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Research Article

Coexistence Analysis of D2D-Unlicensed and Wi-Fi Communications

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By enabling direct communications between nearby user equipment (UE), device-to-device (D2D) communication has become one of the key technologies in 5th generation (5G) mobile networks. D2D communication brings new communication opportunities for mobile devices, especially in a highly dense network. In this paper, D2D communication in the unlicensed spectrum, namely, D2D-Unlicensed (D2D-U), is discussed. The use of unlicensed frequency bands can ease the shortage of spectrum resources and improve network performance. However, the D2D-U in 5G has significant effects on the network performance of existing unlicensed networks sharing the same frequency bands, such as Wi-Fi and Bluetooth. Therefore, it is necessary to design a fair coexistence scheme for D2D-U. To understand the coexistence problem, in this paper, we first formulate the network performance of D2D-U and Wi-Fi under two different coexistence schemes, namely, listen before talk (LBT) and duty cycle mechanism (DCM). Then, we use computer simulations to investigate a mode selection scheme that switches between these two schemes and point out the best possible solution for the coexistence between D2D-U and Wi-Fi.

1. Introduction

A 5G mobile network has been rapidly developed to satisfy the dramatically increasing transmission demand of mobile devices [1–3]. 5G provides multi-Gbps transmission rate, low latency, flexible mobility, and high reliability, benefiting a diverse range of applications, including massive Internet of things (IoT). The underlying 5G technologies, including millimeter wave (mmWave), massive multiple-input and multiple-output (MIMO), small cell, full duplex, and beamforming, have led to the emergence of device-to-device (D2D) communication, which is foreseen to bring about significant network performance enhancement.

The explosive increase in UE in communication has brought new opportunities. By enabling direct transmissions between UE without traversing the core network, D2D communication has attracted remarkable attention for its high throughput gain and high spectral efficiency. The Third Generation Partnership Project (3GPP), which defines standards for 5G, has covered D2D earlier in Release 12 [4]. While this version recognizes some limitations, it is believed that D2D will be explored in 5G. A D2D link enables a single-hop direct communication between a pair of UE in vicinity, and so cellular links for two-hop indirect communication between them, which need to go through the base station (BS), are not needed (see Figure 1). D2D communication reduces the transmission power and latency of both BS and UE and improves the throughput of the entire network by efficiently utilizing the unlicensed spectrum [5]. Figure 1 shows an example of a 5G communication environment

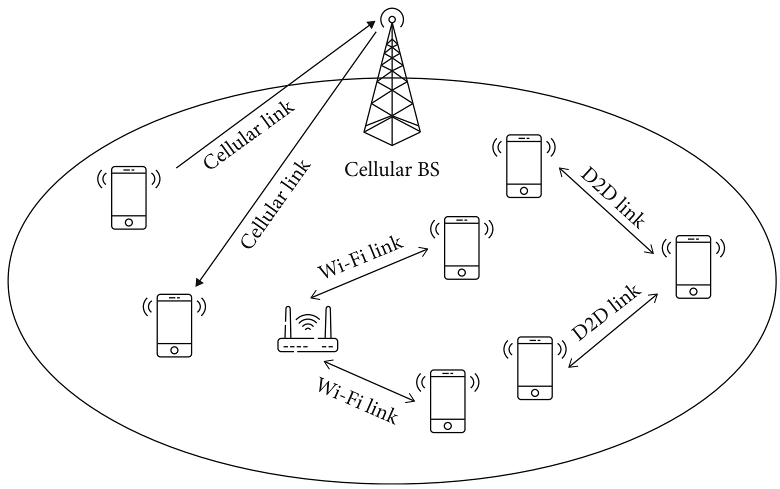

Figure 1: An example of D2D communications in a 5G network coexisting with a Wi-Fi system.

including cellular link, D2D link, and Wi-Fi link. Cellular link may use 1.6 GHz, 2.1 GHz, or other licensed band, while D2D may use a licensed band or unlicensed band (such as the same band with Wi-Fi) for transmissions.

A licensed spectrum is always a relatively scarce resource although the spectrum utilization rate in many licensed bands is often less than 30% [6]. This inefficient use of licensed bands, which have been assigned exclusively to licensed users based on the static frequency assignment scheme, is one of the main causes of spectrum resource scarcity. With the rapid development of mobile Internet and the rapid increase in mobile data traffic, exploring and exploiting the dynamically available frequency bands have become a particularly important opportunity for many mobile network operators. Compared with the limited licensed spectrum resources, most of the unlicensed spectrum resources used by Bluetooth, Wi-Fi, and other networks are not fully utilized. There are a large amount of unused unlicensed spectrum resources especially in the vicinity of the 5 GHz frequency band [7]. LTE-Unlicensed (LTE-U), which has been deployed in many countries in recent years, is a technology that enables an LTE network to offload its traffic to the unlicensed 5 GHz frequency bands in order to provide an efficient use of spectrum resources. Similar to LTE-U, which has shown a good network performance improvement and spectrum utilization efficiency, D2D-U is a promising technology that provides D2D communication in the unlicensed spectrum to provide further improvement.

As the spectrum of D2D-U is also utilized by other traditional unlicensed networks, including Wi-Fi and Bluetooth, interference management between systems is important. Therefore, we need to solve the problem of how to ensure a fair coexistence between these unlicensed networks; otherwise, D2D-U can cause a huge impact on these traditional unlicensed networks [8, 9], which do not consider the coexistence with D2D-U networks. In addition, the MAC layer and physical layer frame structure of the traditional unlicensed networks and D2D-U are different [10]. Fortunately, since D2D-U resembles LTE-U, the coexistence solutions designed for LTE-U can provide some references for us in discussing the coexistence problem of D2D-U.

In this paper, the coexistence problem between D2D-U and Wi-Fi system is considered. Two different coexistence schemes, namely, listen before talk (LBT) and duty cycle mechanism (DCM), are considered. According to the current Wi-Fi traffic load and other factors in the transmission environment, D2D-U selects an appropriate mode (scheme) to ensure that it does not jeopardize the performance of the Wi-Fi traffic. To achieve this, we first understand the performances of D2D-U and Wi-Fi in an environment where these two types of communication approaches coexist. Then, this paper is aimed at understanding the performance of the D2D-U and Wi-Fi systems under the LBT and DCM schemes by using both theoretical analysis and computer simulations. This paper is an extension of our previous conference paper [11]. While [11] only discusses the performance of D2D-U communications using simple computer simulations, this paper includes a mathematical analysis and new simulation results under more realistic network settings. The main contributions of this work can be summarized as follows:

(i) We introduce a mechanism for D2D-U users to access unlicensed bands based on the exchange of signaling information through an existing licensed D2D link. This mechanism ensures that D2D users cannot use the unlicensed bands for data transmissions before verifying the channel conditions

(ii) We use theoretical analysis to formulate the performance of D2D-U and Wi-Fi communications under two different coexistence schemes, namely, LBT and DCM

(iii) We evaluate the performance of the D2D-U and Wi-Fi communications under LBT and DCM modes through computer simulations. We also introduce a D2D-U mode selection scheme to improve the performance of the whole system while ensuring the performance of existing Wi-Fi communications. By selecting different modes for data transmission flexibly according to different communication environments and link conditions, a much better performance can be expected

The rest of this paper is organized as follows. In Section 2, we review recent studies on D2D-U. In Section 3, we discuss the procedure for accessing an unlicensed band in D2D-U. In Section 4, we explain the system model and coexistence schemes we discuss in this paper. In Section 5, we make a mathematical analysis on the performance of D2D-U and Wi-Fi systems under different coexistence schemes. The relevant computer simulations are carried out in Section 6. Finally, we make a conclusion about this paper in Section 7.

2. Related Work

Enabling D2D in mobile communication networks can improve system performance, and this has been shown in many studies, including licensed D2D [12, 13] and unlicensed D2D [14–16]. In [17], Zhang et al. show that by enabling D2D-U with a duty cycle mechanism, the overall system throughput of D2D-U, Wi-Fi, and cellular systems can be improved significantly. They also point out that the use of D2D-U should consider the corresponding effect on the performance of existing Wi-Fi systems. In [18], an access mechanism for both licensed and unlicensed spectra based on soft frequency reuse is proposed. The numerical results also show that D2D-U can significantly improve the system performance, and further improvements can be made by using an unlicensed spectrum.

The problem of Wi-Fi and D2D-U coexistence and their mutual influence on each other have been widely discussed in recent years, and many different solutions have been proposed. Since the coexistence of LTE-U and Wi-Fi systems is similar to the coexistence of D2D-U and Wi-Fi, we can refer to the studies on the coexistence problem of LTE-U and Wi-Fi, such as [8, 19–23].

Girmay et al. [24] have discussed a joint mode selection and resource allocation scheme based on the particle swarm optimization algorithm that allows multiple D2D pairs to share the same channel with a traditional cellular user. They introduce an algorithm to identify D2D pairs that cause severe interference to cellular users and use the duty cycle method among these targeted D2D pairs to ensure that the minimum performance requirements of Wi-Fi users are achieved. It can be seen from the simulation results that this solution improves the throughput of the entire network while protecting the performance of the Wi-Fi system.

In the existing studies on D2D-U, the allocation of spectrum resources is a widely discussed topic. An LBT-based D2D-U access protocol with a subchannel allocation scheme has been proposed in [14] for D2D-U and LTE-U users. This scheme reduces mutual interference between D2D-U, LTE-U, and Wi-Fi systems. By considering the effect of D2D-U communications on the performance of Wi-Fi systems, [14] achieves a great performance improvement in the entire system throughput.

In [15], a spectrum access algorithm based on sequential quadratic programming is proposed for a scenario where D2D, LTE, and Wi-Fi systems coexist. LTE and D2D users are more inclined to access an unlicensed spectrum when the volume of Wi-Fi traffic is low. In contrast, when the volume of Wi-Fi traffic is high, LTE and D2D users are more inclined to access a licensed spectrum in order to reduce congestion in the unlicensed spectrum. As compared with conventional LTE users, the physical distance between D2D users is shorter, resulting in a higher chance of utilizing an unlicensed spectrum. Sun et al. [16] have proposed an unlicensed subchannel access mechanism for D2D-U where the Stackelberg game is introduced to model the power control and spectrum resource access of D2D links while ensuring the throughput requirements of the Wi-Fi systems. Simulation results show that the mechanism can significantly improve the system performance, including throughput and spectrum utilization efficiency.

In [25], a resource allocation algorithm based on quality of experience (QoE) is discussed. The algorithm is based on a duty cycle mechanism to maximize the throughput of the entire D2D-U system while ensuring a low computational complexity and a high QoE, which are important indicators in 5G networks.

The application of machine learning on D2D can also significantly improve the performance of the system. In an environment with a large number of devices, machine learning can improve the operating efficiency, reliability, and robustness of the entire system. A distributed power and spectrum allocation algorithm based on deep reinforcement learning for both licensed and unlicensed spectra is proposed in [26]. This algorithm can learn the environment information without knowing the Wi-Fi traffic load and optimize resource allocation for every D2D link. Gu et al. [27, 28] have proposed distributed subcarrier power allocation algorithm with low signaling overhead, which is based on double DQN. The proposed algorithm provides near-optimal spectrum efficiency for D2D communication.

An interoperable network model for network-assisted D2D communications in licensed and unlicensed spectra is designed in [29]. The network model provides a higher D2D system throughput and a better network management between different kinds of networks and spectra, but it is difficult to maintain network quality of service (QoS). In [30], a new RTS/CTS mechanism based on free-to-receive multiple network allocation vector (MNAV) is proposed for D2D-U networks to improve spectrum efficiency and network capacity. This mechanism can reduce blocking time by using MNAV, resulting in a more efficient use of an unlicensed spectrum.

As mentioned above, there have been many studies discussing the importance of considering the effect of D2D-U communications on existing unlicensed systems, such as Wi-Fi. However, the performance of a D2D-U/Wi-Fi coexisting system has not been adequately discussed. In order to achieve a more efficient use of D2D-U communications, this paper addresses the coexistence problem of D2D-U and Wi-Fi systems.

3. Unlicensed Band Access Mechanism for D2D-U

There are some problems that need to be solved before D2D-U users should access unlicensed bands. D2D-U users must

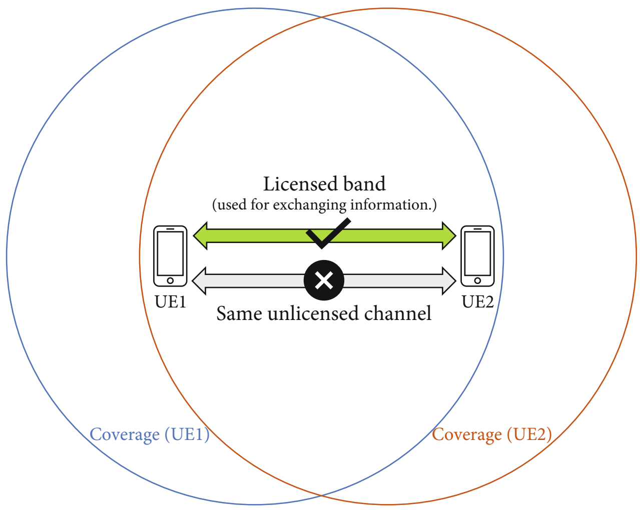

FIGURE 2: In order to establish a common idle unlicensed channel, UE1 and UE2 exchange signaling information with each other through the licensed band.

ensure that they meet the conditions for using unlicensed bands. The first condition is coverage. If there is no overlapping between the physical coverage of two devices through an unlicensed band, D2D-U users cannot communicate with each other. The device needs to confirm that its communication partner can exchange packets with itself. The second one is the common accessible channel. If two devices do not have a common idle unlicensed channel, they also fail to communicate as shown in Figure 2.

It is worth noting that, even though both conditions are satisfied, there is still a concern. Before a D2D-U link is established, there is a lack of a common idle unlicensed channel for an efficient exchange of signaling information, including the available idle channels and coverage, which is important for D2D-U users to determine whether they satisfy the two conditions. Therefore, the establishment of D2D-U link needs the support from a licensed band.

Therefore, we use a licensed band to exchange the signaling information in order to make an agreement between the sender and receiver about the common channel for D2D-U link. If the unlicensed band is confirmed to be able to access, D2D users will make data transmission and exchange of signaling information on an unlicensed band. If there is no available unlicensed band, D2D users will use the licensed D2D link to continue D2D transmissions.

4. System Model and Coexistence Schemes

4.1. System Model. We consider a scenario where D2D-U and Wi-Fi communications coexist in the unlicensed spectrum, and they share the same set of channels, as shown in Figure 3. The D2D-U link is successfully established using the aforementioned unlicensed band access mechanism (see Section 3). The licensed D2D link is only used to exchange basic signaling information before the unlicensed D2D link is established, and D2D-U users use the unlicensed D2D link

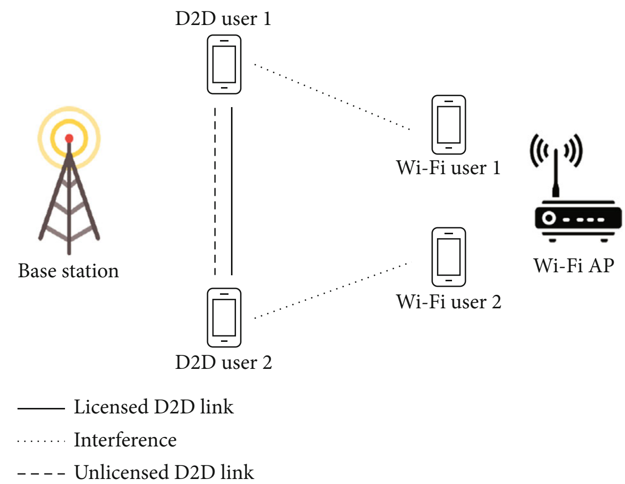

FIGURE 3: System model.

to transmit user data. The Wi-Fi system has an access point (AP) and n Wi-Fi users.

We assume that the D2D-U users and the Wi-Fi AP can monitor transmissions in the vicinity. At the same time, the BS knows the channel state information (CSI) of all D2D-U users in its coverage in the licensed band and the unlicensed band.

4.2. Listen before Talk. LBT is one of the widely recognized unlicensed spectrum access mechanisms. LBT is used in the LTE-U solution, namely, licensed assisted access (LAA), to solve the problem of coexistence with other unlicensed networks, including Wi-Fi. LBT can achieve an efficient use of unlicensed spectrum by selecting idle channels dynamically. If there is no idle channel, it shares the unlicensed channel fairly with other unlicensed networks. As shown in Figure 4, a D2D-U user uses clear channel assessment (CCA), which is also called "LISTEN," to monitor an unlicensed channel shared with a Wi-Fi user. If CCA fails, which indicates that the channel is busy, the D2D-U user back offs for a certain period (e.g., 20 ms). If CCA succeeds, which indicates that the channel is idle, the D2D-U user "TALK" or transmits data.

There are two main types of LBT: (a) frame-based equipment (FBE), which is based on channel sensing at fixed time instants, enables a sender to monitor the channel periodically and back off for a fixed time period if the channel is busy and (b) load-based equipment (LBE), which performs channel sensing at any time instant based on load, enables a sender to monitor the channel in a reactive manner and back off for a random time period if the channel is busy [31]. When the load is variable, LBE has shown to achieve a higher performance and better network resource utilization than FBE. Therefore, we choose LBE in this paper.

In the Release 13 version of 3GPP, LBT is formulated as one of the functions of LAA. LBT has four different categories, namely, Cat-1, Cat-2, Cat-3, and Cat-4. Cat-1 is without LBT, and so it allows immediate transmissions in unlicensed bands in some exclusive cases. Cat-2 is the LBT without random backoff with a fixed-length contention window. Cat-3 is

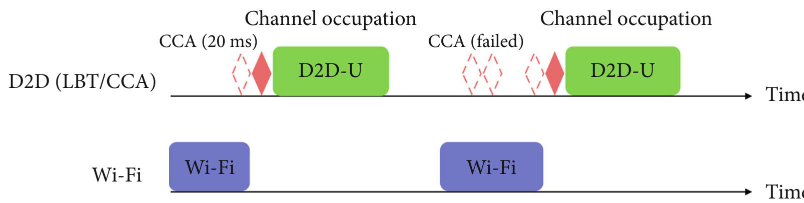

Figure 4: Listen-before-talk (LBT) scheme. Both D2D and Wi-Fi users coexist in a single unlicensed channel.

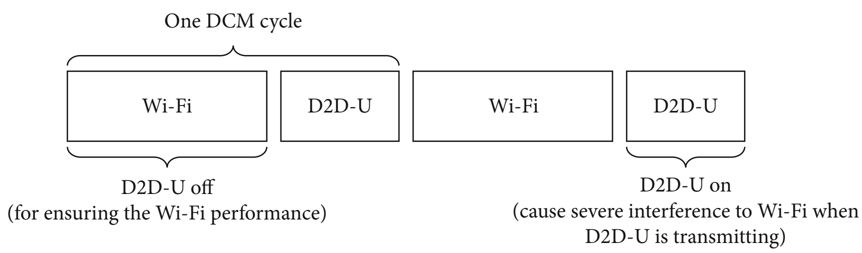

Figure 5: Duty cycle mechanism (DCM).

the LBT with random backoff and a fixed-length contention window. Cat-4 is the LBT with random backoff and a variable-length contention window, where the difference with Cat-3 is that the length of the backoff window can be selected by the sender. As compared with Cat-3, Cat-4 can provide a lower Wi-Fi latency and a higher Wi-Fi throughput. Cat-3 is more conducive for cellular or D2D-U transmissions compared to Cat-4, although it cannot provide an efficient way for ensuring Wi-Fi performance [32].

According to an analysis of the coexistence of Wi-Fi and LAA networks based on the distributed coordination mode in [33], a larger backoff window size for LAA-LTE reduces negative impacts on the Wi-Fi performance and a backoff window size of 32 achieves the best possible performances for both Wi-Fi and LAA-LTE. Due to the similarity between LTE-U and D2D-U, the maximum backoff window size of D2D-U is 32 in the following simulations.

4.3. Duty Cycle Mechanism. The duty cycle mechanism determines the transmission times for both D2D-U and Wi-Fi as shown in Figure 5. The duty cycle is a fixed value that controls D2D-U transmissions, and it is independent of the number of Wi-Fi nodes. Nevertheless, the transmission time allocated for Wi-Fi ensures the Wi-Fi performance. DCM has been widely used in many studies for solving the coexistence problem. Although DCM is a simple and effective coexistence scheme, it does not consider collisions with Wi-Fi communications during the D2D-U transmission time of the duty cycle.

Compared with LBT, DCM causes a larger delay for Wi-Fi transmissions because Wi-Fi users must wait for the completion of D2D-U transmissions in every duty cycle. In addition, the DCM scheme cannot be applied in some countries, such as Japan and some European countries, because these countries require that LBT must be used for interference management when using unlicensed frequency bands [7].

4.4. Mode Selection. Both LBT and DCM schemes are coexistence solutions that support D2D-U while ensuring the performance requirements of Wi-Fi users. However, they show different performances in different scenarios. Therefore, compared to using a single coexistence solution only, a network system selects an appropriate coexistence solution under a particular network environment and traffic load, and this is expected to achieve a better performance. For solving the coexistence problem of Wi-Fi and D2D-U networks that interfere with each other in the same frequency band, mode selection is considerably meaningful.

In this paper, the D2D-U system selects an appropriate coexistence mode between the LBT and DCM modes for ensuring the performance of both Wi-Fi and D2D-U communications. We will introduce a simple mode selection scheme and evaluate it by using computer simulations in Section 6.3 based on different properties of different modes analyzed in Sections 6.1 and 6.2.

5. Performance Analysis

To meet the coexistence fairness requirement of Wi-Fi while increasing the D2D-U throughput, the D2D-U users must select the appropriate mode between the LBT and DCM modes in different transmission environments. In all modes, the Wi-Fi system uses the CSMA/CA protocol in IEEE 802.11 and uses the truncated binary exponential backoff (TBEB) algorithm during contention. The LBT mode uses LBE and Cat-4. In this section, we analyze the performance of both Wi-Fi and D2D-U under LBT and DCM modes. We also analyze the performance of D2D-U under the fully occupied mode, a special type of DCM mode.

5.1. Wi-Fi Performance under the LBT Mode. Under the LBT mode, based on the performance analysis of the Wi-Fi system in [34], the performance analysis of the coexistence mode in [32], and the delay analysis method in [19, 33, 35], the average Wi-Fi throughput when there are n Wi-Fi users served by a Wi-Fi AP can be expressed as follows:

$$R_W^L = \frac{P_t^L P_s^{W,L} E\{\ell\} n^{-1}}{\left(1 - P_t^L\right) T_\delta + P_t^L P_s^{W,L} T_s + P_t^L \left(1 - P_s^{W,L}\right) T_c}, \quad (1)$$

where P_t^L is the probability that at least one of the network entities, which can be either the Wi-Fi AP or the D2D-U user, is transmitting under the LBT mode, $P_s^{W,L}$ is the probability that the Wi-Fi AP transmits successfully under the LBT mode, T_δ is the average channel idle time, T_s is the average time of a successful Wi-Fi transmission, and T_c is the average time of a Wi-Fi contention. $E\{\ell\}$ represents the average packet payload length. P_t^L and $P_s^{W,L}$ are given by

$$P_t^L = 1 - \left(1 - \tau_W^L\right)^n (1 - \tau_l), \quad (2)$$

$$P_s^{W,L} = \frac{n\tau_W^L \left(1 - \tau_W^L\right)^{n-1} (1 - \tau_l)}{P_t^L}, \quad (3)$$

where τ_W^L is the probability of one Wi-Fi user occupying one of the unlicensed channels under the LBT mode and τ_l is the probability of one of the D2D-U pairs occupying one of the unlicensed channels under the LBT mode. These two probabilities are given by

$$\tau_W^L = \frac{2\left(1 - 2P_W^L\right)}{\left(1 - 2P_W^L\right)(S + 1) + P_W^L S\left(1 - \left(2P_W^L\right)^m\right)}, \quad (4)$$

$$\tau_l = \frac{(1/Q) P_D^L \sum_{j=1}^{Q} \left(1 - P_D^L\right)^{j-1}}{1 - (1/Q)\left(1 - P_D^L\right) \sum_{j=1}^{Q} \left(1 - P_D^L\right)^{j-1}}, \quad (5)$$

where S is the minimum Wi-Fi backoff window size, m is the maximum Wi-Fi backoff time, and Q is the maximum D2D-U backoff window size. P_D^L is the contention probability of D2D-U transmission, and P_W^L is the contention probability of Wi-Fi transmission. They are given by

$$P_W^L = 1 - (1 - \tau_l)\left(1 - \tau_W^L\right)^{n-1}, \quad (6)$$

$$P_D^L = 1 - \left(1 - \tau_W^L\right)^n. \quad (7)$$

The above analysis is based on the Markov chain model for the backoff window of Wi-Fi. Since this is a fixed-point problem, the solutions for the transmission probability and the collision probability can be obtained by solving the simultaneous equations using the fsolve function in MATLAB or using the approximation method.

Under the LBT mode, the latency of Wi-Fi users served by the AP is given as follows:

$$D\left(P_W^L\right) = E_L[X] E_L[T], \quad (8)$$

where $E_L[X]$ is the number of time slots to wait before data transmission takes place and $E_L[T]$ is the average length of time slots. $E_L[X]$ is given by

$$E_L[X] = \sum_{j=0}^{n} \frac{1}{1 - P_W^L} \cdot \frac{S_j - 1}{2} \cdot \frac{\left(P_W^L\right)^j - \left(P_W^L\right)^{k+1}}{1 - \left(P_W^L\right)^{k+1}}, \quad (9)$$

where j is the backoff stage number and S_j is the backoff window size of stage j.

Here, $E_L[X]$ can be rewritten as follows:

$$E_L[T] = \left(1 - P_D^L\right)(1 - \tau_l)\sigma_{\text{idle}} + P_D^L \tau_l (1 - \tau_l) T_{s,W} + P_D^L \left(1 - p_{s,W}\right) \cdot (1 - \tau_l) T_{c,W} + \left(P_D^L p_{s,W} \tau_l + P_D^L \left(1 - p_{s,W}\right)\tau_l\right) T_{c,M}, \quad (10)$$

where $T_{s,W}$ is the expected value of the Wi-Fi successful transmission time, $T_{c,W}$ is the expected value of the contention time between Wi-Fi users, $T_{c,M}$ is the expected value of the contention time between Wi-Fi and D2D-U, and σ_{idle} is the idle slot time. $p_{s,W}$ is the probability that one Wi-Fi user initiates a transmission request when at least another one Wi-Fi user is transmitting, and it is calculated as follows:

$$p_{s,W} = \frac{n\tau_W^L \left(1 - \tau_W^L\right)^{n-1}}{P_D^L}. \quad (11)$$

5.2. Wi-Fi Performance under the DCM Mode. Since the Wi-Fi performance analysis under the DCM mode is similar to that in the LBT mode, the throughput is given by

$$R_W^L = \frac{P_t^D P_s^{W,D} E\{\ell\} n^{-1}}{\left(1 - P_t^D\right) T_\delta + P_t^D P_s^{W,D} T_s + P_t^D \left(1 - P_s^{W,D}\right) T_c}, \quad (12)$$

where P_t^D is the probability that at least one of the network entities, which can be either the Wi-Fi AP or the D2D-U user, is transmitting under the DCM mode and $P_s^{W,D}$ is the probability that the Wi-Fi AP transmits successfully under the DCM mode. P_t^D and $P_s^{W,D}$ are given by

$$P_t^D = 1 - (1 - D)\left(1 - \tau_W^D\right)^n, \quad (13)$$

$$P_s^{W,D} = \frac{n\tau_W^D \left(1 - \tau_W^D\right)^{n-1} (1 - D)}{P_t^D}, \quad (14)$$

where D is the duty cycle of D2D-U. τ_W^D is the probability of one Wi-Fi user occupying one of the unlicensed channels under the DCM mode, and it is given by

$$\tau_W^D = \frac{2\left(1 - 2P_W^D\right)}{\left(1 - 2P_W^D\right)(S + 1) + P_W^D S\left(1 - \left(2P_W^D\right)^m\right)}, \quad (15)$$

where P_W^D is the contention probability of Wi-Fi users given by

$$P_W^D = 1 - (1 - D)\left(1 - \tau_W^D\right)^{n-1}. \quad (16)$$

The Wi-Fi latency analysis under the DCM mode is also similar to that in the LBT mode, and therefore, it is given as follows:

$$D\left(P_W^D\right) = E_D[X]E_D[T], \tag{17}$$

$$E_D[X] = \sum_{j=0}^{n} \frac{1}{1-P_W^D} \cdot \frac{S_j - 1}{2} \cdot \frac{\left(P_W^D\right)^j - \left(P_W^D\right)^{k+1}}{1-\left(P_W^D\right)^{k+1}}, \tag{18}$$

$$E_D[T] = \left(1 - P_D^L\right)\sigma_{\text{idle}} + P_D^L \tau_l T_{c,M}. \tag{19}$$

5.3. D2D-U Performance under the LBT Mode. The D2D-U throughput under the LBT mode is given by

$$R_U^L = P_t^L P_s^{U,L} B_U \log\left(1 + \frac{p_U h_U}{B_U N_0}\right), \tag{20}$$

where B_U is the channel bandwidth, p_U is the transmission power, h_U is the channel gain, and N_0 is the channel noise. $P_s^{U,L}$ is the probability that a D2D-U user transmits successfully under the LBT mode, and it is calculated as follows:

$$P_s^{U,L} = \frac{\tau_l\left(1-\tau_W^L\right)^n}{P_t^L}. \tag{21}$$

5.4. D2D-U Performance under the DCM Mode. The D2D-U throughput under the LBT mode is given by

$$R_U^D = DB_U \log\left(1 + \frac{p_U h_U}{B_U N_0}\right). \tag{22}$$

5.5. Fully Occupied Mode. A fully occupied mode is a special type of the DCM mode. In this mode, D2D-U completely occupies the unlicensed channel for transmissions when the Wi-Fi traffic load is small. However, it must switch to the other mode when the Wi-Fi load changes.

Because the Wi-Fi traffic load is very small, the D2D-U throughput under the fully occupied mode is given by

$$R_U^F = B_U \log\left(1 + \frac{p_U h_U}{B_U N_0}\right). \tag{23}$$

6. Simulation Results

In this section, we compare the network performance achieved in different modes and evaluate the performance and significance of the mode selection scheme for D2D-U using MATLAB. The parameter settings are shown in Table 1.

As analyzed in the previous sections, both D2D-U and Wi-Fi systems show different performances under different coexistence modes (i.e., LBT and DCM). First, we evaluate the effects of the number of Wi-Fi users on the Wi-Fi and D2D-U network performances. Then, we show the effects of different duty cycles on the Wi-Fi and D2D-U network performances. Finally, we show the effects of the number of Wi-Fi users on the Wi-Fi and D2D-U network performances under the mode selection scheme.

6.1. Effects of the Number of Wi-Fi Users on the Wi-Fi and D2D-U Network Performances. The delay of the Wi-Fi network under different modes is shown in Figure 6. We compare the delay of Wi-Fi users under the DCM mode with different duty cycles (i.e., 0.35, 0.5, and 0.65) and the LBT mode. As the number of users in the Wi-Fi system increases, the delay experienced by Wi-Fi users increases, and the delay under the LBT mode is generally lower than that in the DCM mode. In the DCM mode, the delay increases with the duty cycle, which reduces the Wi-Fi transmission time.

Table 1: Parameter settings.

Parameters	Settings
Path loss model	$15.3 + a\log(d)$, $a = 5$
Transmission power	24 dBm
Noise power	-95 dBm
Distance of D2D-U users	50 m
Channel bandwidth	20 MHz
D2D-U maximum backoff window size Q	32
Packet size $E\{\ell\}$	8,224 bits
Wi-Fi bit rate	130 Mbps
Wi-Fi minimum backoff window size W	16
Wi-Fi maximum backoff times m	6
Physical layer header size	192 bits
MAC layer header size	224 bits
Time slot duration $E_L\{X\}$	9 μs
Channel idle time T_δ	20 μs
Wi-Fi SIFS time	16 μs
Wi-Fi DIFS time	50 μs

Then, we compare the Wi-Fi throughput under the two coexistence modes, and the results are shown in Figure 7. We evaluate the DCM mode by using different duty cycles (i.e., 0.35, 0.5, and 0.65). It can be seen that the Wi-Fi throughput under the LBT mode is generally higher than that under the DCM mode. These results, together with the above Wi-Fi delay results, show that the LBT mode ensures or protects the performance of the Wi-Fi system better than the DCM mode. Under the LBT mode, as the number of Wi-Fi users increases, the throughput increases, achieves an optimal value, and then decreases. A similar trend is observed in the analytical results shown in [34]. Under the DCM mode, as the D2D-U duty cycle increases, the Wi-Fi throughput decreases.

Figure 8 shows the D2D-U throughput under the LBT and DCM modes. D2D-U achieves a higher throughput in the DCM mode than in the LBT mode, even when the DCM duty cycle is small. The D2D-U throughput under the DCM mode increases with the duty cycle because D2D-U users have more opportunities to transmit data in each cycle when the duty cycle increases.

We have analyzed the performance of Wi-Fi and D2D-U under the LBT and DCM modes. We can summarize the performance as follows. The LBT mode can ensure a lower latency and a higher throughput for Wi-Fi users; however, at the same time, the throughput of D2D-U is limited. In the DCM mode, the performance of D2D-U is better exerted while protecting the performance of Wi-Fi to some extent. In

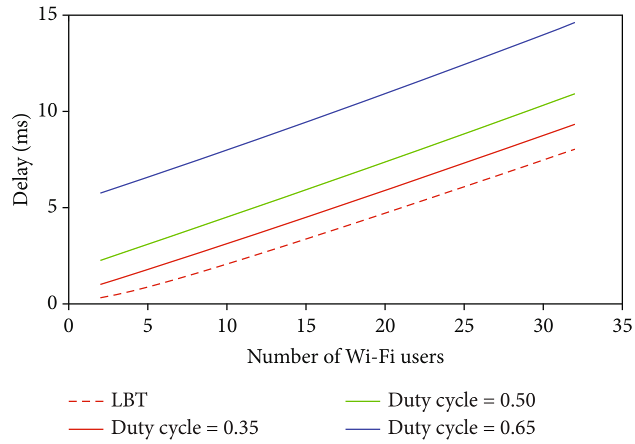

FIGURE 6: Wi-Fi latency under the LBT and DCM modes.

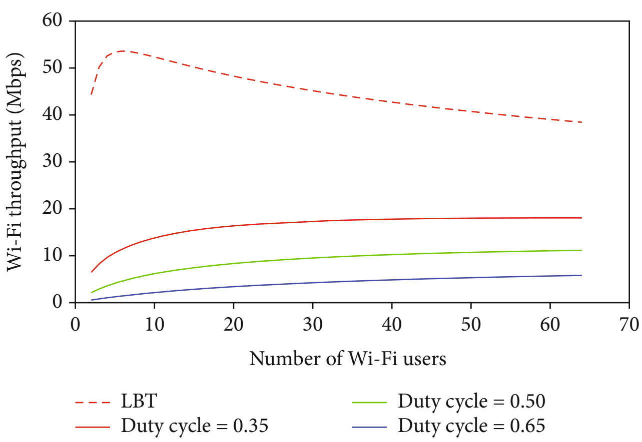

FIGURE 7: Wi-Fi throughput under the LBT and DCM modes.

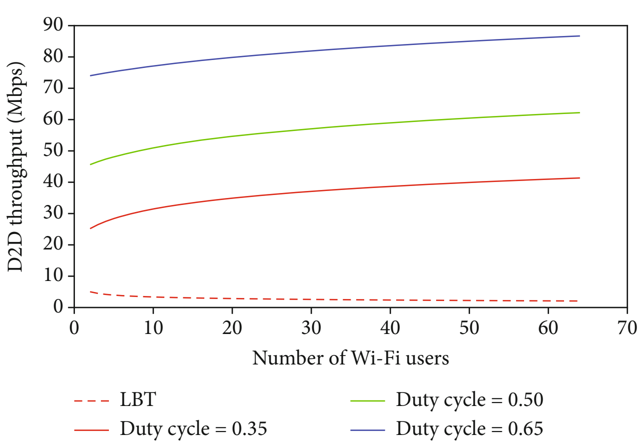

FIGURE 8: D2D-U throughput under the LBT and DCM modes.

the DCM mode, when the D2D-U duty cycle increases, there are more D2D-U access opportunities in a cycle, and so the D2D-U throughput increases at the expense of increased Wi-Fi delay and reduced Wi-Fi throughput.

6.2. Effects of Different Duty Cycles on the Wi-Fi and D2D-U Network Performances. Figures 9 and 10 show the effects of different duty cycles ranging from 0.2 to 0.75 on network performance under the DCM mode. Figure 9 shows that the latency of Wi-Fi increases exponentially with the duty cycle. Figure 10 shows that, as the duty cycle increases, the Wi-Fi throughput decreases and the D2D-U throughput increases. When the duty cycle is larger than 0.3, the D2D-U throughput is generally higher than the Wi-Fi throughput. However, when the duty cycle is small, the throughput of Wi-Fi is higher than that of D2D-U. This finding is important in the design of an efficient mode selection scheme.

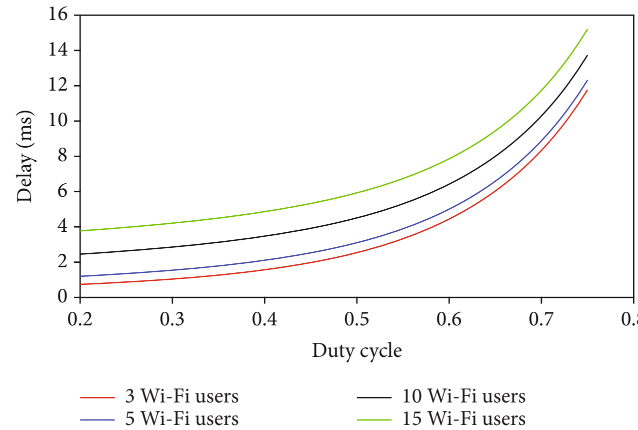

FIGURE 9: Wi-Fi latency comparison with different duty cycles under the DCM mode.

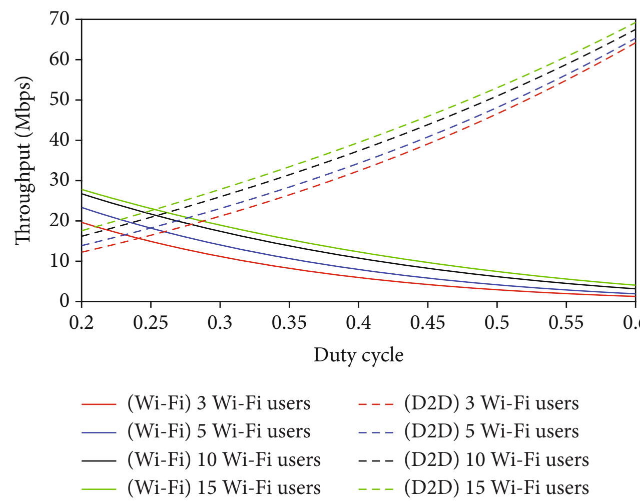

FIGURE 10: Wi-Fi and D2D-U throughput comparison with different duty cycles under the DCM mode.

6.3. Effects of the Number of Wi-Fi Users on the Wi-Fi and D2D-U Network Performances under the Mode Selection Scheme. We also introduce a simple mode selection scheme and evaluate it. The prerequisite of the D2D-U fully occupied mode (see Section 5.5) proposed in this paper is that the Wi-Fi load must be extremely low, and so the impact on Wi-Fi is not considered in this mode. Therefore, our next discussion focuses on the analysis of mode selection between the LBT mode and the typical DCM mode.

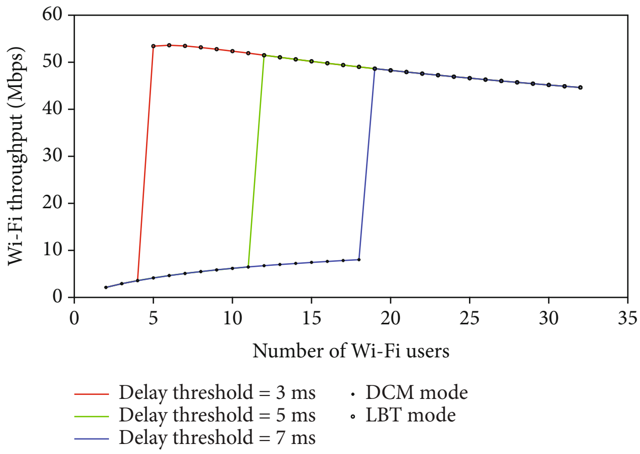

FIGURE 11: Wi-Fi throughput under different delay thresholds in the mode selection scheme.

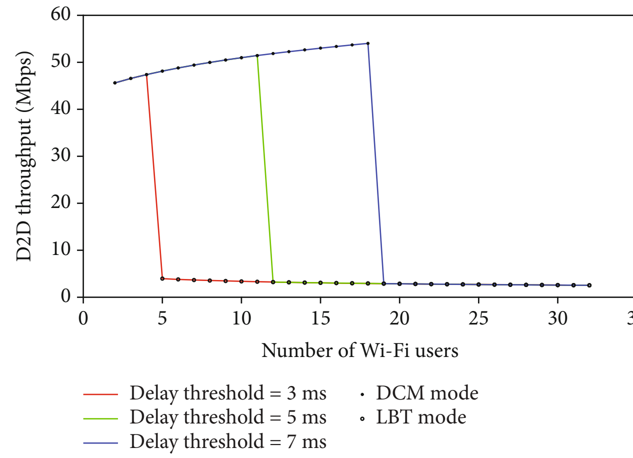

FIGURE 12: D2D-U throughput under different delay thresholds in the mode selection scheme.

In the mode selection scheme, the operating mode is mainly selected based on the Wi-Fi traffic load and the delay of the Wi-Fi users. We assume that each Wi-Fi user transmits data at the same bit rate, and therefore, the traffic load of Wi-Fi can be represented by the number of users connected to the Wi-Fi AP.

In the mode selection scheme used in this paper, we set a delay threshold for the Wi-Fi system to protect the performance of Wi-Fi users. According to the results of the above simulation, compared to the DCM mode, the LBT mode can better protect the performance of the Wi-Fi system when the Wi-Fi traffic load is high. D2D-U will select DCM mode preferentially which provides better D2D-U performance. However, if Wi-Fi performance drops due to a high traffic load, and Wi-Fi delay is higher than the threshold, D2D-U will select the LBT mode instead of the DCM mode because the LBT mode provides a better Wi-Fi performance.

Figure 11 shows the Wi-Fi throughput under the mode selection scheme (e.g., the duty cycle is 0.5 when DCM is used). We can observe that the performance changes with different delay thresholds and different traffic loads. When the delay threshold is high, in other words, Wi-Fi communication has a looser requirement on latency, the D2D-U system tends to choose the DCM mode and vice versa. Figure 12 shows that, as the D2D-U throughput is greatly affected when the transmission mode switches to the LBT mode, a larger delay threshold is required to ensure a higher throughput for the D2D-U system.

We also compare the performance under different duty cycles in this scheme when the delay threshold is set to 4 ms. As shown in Figures 13 and 14, when the duty cycle increases, D2D-U is more likely to choose the LBT mode for transmissions. In the current parameter settings, the D2D-U system only uses the LBT mode to transmit when the duty cycle is 0.65, resulting in a relatively low D2D-U performance, even though Wi-Fi traffic load is exceedingly small. Therefore, we can observe that blue lines (when the duty cycle is 0.65) show different trends as compared with other lines in Figures 13 and 14.

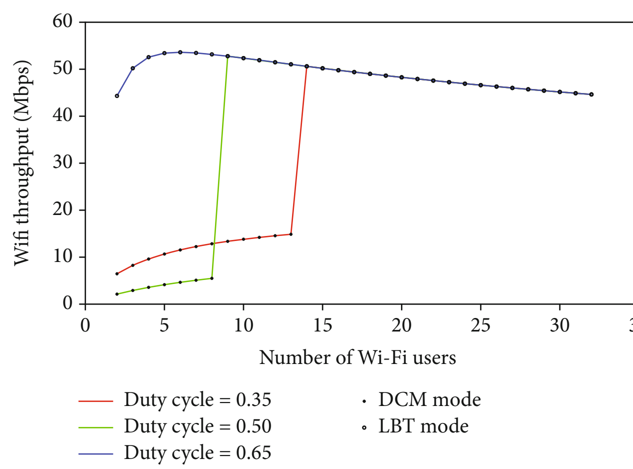

FIGURE 13: Wi-Fi throughput under different duty cycles in the mode selection scheme.

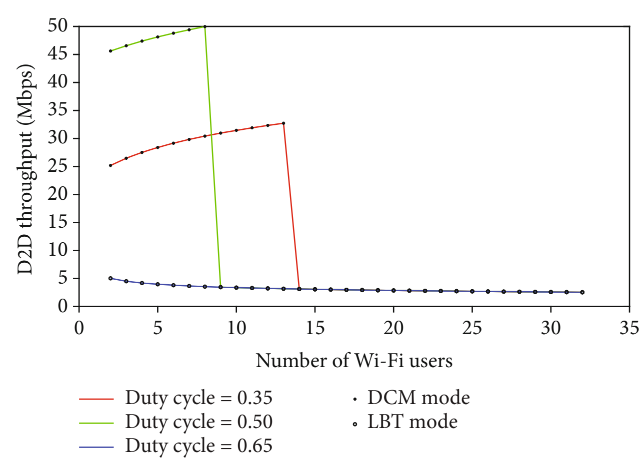

FIGURE 14: D2D-U throughput under different duty cycles in the mode selection scheme.

7. Conclusions and Future Work

With the rapid growth in the traffic of mobile communication networks, licensed spectrum resources are approaching saturation, and therefore, the use of an unlicensed spectrum has gradually become an important research topic. D2D-Unlicensed (D2D-U) communication inherits the high-throughput and low-latency characteristics of D2D and achieves better performance by extending communications to unlicensed bands, showing a great significance in solving the problem of spectrum resource shortage.

In this paper, the coexistence mechanism of D2D-U and Wi-Fi is considered. We first point out the importance of exchanging signaling information through the licensed D2D link before using the unlicensed bands and explain the conditions for establishing D2D-U link between a communication pair. We then use theoretical analysis and computer simulations to show the performance of D2D-U and Wi-Fi systems in a coexistence scenario. With simulation results, it is shown that the performance of the Wi-Fi network can be better guaranteed in the LBT mode and D2D-U can get better performance in the DCM mode. An appropriate transmission mode should be selected in different scenarios according to the Wi-Fi traffic load and the delay constraint of Wi-Fi communications in order to ensure that both D2D-U and Wi-Fi systems work in a good condition.

In future work, we will apply machine learning to the mode selection problem for better performance of D2D-U and Wi-Fi in a more complex coexistence scenario. We will also discuss the use of multihop D2D-U communications in dynamic environments that involve highly mobile user devices.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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