Enabling Device-to-Device Communications in LTE-Unlicensed Spectrum

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***Abstract*—LTE-Unlicensed (LTE-U) is considered as a groundbreaking technology to address the increasing scarcity of available spectrum by extending cellular communications to unlicensed band. In this paper, we investigate the performance of D2D communications in conjunction with LTE-U, which can alleviate traffic load of cellular networks. However, in the same unlicensed band, the coexistence of D2D and WiFi technologies should be carefully designed to satisfy user's quality of service (QoS) and to avoid severe interferences and contentions among devices using unlicensed spectrum. We model the transmissions in unlicensed band as hard core point processes (HCPPs) and thus the transmission probabilities of D2D and WiFi access points (APs) are obtained via the clear channel assessment (CCA) mechanism. Furthermore, by characterizing the intra-tier and inter-tier interferences in such complex communication networks, the average transmit power for the D2D link is investigated given that the user's QoS can be guaranteed. Moreover, the throughput of a typical WiFi AP in the large scale networks is theoretically analyzed, and the outage probability of a D2D link is characterized which results from insufficient transmit power under a pre-determined QoS requirement. Simulations justify successful D2D communications in the LTE-U operation and validate the accuracy of this analytical approach.**

***Index Terms*—LTE-Unlicensed, D2D communications, WiFi, coexistence, stochastic geometry, hard core point process.**

I. INTRODUCTION

To alleviate the ever-growing data traffic volume in cellular networks suffering from the scarcity of licensed radio spectrum, deploying LTE in the Unlicensed (LTE-U) industrial, scientific, and medical (ISM) bands has been recently proposed [1], particularly focusing on the less congested 5GHz band with carrier aggregation [2]. At the same time, as the density of mobile devices dramatically increases, users in proximity can communicate with each other through the direct links, known as device-to-device (D2D) communications [3]. The advantages of incorporating D2D communications into cellular networks include providing high-speed data rate, traffic offloading and coverage expansion, etc. However, the mutual interference between cellular networks and D2D communications utilizing licensed band would be more significant in hot-spots areas as well as ultra-dense networks (UDN) that plays a dominant role in wireless evolution to 5G. In accordance with these challenges, we investigate the case that D2D communications under LTE-U scenario by leveraging the analysis of stochastic geometry.

Compared with the existing direct technologies on unlicensed band such as WiFi direct, Bluetooth, etc., LTE-U D2D has the advantages of efficient peer discovery and link establishment, as well as flexible power control and radio resource management (RRM). Since the unlicensed band is mainly occupied by WiFi technology, the effective heterogeneity and harmonious coexistence between D2D and WiFi should be characterized. In [4], authors studied the coexistence of LTE and WiFi in the same frequency band based on a system-level simulator analysis in a small scale indoor scenario. In [5], a simultaneous transmission scheme for LTE small cell is proposed to coexist with WiFi in unlicensed band. The routing algorithm and RRM mechanism for LTE-U enabled multihop D2D is proposed in [6]. However, very limited theoretical analysis of the coexistence between LTE-U D2D and WiFi networks is available in the literature.

In this paper, we leverage stochastic geometry to model the locations of D2D transmitters, mobile users and WiFi APs as independent homogeneous Poisson Point Processes (PPPs) with diverse densities, and the mutual interferences in unlicensed band are characterized later. We extend the Matern hard core point process (HCPP) to comprehend the impact of Listen-Before-Talk (LBT) regulation through the contention based medium access such as CSMA/CA, where a node can transmit if it determines the channel is idle. The transmission probability of a typical LTE-U D2D or WiFi access point (AP) is derived based on the total received energy detection. Considering the interferences and service link distance, we further derive the average transmit power at LTE-U D2D with a certain data rate requirement. Moreover, the throughput of an arbitrary WiFi user is studied to evaluate the performance degradation of WiFi networks while allowing D2D to use LTE-U. Finally, the outage probability of an arbitrary D2D receiver by failing to achieve QoS requirement due to the inaccessible transmit power at D2D transmitter is presented in section IV.

II. SYSTEM MODEL

A. Network Layout

We consider an integrated network where D2D and WiFi technologies coexist in the same unlicensed band as Fig. 1. To find more realistic tractable approaches for the characterization of network topology and interference modeling in the large-scale system, stochastic geometry is regarded as an efficient way to model the network and is generally applied. We assume that base stations (BSs) are distributed on the entire network plane $\mathbb{R}^2$ according to a homogeneous PPP with density λ_B

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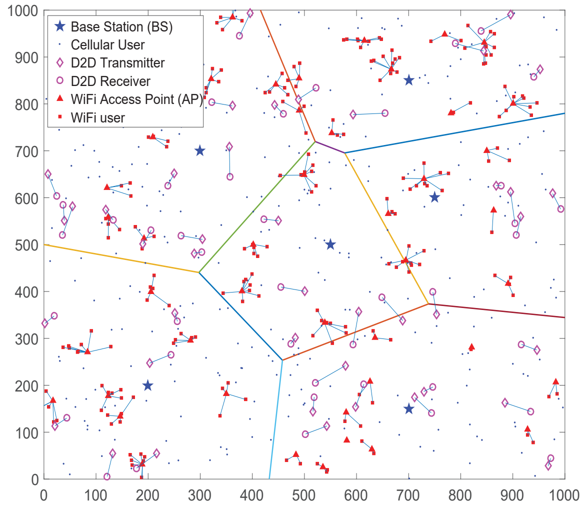

Fig 1: A complex networks with D2D pairs and WiFi APs randomly deployed, where $\lambda_u = 7\lambda_W = 7\lambda_D = 50\lambda_B$.

denoted as the set of $\Psi_B = \{b_j\}$. Similarly, cellular users denoted by the set of Ψ_U are spatially scattered in $\mathbb{R}^2$ according to another independent homogeneous PPP with a density of λ_u. We enable the D2D communications to establish when the two potential users are in proximity within the distance of R_D. The intended D2D transmitters indicated by Ψ_{DT} are located in $\mathbb{R}^2$ with a density of λ_D. At each D2D transmitter, the device has the maximum allowable transmit power indicated by P_D. For WiFi network, we focus on the downstream traffic since downlink traffic are often statistically dominant for users to access the Internet currently. We assume that WiFi access points (APs) are randomly deployed over the network plane following an another independent homogeneous PPP with the density of λ_W denoted by Ψ_W. In fact, Poisson distribution implies that these APs have no coordination deployments, but uniform and unplanned locations.

B. *Association and Radio Channel*

In most of the studies in the literature, cellular users can access to the nearest BS or the BS with the strongest signal strength at the end-user. However, in this paper, we focus on the operation in unlicensed band and thus the analysis of cellular networks in licensed band will not be investigated.

1) D2D link: We denote the target unlicensed band for the intended D2D pair (i.e., D2D transmitter and receiver) to use as B_U, while the distance between tx-rx pair is within a constant value of R_D (i.e., the service link distance r_d satisfies $r_d \leqslant R_D$). If the distance between the intended D2D pairs exceeds R_D (i.e., $r_d > R_D$), the transmission will return back to the conventional cellular networks. According to Shannon theorem, the data rate of the j^{th} D2D receiver d_j^{DR} associated with its transmitter d_j^{DT} can be expressed as follows:

$$R_j^D = B_U \log_2 \left(1 + \frac{P_j^D h_j^D \left\| d_j^{DR} - d_j^{DT} \right\|^{-\alpha}}{I_{D,j}^{WiFi} + I_{D,j}^{D2D} + \sigma^2} \right), \tag{1}$$

where P_j^D ($P_j^D \leqslant P_D$) represents the transmit power at d_j^{DT}, and accordingly h_j^D is the square of the magnitude of fading coefficient (i.e., $h_j^D \sim \exp(1)$), $\left\| d_j^{DR} - d_j^{DT} \right\| = r_d$ denotes the service link distance between d_j^{DR} and d_j^{DT}, α expresses the path-loss exponent, $I_{D,j}^{WiFi}$ indicates the interference from WiFi APs at the j^{th} D2D receiver d_j^{DR}, $I_{D,j}^{D2D}$ denotes the intra-tier interference from other D2D transmitters which can access B_U, and σ^2 denotes the variance of channel-noise.

2) WiFi network: Although IEEE 802.11 standards provide several non-overlapping channels over the unlicensed band, without loss of generality, we consider the case that only one channel (B_U) is occupied and each AP transmits on the power of P_A. In practical scenarios, as WiFi APs are generally deployed in the hot-spots areas, we assume that WiFi users are distributed around the AP, and the users can access to the WiFi networks if the received signal strength satisfies a given threshold δ_{AP}. Moreover, we characterize the signal-to-interference-plus-noise-ratio (SINR) of i^{th} WiFi user ($u_{i,j}^W$) attached to j^{th} AP (a_j^{AP}) as follows:

$$SINR_{i,j}^W = \frac{P_A h_{i,j}^W \left\| u_{i,j}^W - a_j^{AP} \right\|^{-\alpha}}{I_{w,i,j}^{WiFi} + I_{w,i,j}^{D2D} + \sigma^2}, \tag{2}$$

where $h_{i,j}^W$ denotes the square of the magnitude of fading coefficient (i.e., $h_{i,j}^W \sim \exp(1)$), $I_{w,i,j}^{WiFi}$ represents the aggregated interference from WiFi network at $u_{i,j}^W$ and $I_{w,i,j}^{D2D}$ indicates the aggregated interference from D2D transmitters towards the WiFi user $u_{i,j}^W$.

C. *MAC Protocol Model*

Various coexistence mechanisms have been proposed for LTE-U, such as LTE blank subframe allocation [7], LBT [8] and Carrier Sensing and Adaptive Transmission (CSAT) [9], etc. As the global solution known as Licensed-Assisted Access (LAA) allows LTE to be deployed in unlicensed band with LBT under the standardization in 3GPP Rel-13, we adopt LBT mechanism at the LTE-U D2D transmitters in this paper.

Furthermore, in order to guarantee the fairness of channel access, we assume that a random back-off mechanism in LBT regulation similar to CSMA/CA is implemented, where each transmitter has a timer to indicate the operation timing of back-off operation. Furthermore, we leverage HCPP to characterize the remaining time, where the transmitter x is assigned a mark denoted by $m(x)$ uniformly distributed in the interval [0,1].

We suppose that the detection of the total received power as the clear channel assessment (CCA). More specifically, the channel is sensed busy by a D2D transmitter or a WiFi AP when the total combined power from all existing active nodes exceeds the energy detection threshold γ_{ED}^D or γ_{ED}^W, respectively. We define $\Psi_D^{act}(t)$ as the set of D2D transmitters that are simultaneously accessing the channel at time t. That is, $d_j^{DT} \in \Psi_D^{act}(t)$, if the following condition satisfies:

$$\sum_{y \in \Psi_{DT}^{\varepsilon}} \frac{P_D g_y^D}{\left\| d_j^{DT} - y \right\|^{\alpha}} + \sum_{y \in \Psi_W^{\varepsilon}} \frac{P_A g_y^W}{\left\| d_j^{DT} - y \right\|^{\alpha}} < \gamma_{ED}^D, \tag{3}$$

$$\text{given } \Psi_{\mathrm{DT}}^{\varepsilon} = \left\{ \mathrm{z} \in \Psi_{\mathrm{DT}} : \mathrm{m}(\mathrm{z}) < \mathrm{m}\left(\mathrm{d}_{\mathrm{j}}^{\mathrm{DT}}\right) = \varepsilon \right\}, \text{and}$$
$$\Psi_W^{\varepsilon} = \left\{ z \in \Psi_W : m(z) < m\left(d_j^{DT}\right) = \varepsilon \right\},$$

where g_y^D or g_y^W denotes the square of the magnitude of fading coefficients between d_j^{DT} and y with D2D link or WiFi link, respectively. Similarly, we define $\Psi_W^{act}(t)$ as the set of WiFi APs that simultaneously access unlicensed channel at a given time t, $a_j^{AP} \in \Psi_W^{act}(t)$, if the following condition satisfies:

$$\sum_{y \in \Psi_{DT}^{\omega}} \frac{P_D g_y^D}{\left\| a_j^{AP} - y \right\|^{\alpha}} + \sum_{y \in \Psi_W^{\omega}} \frac{P_A g_y^W}{\left\| a_j^{AP} - y \right\|^{\alpha}} < \gamma_{ED}^{W}, \tag{4}$$

$$\text{given } \Psi_{\mathrm{DT}}^{\omega} = \left\{ \mathrm{z} \in \Psi_{\mathrm{DT}} : \mathrm{m}\left(\mathrm{z}\right) < \mathrm{m}\left(\mathrm{a_j^{AP}}\right) = \omega \right\}, \text{and}$$

$$\Psi_W^{\omega} = \left\{ z \in \Psi_W : m\left(z\right) < m\left(a_j^{AP}\right) = \omega \right\}.$$

We assume all nodes as backlogged in a large networks to simplify the analysis.

III. MEDIUM ACCESS PROBABILITY

We first derive the medium access probability of a typical D2D transmitter in unlicensed spectrum, and thus we obtain the density of simultaneously transmitting D2D. The medium access probability of a typical D2D transmitter is $\mathbb{P}\left(P_{ED}^{total} \leqslant \gamma_{ED}^{D}\right)$, given that

$$P_{ED}^{total} = \sum\nolimits_{d_k^{DT} \in \Psi_{DT}^{\varepsilon}} \frac{P_D g_k^D}{\left\| d_j^{DT} - d_k^{DT} \right\|^{\alpha}} + \sum\nolimits_{a_k^{AP} \in \Psi_W^{\varepsilon}} \frac{P_A g_k^W}{\left\| d_j^{DT} - a_k^{AP} \right\|^{\alpha}}. \tag{5}$$

We leverage the Laplace transform inversion method to specifically derive the target function $f_{P_{ED}^{total}}(t)$, which is the PDF of the total received power P_{ED}^{total} at an arbitrary potential LTE-U D2D transmitter.

$$\mathcal{L}_{P_{ED}^{total}}(s) = \mathbb{E}\left[e^{-sP_{ED}^{total}} \right] = \int_0^{\infty} e^{-st} f_{P_{ED}^{total}}(t) dt, \tag{6}$$

$$f_{P_{ED}^{total}}(t) = \mathcal{L}^{-1}\left\{ \mathcal{L}_{P_{ED}^{total}}(s) \right\}, \tag{7}$$

where $\mathcal{L}_{P_{ED}^{total}}(s)$ denotes the Laplace transform of P_{ED}^{total} and $\mathcal{L}^{-1}\left\{\mathcal{L}_{P_{ED}^{total}}(s)\right\}$ represents the inverse Laplace transform.

More specifically, $\mathcal{L}_{P_{ED}^{total}}(s)$ can be expressed as

$$\mathcal{L}_{P_{ED}^{total}}(s) = \mathcal{L}_{P_{ED}^{D2D}}(s)\, \mathcal{L}_{P_{ED}^{WiFi}}(s), \tag{8}$$

where P_{ED}^{D2D}, P_{ED}^{WiFi} denotes the first term and the second term of P_{ED}^{total} in (5), respectively.

Since the point process $\Psi_{DT}^{\varepsilon} = \left\{ z \in \Psi_{DT} : m\left(z\right) < \varepsilon \right\}$ is i.i.d. thinning of a Poisson process, Ψ_{DT}^{ε} is also a Poisson process with density $\varepsilon \lambda_D$. Furthermore, according to the properties of PPP, $\mathcal{L}_{P_{ED}^{D2D}}(s)$ can be given as follows:

$$\begin{aligned} \mathcal{L}_{P_{ED}^{D2D}}(s) &= \mathbb{E}_{\Psi_{DT}^{\varepsilon}, g}\left[\exp\left(-sP_{ED}^{D2D} \right) \right] \\ &\overset{(a)}{=} \mathbb{E}_{\Psi_{DT}^{\varepsilon}} \left\{ \prod_{d_k^{DT} \in \Psi_{DT}^{\varepsilon}} \mathbb{E}_g\left[\exp\left(-sP_D g_k^D {x_k}^{-\alpha} \right) \right] \right\} \\ &\overset{(b)}{=} \mathbb{E}_{\Psi_{DT}^{\varepsilon}} \left[\prod_{d_k^{DT} \in \Psi_{DT}^{\varepsilon}} \frac{1}{1 + sP_D {x_k}^{-\alpha}} \right], \end{aligned} \tag{9}$$

where, in (a), $x_k = \left\| d_j^{DT} - d_k^{DT} \right\|$ indicates the link distance between the typical D2D transmitter d_j^{DT} and other k^{th} potential D2D transmitter d_k^{DT} whose mark satisfies $m\left(d_k^{DT}\right) < \varepsilon$, and (b) follows from $g_k^D \sim \exp\left(1\right)$.

Applying the probability generating functional (PGFL) of the PPP [10], we can calculate the equation (9) as follows:

$$\begin{aligned} \mathcal{L}_{P_{ED}^{D2D}}(s) &= \exp\left[-2\pi\lambda_D\varepsilon \int_0^{\infty} \left(1 - \frac{1}{1 + sP_D x^{-\alpha}} \right) x dx \right] \\ &\overset{(a)}{=} \exp\left(-\frac{2\lambda_D \pi^2 \varepsilon}{\alpha \Im {P_D}^{-2/\alpha}} s^{\frac{2}{\alpha}} \right) = e^{-\omega_1 s^{\frac{2}{\alpha}}} \end{aligned} \tag{10}$$

$$\text{where } \omega_1 = \frac{2\lambda_D \pi^2 \varepsilon}{\alpha \Im {P_D}^{-2/\alpha}}, \Im = \sin\left(\frac{2\pi}{\alpha}\right),$$

where (a) can be evaluated by using the substitution $y^{\alpha} = \left(sP_D\right)^{-1} x^{\alpha}$. In addition, $\mathcal{L}_{P_{ED}^{WiFi}}(s)$ can be obtained as

$$\mathcal{L}_{P_{ED}^{WiFi}}(s) = \exp\left(-\frac{2\lambda_W \pi^2 \varepsilon}{\alpha \Im {P_A}^{-2/\alpha}} s^{\frac{2}{\alpha}} \right) = e^{-\omega_2 s^{\frac{2}{\alpha}}}, \tag{11}$$

where $\omega_2 = \frac{2\lambda_W \pi^2 \varepsilon}{\alpha \Im {P_A}^{-2/\alpha}}$ and $\Im$ is the same with (10).

Therefore, the Laplace transform of the total received power at a typical D2D transmitter d_j^{DT} with mark $m\left(d_j^{DT}\right) = \varepsilon$ is

$$\mathcal{L}_{P_{ED}^{total}}(s) = e^{-\omega_3 s^{\frac{2}{\alpha}}}, \omega_3 = \frac{2\pi^2\varepsilon}{\alpha\Im} \left(\frac{\lambda_D}{{P_D}^{-\frac{2}{\alpha}}} + \frac{\lambda_W}{{P_A}^{-\frac{2}{\alpha}}} \right). \tag{12}$$

The cumulative distribution function (CDF) of P_{ED}^{total} is

$$\begin{aligned} F_{P_{ED}^{total}}(x) &= \mathbb{P}\left(P_{ED}^{total} \leqslant x\right) = \int_0^x f_{P_{ED}^{total}}(t) dt \\ &= \int_0^x \frac{1}{2\pi i} \lim_{T \to \infty} \int_{c-iT}^{c+iT} e^{st} \mathcal{L}_{P_{ED}^{total}}(s) ds dt \\ &= \frac{1}{2\pi i} \lim_{T \to \infty} \int_{c-iT}^{c+iT} \frac{e^{sx - \omega_3 s^{\frac{2}{\alpha}}}}{s} ds. \end{aligned} \tag{13}$$

Considering the equation (13) has a branch point at origin, we use the Bromwich inversion method with a specified contour to calculate the integral [11] to have

$$\begin{aligned} F_{P_{ED}^{total}}(x) = &- \lim_{\substack{R \to \infty \\ r \to 0}} \frac{1}{2\pi i} \left\{ \int_{\pi}^{-\pi} e^{re^{i\theta} x - \omega_3 r^{\frac{2}{\alpha}} e^{\frac{2i\theta}{\alpha}}} \frac{ire^{i\theta} d\theta}{re^{i\theta}} \right. \\ &\left. + \int_R^r e^{ue^{i\pi} x - \omega_3 u^{\frac{2}{\alpha}} e^{\frac{2i\pi}{\alpha}}} \frac{du}{u} + \int_r^R e^{ue^{-i\pi} x - \omega_3 u^{\frac{2}{\alpha}} e^{\frac{-2i\pi}{\alpha}}} \frac{du}{u} \right\} \\ = 1 &- \lim_{\substack{R \to \infty \\ r \to 0}} \int_R^r \frac{-i2\sin\left(\omega_3 u^{2/\alpha} \sin\left(\frac{2\pi}{\alpha}\right)\right)}{2\pi i \exp\left[ux + \omega_3 u^{2/\alpha} \cos\left(\frac{2\pi}{\alpha}\right)\right]} \frac{du}{u} \\ \overset{(a)}{=} 1 &- \frac{\alpha}{2\pi} \int_0^{\infty} \frac{\sin\left[z \sin\left(\frac{2\pi}{\alpha}\right)\right]}{\exp\left[\left(\frac{z}{\omega_3}\right)^{\alpha/2} x + z\cos\left(\frac{2\pi}{\alpha}\right)\right]} \frac{dz}{z}, \end{aligned} \tag{14}$$

where (a) is obtained by using the substitution $\xi_3 u^{2/\beta} \to z$.

Hence the medium access probability of a typical D2D transmitter is obtained by deconditioning with respect to ε:

$$\begin{aligned} p_D^{act} = \left(P_{ED}^{total} \leqslant \gamma_{ED}^{D}\right) = 1 - \frac{\alpha}{2\pi} \int_0^{\infty} \int_0^1 \frac{\sin\left(z\Im\right)}{e^{z\cos\left(\frac{2\pi}{\alpha}\right)} z} \\ e^{-\gamma_{ED}^{D} \left(\frac{z\alpha\Im / \left(2\varepsilon\pi^2\right)}{\lambda_D {P_D}^{\frac{2}{\alpha}} + \lambda_W {P_A}^{\frac{2}{\alpha}}} \right)^{\alpha/2}} d\varepsilon dz. \end{aligned} \tag{15}$$

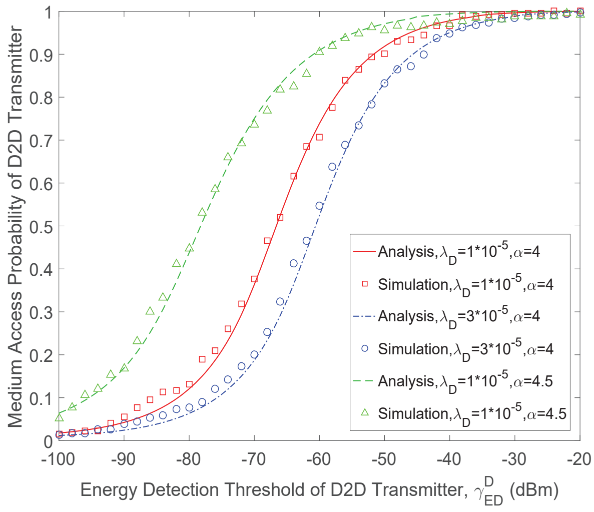

Fig 2: Effects of D2D density and path-loss factor on the medium access probability for the typical D2D transmitter.

Similarly, the probability that a typical WiFi AP can access to the unlicensed spectrum can be obtained as:

$$p_W^{act} = \left(P_{ED}^{total} \leqslant \gamma_{ED}^W\right) = 1 - \frac{\alpha}{2\pi}\int_0^\infty \int_0^1 \frac{\sin\left(z\Im\right)}{e^{z\cos\left(\frac{2\pi}{\alpha}\right)}z} e^{-\gamma_{ED}^W \left(\frac{z\alpha\Im/\left(2\omega\pi^2\right)}{\lambda_D P_D{}^{\frac{2}{\alpha}} + \lambda_W P_A{}^{\frac{2}{\alpha}}}\right)^{\alpha/2}} d\omega dz. \quad (16)$$

Although p_W^{act} has a double integral, it can be efficiently obtained by numerical calculation. The analytical results, which are obtained from (15), are validated by Monte Carlo simulations as in Fig. 2., where $\lambda_W = 1 \times 10^{-5} APs/m^2$, $P_D = P_A = 100mW$, $\gamma_{ED}^W = -62dBm$. It can be observed from Fig. 2. that a large number of transmission nodes results in the degradation of medium access probability. In addition, the smaller path-loss factor α has less impact on the total received power, which would lead to higher medium access probability. The density of simultaneously transmitting D2Ds (λ_D^{act}) and that of WiFi APs (λ_W^{act}) can be determined by $\lambda_D^{act} = \lambda_D p_D^{act}$ and $\lambda_W^{act} = \lambda_W p_W^{act}$, respectively.

IV. INTERFERENCE AND D2D TRANSMIT POWER

In this section, we derive the LTE-U D2D transmit power when the user's QoS is guaranteed. We assume that each LTE-U D2D is capable of performing adaptive power control according to zero-delay *channel state information* (CSI). Therefore, the average LTE-U D2D's transmit power can be obtained by a transformation of equation (1) as

$$\mathbb{E}\left[P_j^D \middle| r_d\right] = \frac{2^{R_j^D/B_U} - 1}{{r_d}^{-\alpha}}\left(I_{D,j}^{D2D} + I_{D,j}^{WiFi} + \sigma^2\right), \quad (17)$$

where $r_d = \left\|d_j^{DR} - d_j^{DT}\right\|$ is the service link distance between the D2D receiver d_j^{DR} and D2D transmitter d_j^{DT}, and we have utilized $\mathbb{E}\left[h_j^D\right] = 1$. Since the probability generating functional of the HCPP is unknown to be expressed, it is extremely difficult (if not impossible) to characterize the exact distribution of the intra-tier and inter-tier aggregated interference. Therefore, the interferers are approximated by the PPPs with the same intensities (i.e., $\lambda_D p_D^{act}$ and $\lambda_W p_W^{act}$), which can be validated by simulations. In order to evaluate the aggregated interference at the D2D receiver d_j^{DR}, without loss of generality, we can suppose that the locations of d_j^{DR} and d_j^{DT} are $(r_d, 0)$ and $(0, 0)$, respectively. The worst-case scenario happens where the interferers transmit on their maximum power (i.e., D2D transmits on P_D and WiFi AP transmits on P_A), and thus the average aggregated interference $I_{D,j}^{D2D}$ can be obtained by applying Campbell's Theorem, as

$$\begin{aligned} I_{D,j}^{D2D} &= \mathbb{E}_{\Psi_{DT}^{act},g}\left[\sum_{d_k^{DT} \in \Psi_{DT}^{act} \backslash d_j^{DT}} P_D p_D^{act} g_j^{DT} \left\|d_j^{DR} - d_k^{DT}\right\|^{-\alpha}\right] \\ &\overset{(a)}{=} P_D \lambda_D p_D^{act} \int\limits_{x \in \mathbb{R}^2 / B\left(d_j^{DT}, x_D\right)} \left\|d_j^{DR} - x\right\|^{-\alpha} dx \\ &\overset{(b)}{=} \lambda_D p_D^{act} P_D \int_0^{2\pi} \int_{x_D}^\infty \mathcal{H}^{-\frac{\alpha}{2}}\left(x, \theta, r_d\right) x dx d\theta, \end{aligned} \quad (18)$$

where, in (a), $B\left(d_j^{DT}, x_D\right)$ denotes the disk of radius x_D centered on d_j^{DT}, and $x_D = \left[P_D/\left(10^{\frac{\gamma_{ED}^D}{10} - 3}\right)\right]^{1/\alpha}$, and $\mathcal{H}\left(x, \theta, r_d\right) = x^2 + {r_d}^2 - 2xr_d\cos\theta$ follows from cosine law in (b). Note that any D2D transmitter with a distance x_D from d_j^{DT} can supply received power higher than the energy detection threshold γ_{ED}^D.

Similarly, the aggregated interference from the accessed WiFi APs is given by

$$I_{D,j}^{WiFi} = \lambda_W p_W^{act} P_A \int_0^{2\pi} \int_{x_W}^\infty \mathcal{H}^{-\frac{\alpha}{2}}\left(x, \theta, r_d\right) x dx d\theta, \quad (19)$$

where $x_W = \left[P_A/\left(10^{\frac{\gamma_{ED}^D}{10} - 3}\right)\right]^{1/\alpha}$ indicates the nearest distance between any WiFi AP and the transmitting d_j^{DT}.

Therefore, the average transmit power of an arbitrary LTE-U D2D transmitter can be derived by combining (18) and (19) into (17) and deconditioning r_d with the probability density function (PDF) (i.e., $f_{r_d}(r) = \frac{2r}{{R_D}^2}$), as follows:

$$\begin{aligned} \mathbb{E}\left[P_j^D\right] &= \int_0^{R_D} \mathbb{E}\left[P_j^D \middle| r\right] f_{r_d}(r) dr \quad (20) \\ &= \frac{2^{\frac{R_j^D}{B_U}+1} - 2}{{R_D}^2}\left[\lambda_D p_D^{act} P_D \xi_1 + \lambda_W p_W^{act} P_A \xi_2 + \frac{\sigma^2 {R_D}^{\alpha-2}}{\alpha+2}\right] \end{aligned}$$

where $\xi_1 = \int_0^{R_D} \int_0^{2\pi} \int_{x_D}^\infty \mathcal{G}\left(x, \theta, r\right) dx d\theta dr$

$$\xi_2 = \int_0^{R_D} \int_0^{2\pi} \int_{x_W}^\infty \mathcal{G}\left(x, \theta, r\right) dx d\theta dr$$

and $\mathcal{G}\left(x, \theta, r\right) = xr\left[\left(\frac{x}{r}\right)^2 + 1 - \frac{2x}{r}\cos\theta\right]^{-\frac{\alpha}{2}}$,

where ξ_1 and ξ_2 can be calculated numerically. It is worth noting that the transmit power of LTE-U D2D can be set a certain value according to (20) in order to guarantee D2D user's data rate requirement R_j^D.

In Fig.3., the LTE-U D2D transmit power is shown respective to the D2D service link distance r_d, when user's

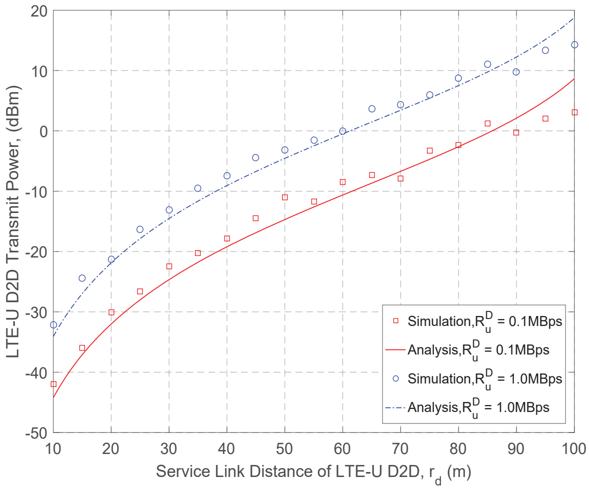

Fig 3: LTE-U D2D transmit power with respect to service link distance r_d on different data rate requirements, where $\lambda_D = 3\lambda_W = 3 \times 10^{-5}$, $P_A = 100mW$, $\gamma_{ED}^D = \gamma_{ED}^W = -62dBm$, $\alpha = 4$.

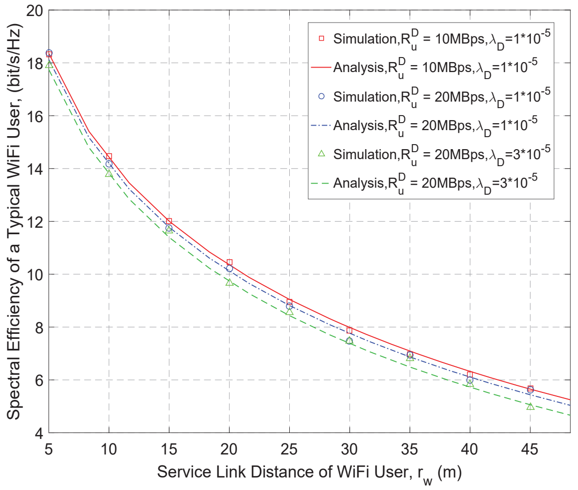

Fig 4: Spectral efficiency of WiFi user with respect to service link distance r_w under various QoS requirements and densities of LTE-U D2D, where $\lambda_W = 1 \times 10^{-5}$, $r_d = 70m$,$P_A = 100mW$, $\gamma_{ED}^D = \gamma_{ED}^W = -62dBm$, $\alpha = 4$.

required data rate is $0.1MBps$ and $1MBps$, respectively, and we assume $R_j^D = R_u^D, \forall d_j^{DR} \in \Psi_{DR}$. It is obvious that the LTE-U D2D transmit power increases with the service link distance r_d in order to guarantee the user's QoS requirement. This is because the higher interferences are likely generated by the closer active D2Ds and WiFi APs on one hand, and the less signal strength is received from the typical D2D transmitter d_j^{DT} on the other hand.

Since D2D communications are introduced in LTE-Unlicensed spectrum, the performance degradation of WiFi users should not be severe. In the next section, we will therefore characterize the spectral efficiency of a typical WiFi user as a performance index of WiFi networks.

V. SPECTRAL EFFICIENCY OF WIFI USER

In order to compute the spectral efficiency of the WiFi user, we derive the distribution of SINR at the origin. By assuming that the interferers can be approximated by the PPPs with the same intensities, the complementary cumulative distribution function (CCDF) of SINR at WiFi user $u_{i,j}^W$ with service link distance $r_w = \left\| u_{i,j}^W - a_j^{AP} \right\|$ can be derived as:

$$\begin{aligned}
\mathbb{P}\left(SINR_{i,j}^W\left(r_w\right) > \tau\right) &= \mathbb{P}\left(\frac{P_A h_{i,j}^W {r_w}^{-\alpha}}{I_{w,i,j}^{WiFi} + I_{w,i,j}^{D2D} + \sigma^2} > \tau\right) \\
&= \mathbb{P}\left(h_{i,j}^W > \frac{\tau\left(I_{w,i,j}^{WiFi} + I_{w,i,j}^{D2D} + \sigma^2\right)}{P_A {r_w}^{-\alpha}}\right) \qquad (21) \\
&\approx \exp\left(-\frac{\tau\sigma^2 {r_w}^{\alpha}}{P_A}\right)\mathcal{L}_{I_{w,i,j}^{WiFi}}^W\left(\frac{\tau {r_w}^{\alpha}}{P_A}\right)\mathcal{L}_{I_{w,i,j}^{D2D}}^W\left(\frac{\tau {r_w}^{\alpha}}{P_A}\right).
\end{aligned}$$

In addition, the Laplace transform of the interference from all other active WiFi APs can be evaluated as follows:

$$\begin{aligned}
\mathcal{L}_{I_{w,i,j}^{WiFi}}^W(s) &= \mathbb{E}\left[\exp\left(-s\sum_{a_k^{AP}\in\Psi_W^{act}} P_A g_k^W \left\|u_{i,j}^W - a_k^{AP}\right\|^{-\alpha}\right)\right] \\
&= \mathbb{E}_{\Psi_W^{act}}\left\{\prod_{a_k^{AP}\in\Psi_W^{act}} \mathbb{E}_g\left[\exp\left(-sP_A g_k^W \left\|u_{i,j}^W - a_k^{AP}\right\|^{-\alpha}\right)\right]\right\} \\
&\overset{(a)}{=} \mathbb{E}_{\Psi_W^{act}}\left[\prod_{a_k^{AP}\in\Psi_W^{act}} \left(1 + sP_A\left\|u_{i,j}^W - a_k^{AP}\right\|^{-\alpha}\right)^{-1}\right] \qquad (22) \\
&\overset{(b)}{=} \exp\left\{-\lambda_W p_W^{act}\int_0^{2\pi}\int_{y_W}^{\infty} x\right. \\
&\quad \left.\cdot\left[1 - \left[1 + sP_A\left(x^2 + {r_w}^2 - 2xr_w\cos\theta\right)^{-\alpha/2}\right]^{-1}\right]dxd\theta\right\} \\
&= \exp\left[-\lambda_W p_W^{act}\int_0^{2\pi}\int_{y_W}^{\infty}\frac{sP_A\mathcal{H}^{-\frac{\alpha}{2}}\left(x,\theta,r_w\right)x}{1 + sP_A\mathcal{H}^{-\frac{\alpha}{2}}\left(x,\theta,r_w\right)}dxd\theta\right],
\end{aligned}$$

where (a) follows from $g_k^W \sim \exp\left(1\right)$, (b) is obtained according to the PGFL of PPP, and $y_W = \left(P_A \Big/ 10^{\frac{\gamma_{ED}^W}{10} - 3}\right)^{\frac{1}{\alpha}}$, $\mathcal{H}\left(x,\theta,r_w\right) = x^2 + {r_w}^2 - 2xr_w\cos\theta$. Similarly, the Laplace transform of the interference from all other active LTE-U D2Ds is given by

$$\begin{aligned}
\mathcal{L}_{I_{w,i,j}^{D2D}}^W(s) &= \mathbb{E}\left[e^{-s\sum_{d_k^{DT}\in\Psi_{DT}^{act}} P_D g_k^D \left\|u_{i,j}^W - d_k^{DT}\right\|^{-\alpha}}\right] \qquad (23) \\
&= \exp\left[-\lambda_D p_D^{act}\int_0^{2\pi}\int_{y_D}^{\infty}\frac{s\widetilde{P_D}\mathcal{H}^{-\frac{\alpha}{2}}\left(x,\theta,r_w\right)x}{1 + s\widetilde{P_D}\mathcal{H}^{-\frac{\alpha}{2}}\left(x,\theta,r_w\right)}dxd\theta\right],
\end{aligned}$$

where $y_D = \left(\widetilde{P_D} \Big/ 10^{\frac{\gamma_{ED}^W}{10} - 3}\right)^{\frac{1}{\alpha}}$, and $\widetilde{P_D}$ denotes the transmit power of D2D given in (20).

Combining (22) and (23) into (21), we obtain the CCDF of SINR at user $u_{i,j}^W$ as follows:

$$\begin{aligned}
&\mathbb{P}\left(SINR_{i,j}^W\left(r_w\right) > \tau\right) \qquad (24) \\
&\approx \exp\left(-\frac{\tau\sigma^2 {r_w}^{\alpha}}{P_A} - \lambda_W p_W^{act}\mathcal{K}_w\left(\tau,r_w\right) - \lambda_D p_D^{act}\mathcal{T}_D\left(\tau,r_w\right)\right)
\end{aligned}$$

where $\mathcal{K}_w\left(\tau,r_w\right) = \int_0^{2\pi}\int_{y_W}^{\infty}\frac{\tau\mathcal{H}^{-\frac{\alpha}{2}}\left(x,\theta,r_w\right)x}{{r_w}^{-\alpha} + \tau\mathcal{H}^{-\frac{\alpha}{2}}\left(x,\theta,r_w\right)}dxd\theta$

$$\mathcal{T}_D\left(\tau,r_w\right) = \int_0^{2\pi}\int_{y_D}^{\infty}\frac{\tau\widetilde{P_D}\mathcal{H}^{-\frac{\alpha}{2}}\left(x,\theta,r_w\right)x}{{r_w}^{-\alpha}P_A + \tau\widetilde{P_D}\mathcal{H}^{-\frac{\alpha}{2}}\left(x,\theta,r_w\right)}dxd\theta.$$

According to $\mathbb{E}\left[X\right] = \int_0^\infty \mathbb{P}\left(X > x\right)dx, \left(X > 0\right)$, the expectation of the spectral efficiency at user $u_{i,j}^W$ conditioned on the service link distance r_w is

$$\begin{aligned} SE_{i,j}^W\left(r_w\right) &= \mathbb{E}_{SINR_{i,j}^W}\left[\log_2\left(1 + SINR_{i,j}^W\left(r_w\right)\right)\right] \\ &= \int_0^\infty \mathbb{P}\left(SINR_{i,j}^W\left(r_w\right) > 2^\tau - 1\right)d\tau, \qquad (25) \end{aligned}$$

where $\mathbb{P}\left(SINR_{i,j}^W\left(r_w\right) > 2^\tau - 1\right)$ is obtained from (24).

Simulations are carried out to validate our theoretical results as in Fig.4, which demonstrates the impact of LTE-U D2D on the WiFi user spectral efficiency under various r_w. From the figure, satisfying higher D2D user's required data rate or increasing the density of D2D pairs would lead to the performance degradation of WiFi networks, since the transmit power of D2D increases with user's QoS requirement and thus the aggregated interference at WiFi user becomes severe.

VI. OUTAGE PROBABILITY OF LTE-U D2D

In this paper, our main attention is the network performance evaluation. Therefore, the LTE-U D2D user's outage probability should be characterized. We define the outage probability of a typical LTE-U D2D receiver d_j^{DR} as

$$O_j^{DR} = \mathbb{P}\left(P_j^D > P_D\right), \qquad (26)$$

which is the probability that the required data rate of D2D user d_j^{DR} cannot be guaranteed even under the maximum allowable transmit power P_D. According to the above definition, the outage probability of D2D user d_j^{DR} conditioned on the service link distance r_d is given by

$$\begin{aligned} O_j^D\left(r_d\right) &= 1 - \mathbb{P}\left(P_j^D < P_D \middle| r_d\right) \qquad (27) \\ &= 1 - \mathbb{P}\left[h_{i,j}^D > \frac{2^{R_u^D/B_U} - 1}{{r_d}^{-\alpha}P_D}\left(I_{d,i,j}^{D2D} + I_{d,i,j}^{WiFi} + \sigma^2\right)\right] \\ &= 1 - e^{-\frac{M\sigma^2}{P_D}{r_d}^\alpha}\mathcal{L}_{I_{d,i,j}^{D2D}}^D\left(\frac{M}{P_D}{r_d}^\alpha\right)\mathcal{L}_{I_{d,i,j}^{WiFi}}^D\left(\frac{M}{P_D}{r_d}^\alpha\right), \end{aligned}$$

where $M = 2^{R_u^D/B_U} - 1$. More specifically, according to (22), $\mathcal{L}_{I_{D,j}^{D2D}}^D\left(\frac{M}{P_D}{r_d}^\alpha\right)$ can be derived as

$$\begin{aligned} \mathcal{L}_{I_{D,j}^{D2D}}^D\left(\frac{M}{P_D}{r_d}^\alpha\right) &= \mathbb{E}\left[e^{-\frac{M}{P_D}{r_d}^\alpha \sum\limits_{d_k^{DT} \in \Psi_{DT}^{act}} \frac{P_D g_k^D}{\left\|d_j^{DR} - d_k^{DT}\right\|^\alpha}}\right] \\ &= \exp\left[-\lambda_D p_D^{act}\int_0^{2\pi}\int_{x_D}^\infty \frac{M{r_d}^\alpha \mathcal{H}^{-\frac{\alpha}{2}}\left(x,\theta,r_d\right)x}{1 + M{r_d}^\alpha \mathcal{H}^{-\frac{\alpha}{2}}\left(x,\theta,r_d\right)}dxd\theta\right]. \end{aligned} \qquad (28)$$

where $\mathcal{H}\left(x,\theta,r_d\right) = x^2 + {r_d}^2 - 2xr_d\cos\theta$ is the same with (18). In addition, $\mathcal{L}_{I_{D,j}^{WiFi}}^D\left(\frac{M}{P_D}{r_d}^\alpha\right)$ is given by

$$\begin{aligned} \mathcal{L}_{I_{D,j}^{WiFi}}^D\left(\frac{M}{P_D}{r_d}^\alpha\right) &= \mathbb{E}\left[e^{-\frac{M}{P_D}{r_d}^\alpha \sum\limits_{a_k^{AP} \in \Psi_W^{act}} \frac{P_A g_k^W}{\left\|d_j^{DR} - a_k^{AP}\right\|^\alpha}}\right] \\ &= e^{-\lambda_W p_W^{act}\int_0^{2\pi}\int_{x_W}^\infty \frac{\mathcal{H}^{-\frac{\alpha}{2}}\left(x,\theta,r_d\right)x}{\frac{P_D}{P_A M{r_d}^\alpha} + \mathcal{H}^{-\frac{\alpha}{2}}\left(x,\theta,r_d\right)}dxd\theta}, \end{aligned} \qquad (29)$$

Note that the PDF of r_d is $f_{r_d}\left(r\right) = \frac{2r}{{R_D}^2}, 0 \leqslant r \leqslant R_D$, and then we have

$$O_j^D = 1 - \int_0^{R_D} O_j^D\left(r\right)f_{r_d}\left(r\right)dr, \qquad (30)$$

It can be observed that the outage probability of LTE-U D2D increases with the required data rate R_u^D, when the unlicensed bandwidth is given.

VII. CONCLUSIONS

In this paper, we evaluate the performance of the large-scale complex networks where D2D communications utilize LTE-Unlicensed band. Medium access probability for each device is characterized by considering the energy detection mechanism before transmission. More importantly, we study the dynamic power control at LTE-U D2D transmitter in order to guarantee the receiver's QoS requirement, and a tractable approach to estimate the aggregated interference is provided. In addition, the spectral efficiency of WiFi user is derived to show the impacts of LTE-U D2D on the WiFi networks, together with the outage probability of D2D communications.

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