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# Device-to-Device Communications in Unlicensed Spectrum: Mode Selection and Resource Allocation

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**ABSTRACT** In this paper, a novel technology, namely, device-to-device communications in the unlicensed spectrum (D2D-U) is proposed, which can allow D2D users to transmit on the unlicensed spectrum and coexist with the incumbent Wi-Fi networks. In D2D-U networks, D2D users can share the licensed spectrum with the existing cellular users or share the unlicensed spectrum with legacy Wi-Fi networks. Therefore, mutual interference across different networks and different users should be properly coordinated to optimize the system performance. In this paper, within the framework of D2D-U, we propose a joint mode selection and resource allocation algorithm to minimize the overall interference that cellular and Wi-Fi users suffer from the D2D communications while guaranteeing the signal-to-noise-and-interference ratio requirements of all users, including those of cellular, D2D, and Wi-Fi. Through theoretical analysis and numerical simulation, we show that using unlicensed spectrum can significantly mitigate the interference to both cellular and Wi-Fi users. Moreover, the duty cycle-based unlicensed spectrum access method achieves better system throughput than the listen-before-talk-based access method in most of the cases.

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

## I. INTRODUCTION

LTE in the unlicensed spectrum (LTE-U) is an appealing technology for enhancing the system throughput by allowing cellular users transmit on the unlicensed spectrum [1], [2]. The main challenge of the LTE-U technology is how to fairly and harmoniously coexist with the legacy WiFi networks. To deal with this issue, two kinds of protocols have been proposed, namely, the listen-before-talk (LBT) method and the duty-cycle method. In the LBT method, LTE users adopt the mechanism of the carrier sensing multiple access with collision avoidance (CSMA/CA) to prevent potential packet collision with WiFi users [3]–[5]. On the other hand, in the duty-cycle method (also known as the carrier sensing adaptive transmission mechanism), LTE-U users vacate the channel resource for WiFi users by muting for some periods of time to ensure orthogonality [6]–[8].

The unlicensed spectrum can only be used for short-range communications due to the following two reasons: the channel fading on the 5GHz unlicensed spectrum is generally larger than that on the lower carrier licensed spectrum; and the transmit power on the unlicensed spectrum is limited according to regulation restriction. Therefore, the LTE-U technique would be better used for small cell base stations rather than macro base stations. With this regards, there have been a number of studies on improving the small cell network capacity through aggregating the unlicensed spectrum. In [9], three methods for delivering cellular data traffic over unlicensed spectra, namely resource sharing, traffic offloading and hybrid method, have been investigated and compared. Leveraging the emerging LTE-U technology, the authors in [10] have proposed a scheme to transfer WiFi users to the LTE-U system, which can create a win-win situation for both networks. In [11], an LBT access mechanism featuring a distributed coordination function (DCF) protocol with adaptive backoff window size has been proposed.

On the other aspects, device-to-device (D2D) communication is another effective way to enhance the cellular throughput by allowing two users in proximity communicate directly rather than going through the base station. It has been shown that proximity gain, hop gain, and reuse gain can be achieved by D2D communications [12]. Since D2D communications often happen when the transmitters and the receivers are nearby, the unlicensed spectrum can also be used to enhance the throughput. There is currently no work investigating the application of LTE-U in the D2D communications. In this paper, we propose a new technology, namely device-to-device communications in unlicensed spectrum (D2D-U), which can allow D2D users to transmit on the unlicensed spectrum and coexist with the incumbent WiFi networks. In D2D-U networks, D2D users can share the licensed spectrum with existing cellular users or share the unlicensed spectrum with WiFi users. Therefore, three issues are important but challenging for deploying D2D-U. First, the optimal communication mode should be determined, that is, whether D2D users should use the licensed spectrum or the unlicensed spectrum and which LTE-U access method should be utilized (LBT or duty-cycle). Secondly, the channel allocation and power control on both licensed and unlicensed spectra should also be determined. Finally, the interference mitigation among D2D, cellular, and WiFi users should be carefully designed.

The joint mode selection and resource allocation in D2D communications has already been investigated in many existing works. The optimal power control and resource allocation in the scenario of single cellular user and single D2D pair has been investigated in [13]. In [14], a joint mode selection, channel assignment and power control problem for multiple D2D users has been proposed to maximize the overall system throughput. An interference-aware graph-based resource sharing algorithm has been proposed in [15], which achieves a near-optimal performance with a low computational complexity. In [16], the mode selection taking into account the quality-of-service (QoS) of both D2D and cellular links has been proposed to minimize the interference caused by D2D communications. With proper channel allocation and power control, the mutual interference caused by D2D users can be minimized in the single base station network [17].

Inspired by the above works, we present a framework of mode selection and resource allocation for D2D-U networks to minimize the mutual interference that cellular and WiFi users suffer from D2D communications while guaranteeing the QoS requirements for all users. First, the mathematical optimization problems are formulated for both LBT and duty-cycle based unlicensed spectrum access methods. Since the studied problems are NP-hard, we develop the corresponding heuristic algorithms with low complexity for both cases, which are demonstrated to achieve performances very close to the optimal algorithms based on the branch-and-bound approach. In addition, we analytically compare the performance of the duty-cycle and the LBT methods and derive a closed-form criterion to guide a D2D pair to choose which method to access the unlicensed spectrum. Our analyses and proposals are finally verified by numerical simulation results.

The rest of this paper is organized as follows. In Section II, the system model is described and the problem is formulated. The joint mode selection and resource allocation algorithms are presented in Section III. Numerical results are provided in Section IV and the paper is finally concluded in Section V.

## II. SYSTEM MODEL AND PROBLEM FORMULATION

In this section, we will first introduce the system model for D2D-U and then formulate the joint mode selection and resource allocation problem.

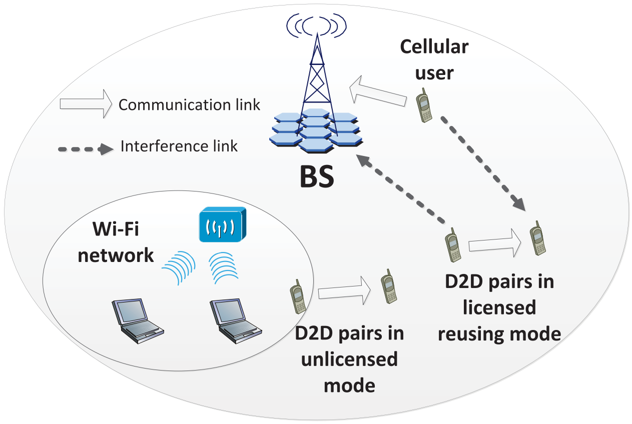


**FIGURE 1.** System model.

### A. SYSTEM MODEL

As depicted in Fig. 1, we consider a single cell network with $M$ cellular users which connect to the base station (BS) in addition to $K$ pairs of potential D2D users communicate with each other directly. We assume that both BS and user devices support the D2D communications and the LTE-U technology simultaneously. There is also a coexisting WiFi network with $N$ WiFi users working on the 5.8 GHz unlicensed spectrum. We further assume that the number of cellular users is larger than that of D2D users, i.e., $M > K$ since it does not frequently happened that two users in the same cell will communicate with each other. It is further assumed that D2D users can transmit on both licensed and unlicensed spectra, as elaborated in the following.

- If D2D user $k$ transmits on the licensed spectrum, it will reuse the channel with existing cellular users, leading to co-channel interference between D2D and cellular users. Here, we assume that the system is heavy-loaded, i.e., there is no unused uplink or downlink channel available for D2D users. Moreover, rather than downlink resource sharing, uplink resource sharing is considered since dealing with co-channel interference in uplink will be much easier than in downlink. Furthermore, to avoid severe co-channel interference, we assume that one channel can be reused by at most one D2D pair.

Besides, it is also assumed that each D2D pair can only reuse one channel.
- If D2D users transmit on the unlicensed spectrum, interference between D2D and WiFi users would occur. As mentioned above, D2D users can access the unlicensed spectrum by two different methods: the LBT method and the duty-cycle method. In the following, we will describe the two unlicensed access methods in more detail.

In this paper, it is assumed that the BS can get full knowledge of the instantaneous channel state information (CSI) since we will utilize the centralized algorithm to allocate the licensed and unlicensed resource to D2D users. We shall note that the centralized scheduling with full CSI can serve as an upper-bound benchmark for any other distributed algorithms.

### B. WiFi THROUGHPUT MODEL

The saturation system throughput of the WiFi network is related to the number of competing WiFi users. Let $P_{\mathrm{tr}}$ be the probability that there is at least one transmit signal in a time-slot and $P_{\mathrm{s}}$ be the probability that there is no collision in a channel, respectively, then they can be expressed as

$$P_{tr} = 1 - (1-\tau)^n, \tag{1}$$

$$P_s = n\tau(1-\tau)^{n-1}/P_{tr}, \tag{2}$$

where $\tau$ is the transmission probability of each user and $n$ is the number of competing WiFi users. According to [18], the saturation throughput of the whole WiFi network can be expressed as

$$R(n) = \frac{P_{\mathrm{tr}} P_{\mathrm{s}} E\left[P\right]}{\left(1-P_{\mathrm{tr}}\right) T_\sigma + P_{\mathrm{tr}} P_{\mathrm{s}} T_{\mathrm{s}} + P_{\mathrm{tr}}\left(1-P_{\mathrm{s}}\right) T_{\mathrm{c}}}, \tag{3}$$

where $T_{\mathrm{s}}$ is the average time that the channel is sensed busy caused by a successful transmission, $T_{\mathrm{c}}$ is the average time that the channel is sensed busy by each station during a collision, $E\left[P\right]$ is the average packet size, and $T_\sigma$ is the duration of an empty slot time.

It is noted that our work can also be extended into a non-saturation scenario since a similar throughput expression as in (3) could be used in this situation [19], [20].

### C. CELLULAR AND D2D THROUGHPUT MODELS

The throughput models for cellular and D2D users depend on the particular communication mode they are using, just as elaborated in the following.

- Licensed reusing mode: In this mode, two D2D users communicate directly by reusing the uplink channel of one existing cellular user. The spectral efficiency of D2D pair $k$ reusing the channel of cellular user $m$ can be expressed as

$$\begin{aligned} A_{k,m} &= \log_2\left(1+\xi^{(1)}_{k,m}\right) \\ &= \log_2\left(1+\frac{p_{k,m}h^D_k}{p^c_m h_{k,m} + B^C\sigma^2_N}\right), \end{aligned} \tag{4}$$

where $p_{k,m}$ is the transmit power of D2D pair $k$, $p^c_m$ is the transmit power of cellular user $m$, $h^D_k$ is the channel power gain between D2D pair $k$, $B^C$ is the licensed channel bandwidth, $\sigma^2_N$ is the noise power density, and $h_{k,m}$ is the interference power gain between cellular user $m$ and the receiver of D2D pair $k$. Here, it is assumed that $p^c_m$ is a pre-determined constant, as in [17]. On the other aspect, the channel reusing will also bring about interference to the co-channel cellular users. The spectral efficiency of cellular user $m$ when being reused by D2D pair $k$ can be expressed as

$$\begin{aligned} A^C_{k,m} &= \log_2\left(1+\xi^c_{k,m}\right) \\ &= \log_2\left(1+\frac{p^c_m h^c_m}{p_{k,m}h_{k,B} + B^C\sigma^2_N}\right), \end{aligned} \tag{5}$$

where $h^c_m$ is the channel power gain between the cellular user $m$ and the BS and $h_{k,B}$ is the channel power gain between the transmitter of D2D pair $k$ and the BS.
- LBT based unlicensed mode: In this mode, D2D users compete for the unlicensed channel opportunities by using the LBT method. If there are $L$ D2D users using the LBT method to access the unlicensed spectrum in addition to $N$ WiFi users already being served in the WiFi network, the per-user saturation throughput for each D2D pair and each WiFi user can be expressed as $\frac{R(N+L)}{N+L}$, where $R(N+L)$ has been defined in (3).
- Duty-cycle based unlicensed mode: In this mode, D2D users and WiFi users transmit alternatively on different time-slots according to the duty-cycle method. The SINR of D2D pair $k$ in this mode can be expressed as

$$\xi^u_k = \frac{p^u_k h^u_k}{B^U\sigma^2_N}, \tag{6}$$

where $p^u_k$ is the transmit power and $h^u_k$ is the channel power gain of D2D pair $k$ on the unlicensed spectrum. Here, $p^u_k$ is fixed according to the regulation restriction of the unlicensed spectrum. Assume the D2D pair $k$ occupies $\rho_k$ fraction of the overall time-slots on the unlicensed spectrum and let $B^U$ denote the bandwidth of the unlicensed spectrum, then the throughput of D2D pair $k$ can be expressed as $\rho_k B^U \log\left(1+\xi^u_k\right)$.

### D. PROBLEM FORMULATION

The existence of D2D communications will definitely affect both cellular and WiFi users. Therefore, in this paper, we investigate joint communication mode selection and resource allocation to minimize the performance degradation of cellular and WiFi users caused by the D2D communications. To be more specific, we aim at maximizing the overall throughput of cellular and WiFi users for a given data rate requirement of D2D users.

Denote $x = \left\{x^{(1)}, x^{(2)}, x^{(3)}\right\}$ as the mode selection and channel assignment matrix, where $x^{(1)}$ is a $K \times M$ channel assignment matrix for the licensed reusing mode,

$x^{(2)}$ and $x^{(3)}$ are the $K$ dimensional indicator vectors for duty-cycle based and LBT based unlicensed modes, respectively. To be specific, if $x_{k,m}^{(1)} = 1$, D2D pair $k$ will reuse the uplink channel of cellular user $m$; if $x_k^{(2)} = 1$, it will adopt the duty-cycle method to access the unlicensed channel; and if $x_k^{(3)} = 1$, it will adopt the LBT method to access the unlicensed channel. Denote $p$ as the transmit power matrix of D2D pairs which is with the same size as $x^{(1)}$ and $\boldsymbol{\rho}$ as the unlicensed time-slots vector reused by D2D pairs which is with the same size as $x^{(2)}$ and $x^{(3)}$.

In what follows, we further assume that all D2D pairs can only apply either LBT or duty-cycle method to access the unlicensed spectrum. Based on this assumption, we formulate the mathematical optimization problems for the LBT method and the duty-cycle method, respectively, as in the following.

1) The optimization problem for the LBT based unlicensed spectrum access can be formulated as

$$\max_{\{x,p\}} \left\{ \sum_{k=1}^{K} \sum_{m=1}^{M} x_{k,m}^{(1)} B^C A_{k,m}^C + \sum_{m=1}^{M} \left(1 - \sum_{k=1}^{K} x_{k,m}^{(1)}\right) B^C C_m + \frac{NR\left(N + \sum_{k=1}^{K} x_k^{(3)}\right)}{N + \sum_{k=1}^{K} x_k^{(3)}} \right\}, \quad (7)$$

subject to

$$x_{k,m}^{(1)}, x_k^{(3)} \in \{0, 1\}, \quad \forall k, m, \quad (7a)$$

$$\sum_{k=1}^{K} x_{k,m}^{(1)} \le 1, \quad \forall m, \quad (7b)$$

$$\sum_{m=1}^{M} x_{k,m}^{(1)} + x_k^{(3)} = 1, \quad \forall k, \quad (7c)$$

$$x_{k,m}^{(1)} \frac{p_m^c h_m^c}{p_{k,m} h_k^B + B^C \sigma_N^2} + \left(1 - \sum_{k=1}^{K} x_{k,m}^{(1)}\right) \frac{p_m^c h_m^c}{B^C \sigma_N^2} \ge \xi_c, \quad \forall k, m, \quad (7d)$$

$$\frac{R\left(N + \sum_{k=1}^{K} x_k^{(3)}\right)}{N + \sum_{k=1}^{K} x_k^{(3)}} \ge R^T, \quad (7e)$$

$$x_{k,m}^{(1)} \frac{p_{k,m} h_k^D}{p_m^c h_{k,m} + B^C \sigma_N^2} \ge \xi_d, \quad \forall k, m, \quad (7f)$$

$$x_{k,m}^{(1)} p_{k,m} \le P_{\max}, \quad \forall k, m. \quad (7g)$$

In the above, $C_m = \log_2\left(1 + \frac{p_m^c h_m^c}{B^C \sigma_N^2}\right)$ is the spectral efficiency of cellular user $m$ without the mutual interference, $P_{\max}$ denotes the maximal transmit power of D2D pairs, $\xi_c$ and $\xi_d$ denote the SINRs of cellular users and D2D pairs, $R^T$ denote the throughput threshold of WiFi users, (7b) restricts that one cellular user can only be reused by one D2D pair, (7c) implies that each D2D pair can only choose one communication mode, (7d), (7e), and (7f) guarantee the SINR thresholds for cellular, WiFi, and D2D users, respectively, and (7g) denotes that the transmit power of D2D users cannot exceed the maximum.

We shall note that the objective function of the above optimization problem is to maximize the aggregated throughput of cellular and WiFi users. Whereas the minimum data rate of the D2D communications should be guaranteed, as indicated in (7e) and (7f). By this mean, the interference to the cellular and WiFi users caused by D2D communications is minimized.

2) Similarly, the optimization problem for the duty-cycle based unlicensed spectrum access can be formulated as

$$\max_{\{x,p,\boldsymbol{\rho}\}} \left\{ \sum_{k=1}^{K} \sum_{m=1}^{M} x_{k,m}^{(1)} B^C A_{k,m}^C + \sum_{m=1}^{M} \left(1 - \sum_{k=1}^{K} x_{k,m}^{(1)}\right) B^C C_m + \left(1 - \sum_{k=1}^{K} x_k^{(2)} \rho_k\right) R(N) \right\}, \quad (8)$$

subject to (7b), (7d), (7g), and

$$x_{k,m}^{(1)}, x_k^{(2)} \in \{0, 1\}, \quad \forall k, m, \quad (8a)$$

$$\sum_{m=1}^{M} x_{k,m}^{(1)} + x_k^{(2)} = 1, \quad \forall k, \quad (8b)$$

$$\left(1 - \sum_{k=1}^{K} x_k^{(2)} \rho_k\right) R(N) \ge R^T, \quad (8c)$$

$$\rho_k B^U \log\left(1 + \xi_k^u\right) \ge R^T, \quad \forall k. \quad (8d)$$

In the above, the objective function and constraints have the same implications as those in the LBT based access mode.

## III. JOINT MODE SELECTION AND RESOURCE ALLOCATION

In this section, we will solve the optimization problems in (7) and (8), respectively.

### A. POWER CONTROL AND UNLICENSED RESOURCE ALLOCATION

The problems in (7) and (8) are both mixed integer non-linear programming (MINLP), which are NP-hard in general. In what follows, we will first decouple the problem into several subproblems. The problem in (7) can be rewritten as

$$\max_{\{x,p\}} \left\{ \sum_{k=1}^{K} \sum_{m=1}^{M} x_{k,m}^{(1)} B^C Q_1 + \sum_{m=1}^{M} \left(1 - \sum_{k=1}^{K} x_{k,m}^{(1)}\right) B^C C_m + \frac{NR\left(N + \sum_{k=1}^{K} x_k^{(3)}\right)}{N + \sum_{k=1}^{K} x_k^{(3)}} \right\}, \quad (9)$$

where

$$Q_1 = \arg\max_{p} \left\{ \log_2\left(1 + \frac{p_m^c h_m^c}{p_{k,m} h_{k,m} + B^C \sigma_N^2}\right) \right\}. \quad (10)$$

In light of this, we can first solve the problem $Q_1$ to find the optimal power allocation. After that, the optimal mode selection can be solved. As for the problem in (8), it can be rewritten as

$$\max_{x}\left\{\sum_{k=1}^{K}\sum_{m=1}^{M}x_{k,m}^{(1)}B^{C}Q_{1}+\sum_{m=1}^{M}\left(1-\sum_{k=1}^{K}x_{k,m}^{(1)}\right)B^{C}C_{m}\right.$$
$$\left.+R(N)-R(N)\sum_{k=1}^{K}x_{k}^{(2)}Q_{2}\right\}, \quad (11)$$

where

$$Q_2 = \min \rho_k. \quad (12)$$

Therefore, the optimization problem can also be decoupled into two layers: the inner layer ($Q_1$ and $Q_2$) finds the optimal time-slot allocation and power control, while the outer layer solves the optimal mode selection.

Since we aim to maximize the throughput of WiFi and cellular users while guaranteeing the minimum data rate requirement of D2D users, the optimal power, $p_{k,m}$, and the optimal unlicensed resource allocation, $\rho_k$, can be achieved at their minimum values, which are

$$p_{k,m} = \frac{\xi_d\left(p_m^c h_{k,m} + B^C\sigma_N^2\right)}{h_k^D}, \quad (13)$$

and

$$\rho_k = \frac{R^T}{B^U\log(1+\xi_k^u)}. \quad (14)$$

After obtaining the optimal power control and resource allocation, we now try to solve the optimal mode selection for the two different unlicensed access methods, respectively.

### B. LBT METHOD

In the LBT based unlicensed access mode, after the power allocation $p_{k,m}$ is obtained, the remaining variables in (7) are $x_{k,m}^{(1)}$ and $x_k^{(3)}$. This is a combinatorial optimization problem, which is still NP-hard. We can utilize the branch-and-bound (BnB) algorithm to find the optimal solution; however, the computational complexity of the BnB is extremely high, making it impossible to implement practically. Thereby, in this section, we will develop a heuristic algorithm to approach it.

In this mode, D2D users access the unlicensed spectrum by using the LBT method. As implied in (7e), each D2D user would bring about the same interference to the WiFi network due to the DCF in the CSMA/CA protocol. However, in the licensed reusing mode, different D2D pairs would cause different levels of interference to the cellular users according to their locations and channel power gains. Based on the above discussion, the main idea of the heuristic algorithm is to let those D2D pairs causing large interference to the cellular users access the unlicensed spectrum. However, how many D2D users and which D2D users should access the unlicensed spectrum must be properly handled.

To tackle it, we first rewrite the problem in (7) as

$$\max_{x}\left\{\sum_{k=1}^{K}\sum_{m=1}^{M}x_{k,m}^{(1)}B^{C}G_{k,m}+\frac{NR\left(N+\sum_{k=1}^{K}x_k^{(3)}\right)}{N+\sum_{k=1}^{K}x_k^{(3)}}\right\}, \quad (15)$$

where

$$G_{k,m} = A_{k,m}^c - C_m, \quad (16)$$

is the negative throughput loss of cellular user $m$ when being reused by D2D pair $k$. Then, define the throughput loss matrix as

$$G = \begin{bmatrix} G_{1,1} & \dots & G_{1,m} & \dots & G_{1,M} \\ \dots & \dots & \dots & \dots & \dots \\ G_{k,1} & \dots & G_{k,m} & \dots & G_{k,M} \\ \dots & \dots & \dots & \dots & \dots \\ G_{K,1} & \dots & G_{K,m} & \dots & G_{K,M} \end{bmatrix}. \quad (17)$$

Now, we can utilize the Hungarian algorithm to find the optimal channel assignment for each D2D pair by assuming only licensed reusing mode can be used by D2D communications. Denote $\omega(k)$ as the resulting channel index reused by D2D pair $k$. To find those D2D users that cause strong interference to cellular users, we rearrange $G_{k,\omega(k)}$ into non-decreasing order and let $J$ be the resulting vector after rearranging, which is a permutation on $G_{k,\omega(k)}$.

Furthermore, the maximum number of D2D pairs, $N_{\max}$, that the cellular network can admit could be found by the following equation

$$\frac{R(N+N_{\max})}{N+N_{\max}} = R^T. \quad (18)$$

In the above, with the additional $N_{\max}$ D2D pairs accessing the unlicensed spectrum like WiFi users, the per-user throughput of each WiFi user can still be guaranteed to be $R^T$.

Now, we define $f(n)$ as

$$f(n) = N\left(\frac{R(N+n)}{N+n} - \frac{R(N)}{N}\right) - \sum_{i=1}^{n} J_i,$$
$$n = 0, 1, 2, \cdots, \max\{K, N_{\max}\}, \quad (19)$$

which stands for the throughput gain when transferring $n$ D2D pairs from licensed reusing mode to the LBT based unlicensed access mode.

In the next step, we shall find the optimal $l$ that maximizes the throughput gain, i.e.,

$$l = \arg\max_{n}(f(n)). \quad (20)$$

In this way, the overall system throughput can be maximized. In summary, the heuristic algorithm mainly includes three steps: a) find the optimal channel assignment for each D2D pair by the Hungarian algorithm; b) rearrange $G_{k,\omega(k)}$ into non-decreasing order; c) find the optimal number of D2D pairs to be accessed in the unlicensed spectrum according to (20).

**Algorithm 1** The Heuristic Algorithm for the LBT Based Unlicensed Access

1: Utilize the Hungarian algorithm to find the optimal licensed channel reusing for each D2D pair.
2: Rearrange the throughput loss caused by D2D pairs in non-decreasing order.
3: Find the maximum number of allowed D2D pairs in unlicensed spectrum, $N_{\max}$.
4: Find $l = \arg \max_{1 \le n \le N_{\max}} (f(n))$.
5: Move these $l$ D2D pairs to the unlicensed spectrum using the LBT method.

The detailed procedures of the proposed heuristic algorithm for the LBT based unlicensed spectrum access are summarized in Algorithm 1. Note that the main computational complexity of Algorithm 1 is the Hungarian algorithm, which has a computational complexity of $O(M^3)$.

### C. DUTY-CYCLE BASED UNLICENSED MODE

In the duty-cycle based unlicensed spectrum access mode, after the power allocation $p_{k,m}$ and unlicensed resource allocation $\rho_k$ are obtained, the remaining variables in (8) are $x_{k,m}^{(1)}$ and $x_k^{(2)}$. Again, this is a combinatorial optimization problem and is difficult to solve. Similar to the LBT case, we will also develop a heuristic algorithm to approach it.

Recall that D2D users access the unlicensed spectrum using the duty-cycle method in this mode, i.e., the D2D pair $k$ occupies $\rho_k$ fraction of the unlicensed resource. However, unlike the LBT mode, the WiFi throughput loss caused by the D2D pair $k$ can be expressed as

$$\rho_k R(N), \quad \forall k, \tag{21}$$

which only depends on the $k$-th D2D pair itself. This can significantly simplify the development of the heuristic algorithm in the duty-cycle mode.

To solve this problem, we will rewrite the problem in (8) as

$$\max_x \left\{ \sum_{k=1}^{K} \sum_{m=1}^{M} x_{k,m}^{(1)} B^C G_{k,m} + \sum_{m=1}^{M} \left( 1 - \sum_{k=1}^{K} x_k^{(2)} \rho_k \right) R(N) \right\}, \tag{22}$$

where $G_{k,m}$ is formerly given in (16). Similar to the LBT mode, we first utilize the Hungarian algorithm to select the optimal reusing licensed channel for each D2D pair, with the aim of minimizing the overall throughput loss of cellular users. Let $\omega(k)$ denote the selected channel index for D2D pair $k$, then the throughput gain when transferring the D2D pair $k$ from the licensed spectrum to the unlicensed spectrum can be expressed as

$$H_k = -\rho_k R(N) - G_{k,\omega(k)}. \tag{23}$$

Furthermore, the maximum number of time-slots for D2D pairs, $\rho_{\max}$, that the WiFi network can share could be found by the following equation

$$\rho_{\max} = 1 - \frac{NR^T}{R(N)}. \tag{24}$$

Obviously, to maximize the overall throughput of LTE and WiFi users, the D2D pairs with the largest $H_k$ should be moved to the unlicensed spectrum. We will search for the maximum positive $H_k$ among all D2D pairs and denote its index as $k^*$. In case that $\rho_k{}^* > \rho_{\max}$, which means that the QoS of WiFi users cannot be satisfied if the D2D pair $k^*$ is accessed into the unlicensed spectrum, we should skip this D2D pair and continue the process with the remaining D2D pairs. Otherwise, the D2D pair $k^*$ will be allowed to transmit on the unlicensed spectrum. This process continues until there is no positive $H_k$ or the maximum time-slot occupancy, $\rho_{\max}$, is reached.

**Algorithm 2** The Heuristic Algorithm for the Duty-Cycle Based Unlicensed Mode

1: Utilize the Hungarian algorithm to find the optimal licensed channel reusing for each D2D pair.
2: Initialize $\mathcal{K} = \{1, \cdots, k, \cdots, K\}$, $H_k = -\rho_k R(N) - I_{k,\omega(k)}, \forall k$.
3: **while** $\mathcal{K} \neq \emptyset$ **do**
4: $\quad k^* = \arg\max_{k \in \mathcal{K}}(H_k)$.
5: $\quad$**if** $H_{k^*} > 0$ **then**
6: $\quad\quad$**if** $\rho_{k^*} > \rho_{\max}$ **then**
7: $\quad\quad\quad \mathcal{K} = \mathcal{K} - k^*$
8: $\quad\quad$**else**
9: $\quad\quad\quad$Move D2D user $k^*$ to the unlicensed spectrum using the duty-cycle method.
10: $\quad\quad\quad$Set $\mathcal{K} = \mathcal{K} - k^*$ and $\rho_{\max} = \rho_{\max} - \rho_k$
11: $\quad\quad$**end if**
12: $\quad$**else**
13: $\quad\quad$break
14: $\quad$**end if**
15: **end while**

The detailed procedures of the proposed heuristic algorithm for the duty-cycle method are summarized in Algorithm 2. It can be found that the main computational complexity of Algorithm 2 is also the Hungarian algorithm, which is with $O(M^3)$-order computational complexity.

### D. COMPARISON BETWEEN THE DUTY-CYCLE BASED AND LBT BASED UNLICENSED MODES

In this section, we compare the performance of the duty-cycle based and the LBT based unlicensed accessing modes. A criterion is tried to be derived to judge whether a D2D pair should choose the duty-cycle method or the LBT method. We introduce the following theorem, which is proved later in the Appendix.

*Theorem 1:* Consider that there are already $L$ D2D pairs accessing the unlicensed spectrum using the LBT mode and $\rho$ fraction of unlicensed time-slot has already been occupied by D2D pairs in the duty-cycle mode. Then, the new

D2D pair, say D2D pair $k$, will access the unlicensed spectrum using the duty-cycle mode rather than the LBT mode if the following equation is satisfied

$$\rho_k < (1-\rho)\left(1 - \frac{(N+L)R(N+L+1)}{(N+L+1)R(N+L)}\right), \tag{25}$$

where $\rho_k$ is calculated according to (14).

*Remark 1:* Theorem 1 shows that the duty-cycle based unlicensed mode is better than the LBT based unlicensed mode only if the required amount of unlicensed spectrum resource, $\rho_k$, is small, which can be intuitively explained later. The WiFi throughput loss caused by the LBT based D2D-U access is equal for each D2D pair whereas that caused by the duty-cycle based D2D-U access is different for different D2D pairs, i.e., $\rho_k R(N+L)$ for D2D pair $k$. Therefore, when $\rho_k$ is small, it is obvious that the duty-cycle based unlicensed mode can achieve better performance than the LBT based unlicensed mode. Through numerical simulation, we will demonstrate that, in most cases, the duty-cycle based unlicensed spectrum access method achieves better system throughput than the LBT based access method, i.e., the equation in (25) can often be satisfied.

## IV. NUMERICAL RESULTS

We consider a single cell network with a radius of 500m where the BS is located in the center and cellular users are distributed uniformly. We assume that D2D users are distributed according to the clustered distribution model in [21]. D2D transmitters and receivers are both distributed uniformly, but the scope of the latter is a circle with the corresponding former as the center and $r$ as its radius. A WiFi network is co-located in the cellular coverage area. We adopt the IEEE 802.11n protocol working at 5Ghz as well as the RTS/CTS mechanism in the simulations. The major simulation parameters are summarized in Table 1, which are similar to the parameters of licensed spectrum in [14] and the parameters of unlicensed spectrum and WiFi network in [10].

In the simulation, we will consider the traditional D2D communications without the LTE-U technology as a baseline. The optimal solutions based on the BnB approach are also tested as the benchmark for both duty-cycle and LBT based unlicensed accessing modes. In the following figures, the system throughput represents the aggregated throughput of cellular and WiFi users.

The probabilities of choosing the LBT and the duty-cycle unlicensed access modes for different numbers of D2D pairs ($K$) and different D2D communication distances ($r$) are given in Tables 2 and 3, respectively. From the tables, the unlicensed mode probability (UMP) increases with the number of D2D pairs in both access modes. The reason of this is that, the more D2D pairs are, the more prone D2D pairs are to cause strong mutual interference to existing cellular users. So to avoid it, a certain number of D2D pairs should be offloaded to the unlicensed spectrum. It is also observed that the UMP increases with the D2D distance since interference to cellular users increases when the D2D distance becomes large. From the results, we can demonstrate the performance advantage of D2D-U especially when there are many D2D pairs or the distance between D2D pairs is large.

Fig. 2 depicts the system throughput for different maximum transmit powers. From the figure, it is obvious that the overall system throughput increases with the maximum transmit power of cellular users. It is also observed that both

**TABLE 1.** System parameters.

| Parameters | Settings |
|---|---|
| Cell radius | 500 m |
| D2D distance, $r$ | 20,..., 100 m |
| Uplink bandwidth | 3 MHz |
| Noise power | $-174$ dBm/Hz |
| Path loss for cellular links | $128.1 + 37.6\log_{10}(d[\text{km}])$ |
| Path loss for D2D links (Licensed, unlicensed) | $148 + \alpha \times 10\log_{10}(R)$ $\alpha = 4, 5$ |
| Transmit power of CU | $18 - 27$ dBm |
| Unlicensed transmit power | 24 dbm |
| Number of CUs | 15 |
| Number of D2D users | $1 - 10$ |
| Number of WiFi users | $5 - 15$ |
| $E[P]$ | 8224 bits |
| $B^{\mathrm{S}}$, $B$ | 20 MHz, 20 MHz |
| $CW_{\min}$ | 32 |
| $CW_{\max}$ | 1024 |
| $R_{\text{limit}}$ | 7 |
| WiFi bit rate | 300 Mbps |
| PHY header | 192 bits |
| MAC header | 224 bits |
| $T_\delta$ | 20 $\mu s$ |
| SIFS | 16 $\mu s$ |
| DIFS | 50 $\mu s$ |
| Slot time | 9 $\mu s$ |
| ACK | 112 bits + PHY header |
| RTS | 160 bits + PHY header |
| CTS | 112 bits + PHY header |

**TABLE 2.** The probability of the LBT based unlicensed mode.

| | $K=5$ | $K=8$ | $K=10$ | $K=12$ |
|---|---|---|---|---|
| $r=20m$ | 1.46% | 2.33% | 2.97% | 3.61% |
| $r=50m$ | 7.54% | 12.93% | 17.02% | 21.53% |
| $r=80m$ | 14.71% | 26.03% | 34.64% | 43.29% |
| $r=100m$ | 19.33% | 33.80% | 44.63% | 56.15% |

**TABLE 3.** The probability of the duty-cycle based unlicensed mode.

| | $K=5$ | $K=8$ | $K=10$ | $K=12$ |
|---|---|---|---|---|
| $r=20m$ | 6.69% | 10.77% | 13.38% | 16.22% |
| $r=50m$ | 18.85% | 29.79% | 37.60% | 44.98% |
| $r=80m$ | 26.01% | 41.91% | 52.52% | 63.02% |
| $r=100m$ | 29.48% | 47.19% | 59.01% | 71.08% |

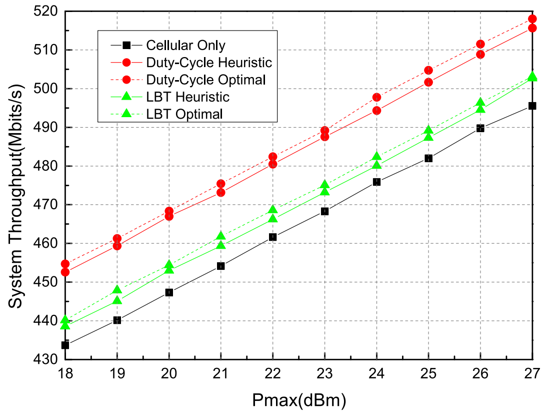


**FIGURE 2.** System throughput with different $P_{\max}$. $N = 10$, $K = 10$, $M = 15$, and $r = 50$ m.

duty-cycle based and LBT based unlicensed access modes can improve the system throughput as compared to the conventional D2D communications without the unlicensed spectrum. As for the comparison between the two different modes, the duty-cycle mode can always achieve better performance than the LBT mode, which has been explained in Theorem 1. Moreover, for both modes, the suboptimal algorithm has a performance very close to the optimal algorithm based on the BnB method, which validates the effectiveness of our proposals.

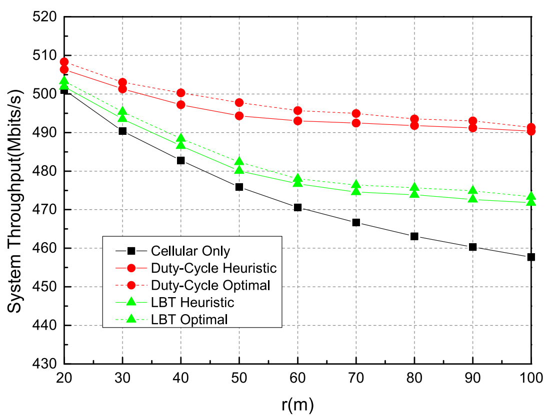


**FIGURE 3.** System throughput with different $r$. $N = 10$, $K = 10$, $M = 15$, and $P_{\max} = 24$ dBm.

In Fig. 3, we show the system throughput for different distances between D2D pairs. Again, the duty-cycle method achieves better throughput than the LBT method and the suboptimal algorithm performs closely to the corresponding optimal algorithm. We can also see that with the increasing distance between D2D pairs, the duty-cycle mode demonstrates the performance advantage over the LBT mode.

Fig. 4 plots the system throughput for different numbers of D2D pairs. From the figure, it is observed that with more D2D pairs accessed into the system, the system throughput will decrease in all considered methods. The reason

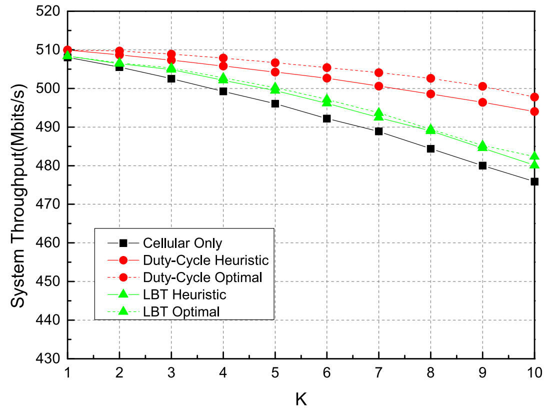


**FIGURE 4.** System throughput with different $K$. $N = 10$, $M = 15$, $r = 50$ m, and $P_{\max} = 24$ dBm.

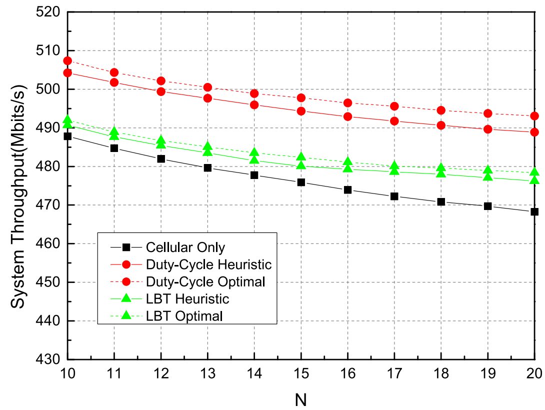


**FIGURE 5.** System throughput with different $N$. $K = 10$, $M = 15$, $r = 50$ m, and $P_{\max} = 24$ dBm.

is rather intuitive since more D2D pairs certainly cause larger interference to both cellular and WiFi users, leading to the degradation of their throughputs. Fig. 5 shows the system throughput for different numbers of existing WiFi users, $N$. Since $R(N)$ is a strictly decreasing function of $N$, the system throughput decreases with the number of WiFi users.

In all figures, it is interesting that the duty-cycle based unlicensed spectrum access method always achieves better system throughput than the LBT based access method. Note that in the duty-cycle mode, D2D users utilize the unlicensed spectrum based on LTE protocols by exploiting the available CSI whereas in the LBT mode, D2D users utilize the unlicensed spectrum based on WiFi protocols without CSI, such as DCF and CSMA/CA. Therefore, this result demonstrates that LTE-U can better utilize the unlicensed spectrum than WiFi, as already been indicated in many existing works [22].

## V. CONCLUSION

In this paper, leveraging the emerging LTE-U technology, we have proposed a novel technique, namely D2D-U, which can allow D2D users to share unlicensed spectrum with existing

WiFi networks. Two different unlicensed spectrum accessing mechanisms are considered: the LBT method and the duty-cycle method. To minimize the interference introduced by the D2D users, we formulate the joint communication mode selection and resource allocation problem for each accessing mechanism. The optimization problems turn out to be complicate MINLP problems. Thereby, two heuristic algorithms are developed for the LBT based and the duty-cycle based accessing mechanisms, respectively. In addition, we have also derived a closed-form criterion to judge whether a D2D pair should use the duty-cycle method or the LBT method. Through numerical simulation, the proposed heuristic algorithms can achieve a performance very close to the corresponding optimal solutions by the branch-and-bound algorithm. Also, it is demonstrated that the duty-cycle method achieves better performance than the LBT method in most cases.

## APPENDIX

## PROOF OF THEOREM 1

When D2D pair $k$ transmits on the unlicensed spectrum using the LBT mode, the throughput loss of the WiFi network can be expressed as

$$\Delta_{LBT} = (1-\rho)\left(\frac{R(N+T)}{N+T} - \frac{R(N+T+1)}{N+T+1}\right). \quad (26)$$

On the other aspect, when D2D pair $k$ transmits on the unlicensed spectrum using the duty-cycle mode, the throughput loss of the WiFi network can be expressed as

$$\Delta_{DT} = \rho_k \frac{R(N+T)}{N+T}. \quad (27)$$

By assuming $\Delta_{DT} < \Delta_{LBT}$, we have

$$\rho_k \frac{R(N+T)}{N+T} < (1-\rho)\left(\frac{R(N+T)}{N+T} - \frac{R(N+T+1)}{N+T+1}\right), \quad (28)$$

which leads to the criterion in (25).

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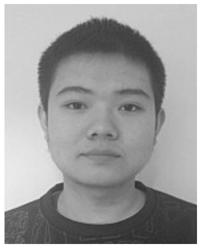

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