = \frac{P_{tr}P_sE(P)}{(1-P_{tr})T_\delta + P_{tr}P_sT_s + P_{tr}(1-P_s)T_c},$$

where $E(P)$ is the average packet size, T_δ is the duration of an empty slot time, T_s is the average time that the channel is sensed busy caused by a successful transmission and T_c is the average time that the channel is sensed busy by each station during a collision.

2) CELLULAR AND D2D THROUGHPUT MODELS

In the cellular network, we consider as the whole network is provided with N orthogonal channels. The channels are assigned to the cellular users orthogonally, hence, there is no interference amongst the CUs. The throughput of the cellular and D2D users depends on the communication mode they are using as explained in the following:

- Licensed reusing mode: In this mode the D2D pairs communicate by reusing the uplink channel of a single cellular user. The SINR of D2D pair d on subchannel n is expressed as:

$$SINR_d^n = \frac{x_{d,n}^l P_d h_{d,d}}{x_{c,n}^l P_c h_{c,d} + \sum_{j\in\mathcal{D},j\neq d} x_{j,n}^l P_j h_{j,d} + N_0},$$

  where $h_{j,d}$ is the channel gain from the D2D transmitter j to the D2D receiver d, P_d is the power of D2D pair d, P_c is the power of cellular user c and N_0 is the Gaussian white noise, $x_{c,n}^l$ and $x_{d,n}^l$ are channel assignment indicators and $x_{d,n}^l$=1 if the channel n is assigned to the D2D pair d otherwise its value is zero. Similarly if $x_{c,n}^l$=1 the channel n is assigned to the cellular user c.
  The SINR of the cellular user c on the channel n is expressed as:

$$SINR_c^n = \frac{x_{c,n}^l P_c h_{c,Bs}}{\sum_{d\in\mathcal{D}} x_{d,n}^l P_d h_{d,Bs} + N_0},$$

  where $h_{c,Bs}$ is the channel gain between the cellular user c and the BS and $h_{d,Bs}$ is the channel gain between the transmitter of D2D pair d and the BS.
  According to Shannon's formula the throughput of CU c on channel n is expressed as follows:

$$R_c^n = B\log_2(1 + SINR_c^n),$$

  where B is the bandwidth of the channel. Similarly, the throughput of D2D pair d on the channel n is expressed as:

$$R_d^n = B\log_2(1 + SINR_d^n),$$

  The rates achieved by the cellular user c and D2D pair d is the summation of the throughput on all the channels and are expressed respectively as follows:

$$R_c = \sum_{n=1}^{N} R_c^n,$$
$$R_d = \sum_{n=1}^{N} R_d^n.$$

  The throughput of all the cellular users in the network is the summation of all the throughput achieved by each of the CUs in the set $\mathcal{C}$ as expressed in the following equation:

$$R_{CUs} = \sum_{i=c}^{\mathcal{C}} R_c.$$

  Similarly the throughput of all the D2D pairs in the network is the summation of all the throughput achieved by each of the D2D pairs in the set $\mathcal{D}$ and can be expressed as follows:

$$R_{D2Ds} = \sum_{i=d}^{\mathcal{D}} R_d.$$

  The overall system throughput is the summation of the throughput of all users in the network which can be expressed as follows:

$$R = R_{CUs} + R_{D2Ds}.$$

- Duty cycle based Unlicensed Mode: In this mode, both D2D users and WiFi users transmit alternatively on different time slots by using the duty cycle method on the unlicensed band. The SINR of the D2D pair d in this mode can be calculated as:

$$SINR_d^u = \frac{P_d^u h_d^u}{N_0},$$

  where P_d^u is the transmit power and h_d^u is the channel power gain of D2D pair d on the unlicensed spectrum.
  Assume the D2D pair d occupies ρ_d fraction of the overall time slots on the unlicensed band, then the throughput of the D2D pair d can be written as follows:

$$R_d^u = \rho_d B^u \log_2(1 + SINR_d^u),$$

  where B^u denotes the bandwidth of the unlicensed band.

B. PROBLEM FORMULATION

It is obvious that the existence of D2D communications definitely degrades the performance of both cellular and WiFi users. Hence, in this paper we investigate joint communication mode selection, channel allocation and power control to minimize the performance degradation of cellular and WiFi users caused by the D2D communication. More specifically, our goal is to maximize the overall throughput of both the cellular and D2D users for a given data rate requirement of WiFi users.

Denote $\mathbf{x} = \{\mathbf{x}^l, \mathbf{x}^u\}$ as the channel assignment matrix and mode selection, where $\mathbf{x}^l = \{x^l_{1,n}, x^l_{2,n}, \ldots, x^l_{i,n}\}\ \forall i \in \mathcal{C} \cup \mathcal{D}$ is channel assignment matrix in the licensed reusing mode and $\mathbf{x}^u = \{x^u_1, x^u_2, \ldots, x^u_D\}$ is unlicensed mode access indicator. Denote $\mathbf{p}$ as the transmit power matrix of the CUs and D2D pairs. Based on this assumption we formulate the mathematical optimization problems for the duty cycle based unlicensed access as follows:

$$\max_{\mathbf{x},\mathbf{p}}\ R \tag{1a}$$
$$\text{s.t}\ x^l_{i,n}, x^u_d \in \{0, 1\}, \quad \forall i \in \mathcal{C} \cup \mathcal{D}, \quad \forall d \in \mathcal{D} \tag{1b}$$
$$0 \leq P_c \leq P^{\max}_{CU}, \quad \forall c \in \mathcal{C} \tag{1c}$$
$$0 \leq P_d \leq P^{\max}_{D2D}, \quad \forall d \in \mathcal{D} \tag{1d}$$
$$R_i \geq R_{\min}, \quad \forall i \in \mathcal{C} \cup \mathcal{D} \tag{1e}$$
$$\sum_{i \in \mathcal{C}} x^l_{i,n} \leq 1, \quad \forall n \tag{1f}$$
$$\sum_{i=1}^{N} x^l_{d,i} + x^u_d \leq 1, \quad \forall d \in \mathcal{D} \tag{1g}$$
$$\left(1 - \sum_{d=1}^{D} x^u_d \rho_d\right) S(L) \geq S^T \tag{1h}$$
$$\rho_d B^u log_2 \left(1 + \frac{P^u_d h^u_d}{N_0}\right) \geq R_{\min}. \tag{1i}$$

In the above optimization problem $P^{\max}_{CU}$, $P^{\max}_{D2D}$ denotes the maximum transmit powers of cellular and D2D pairs respectively. $R_{\min}$ and S^T denotes the throughput thresholds of cellular, D2D users and WiFi users respectively. The constraint $(1b)$ ensures that the licensed and unlicensed channel allocation indicators have binary values. The constraint $(1c)$ and $(1d)$ ensures that the transmit power cannot exceed the maximum. The constraint $(1e)$ guarantees the minimum throughput for both cellular and D2D users on the licensed band. Constraints $(1f)$ and $(1g)$ limits that no two CUs share the same channel and each D2D pair can only chose one communication mode respectively. Constraints $(1h)$ and $(1i)$ guarantee the throughput threshold of WiFi and D2D pairs on the unlicensed band respectively.

The above joint channel allocation, power control and mode selection problem is mixed-integer nonlinear programming problem with a large solution space. These optimization problems are recognized to be NP-hard problems. We adopt the bio-inspired PSO algorithms to solve this optimization problem because it has better global search ability and it is simple and efficient in dealing with difficult problems in comparison with conventional mathematical programming techniques.

The D2D users access the unlicensed band using the duty cycle method, i.e., the D2D pair d occupies ρ_d fraction of the unlicensed resource. On the other hand, in the licensed reusing mode more than one D2D pair reuses the uplink resource of a CU. Therefore, different D2D pairs would cause different levels of interference to the cellular users based on their locations and channel power gains. So the main role of the PSO algorithm is to identify those D2D users causing strong interference and let them access the unlicensed spectrum using the duty cycle method. However, the number of the D2D users that should access the unlicensed band should be determined so that the performance of the WiFi users is not degraded. We first introduce the standard continuous PSO algorithm and standard binary PSO algorithm before introducing the proposed algorithm.

1) STANDARD CONTINUOUS PSO ALGORITHM

The PSO is a population-based optimization method which is inspired by the social behavior of bird flocks [27]. The position of each particle represents a candidate solution (i.e., channels and powers assigned to users in this study) for the problem and a fitness function is defined to evaluate the feasibility of the solution. In PSO, each particle in a swarm moves around in the search space seeking for the local optima or appropriate solution by updating its position guided by some rules.

Consider a swarm consisting of M particles, assume that the position of the m^{th} particle of the swarm is represented by $\mathbf{z}_m = (z_{m,1}, z_{m,2}, \ldots, z_{m,I})$ and the velocity of the m^{th} particle is $\mathbf{v}_m = (v_{m,1}, v_{m,2}, \ldots, v_{m,I})$, where I is the total number of cellular and D2D pair users, i.e, $I = C + D$. According to [27], the velocity and position of the particles are updated as follows:

$$\mathbf{v}_m = w\mathbf{v}_m + c_1 r_1(\mathbf{y}_m - \mathbf{z}_m) + c_2 r_2(\mathbf{g} - \mathbf{z}_m), \tag{2}$$
$$\mathbf{z}_m = \mathbf{z}_m + \mathbf{v}_m, \tag{3}$$

where $\mathbf{y}_m$ represents the best position of the m^{th} particle, $\mathbf{g}$ represents the global best position of m^{th} particle, w denotes the weight, r_1 and r_2 are random variables within the range of (0, 1).

According to [27] the velocity $\mathbf{v}_m$ of the m^{th} particle is determined by three parts: (i) the "*momentum*" part $\mathbf{v}_m$ represents the previous velocity term which is used to guide the particle in the direction it traveled so far; (ii) the "*cognitive*" part $r_1 c_1(\mathbf{y}_m - \mathbf{z}_m)$ which represents the tendency of the particle to return to the best position it has visited so far and (iii) the "*social*" part $r_2 c_2(\mathbf{g} - \mathbf{z}_m)$ which represents the tendency of the particle to be attracted towards the position of the best position found by the entire swarm.

The pseudocode of the standard continuous PSO algorithm is shown in Algorithm 1. Where f is the fitness function to evaluate the feasiblity of each particle.

Algorithm 1 The Standard Continuous PSO Algorithm

Generate m different particles and initialize them randomly
Repeat
```
for each particle m ∈ [1...M] do
    if f(z_m) > f(y_m) then
        y_m ← z_m
        if f(y_m) > f(g) then
            g ← y_m
            Update velocity v_m according to 2.
            Update position z_m according to 3.
        end if
    end if
end for
```
Until stopping condition is true.

2) STANDARD BINARY PSO ALGORITHM

Since the channel assignment is a discrete problem the continuous standard PSO algorithm cannot be used to solve this problem. The binary version of PSO was introduced by Kennedy and Eberhart to solve binary problems [28]. The binary PSO restricts the component values of $\mathbf{z}_m$ and $\mathbf{y}_m$ to be taken from the set $\{0, 1\}$. However, there is no such restriction in case of the velocity $\mathbf{v}_m$ of the particles. But when the velocity is used to update the position of the particle the velocity is restricted to the range [0, 1] and treated as a probability. To accomplish this, we introduced the sigmoid function as follows:

$$sig(\mathbf{v}_m) = \frac{1}{1 + \exp(-\mathbf{v}_m)}.$$

Further the position of the i^{th} element of the m^{th} particle is updated as:

$$z_{m,i} = \begin{cases} 0, & \text{if } r_{m,i} \geq sig(v_{m,i}) \\ 1, & \text{if } r_{m,i} < sig(v_{m,i}) \end{cases} \tag{4}$$

where $r_{m,i}$ is a uniform random number in the range [0, 1]. Note that the pseudocode of the standard binary PSO algorithm is same as the standard continuous PSO algoritm except position of each particle is updated according to Eq. (4).

IV. PSO BASED JOINT MODE SELECTION, CHANNEL ALLOCATION AND POWER CONTROL ALGORITHM

A. PSO BASED JOINT CHANNEL AND POWER ALLOCATION ALGORITHM IN THE LICENSED BAND

In this subsection, we developed a PSO based algorithm to deal with the joint channel allocation and power control problems for both the cellular and D2D pairs in the licensed reusing mode. As in [25] we solve the problem by the joint channel allocation and power control algorithm based on PSO (JCPPSO) where both continuous powers and discreet channels can be solved simultaneously. The coding of variables and designing of fitness values are the factors that affect the performance of the algorithm. We introduce these in the following subsections.

1) CODING OF VARIABLES

As can be seen in the mathematical optimization problem in ($1a$) the constraints that channels need to meet are: (i) as in the constraint ($1f$) the channel assigned to CUs need to be orthogonal; (ii) each user is assigned at most one channel. To satisfy these requirements we adopt binary coding. Thus in the JCPPSO algorithm, we use an integer k_i within the range $[1, N]$ to represent the channels assigned to the user i ($i = 1, \ldots, D + C$). And k_i is coded using the binary coding scheme when executing the JPPSO, also it can be decoded back into integers. For example, if in total there are 4 channels, we can use two bits to represent the channels assigned to users, like 01 represent channel 1 and 10 represent channel 2, etc. The above coding scheme is illustrated in Fig. 2 by considering two cellular users and 3 D2D pairs. Further, We assumed the channels assigned to the users are (1, 2, 2, 1, 2).

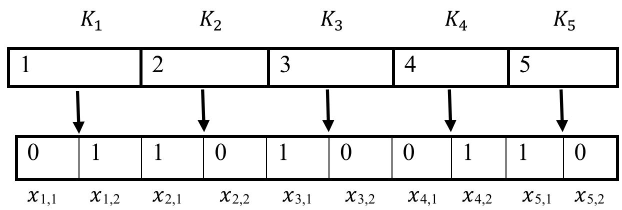

FIGURE 2. Binary coding of the channels.

For the case of the powers, they are denoted by real values within the range limited by the lower and upper constraints of the powers. Generally, in the proposed algorithm the discreet channels and continuous powers are updated simultaneously by considering the rules mentioned in the optimization problem ($1a$).

2) FITNESS VALUE

As we explained earlier the constraints on the channels are solved by using variable coding and the power constraints are met by rounding the powers out of the infeasible range into the feasible range. On the other hand, the fitness values are used to guarantee the constraints on the minimum achievable rate of each user.

For the problem in ($1a$) the fitness value is defined as follows:

$$f(\mathbf{z_m}) = \begin{cases} R(\mathbf{z}_m), & \text{if } R_m(\mathbf{z}_m) \geq R_{m,\min} \\ 0, & \text{otherwise} \end{cases} \tag{5}$$

where $\mathbf{z}_m$ is the location of the m^{th} particle which combines the channels and powers assigned to users, R_m and $R_{m,\min}$ are the throughput of the m^{th} particle and minimum throughput respectively.

B. DUTY CYCLE BASED UNLICENSED MODE

After finding the optimal joint channel allocation and power control in the licensed band using the PSO algorithm, the D2D users that cause strong interference are forced to access the unlicensed band by using the duty cycle method.

Therefore, once in the unlicensed band, the D2D pair d occupies ρ_d fraction of the unlicensed resource. In this case, the WiFi throughput loss caused by the D2D pair d is expressed as:

$$-\rho_d S(l) \quad \forall d.$$

Then the throughput gain when transferring the D2D pair d from the licensed band to the unlicensed band can be expressed as:

$$H_d = -\rho_d S(l) - G_{d,n} \quad \forall d. \tag{6}$$

where $G_{d,n} = R_c^n - A_c^n$ is the throughput loss on the licensed band due to the D2D pair d reusing same channel with the cellular user, $R_c^n = \log_2(1 + \frac{x_{c,n}^l P_c h_{c,Bs}}{\sum_{d \in \mathcal{D}} x_{d,n}^l P_d h_{d,Bs} + N_0})$ is the throughput of CU c on channel n, $A_c^n = \log_2(1 + \frac{x_{c,n}^l P_c h_{c,B}}{N_o})$ is the throughput of CU c on channel n without mutual interference and $-\rho_d S(l)$ is the WiFi throughput loss caused by the D2D pair d.

Since our goal is to maximize the throughput of the network while guaranteeing the minimum data rate requirement of WiFi users, the optimal unlicensed resource allocation, ρ_d, can be achieved at its minimum value from $(1i)$ as follows:

$$\rho_d = \frac{R_{\min}}{B^u \log_2(1 + SINR_d^u)}.$$

Furthermore, the maximum number of time-slots for D2D pairs, $\rho_{\max}$, that can share the unlicensed band without affecting the regular performance of WiFi users can be obtained from the constraint $(1h)$ as follows:

$$\rho_{\max} = 1 - \frac{LS^T}{S(L)}.$$

As we can see from Eq. (6) to maximize the throughput of the cellular and D2D users, the D2D pairs with the largest positive H_d should be moved to the unlicensed spectrum. That is before letting the D2D pairs access the unlicensed band we have to check the throughput gain H_d. H_d is positive means that moving the D2D pair d to the unlicensed band is better (there is less interference as compared to the licensed band). However, if H_d is negative it implies that there is a strong interference in the unlicensed band and hence moving the D2D pair d to the unlicensed band will lead to degrade the performance of the WiFi users as well as the performance of D2D pair d will also be degraded. Therefore, the D2D pair d is allowed to access the unlicensed band only if $\rho_d < \rho_{max}$. If $\rho_d > \rho_{\max}$ we should skip this D2D pair and proceed with the remaining D2D pairs. Besides, the D2D pair d with the largest positive H_d value is moved first and the others will follow in sequence from the largest H_d value till the smallest positive value of H_d in order to achieve maximum overall throughput. The process continues until there is no positive H_d or the maximum time slot occupancy is reached. This is summarized in the algorithm shown in Algorithm 2.

It can be found that the main time complexity of Algorithm 2 is the PSO algorithm. At each iteration, the algorithm needs to update velocity and position in all dimensions

Algorithm 2 JCPPSO Based Algorithm for the Duty Cycle Based Unlicensed Access

Generate m different particles and initialize them randomly, each particle contains binary variables $\mathbf{z}_m^b$ and continuous variables $\mathbf{z}_m^c$.

Repeat

for each particle $m \in [1 \ldots M]$ **do**
  Calculate the fitness value according to Eq. (5).
  if $f(\mathbf{z}_m) > f(\mathbf{y}_m)$ **then**
    $\mathbf{y}_m \leftarrow \mathbf{z}_m$, i.e, $\mathbf{y}_m^b \leftarrow \mathbf{z}_m^b$, $\mathbf{y}_m^c \leftarrow \mathbf{z}_m^c$
    if $f(\mathbf{y}_m) > f(\mathbf{g})$ **then**
      $\mathbf{g} \leftarrow \mathbf{y}_m$ i.e, $\mathbf{g}^b \leftarrow \mathbf{y}_m^b$, $\mathbf{g}^c \leftarrow \mathbf{y}_m^c$
      The channels are updated according to the following rules:

$$\mathbf{v}_m^b = w\mathbf{v}_m^b + c_1 r_1(\mathbf{y}_m^b - \mathbf{z}_m^b) + c_2 r_2(\mathbf{g}^b - \mathbf{z}_m^b)$$

$$sig(\mathbf{v}_m^b) = \frac{1}{1 + \exp(-\mathbf{v}_m^b)}$$

      Generate the uniform random number r_m in the range (0, 1)
      Update z_m^b : $\mathbf{z}_m^b = (sig(\mathbf{v}_m^b) > r_m)$
      Update the continuous variables (powers) $\mathbf{v}_m^c$ *and* $\mathbf{z}_m^c$ according to Eq. (2) and (3)
      If some items in $\mathbf{z}_m^c$ are lower or greater than the bound, set it to be the smallest or largest of the bound
      The new position of the m^{th} particle is updated to be $\mathbf{z}_m(\mathbf{z}_m^b, \mathbf{z}_m^c)$
    end if
  end if
end for
Until stopping condition is true
Initialize $\mathcal{D}$={1, ..., d, ..., D}
for each D2D pair $d \in [1 \ldots D]$ **do**
  Calculate $H_d = -\rho_d S(L) - G_{d,n} \quad \forall d$
end for
while $\mathcal{D} \neq \emptyset$ **do**
  $d^* = \text{argmax}_{d \in \mathcal{D}}(H_d)$
  if $H_{d^*} > 0$ and $\rho_{d^*} < \rho_{\max}$ **then**
    Move D2D pair d^* to the unlicensed band by using the duty cycle method
    $\rho_{\max} = \rho_{\max} - \rho_{d^*}$ and set $\mathcal{D} = \mathcal{D} - d^*$
  else if $H_{d^*} > 0$ and $\rho_{d^*} > \rho_{\max}$ **then**
    Set $\mathcal{D} = \mathcal{D} - d^*$
  else
    break
  end if
end while

of the particles which has a time complexity of $\mathcal{O}(q(C+D))$. For fitness calculation, the algorithm visits all CUs and D2D users calculating SINR and the achieving rate of each user which costs $\mathcal{O}(q(C+D))$. Finally, the algorithm needs to compare the fitness value and update the private best and global best which has a time complexity of $\mathcal{O}(2*q)$. If the algorithm terminates after running t iterations the complexity of the algorithm is: $\mathcal{O}(t(q(C+D)+q(C+D)+2*q))$ which is polynomial time complexity.

V. NUMERICAL RESULTS

In this simulation we consider a single cell network with a radius of 500 m where the base station is located at the center. Cellular users and D2D users are uniformly distributed over the cell area. A WiFi network is also co-located in the cellular coverage area. We adopt the IEEE 802.11n protocol working at 5Ghz. The path loss is modeled as $128.1 + 37.6\log_{10}$ (d[km]) for the links between BS to users, $148 + 40\log_{10}$ (d[km]) for the D2D links in the licensed band and $148 + 50\log_{10}$ (d[km]) for the D2D links in the unlicensed band, where d is distance in kilometers [29]. The shadowing is modeled as log-normal random number with zero mean and standard deviation of 4dB. The noise variance is assumed as -120 dBm [30]. The main simulation parameters are summarized in Table 1. The parameters of the unlicensed spectrum are similar to the ones in [31]. For the case of the PSO parameters, we set the values of c_1 and c_2 to be 1.49445, and w to be 0.729. This parameter setting was used in [32] and [33] which ensured the convergence of PSO algorithm. In the simulation we consider the traditional D2D communications without the LTE-U technology as a baseline [25]. Considering the fact that there are no state of the art that use the unlicensed band having same goal as ours, we propose a PSO based joint mode selection, channel allocation and power control that limits the number of D2D pairs sharing same channel with licensed band users to one. The main difference with our proposed algorithm is in this case one channel can be reused by at most one D2D pair. The optimization problem is same as in $(1a)$ except one more constraint is added. The constraint limits the number of D2D pairs sharing same channel to one and is given by: $\sum_{i=d}^{D} x_{i,n}^{l} \leq 1 \quad \forall n$. In order to solve this optimization problem we introduced admission control to our proposed algorithm in 2 to make sure that no two D2D pairs are allowed to share same licensed channel. In the following figures, the system throughput refers to the aggregated throughput of cellular and D2D pairs. Moreover, JMCPPSO-Overall refers to our proposed algorithm, JMCPPSO-oned2d refers to the case when no two D2D pairs are allowed to reuse same licensed channel, and JCPPSO-cellular only refers to the conventional JCPPSO scheme without the unlicensed band [25].

To investigate the convergence of the proposed algorithm, we set the maximum distance between the D2D pair to 50 m and the minimum required rate of each user to 250 kbps. As can be seen from the figure, the system throughput keeps increasing for about 60 iterations and becomes constant for the rest of the iterations. This shows that the PSO algorithm converges with a reasonable time. In Fig. 4 we show the

TABLE 1. Configuration of the main parameters.

Parameters	Values
$P_{CU}^{\max}$	23 dBm
$P_{D2D}^{\max}$	23 dBm
unlicensed transmit power	20 dBm
Coverage of the BS	500 m
B, B^u	1 MHz, 1 MHz
Number of WiFi users	10
Number of CUs	8
Number of D2D pairs	10
Local learning factor: c_1	1.49445
Global learning factor:c_2	1.49445
w	0.729
Number of particles: q	20
$E(P)$	8224 bits
PHY header	192 bits
MAC header	224 bits
ACK	112 bits
$CW_{\min}$	32
$CW_{\max}$	1024
slot time	50 μs
T_δ	20 μs
SIFS	16 μs
DIFS	50 μs

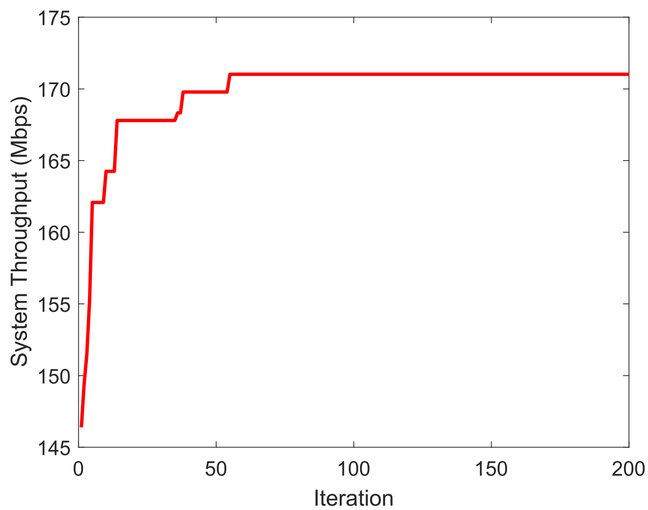

FIGURE 3. Convergence of the JMCPPSO algorithm.

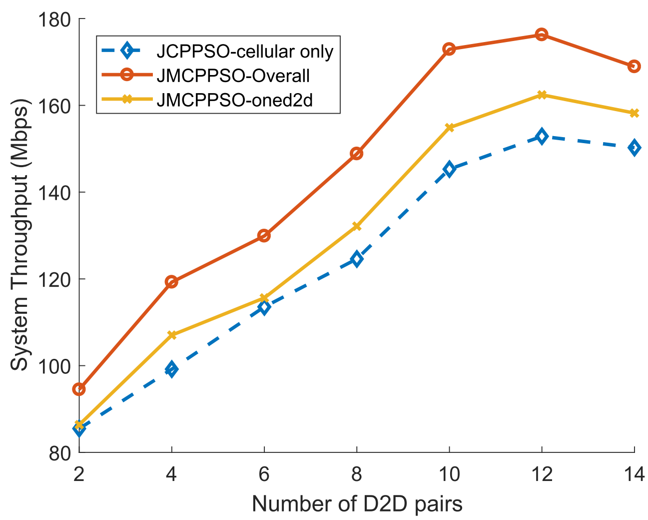

FIGURE 4. The over all throughput of the system for different D2D pairs.

system throughput for different D2D pairs. According to this figure, the system throughput increases with the increasing of D2D pairs but when the number of D2D pairs exceeds from what the system can provide, the system throughput decreases in order to guarantee the minimum rate of the users. This implies that as the number of mobile user increases the system throughput decreases to guarantee the minimum rate requirement of each user which in turn limits the potential of the algorithm to improve the system throughput. As can be seen from the figure our proposed scheme improves the system throughput as compared to the other two schemes. In Fig. 5 we show the system throughput for different distances between D2D pairs. Again our proposed scheme performs better than the other two schemes. We can also see that the system throughput decreases with the increasing of distance between D2D pairs for all schemes. This is because the strength of the desired signal becomes weaker as the distance between D2D pairs increases which results in the decrement of the system throughput. Fig. 6 plots the system

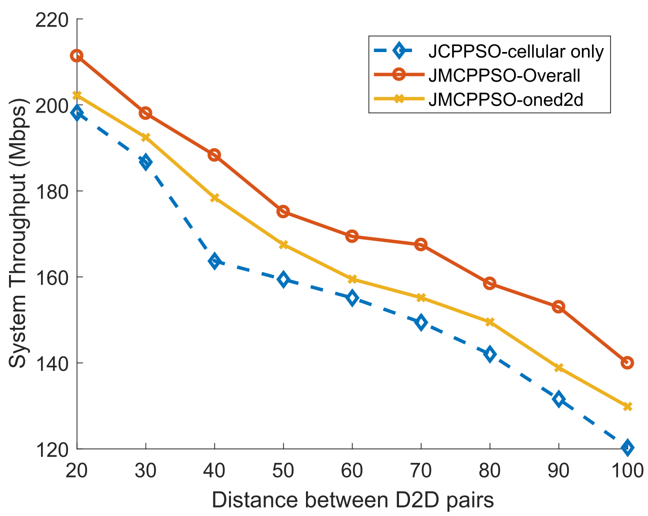

FIGURE 5. System throughput for different distances between D2D pairs.

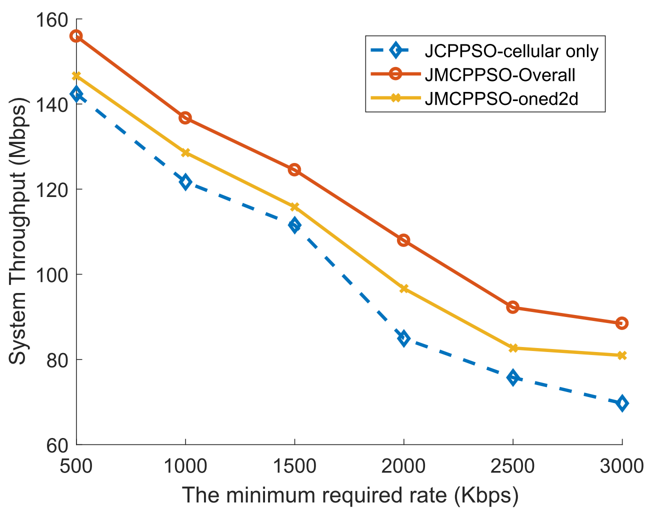

FIGURE 6. System throughput for different minimum rate requirement of the users.

throughput for different minimum data rate requirement of the users. From the figure, it is observed that as the minimum rate requirement of users increases from 500 kbps to 3000 kbps the system throughput decreases for all schemes. This is because meeting the rate requirement of each user is a strict requirement, especially when the rate requirement is larger. As a result the system throughput decreases to meet the minimum rate requirement of each user when the rate requirement increases. As can be seen from the figure our proposed scheme performs better as compared to the other schemes.

VI. CONCLUSION

In this paper, leveraging the emerging LTE-U technology, we have proposed the joint mode selection, channel allocation, and power control using PSO. The algorithm assigns discrete channels and continuous powers to the CUs and D2D pairs jointly. Besides, an arbitrary number of D2D pairs are allowed to share same channel with one CU. The D2D users that cause strong interfernce to the CUs are identified using the PSO algorithm and are forced to access the unlicensed spectrum using duty cycle method in such away that the minimum data rate requirement of WiFi users is not violated. In addition, the rate constraints are guaranteed by designing suitable fitness values which avoids the algorithm from trapping in to infeasible solutions. We have demonstrated that the proposed algorithm converges within a reasonable time. In addition, through various simulation settings, e.g., the minimum rate requirement, distance between D2D pairs, and the number of D2D pairs, we have illustrated that the proposed algorithm achieves better performance as compared to the traditional D2D communications that use the bio-inspired PSO algorithm without the LTE-U technology.

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