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Interference Management in In-band D2D Underlaid Cellular Networks

Junnan Yang, Student Member, IEEE, Ming Ding, Senior Member, IEEE, Guoqiang Mao, Fellow, IEEE, Zihuai Lin, *Senior Member*

***Abstract*—Recently, it has been standardized by the 3rd Generation Partnership Project (3GPP) [1] that device-to-device (D2D) communications should use uplink resources when coexisting with conventional cellular communications. With uplink resource sharing, both cellular and D2D links cause significant co-channel interference. In this paper, we address the critical issue of interference management in the network considering a practical path loss model incorporating both line-of-sight (LoS) and non-line-of-sight (NLoS) transmissions. To reduce the severe interference caused by active D2D links, we consider a mode selection scheme based on the maximum received signal strength (MRSS) for each user equipment (UE) to control the D2D-to-cellular interference. Furthermore, we analyze the performance in terms of the coverage probability and the area spectral efficiency (ASE) for both the cellular network and the D2D one. Analytical results are obtained and the accuracy of the proposed analytical framework is validated through Monte Carlo simulations. Through our theoretical and numerical analyses, we quantify the performance gains brought by D2D communications in cellular networks and we find an optimum mode selection threshold β to maximize the total ASE in the network. This insight is expected to provide a design guideline for D2D mode selections.**

***Index Terms*—Device-to-Device, Inter-cell interference (ICI), Interference management, Line-of-sight (LoS), Non-line-of-sight (NLoS), Coverage probability, Area spectral efficiency (ASE).**

I. Introduction

Driven by the 5-th generation (5G) of wireless user equipment (UE), mobile data traffic and network load are increasing in an exponential manner, and are straining current cellular networks to a breaking point [2]. To deal with such monumental consumer requirement for information communications, several notable technologies have been proposed [3], such as dynamic TDD [4], small cell networks (SCNs), cognitive radio, device-to-device (D2D) communications, etc. D2D communications allow direct information transfer between a pair of neighboring mobile UEs. Because of the inadequate communication distance between such pairs of D2D UEs, D2D communications hold in great promise enhancing network performance like the coverage, spectral efficiency, energy efficiency and so on [5].

The orthogonal frequency division multiple access (OFDMA) based D2D communications adopt two types of spectrum that shares approaches in the 5G networks' standardization, (i) in-band (e.g., using cellular spectrum) or (ii) out-band (e.g., unlicensed spectrum). In particular, in the in-band D2D communications, D2D users can set their communications up in an underlay or overlay manner. More specifically, in an underlying setting, D2D users get to the same spectrum of cellular users (CUs) while in overlay, D2D users get to a dedicated proportion of cellular spectrum [6]. The major challenge in the in-band D2D-underlaid cellular network is the existence of inter-tier and intra-tier interference due to the aggressive frequency reuse, where cellular UEs and D2D UEs share the same spectrum. It is essential to design an effective interference management scheme to control the interference generated by the D2D links to the cellular links, and vice versa. In the uplink of LTE/LTE-A system, the interference scenario is complex when we are reusing the frequency sub-band. The network adopts the overload indicator (OI) method, in more details, a BS measures the intensity of uplink interference on each frequency sub-band caused by UEs from adjacent BSs first. In a case when the interference exceeds a predetermined threshold, the BS will note that an event of interference overload has occurred. Then, the BS will broadcast an overload indicator (OI) control signaling to all BSs through backhaul communication links [7].

In this paper, we show a novel mode selection scheme that is based on the maximum received signal strength for each user equipment (UE) to manage the interference. Such maximum that is received signal strength based mode selection scheme is more realistic than the distance-based mode selection in most existent researches as in practice it is imaginable that the strongest received signal strength is not connected with the nearest BS but the one with the minimum path loss with a line-of-sight (LoS) connection. In more detail, a UE will operate in a cellular mode if its received signal strength from the strongest base station (BS) is larger than a threshold β; otherwise, it will operate in a D2D mode. This will mitigate the potential overlarge interference from the D2D links to the cellular links. To analyze the proposed interference control scheme, we develop a theoretical framework that takes power control, practical path loss model and lognormal fading into account.

Furthermore, the path loss models of cellular connections and D2D connections in a D2D-enabled cellular network are dissimilar owning to the distinction in the positions and the heights of transmitters [8]. Everyone knows that LoS transmission may happen while the distance between a receiver and a transmitter is small-scale, and non-line-of-sight (NLoS) transmission is usual in office surroundings and in key com-

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merce areas. Moreover, when the distance between a receiver and a transmitter declines, the probability that a LoS route occurs between them grows, thereby leading to a transition from NLoS transmission to LoS transmission with a higher probability. Because of the proximity between D2D users, it is expected that the forcible channels which make D2D communications up will be complex, undergoing both LoS and NLoS circumstances throughout these pairs, which are clearly dissimilar from traditional cellular environments [9].

To the best of our knowledge, there have been no researches investigating the interference management in the D2D-Enhanced cellular networks applying mode selection scheme basing on the strongest received signal strength. A distinction is shown by our analysis on the network performance while in the light of Lognormal shadow fading and dissimilar path loss models for the D2D connections and the cellular connections respectively, which captures the dissimilar environmental circumstances D2D connections and cellular connections operate in.

Compared with the existing work, the main contributions of this paper are:

- We investigate a general D2D-enhanced network performance in which UEs can adaptively switch between conventional cellular UEs and D2D UEs. In most previous studies, the authors have considered D2D receiver UEs as an additional tier of nodes, independent of the cellular UEs and the D2D transmitter UEs. In our study, cellular UEs, D2D transmit UEs and D2D receiver UEs constitute the entire UE set, which is a more practical assumption than dropping more UEs for D2D reception only.
- A tractable interference management scheme is proposed based on the mode selection method for each user equipment (UE) to control the co-channel interference. A UE will specifically operate in a cellular mode if its received signal strength from the strongest base station (BS) is larger than a threshold; differently, it will perform an operation in a D2D mode. Potential large interference is mitigated by such an interference management scheme from D2D transmitter to the cellular network.
- We present a general analytic framework using intensity matching approach. Based on the proposed model which incorporating interference management, LOS/NLOS transmission and shadow fading, we derive analytical results of coverage probability and ASE for both cellular mode and D2D mode. Our analysis adopts two different path loss models for cellular links and D2D links, respectively. The results show the interference management scheme mitigates the potential overlarge interference from D2D transmitter to the cellular network, and there is an optimum mode selection threshold to achieve the maximum ASE when cellular tier's performance is ensured.

The rest of this paper is structured as follows. Section II provides a brief review of related work. Section III describes the system model. Section IV presents our theoretical analysis on the coverage probability and the area spectral efficiency (ASE) with applications in a 3GPP special case. The numerical and simulations results are discussed in Section V. Our conclusions are drawn in Section VI.

II. Related Work

The implementation of Device-to-device (D2D) communications underlying cellular networks is a promising approach to offload cellular traffic and avoid congestion in the core network [5]. Stochastic geometry, which is accurate in modeling irregular deployment of base stations and mobile user equipment has been widely used to analyze network performance [10–15]. Andrews, et al. conducted network performance analyses for the downlink (DL) [10] and the uplink (UL) [11] of SCNs, in which UEs and/or BSs were assumed to be randomly deployed according to a homogeneous Poisson point process (HPPP). In [14], the authors developed an analytical framework for the D2D communications underlying cellular network in the DL in terms of the meta distribution of the SIR. Moreover, [15] introduced a self-organized D2D clustering scheme to relieve the congestion on the resources using the stochastic geometry.

On the other hand, as one of the fundamental issue in the D2D communication system, the interference's management has been analyzed in the literature [16–22]. Transmission power control [17, 18, 22, 23], distance-based mode selection [19, 24] and a guard zone interference control scheme [16, 20, 21] have been proposed to sort this issue out.. Specifically, in [22], the authors proposed a power control algorithm to manage the co-channel interference in which worldwide channel state information is needed at BSs. In [19], the authors provided a unified framework to manage the interference in a multi-channel surroundings with Rayleigh fading, where D2D UEs were chose based on the average received signal strength from the closest BS, which correspond to a distance-based selection. These two references [19, 22] only considering the signal power and a single slope path loss model which do not distinguish LoS and NLoS, the 'guard zone' only depended on the distance from the transmitter to receiver. Turn to the the reference [16, 20, 21], they not only consider the power strength of the signal or single slope pathloss model. In [16], the authors proposed a δD-interference limited area interference control scheme which is defined as the area in which the ISR (interference signal ratio) is higher than the threshold δD. The shape of the guard zone is based on the threshold δD. In [20], the authors considered both the path loss and the short-term distributions of the signal and interference, and they model the independent short-term distributions of interference as zero-mean complex Gaussian with matched conditional covariances. In [21], the authors proposed guard zone based D2D-activation scheme by enabling the capabilities of BS interference cancellation where the guard zone is defined as a given BS-centric circular ring area. Meanwhile, limited studies have been conducted to consider D2D networks with general fading channels, for example, in [9] and [25], the authors considered generalized fading conditions and analyzed the network performance, while they did not differentiate the path loss models between D2D links and cellular links.

There are several remaining issues, though the existent

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works have provided precious insights into capacity enhancement and interference management for D2D communications:

- In most researches, the authors viewed D2D receiver UEs to be an extra tier of nodes, independent of the D2D transmitter UEs and the cellular UEs. Such tier of D2D receiver UEs without cellular capabilities appears from nowhere and is hard to justify in practice.
- The mode selection schemes in the literature were not very accurate. Pay attention to that in a number of existing works [19, 24], it was assumed that each UE ought to connect to the closest BS and choice operation mode that is based on the distance. However, maximum received signal strength based mode selection scheme is more practical than the distance-based mode selection since in practice it is possible that the strongest received signal strength is not associated with the closest BS but the one with the minimum path loss with a LoS link.

III. System Model

In this part, the D2D communication enhanced cellular network scenario is first explained. We then present the mode selection scheme and the path loss model.

A. Scenario Description

We consider a D2D underlaid UL cellular network, where BSs and UEs, including cellular uplink UEs and D2D UEs, are assumed to be distributed on an infinite two-dimensional plane $\mathbb{R}^{\mathbf{2}}$. We assume that the cellular BSs are spatially distributed according to a homogeneous PPP of intensity λ_b , i.e., $\Phi_b = \{X_i\}$, where X_i denotes the spatial locations of the ith BS. Moreover, the UEs are also distributed in the network region according to another independent homogeneous PPP Φ_u of intensity λ_u.

B. Path Loss Model

We incorporate both NLoS and LoS transmissions into the path loss model. As a special case to show our analytical results, we consider the two-piece path loss and the liner LoS probability functions defined by the 3GPP [6], in which the path loss $\zeta\left(r\right)$, as a function of the distance r, is segmented into 2 pieces written as

$$\zeta\left(r\right) = \begin{cases} \zeta_1\left(r\right), & \text{when } 0 \le r \le d_1 \\ \zeta_2\left(r\right), & \text{when } r > d_1 \end{cases}, \tag{1}$$

where each piece $\zeta_n\left(r\right), n \in \{1, 2\}$ is modeled as

$$\zeta_n\left(r\right)=\begin{cases} \zeta_n^{\mathrm{L}}\left(r\right) = A_L r^{-\alpha_n^{\mathrm{L}}}, & \text{LoS} \\ \zeta_n^{\mathrm{NL}}\left(r\right) = A_{NL} r^{-\alpha_n^{\mathrm{NL}}}, & \text{NLoS} \end{cases}, \tag{2}$$

where

- $\zeta_n^{\mathrm{L}}\left(r\right)$ and $\zeta_n^{\mathrm{NL}}\left(r\right), n \in \{1, 2\}$ are the n-th piece path loss functions for the LoS transmission and the NLoS transmission, respectively,
- A_L and A_{NL} are the path losses at a reference distance $r = 1$ for the LoS and the NLoS cases, respectively,
- α_n^{L} and α_n^{NL} are the path loss exponents for the LoS and the NLoS cases, respectively.

In practice, A_L, A_{NL}, α_n^{L} and α_n^{NL} are constants obtainable from field tests and continuity constraints [26]. The adopted linear LoS probability function is very useful because it can include other LoS probability functions as its special cases [8].

Moreover, we adopt two different path loss models for cellular links as

$$\zeta_B\left(r\right)=\begin{cases} A_{BL} r^{-\alpha_{BL}}, & \text{LoS Probability: } \Pr_B^{\mathrm{L}}\left(r\right) \\ A_{BN} r^{-\alpha_{BN}}, & \text{NLoS Probability: } 1-\Pr_B^{\mathrm{L}}\left(r\right) \end{cases}, \tag{3}$$

together with a linear LoS probability function as follows [6],

$$\Pr_B^{\mathrm{L}}\left(r\right) = \begin{cases} 1-\frac{r}{d_B} & 0 < r \le d_B \\ 0 & r > d_B \end{cases}, \tag{4}$$

where 'BL' and 'BN' represent the cellular links between BS and cellular UE with LoS and NLoS links. Parameters $A_{BL} = 10^{-3.08}$, $A_{BN} = 10^{-0.27}$, $\alpha_{BL} = 2.42$, $\alpha_{BN} = 4.28$.

For D2D links,

$$\zeta_D\left(r\right)=\begin{cases} A_{DL} r^{-\alpha_{DL}}, & \text{LoS Probability: } \Pr_D^{\mathrm{L}}\left(r\right) \\ A_{DN} r^{-\alpha_{DN}}, & \text{NLoS Probability: } 1-\Pr_D^{\mathrm{L}}\left(r\right) \end{cases}, \tag{5}$$

and

$$\Pr_D^{\mathrm{L}}\left(r\right) = \begin{cases} 1-\frac{r}{d_D} & 0 < r \le d_D \\ 0 & r > d_D \end{cases}, \tag{6}$$

where 'DL' and 'DN' represent the D2D links between D2D transmitter and D2D receiver with LoS and NLoS links. Where d_B and d_D is the cut-off distance of the LoS link for UE-to-BS links and UE-to-UE links.

C. User Mode Selection Scheme

We assume two modes for UEs in the considered D2D-enabled UL cellular network namely the cellular mode and the D2D mode. Each UE is assigned with an operation mode pursuant to the maximum received DL power's comparison from its serving BS with a threshold. It is worth noting that using the downlink power for mode selection is an approximate method. Using the uplink signal as a test signal will be more accurate. However, the performance analysis of the uplink link which is UE to BS communication is particularly challenging because the UL power control mechanism operates according to the random UE positions in the network, which is quite different from the constant power setting in the DL. Moreover, implementing power control requires knowledge of the channel quality of the link. If all users sending test signals at the same time, it will cause the user of the cell edge to be easily ignored.

So, we formulate the regarded user mode selection criterion as

$$Mode = \begin{cases} \text{Cellular}, & \text{if } P^* = \max\limits_{\Phi_b}\left\{P_{\Phi_b}^{\mathrm{rx}}\right\} > \beta \\ \text{D2D}, & \text{otherwise} \end{cases}, \tag{7}$$

where the string variable $Mode$ takes the value of 'Cellular' or 'D2D' to denote the cellular mode and the D2D mode, respectively. P^{rx} is the received signal strength from a BS.

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In particular, for a tagged UE, if P^* is larger than a specific threshold $\beta > 0$. This UE is not appropriate to work in the D2D mode due to its potentially large interference to cellular UEs. Hence, it should operate in the cellular mode and directly connect with the strongest BS; otherwise, it should operate in the D2D mode. For a D2D UE, we adopt the same assumption in [19] that it randomly takes the role of a D2D transmitter (TU) or a D2D receiver (RU) with equal probability at the beginning of each time slot, and each D2D receiver UE selects the strongest D2D transmitter UE for its signal reception, with one D2D receiver only allowed to connect with one D2D transmitter. The UEs which are associated with cellular BSs are referred to as cellular UEs (CUs). The distance from a CU to its associated BS is denoted by R_B. From [18], we assume CUs are distributed following a non-homogeneous PPP Φ_c. Such maximum received signal strength based mode selection scheme is more practical than the distance-based mode selection in most existing studies because in practice it is possible that the strongest received signal strength is not associated with the closest BS but the one with the minimum path loss with a LoS link.

So, we adopt the TDD protocol for this system and formulate the regarded user mode selection criterion as

$$P_b^{\rm rx} = \begin{cases} A_{BL} P_B \mathcal{H}_{\rm B}\left(b\right) R_B^{-\alpha_{BL}} & \text{LoS} \\ A_{BN} P_B \mathcal{H}_{\rm B}\left(b\right) R_B^{-\alpha_{BN}} & \text{otherwise} \end{cases}, \tag{8}$$

where $A_{BL} = 10^{\frac{1}{10} A_{BL}^{\rm dB}}$ and $A_{BN} = 10^{\frac{1}{10} A_{BN}^{\rm dB}}$ denote a constant determined by the transmission frequency for BS-to-UE links in LoS and NLoS conditions, respectively. P_B is the transmission power of a BS, $\mathcal{H}_{\rm B}\left(b\right)$ is the lognormal shadowing from a BS b to the typical UE. Base on the above system model, we can obtain the intensity of CU as $\lambda_c = q\lambda_u$, where q denotes the probability of $P^* > \beta$ and will be derived in closed-form expressions in Section IV. It is apparent that the D2D UEs are distributed as a point process Φ_d, the intensity of which is $\lambda_d = \left(1-q\right)\lambda_u$. Considering that a required content file might not exist in a D2D transmitter, in reality, we assume that $\rho\%$ D2D transmitters possess the required content files and deliver them to D2D receivers. In other words, $\rho\%$ of the D2D links will eventually work in one time slot. The value of is related to the social network interest and the type of dissemination content. Base on [27], we adopt $\rho = 10\%$ in this paper.

There is no intra-cell interference between cellular UEs since we assume an orthogonal multiple access technique in a BS. Here, we consider a fully loaded network with $\lambda_u \gg \lambda_b$, so that on each time-frequency resource block, each BS has at least one active UE to serve in its coverage area. Note that the case of $\lambda_u < \lambda_b$ is not trivial, which even changes the capacity scaling law [28]. In this paper, we focus on the former case, and leave the study of $\lambda_u < \lambda_b$ as our future work. Generally speaking, the active CUs can be treated as a thinning PPP Φ_c with the same intensity λ_b as the cellular BSs.

Moreover, we assume a channel inversion strategy for the power control which has been standardized in 4G [6]for cellular UEs. As a result, the received signal at the BS will be a constant, we will use the results when we calculate the coverage probability of the network rather than the mode selection.

$$P_{c_i} = \begin{cases} P_0 \left(\frac{\rm R_i^{\alpha BL}}{\mathcal{H}_{\rm B}({\rm c_i}){\rm A_{BL}}}\right)^{\varepsilon} & \text{LoS} \\ P_0 \left(\frac{\rm R_i^{\alpha BN}}{\mathcal{H}_{\rm B}({\rm c_i}){\rm A_{BN}}}\right)^{\varepsilon} & \text{otherwise} \end{cases}, \tag{9}$$

where P_{c_i} is the transmission power of the i-th UE in cellular link, R_i is the distance of the i-th link from a CU to the target BS, $\mathcal{H}_{\rm B}\left(c_i\right)$ is the lognormal shadowing between target BS and the i-th cellular UE, $\varepsilon \in \left(0,1\right]$ is the fractional path loss compensation, P_0 is the receiver sensitivity. For downlink BS and D2D transmitters, they use constant transmit powers P_B and P_d, respectively. This is too difficult for the UE to evaluate the position and the channel information. So, on the D2D side, we did not use power control. Using the constant power for D2D transmission has also been standardized in the industry [29]. Besides, we denote the additive white Gaussian noise (AWGN) power by σ^2.

D. Performance Metrics

We define the coverage probability as a probability that a receiver's signal-to-interference-plus-noise ratio (SINR) is above a pre-designated threshold γ [10]:

$$p_{\rm Mode}^{\rm cov}\left(\lambda_{\rm Mode}, \alpha_{\rm Mode}\right) = \Pr\left[{\rm SINR} > \gamma\right], \tag{10}$$

where γ is the SINR threshold, the subscript string variable $Mode$ takes the value of 'Cellular' or 'D2D'. The interference in this paper consists of the interference from both cellular UEs and D2D transmitters.

Furthermore, the area spectral efficiency in bps/Hz/km^2 can be formulated as

$$\begin{aligned} & A_{Mode}^{\rm ASE}\left(\lambda_{Mode}, \gamma_0\right) \\ & = \lambda_{Mode} \int_{\gamma_0}^{\infty} \log_2\left(1+x\right) f_X\left(\lambda_{Mode}, \gamma_0\right) dx, \end{aligned} \tag{11}$$

where γ_0 is the minimum working SINR for the considered network, and $f_X\left(\lambda_{Mode}, \gamma_0\right)$ is the probability density function (PDF) of the SINR observed at the typical receiver for a particular value of λ_{Mode}. Based on the definition of $P_{Mode}\left(\lambda_{\rm Mode}, \alpha_{\rm Mode}\right)$, which is the complementary cumulative distribution function (CCDF) of SINR, $f_X\left(\lambda_{Mode}, x\right)$ can be computed as

$$f_X\left(\lambda_{Mode}, x\right) = \frac{\partial\left(1 - p_{\rm Mode}^{\rm cov}\left(x, \lambda_{Mode}, \alpha_{\rm Mode}\right)\right)}{\partial x} \tag{12}$$

For the whole network consisting of both cellular UEs and D2D UEs, the sum ASE can be written as

$$A^{\rm ASE} = A_{\rm Cellular}^{\rm ASE} + A_{\rm D2D}^{\rm ASE}. \tag{13}$$

In order to make the paper more clearly, the notations are summarized in Table I.

IV. Main Results

In this section, UEs' performance is characterized in terms of their coverage probability and ASE both for the D2D tier and the cellular tier. The percentage of UE that operates in the cellular mode is derived in Section IV-A, the coverage probabilities of cellular UE and D2D UE are derived in Section IV-B1 and Section IV-B2, respectively.

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Table I
NOTATIONS

Notations	Meaning
p_c^{cov}	The coverage probability of the cellular tier
λ_B	The density of the BSs
P_B	The transmit powers of BSs
P_{Mode}	P_{c_i} for the cellular UE and P_D for the D2D UE
$p_{\text{D2D}}^{\text{cov}}$	The coverage probability of the D2D tier
λ_u	The density of the UEs
P_d	The transmit powers of UEs

A. Percentage of UE operating in the cellular mode

In this subsection, we present our results on the percentage of UE operating in the cellular mode and the equivalence distance distributions in the cellular mode and D2D mode, respectively. To obtain the probability of UE operate in the cellular mode, we first choose a UE as the typical UE, using the method of stochastic geometry, we can get the probability that a generic mobile UE registers to the strongest BS and operates in cellular mode.

Due to the consideration of lognormal shadowing in this mode we use the intensity equivalence method in [30] to first obtain an equivalent network for further analysis. In particular, we transform the original PPP with lognormal shadowing to an equivalent PPP which has the matched intensity measure and intensity. More specifically, define $\overline{R}_i^{BL} = \mathcal{H}_{\text{B}}^{-1/\alpha_{\text{BL}}} R_i^{BL}$ and $\overline{R}_i^{BN} = \mathcal{H}_{\text{B}}^{-1/\alpha_{\text{BN}}} R_i^{BN}$, where R_i^{BL} and R_i^{BN} are the distance separating a typical user from its tagged strongest base station with LoS and NLoS. $\overline{R}_i^{BL}$ and $\overline{R}_i^{BN}$ is the equivalent distance separating a typical user from its tagged nearest base station in the new PPP with a LoS or NLoS link. $\mathcal{H}_B$ is the lognormal shadowing between target BS and the UE.

The network consists of two non-homogeneous PPPs with intensities $\lambda p^{NL}(R_i)$ and $\lambda p^{L}(R_i)$, which representing the sets of NLoS and LoS links respectively. Each UE is associated with the strongest transmitter. Moreover, intensities $\lambda^{NL}(\cdot)$ and $\lambda^{L}(\cdot)$ are given by

$$\lambda^{NL}(t) = \frac{d}{dt}\Lambda^{NL}\left([0,t]\right) \tag{14}$$

and

$$\lambda^{L}(t) = \frac{d}{dt}\Lambda^{L}\left([0,t]\right) \tag{15}$$

respectively, where

$$\Lambda^{NL}\left([0,t]\right) = \mathbb{E}_{\mathcal{H}_\mathcal{B}}\left[2\pi\lambda_b\int_0^{t(\mathcal{H}_\mathcal{B})^{1/\alpha_{BN}}} p^{NL}(r)rdr\right] \tag{16}$$

and

$$\Lambda^{L}\left([0,t]\right) = \mathbb{E}_{\mathcal{H}_\mathcal{B}}\left[2\pi\lambda_b\int_0^{t(\mathcal{H}_\mathcal{B})^{1/\alpha_{BL}}} p^{L}(r)rdr\right]. \tag{17}$$

Similar definitions are adopted to D2D tier as well. The transformed network has the exact same performance for the typical receiver (BS or D2D RU) on the coverage probability with the original network. In the following, we present our first result in Lemma 1, which will be used in the later analysis of the coverage probability.

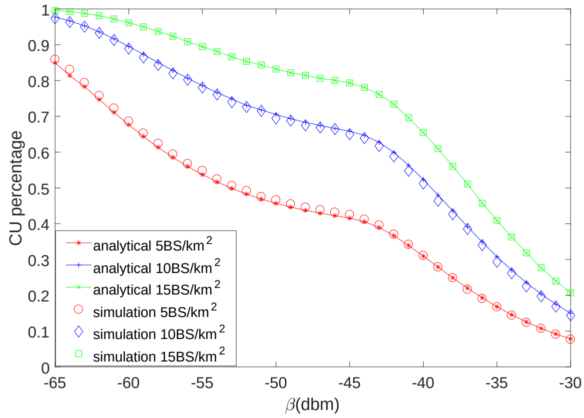

Figure 1. The probability for a UE to operate in the cellular mode vary the RSS threshold β , $\text{P}_B = 46$dBm

Lemma 1. *The percentage of typical UE operates in the cellular mode q is given by*

$$q = 1 - \exp\left[-\mathbb{E}_{\mathcal{H}_\mathcal{B}}\left[2\pi\lambda_b\int_0^{\left(\frac{P_B A_{BL}\mathcal{H}_\mathcal{B}}{\beta}\right)^{1/\alpha_{BL}}} p^{L}(r)rdr\right]\right.$$
$$\left. - \mathbb{E}_{\mathcal{H}_\mathcal{B}}\left[2\pi\lambda_b\int_0^{\left(\frac{P_B A_{BN}\mathcal{H}_\mathcal{B}}{\beta}\right)^{1/\alpha_{BN}}} p^{NL}(r)rdr\right]\right], \tag{18}$$

and the percentage that the UE operating in the D2D mode is $(1-q)$.

Proof: See Appendix A. ∎

Note that Eq.(18) explicitly account for the effects of shadow fading, pathloss, transmit power, spatial distribution of BSs and mode selection threshold β . From the result, one can see that the HPPP ϕ_u can be divided into two point processes: the PP with intensity $q\lambda_u$ and the PP with intensity $(1-q)\lambda_u$. Same as in [18, 19], We assume the two PPs which representing cellular UEs and D2D UEs are independent.

Fig.1 illustrates the probability for a UE to operate in the cellular mode based on Eq.(18). From Fig.1, we can find that the value increases by approximately to -37 dBm and -35 dBm when the BS intensity is 10BS/km^2 and 15BS/km^2, respectively. It indicates that the percentage of CUs will increase as the BS intensity grows.

B. Coverage probability

In this subsection, we investigate the coverage probability that a receiver's signal-to-interference-plus-noise ratio (SINR) is above a pre-designated threshold γ:

$$p_{\text{Mode}}^{\text{cov}}\left(\lambda_{\text{Mode}}, \gamma\right) = \Pr\left[\text{SINR} > \gamma\right] \tag{19}$$

where γ is the SINR threshold, the subscript string variable $Mode$ takes the value of 'Cellular' or 'D2D'. The SINR can be calculated as

$$\text{SINR} = \frac{P_{Mode}\zeta_{Mode}\left(r\right)\mathcal{H}_{Mode}}{I_{cellular} + I_{d2d} + N_0}, \tag{20}$$

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where $\mathcal{H}_{\mathrm{Mode}}$ is the lognormal shadowing between transmitter and receiver in cellular mode or D2D mode. P_B, P_d and N_0 are the transmission power of each cellular and D2D UE transmitter and the additive white Gaussian noise (AWGN) power at each receiver, respectively.

1) Coverage probability of cellular mode: Based on the path loss model in Eq.(3) and the equivalence method in subsection IV-A, we present our main result on $p_c^{\mathrm{cov}}(\lambda,\gamma)$ in Theorem 2.

Theorem 2. *For the typical BS which is located at the origin, considering the path loss model in Eq.(3) and the equivalence method, the coverage probability $p_c^{\mathrm{cov}}(\lambda,\gamma)$ can be derived as*

$$p_c^{\mathrm{cov}}(\lambda,\gamma) = T_c^{\mathrm{L}} + T_c^{\mathrm{NL}}, \tag{21}$$

where

$$T_c^{\mathrm{L}} = \int_0^{t_{LoS}} \left(\int_{-\infty}^{\infty} \left[\frac{1-\mathrm{e}^{-\mathrm{i}\omega/\gamma}}{2\pi\mathrm{i}\omega} \right] \mathcal{F}_{\frac{1}{\mathrm{SINR}^{\mathrm{L}}}}(\omega)d\omega \right) \times f_{\overline{R_{LCU}}}(r)dr \tag{22}$$

and

$$T_c^{\mathrm{NL}} = \int_0^{t_{NLoS}} \left(\int_{-\infty}^{\infty} \left[\frac{1-\mathrm{e}^{-\mathrm{i}\omega/\gamma}}{2\pi\mathrm{i}\omega} \right] \mathcal{F}_{\frac{1}{\mathrm{SINR}^{\mathrm{NL}}}}(\omega)d\omega \right), \times f_{\overline{R_{NLCU}}}(r)dr \tag{23}$$

$$t_{LoS} = \left(\frac{\beta}{P_B A_{BL}} \right)^{-1/\alpha_{BL}} \tag{24}$$

and

$$t_{NLoS} = \left(\frac{\beta}{P_B A_{BN}} \right)^{-1/\alpha_{BN}}, \tag{25}$$

$f_{\overline{R_{LCU}}}(r)$ and $f_{\overline{R_{NLCU}}}(r)$, are represented by

$$f^{\mathrm{L}}_{\overline{R_{LCU}}}(r) = \exp\left(-\int_0^{\overline{r_1}} \left(\mathrm{Pr}^{\mathrm{NL}}(u)\right) \lambda_B^{NL}(u)du \right) \times \exp\left(-\int_0^{r} \mathrm{Pr}^{\mathrm{L}}(u)\, \lambda_B^{L}(u)du \right) \times \mathrm{Pr}^{\mathrm{L}}(r)\, \lambda_B^{L}(r)/q \tag{26}$$

and

$$f^{\mathrm{NL}}_{\overline{R_{NLCU}}}(r) = \exp\left(-\int_0^{\overline{r_2}} \mathrm{Pr}^{\mathrm{L}}(u)\, \lambda(u)du \right) \times \exp\left(-\int_0^{r} \left(\mathrm{Pr}^{\mathrm{NL}}(u)\right) \lambda_B^{NL}(u)du \right) \times \mathrm{Pr}^{\mathrm{NL}}(r)\, \lambda_B^{NL}(r)/q \tag{27}$$

where $\overline{r_1}$ and $\overline{r_2}$ are given implicitly by the following equations as

$$\overline{r_1} = \arg_{\overline{r_1}} \left\{ \zeta^{\mathrm{NL}}(\overline{r_1}) = \zeta_n^{\mathrm{L}}(\overline{r}) \right\} \tag{28}$$

and

$$\overline{r_2} = \arg_{\overline{r_2}} \left\{ \zeta^{\mathrm{L}}(\overline{r_2}) = \zeta_n^{\mathrm{NL}}(\overline{r}) \right\}. \tag{29}$$

In addition, $\mathcal{F}_{\frac{1}{SINR^L}}(\omega)$ and $\mathcal{F}_{\frac{1}{SINR^{NL}}}(\omega)$ are respectively computed by follows.

$\mathcal{F}_{\frac{1}{SINR^L}}(\omega)$ can be written as three parts, namely $\mathcal{L}_{\mathrm{I_c}}(\omega)$, $\mathcal{L}_{\mathrm{I_d}}(\omega)$ and $\mathcal{L}_{\mathrm{n}}(\omega)$,

$$\begin{aligned}\mathcal{L}_{\mathrm{I_c}}(\omega) &= \exp\left(\mathrm{i}\omega \frac{\mathrm{I_{CL}}+\mathrm{I_{CN}}}{\mathrm{S^L}} \right) \\ &= \exp\Bigg\{ -\int_r^{\infty} \Bigg(1 - \int_0^{t_{LoS}} \exp\left(\mathrm{i}\omega \frac{\left(\mathrm{z}^{\alpha_{\mathrm{BL}}}\right)^{\varepsilon} \mathrm{v}^{-\alpha_{\mathrm{BL}}}}{\mathrm{A}_{\mathrm{BL}}^{2\varepsilon}\left(\mathrm{r}^{-\alpha^{\mathrm{BL}}}\right)^{1-\varepsilon}} \right) \\ &\quad f_{\overline{R_{LCU}}}(z)dz \Bigg) \lambda_B^L(v)dv \\ &\quad - \int_r^{\infty} \Bigg(1 - \int_0^{t_{LoS}} \exp\left(\mathrm{i}\omega \frac{\left(\mathrm{z}^{\alpha_{\mathrm{BL}}}\right)^{\varepsilon} \mathrm{v}^{-\alpha_{\mathrm{BN}}}}{\mathrm{A}_{\mathrm{BL}}^{2\varepsilon}\left(\mathrm{r}^{-\alpha^{\mathrm{BL}}}\right)^{1-\varepsilon}} \right) \\ &\quad f_{\overline{R_{LCU}}}(z)dz \Bigg) \lambda_B^{NL}(v)dv \Bigg\}\end{aligned} \tag{30}$$

and

$$\begin{aligned}\mathcal{L}_{\mathrm{I_d}}(\omega) &= \exp\left(\mathrm{i}\omega \frac{\mathrm{I_{DL}}+\mathrm{I_{DN}}}{\mathrm{S^L}} \right) \\ &= \exp\Bigg\{ -\int_{t_{LoS}}^{\infty} \left(1 - \exp\left(\mathrm{i}\omega \frac{\mathrm{P_d}\mathrm{A_{BL}}\mathrm{v}^{-\alpha_{\mathrm{BL}}}}{\mathrm{P_0}\left(\mathrm{A_{BL}}\mathrm{r}^{-\alpha^{\mathrm{BL}}}\right)^{1-\varepsilon}} \right) \right) \\ &\quad \lambda_{tu}^{L}(v)dv \\ &\quad - \int_{t_{LoS}}^{\infty} \left(1 - \exp\left(\mathrm{i}\omega \frac{\mathrm{P_d}\mathrm{A_{BN}}\mathrm{v}^{-\alpha_{\mathrm{BN}}}}{\mathrm{P_0}\left(\mathrm{A_{BL}}\mathrm{r}^{-\alpha^{\mathrm{BL}}}\right)^{1-\varepsilon}} \right) \right) \lambda_{tu}^{NL}(v)dv \Bigg\}\end{aligned} \tag{31}$$

and $\mathcal{L}_{\mathrm{n}}(\omega) = \exp\left(\mathrm{iw}\frac{\sigma^2}{\mathrm{P_0}\left(\mathrm{A_{BL}}\mathrm{r}^{-\alpha^{\mathrm{BL}}}\right)^{1-\varepsilon}} \right)$ which are the cellular interference , D2D interference and noise part in characteristic function.

$$\begin{aligned}&\mathcal{F}_{\frac{1}{SINR^{NL}}}(\omega) = \\ &\exp\Bigg\{ -\int_r^{\infty} \Bigg(1 - \int_0^{t_{NLoS}} \exp\left(\frac{\mathrm{i}\omega \mathrm{z}^{\varepsilon\alpha_{\mathrm{BL}}} \mathrm{A_{BL}} \mathrm{v}^{-\alpha_{\mathrm{BL}}}}{\mathrm{A}_{\mathrm{BL}}^{\varepsilon}\left(\mathrm{A_{BN}}\mathrm{r}^{-\alpha^{\mathrm{BN}}}\right)^{1-\varepsilon}} \right) \\ &\times f_{\overline{R_{NLCU}}}(z)dz \Bigg) \lambda_B^L(v)dv \\ &- \int_r^{\infty} \Bigg(1 - \int_0^{t_{NLoS}} \exp\left(\frac{\mathrm{i}\omega \mathrm{z}^{\varepsilon\alpha_{\mathrm{BL}}} \mathrm{A_{BN}} \mathrm{v}^{-\alpha_{\mathrm{BN}}}}{\mathrm{A}_{\mathrm{BL}}^{\varepsilon}\left(\mathrm{A_{BN}}\mathrm{r}^{-\alpha^{\mathrm{BN}}}\right)^{1-\varepsilon}} \right) \\ &\times f_{\overline{R_{NLCU}}}(z)dz \Bigg) \lambda_B^{NL}(v)dv \\ &- \int_{t_{NLoS}}^{\infty} \left(1 - \exp\left(\frac{\mathrm{i}\omega \mathrm{P_d} \mathrm{A_{BL}} \mathrm{v}^{-\alpha_{\mathrm{BL}}}}{\mathrm{P_0}\left(\mathrm{A_{BN}}\mathrm{r}^{-\alpha^{\mathrm{BN}}}\right)^{1-\varepsilon}} \right) \right) \lambda_{tu}^{L}(v)dv \\ &- \int_{t_{NLoS}}^{\infty} \left(1 - \exp\left(\frac{\mathrm{i}\omega \mathrm{P_d} \mathrm{A_{BN}} \mathrm{v}^{-\alpha_{\mathrm{BN}}}}{\mathrm{P_0}\left(\mathrm{A_{BN}}\mathrm{r}^{-\alpha^{\mathrm{BN}}}\right)^{1-\varepsilon}} \right) \right) \lambda_{tu}^{NL}(v)dv \\ &+ \frac{\mathrm{i}\omega\sigma_{\mathrm{c}}^2}{\mathrm{P_0}\left(\mathrm{A_{BN}}\mathrm{r}^{-\alpha^{\mathrm{BN}}}\right)^{1-\varepsilon}} \Bigg\}\end{aligned} \tag{32}$$

It gives general results that can be applied to various multi-path fading or shadowing model, e.g., Rayleigh fading, Nakagami-m fading, etc, and various NLoS/LoS transmission models as well. When the mode selection threshold β increases, we can find the intensity of D2D transmitter also increases. This will reduce the coverage probability performance of cellular tier, so we make $p_c^{\mathrm{cov}} > \delta$ as a condition to guarantee the performance for the cellular mode when choosing β for the optimal system ASE.

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2) Coverage probability of the typical UE in the D2D mode: Alike to the analysis in subsection IV-B1, we concentrate on a typical D2D UE located at the origin o and scheduled to pick up information from another D2D UE. Following Slivnyak's theorem, the coverage probability result derived for the typical D2D UE also holds for any generic D2D UE located at any location.

Theorem 3. *For a typical D2D receiver, the probability of coverage $p_{D2D}^{\mathrm{cov}}(\lambda,\gamma)$ can be derived as*

$$p_{D2D}^{\mathrm{cov}}(\lambda,\gamma) = T_{D2D}^{\mathrm{L}} + T_{D2D}^{\mathrm{NL}}, \tag{33}$$

where

$$T_{D2D}^{\mathrm{L}} = \int_0^{\infty}\left(\int_{-\infty}^{\infty}\left[\frac{1-\mathrm{e}^{-\mathrm{i}\omega/\gamma}}{2\pi\mathrm{i}\omega}\right]\mathcal{F}_{\frac{1}{\mathrm{SINR}_{\mathrm{D2D}}^{\mathrm{L}}}}(\omega)d\omega\right) \times f_{\overline{R_{LD2D}}}(\overline{R_{d,0}})d\overline{R_{d,0}} \tag{34}$$

and

$$T_{D2D}^{\mathrm{NL}} = \int_0^{\infty}\left(\int_{-\infty}^{\infty}\left[\frac{1-\mathrm{e}^{-\mathrm{i}\omega/\gamma}}{2\pi\mathrm{i}\omega}\right]\mathcal{F}_{\frac{1}{\mathrm{SINR}_{\mathrm{D2D}}^{\mathrm{NL}}}}(\omega)d\omega\right) \times f_{\overline{R_{NLD2D}}}(\overline{R_{d,0}})d\overline{R_{d,0}}, \tag{35}$$

$f_{\overline{R_{LD2D}}}(r)$ and $f_{\overline{R_{NLD2D}}}(r)$ can be calculated from cumulative distribution function (CDF) of $\overline{R}_d^{LOS}$ and $\overline{R}_d^{NLOS}$ in appendix C.

In addition, $\mathcal{F}_{\frac{1}{SINR_{D2D}^{L}}}(\omega)$ and $\mathcal{F}_{\frac{1}{SINR_{D2D}^{NL}}}(\omega)$ are respectively computed by

$$\mathcal{F}_{\frac{1}{SINR_{D2D}^{L}}}(\omega) =$$

$$\begin{aligned}
&\exp\Bigg\{-\int_0^{\infty}\Bigg(1-\int_0^{t_{LoS}}\exp\left(\frac{\mathrm{i}\omega \mathrm{P_0}\overline{\mathrm{R}}_{\mathrm{i}}^{\varepsilon\alpha_{\mathrm{BL}}}\mathrm{v}^{-\alpha_{\mathrm{DL}}}}{\mathrm{A}_{\mathrm{BL}}^{\varepsilon}\mathrm{P_d}(\overline{\mathrm{R}_{\mathrm{d,0}}})^{-\alpha_{\mathrm{DL}}}}\right)\\
&\times f_{\overline{R_{LCU}}}(\overline{R}_i)d\overline{R}_i\Bigg)\lambda_B^L(v)dv\\
&-\int_0^{\infty}\Bigg(1-\int_0^{t_{LoS}}\exp\left(\frac{\mathrm{i}\omega \mathrm{P_0}\overline{\mathrm{R}}_{\mathrm{i}}^{\varepsilon\alpha_{\mathrm{BL}}}\mathrm{A_{DN}}\mathrm{v}^{-\alpha_{\mathrm{DN}}}}{\mathrm{A}_{\mathrm{BL}}^{\varepsilon}\mathrm{P_d}\mathrm{A_{DL}}(\overline{\mathrm{R}_{\mathrm{d,0}}})^{-\alpha_{\mathrm{DL}}}}\right)\\
&\times f_{\overline{R_{LCU}}}(\overline{R}_i)d\overline{R}_i\Bigg)\lambda_B^{NL}(v)dv\\
&-\int_r^{\infty}\left(1-\exp\left(\frac{\mathrm{i}\omega\mathrm{v}^{-\alpha_{\mathrm{DL}}}}{(\overline{\mathrm{R}_{\mathrm{d,0}}})^{-\alpha_{\mathrm{DL}}}}\right)\right)\lambda_{tu}^L(v)dv\\
&-\int_r^{\infty}\left(1-\exp\left(\frac{\mathrm{i}\omega\mathrm{A_{DN}}\mathrm{v}^{-\alpha_{\mathrm{DN}}}}{\mathrm{A_{DL}}(\overline{\mathrm{R}_{\mathrm{d,0}}})^{-\alpha_{\mathrm{DL}}}}\right)\right)\lambda_{tu}^{NL}(v)dv\\
&+\frac{\mathrm{i}\omega\sigma_{\mathrm{d}}^2}{\mathrm{P_d}\mathrm{A_{DL}}(\overline{\mathrm{R}_{\mathrm{d,0}}})^{-\alpha_{\mathrm{DL}}}}\Bigg\}
\end{aligned} \tag{36}$$

and

$$\mathcal{F}_{\frac{1}{SINR_{D2D}^{NL}}}(\omega) =$$

$$\begin{aligned}
&\exp\Bigg\{-\int_0^{\infty}\Bigg(1-\int_0^{t_{NLoS}}\exp\left(\frac{\mathrm{i}\omega \mathrm{P_0}\overline{\mathrm{R}}_{\mathrm{i}}^{\varepsilon\alpha_{\mathrm{BL}}}\mathrm{A_{DL}}\mathrm{v}^{-\alpha_{\mathrm{DL}}}}{\mathrm{A}_{\mathrm{BL}}^{\varepsilon}\mathrm{P_d}\mathrm{A_{DN}}(\overline{\mathrm{R}_{\mathrm{d,0}}})^{-\alpha_{\mathrm{DN}}}}\right)\\
&\times f_{\overline{R_{NLCU}}}(\overline{R}_i)d\overline{R}_i\Bigg)\lambda_B^L(v)dv\\
&-\int_0^{\infty}\Bigg(1-\int_0^{t_{NLoS}}\exp\left(\frac{\mathrm{i}\omega \mathrm{P_0}\overline{\mathrm{R}}_{\mathrm{i}}^{\varepsilon\alpha_{\mathrm{BL}}}\mathrm{v}^{-\alpha_{\mathrm{DN}}}}{\mathrm{A}_{\mathrm{BL}}^{\varepsilon}\mathrm{P_d}(\overline{\mathrm{R}_{\mathrm{d,0}}})^{-\alpha_{\mathrm{DN}}}}\right)\\
&\times f_{\overline{R_{NLCU}}}(\overline{R}_i)d\overline{R}_i\Bigg)\lambda_B^{NL}(v)dv\\
&-\int_r^{\infty}\left(1-\exp\left(\frac{\mathrm{i}\omega\mathrm{A_{DL}}\mathrm{v}^{-\alpha_{\mathrm{DL}}}}{\mathrm{A_{DN}}(\overline{\mathrm{R}_{\mathrm{d,0}}})^{-\alpha_{\mathrm{DN}}}}\right)\right)\lambda_{tu}^L(v)dv\\
&-\int_r^{\infty}\left(1-\exp\left(\frac{\mathrm{i}\omega\mathrm{v}^{-\alpha_{\mathrm{DN}}}}{(\overline{\mathrm{R}_{\mathrm{d,0}}})^{-\alpha_{\mathrm{DN}}}}\right)\right)\lambda_{tu}^{NL}(v)dv\\
&+\frac{\mathrm{i}\omega\sigma_{\mathrm{d}}^2}{\mathrm{P_d}\mathrm{A_{DN}}(\overline{\mathrm{R}_{\mathrm{d,0}}})^{-\alpha_{\mathrm{DN}}}}\Bigg\},
\end{aligned} \tag{37}$$

where $A_{DL} = 10^{\frac{1}{10}A_{DL}^{dB}}$ and $A_{DN} = 10^{\frac{1}{10}A_{DN}^{dB}}$ denote a constant determined by the transmission frequency for UE-to-UE links in LoS and NLoS, respectively.

Proof: See Appendix C. ∎

The coverage probability of D2D users is evaluated by Eq.(33). The typical D2D receiver selects the equivalent nearest UE as a potential transmitter. If the potential D2D transmitter is operating in a cellular mode, D2D RU must search for another transmitter. We approximately consider that the second neighbor can be found as the transmitter under this situation both for LoS/NLoS links, the accuracy of this estimate is compared to the simulation results in appendix C. Although the analytical results are complicated, it provides general results that can be applied to various multi-path fading or shadowing models in the D2D-enhanced cellular networks.

V. Simulation and Discussion

In this section, we use numerical results to validate our results and analyze the performance of the D2D-enabled UL cellular network. To this end, we present the simulation parameters, the results for the coverage probability, the results for the area spectral efficiency in Section V-A, V-B, V-D, respectively.

A. Simulation setup

We set the system parameters according to the 3GPP Long Term Evolution (LTE) specifications [29], the BS intensity to $\lambda_b = 5\,\mathrm{BSs/km^2}$, which results in an average inter-site distance of about 500 m. The UE intensity is chosen as $\lambda = 200\,\mathrm{UEs/km^2}$, which is a typical value in 5G [8]. The transmit power of each BS and each D2D transmitter are set to $P_B = 46\,\mathrm{dBm}$ and $P_D = 10\,\mathrm{dBm}$, respectively. Moreover, the threshold for selecting cellular mode communication is $\beta = -70 \sim -30\mathrm{dBm}$. The standard deviation of lognormal shadowing is 8 dB between UEs to BSs and 7 dB between UEs to UEs. The noise powers are set to -95 dBm for a UE receiver and -114 dBm for a BS receiver, respectively. The simulation parameters are summarized in Table II.

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Table II
SIMULATION PARAMETERS

Parameters	Values	Parameters	Values
BW	10MHz	f_c	2GHz
λ_B	5 BSs/km^2	σ_c^2	-95 dBm
λ_u	200 UEs/km^2	σ_d^2	-114 dBm
ε	0.8	P_0	-70 dBm
α_{BL}	2.42	A_{BL}	$10^{-3.08}$
α_{BN}	4.28	A_{BN}	$10^{-0.27}$
α_{DL}	2	A_{DL}	$10^{-3.845}$
α_{DN}	4	A_{DN}	$10^{-5.578}$
P_B	46 dBm	P_d	10 dBm
d_B	0.3km	d_D	0.1km

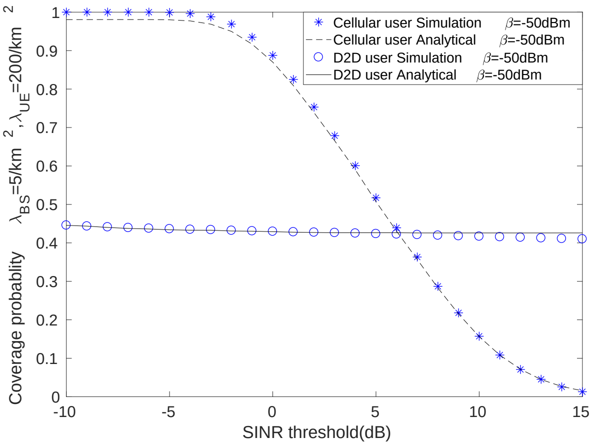

Figure 2. The Coverage Probability $p^{\text{cov}}(\lambda,\gamma)$ vs. SINR threshold ($\lambda_{UE} = 200\,\text{UEs/km}^2$, $\lambda_{BS} = 5\,\text{UEs/km}^2$ and $\rho = 10\%$). The mode select threshold β is -50dBm.

B. Validation of analytical results of $p^{\text{cov}}(\lambda,\gamma)$

In Fig. 2, we plot the results of the coverage probability of cellular tier and D2D tier, we can draw the following observations:

- The analytical results of the coverage probability from Eq.(21) and Eq.(33) match well with the simulation results, which validates our analysis and shows that the adopted model accurately captures the features of D2D communications.
- For the cellular tier, the coverage probability decreases with the increase of SINR threshold because a higher SINR requirement makes it more difficult to satisfy the coverage criterion in Eq.(19).
- The coverage probability reduces very slowly in D2D tier because the signals in most of the successful links are LoS while the interference is most likely NLoS, hence the SINR is relatively large, e.g., well above 15 dB.

To fully study the SINR coverage probability with respect to the values of β , the results of coverage probability with various β and γ_0=0 dB are plotted in Fig 3. From this figure, we can draw the following observations:

- The coverage probability of cellular users increases as β grows from -70 dBm to -57 dBm, which is because a larger β reduces the distance between the typical CU to the typical BS so that the signal link's LoS probability increases. Then, the coverage probability performance decreases because the interference from D2D tier is growing. When we set $\delta = 0.9$, we should choose β no larger than -45 dBm to guarantee the cellular performance.
- In the D2D mode, the coverage probability also increases as β increases from -70 dBm to -60 dBm, this is because the distance between the typical D2D pair UEs decreases while the transmit power is constant. From $\beta = -60$ dBm to $\beta = -45$ dBm, the coverage probability decreases because of the interference from the D2D tier increases. Then, the coverage probability increases when β is larger than -45 dBm because the signal power experience the NLoS to LoS transition while the aggregate interference remains to be mostly NLoS interference.

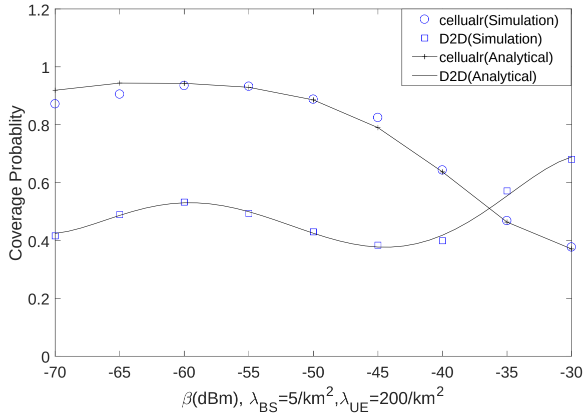

Figure 3. The Coverage Probability $p^{\text{cov}}(\lambda,\gamma)$ vs. β for 3GPP Case 1 ($\gamma_0 = 0\,\text{dB}$, $\lambda_{UE} = 200\,\text{UEs/km}^2$, $\lambda_{BS} = 5\,\text{UEs/km}^2$ and $\rho = 10\%$).

C. Network Performance Without Interference Management

In this subsection, we will show the results in terms of the coverage probability of cellular tier and the D2D tier with and without the proposed interference management scheme. From

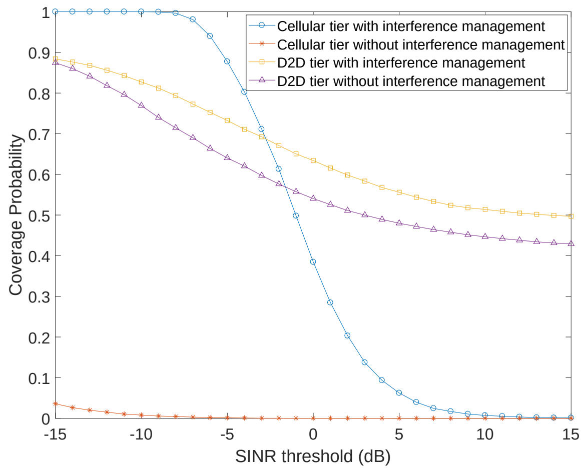

Figure 4. The coverage probability with and without the proposed interference management scheme ($\gamma_0 = 0\,\text{dB}$, $\lambda_{UE} = 300\,\text{UEs/km}^2$, $\lambda_{BS} = 5\,\text{UEs/km}^2$).

Fig.4, we can draw the following observations:

- For the cellular tier, in the absence of the interference management scheme, the coverage probability is almost zero due to interference from the D2D tier.
- For the D2D tier, the interference management scheme also improves coverage probability because this scheme makes D2D UEs more concentrated in location.

D. Discussion on the analytical results of ASE

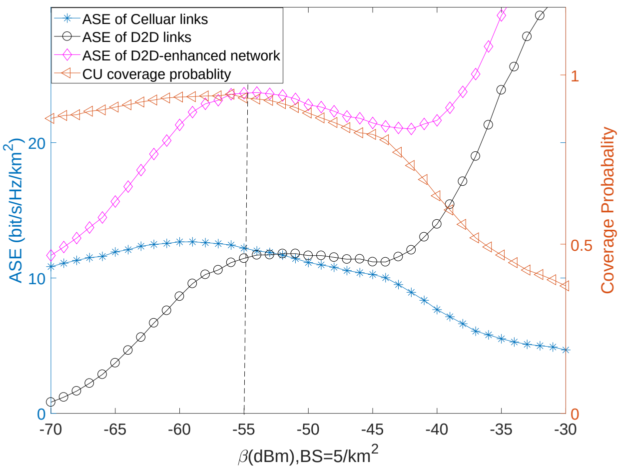

Figure 5. The ASE $A^{\mathrm{ASE}}(\lambda, \gamma_0)$ vs. β for 3GPP Case 1 ($\gamma_0 = 0\,\mathrm{dB}$, $\lambda_{UE} = 200\,\mathrm{UEs/km^2}$, $\lambda_{BS} = 5\,\mathrm{UEs/km^2}$ and $\rho = 10\%$).

In Fig.5, the triangle mark represents coverage probability, and the other three curves represent ASE. The analytical results of ASE with γ_0=0 db vs various β values are shown in Eq.(11). Fig.5 illustrates the ASEs of Cellular links, D2D links and of the whole network with respect to different mode selection thresholds β . From this figure we can draw the following observations:

- The total ASE increases as the D2D links increases when $\beta \in [-70dBm, -55dBm]$ this is because D2D links increase which cellular links keep stable.
- An optimal β around$-$55 dBm can achieve the maximum ASE while the coverage probability of the cellular tier is above 0.9.
- The total ASE decreases when $\beta \in [-55dBm, -42dBm]$, because the D2D links generate more interference which makes the coverage probability of cellular decreases.
- When $\beta \in [-42dBm, -30dBm]$, the additional D2D links make a significant contribution to the ASE performance so that the total ASE grows again. Then, the total ASE approaches that of the D2D ASE because the percentage of D2D UE is approaching 100%, which has been analyzed in Eq.(18). Although the total ASE grows very quickly when $\beta \in [-42dBm, -30dBm]$, the interference from D2D links to the cellular tier remains to be large so that the performance of the cellular tier is poor. Hence, we do not recommend the network operate in this range of β.

From Fig.5 we can find D2D links will increase as β increase for all different densities of BS. In conclusion, there is an optimal beta which can get the optimal ASE of the D2D-enabled cellular while the coverage probability in cellular tier is maximum. The mode selection threshold can control the interference from both cellular tier and D2D tier. D2D tier can bring nearly double ASE for the network when set the optimal threshold for mode selection.

VI. Conclusion

In this paper, we proposed a mode selection method which can eliminate the potential overlarge interferene in a D2D-enhanced uplink cellular network, where the locations of all mobile UEs modeled as a PPP distribution. In particular, each UE selects its operation mode based on its downlink received power and a threshold β. Practical path loss model and slow shadow fading are considered in modeling the power attenuation. This interference management scheme mitigates the potential overlarge interferene from D2D transmitter to the cellular network. Moreover, we analytically evaluated the coverage probability and the ASE for various values of the mode selection threshold β. Our results showed that the D2D links could provide high ASE when the threshold parameter is appropriately chosen. More importantly, we concluded that there exists an optimal β to achieve the maximum ASE while guaranteeing the coverage probability performance of the cellular network. As our future work, we will consider other factors of realistic networks in the theoretical analysis for SCNs, such as practical directional antennas [3].

Appendix A:Proof of Lemma 1

The probability that the RSS is larger than the threshold is given by

$$P = \Pr\left[\max_b \left\{P_b^{\mathrm{rx}}\right\} > \beta\right], \tag{38}$$

where we use the standard power loss propagation model with a path loss exponent α_{BL} (for LoS UE-BS links) and α_{BN} (for NLoS UE-BS links).The probability that a generic mobile UE operates in the cellular mode i

$$\begin{aligned} q &= 1 - \Pr\left[\max_b \left\{P_b^{\mathrm{rx}}\right\} \le \beta\right] \\ &= 1 - \Pr\left[\min \overline{R}_i^{BL} \ge \left(\frac{P_B \mathrm{A}_{BL}}{\beta}\right)^{1/\alpha_{BL}}\right. \\ &\cap \left.\min \overline{R}_i^{BN} \ge \left(\frac{P_B \mathrm{A}_{BN}}{\beta}\right)^{1/\alpha_{BN}}\right] \end{aligned} \tag{39}$$

which means there is no nodes in the disk around the typical UE with a radius $\left(\frac{P_B \mathrm{A}_{BL}}{\beta}\right)^{1/\alpha_{BL}}$ when the link is LoS, and there is no nodes in the disk around the typical UE with a radius $\left(\frac{P_B \mathrm{A}_{BN}}{\beta}\right)^{1/\alpha_{BN}}$ when the link is NLoS. Therefore,

$$\begin{aligned} q =& 1 - \exp\left[-\wedge^{\mathrm{NL}}\left(\left[0, \left(\frac{P_B \mathrm{A}_{BL}}{\beta}\right)^{1/\alpha_{BL}}\right]\right)\right] \\ &\times \exp\left[-\wedge^{\mathrm{L}}\left[0, \left(\frac{P_B \mathrm{A}_{BN}}{\beta}\right)^{1/\alpha_{BN}}\right]\right] \end{aligned}$$

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$$=1-\exp\left[-\mathbb{E}_{\mathcal{H}_{\mathcal{B}}}\left[2\pi\lambda_b\int_0^{\left(\frac{P_B A_{BL}\mathcal{H}_{\mathcal{B}}}{\beta}\right)^{\frac{1}{\alpha_{BL}}}} p^L(r)rdr\right]\right]$$
$$\times\exp\left[-\mathbb{E}_{\mathcal{H}_{\mathcal{B}}}\left[2\pi\lambda_b\int_0^{\left(\frac{P_B A_{BN}\mathcal{H}_{\mathcal{B}}}{\beta}\right)^{\frac{1}{\alpha_{BN}}}} p^{NL}(r)rdr\right]\right], \tag{40}$$

which concludes our proof.

APPENDIX B: PROOF OF THEOREM 2

By invoking the law of total probability, the coverage probability of cellular links can be divided into two parts, i.e., $T_c^{\mathrm{L}}+T_c^{\mathrm{NL}}$, which denotes the conditional coverage probability given that the typical BS is associated with a BS in LoS and NLoS, respectively. First, we derive the coverage probability for LoS link cellular tier. Conditioned on the strongest BS being at a distance $R_{B,0}$ from the typical CU, the equivalence distance$\overline{R_{LoSCU}}=\mathcal{H}_{\mathrm{B}}^{-1/\alpha_{\mathrm{BL}}}\mathrm{R}_{\mathrm{B},0}$ $\left(\overline{R_{LoSCU}}\le\left(\frac{\beta}{P_B A^L}\right)^{-1/\alpha_{BL}}\right)$, probability of coverage is given by

$$T^{\mathrm{L}}=\Pr\left[\frac{1}{SINR^L}<\frac{1}{\gamma}|\mathrm{LOS}\right]$$
$$=\int_0^{t_{LoS}}\left(\int_{-\infty}^{\infty}\left[\frac{1-\mathrm{e}^{-\mathrm{i}\omega/\gamma}}{2\pi\mathrm{i}\omega}\right]\mathcal{F}_{\frac{1}{\mathrm{SINR^L}}}(\omega)d\omega\right)f_{\overline{R_{LCU}}}(r)dr$$

where $i=\sqrt{-1}$ is the imaginary unit. The inner integral is the conditional PDF of $\frac{1}{SINR}$; The intensity of cellular UEs and D2D UEs can be calculated as

$$\lambda_B^L(t)=2\pi\lambda_b\frac{d\left(\mathbb{E}_{\mathcal{H}_{\mathcal{B}}}\left[\int_0^{t(\mathcal{H}_{\mathcal{B}})^{\frac{1}{\alpha_{BL}}}}\Pr^L(r)rdr\right]\right)}{dt} \tag{41}$$

and

$$\lambda_B^{NL}(t)=2\pi\lambda_b\frac{d\left(\mathbb{E}_{\mathcal{H}_{\mathcal{B}}}\left[\int_0^{t(\mathcal{H}_{\mathcal{B}})^{\frac{1}{\alpha_{BN}}}}\Pr^{NL}(r)rdr\right]\right)}{dt} \tag{42}$$

and

$$\lambda_{tu}^L(t)=\frac{d\left(\mathbb{E}_{\mathcal{H}_{\mathcal{D}}}\left[\pi(1-q)\lambda_u\int_0^{t(\mathcal{H}_{\mathcal{D}})^{\frac{1}{\alpha_{DL}}}}\Pr^L(r)rdr\right]\right)}{dt} \tag{43}$$

and

$$\lambda_{tu}^{NL}(t)=\frac{d\left(\mathbb{E}_{\mathcal{H}_{\mathcal{D}}}\left[\pi(1-q)\lambda_u\int_0^{t(\mathcal{H}_{\mathcal{D}})^{\frac{1}{\alpha_{DN}}}}\Pr^{NL}(r)rdr\right]\right)}{dt}. \tag{44}$$

$\mathcal{F}_{SINR^{-1}}(\omega)$ denotes the conditional characteristic function of $\frac{1}{SINR}$, which can be written by

$$\mathcal{F}_{\frac{1}{SINR^L}}(\omega)$$
$$=\int_{R^2}f_{\frac{1}{SINR^L}}(x)e^{i\omega x}dx$$
$$=\mathbb{E}_\Phi\left[\exp\left(\mathrm{i}\omega\frac{\mathrm{I_c}}{\mathrm{S^L}}\right)\exp\left(\mathrm{i}\omega\frac{\mathrm{I_d}}{\mathrm{S^L}}\right)\exp\left(\mathrm{i}\omega\frac{\sigma^2}{\mathrm{S^L}}\right)\bigg|R=\overline{r}\right]. \tag{45}$$

where R is the distance from the typical CU to the typical BS. By applying stochastic geometry and the probability generating functional(PGFL) of the PPP. $\mathcal{F}_{\frac{1}{SINR^L}}(\omega)$ can be written as three parts, namely $\mathcal{L}_{\mathrm{I_c}}(\omega)$,$\mathcal{L}_{\mathrm{I_d}}(\omega)$ and $\mathcal{L}_{\mathrm{n}}(\omega)$,

$$\begin{aligned}\mathcal{L}_{\mathrm{I_c}}(\omega)&=\exp\left(\mathrm{i}\omega\frac{\mathrm{I_{CL}}+\mathrm{I_{CN}}}{\mathrm{S^L}}\right)\\&=\exp\Bigg\{-\int_r^\infty\left(1-\int_0^{t_{LoS}}\exp\left(\mathrm{i}\omega\frac{\left(\mathrm{z}^{\alpha_{\mathrm{BL}}}\right)^{\varepsilon}\mathrm{v}^{-\alpha_{\mathrm{BL}}}}{\mathrm{A}_{\mathrm{BL}}^{2\varepsilon}\left(\mathrm{r}^{-\alpha^{\mathrm{BL}}}\right)^{1-\varepsilon}}\right)\right.\\&\quad f_{\overline{R_{LCU}}}(z)dz\Big)\lambda_B^L(v)dv\\&\quad-\int_r^\infty\left(1-\int_0^{t_{LoS}}\exp\left(\mathrm{i}\omega\frac{\left(\mathrm{z}^{\alpha_{\mathrm{BL}}}\right)^{\varepsilon}\mathrm{v}^{-\alpha_{\mathrm{BN}}}}{\mathrm{A}_{\mathrm{BL}}^{2\varepsilon}\left(\mathrm{r}^{-\alpha^{\mathrm{BL}}}\right)^{1-\varepsilon}}\right)\right.\\&\quad f_{\overline{R_{LCU}}}(z)dz\Big)\lambda_B^{NL}(v)dv\Bigg\}\end{aligned} \tag{46}$$

and

$$\begin{aligned}\mathcal{L}_{\mathrm{I_d}}(\omega)&=\exp\left(\mathrm{i}\omega\frac{\mathrm{I_{DL}}+\mathrm{I_{DN}}}{\mathrm{S^L}}\right)\\&=\exp\Bigg\{-\int_{t_{LoS}}^\infty\left(1-\exp\left(\mathrm{i}\omega\frac{\mathrm{P_d}\mathrm{A_{BL}}\mathrm{v}^{-\alpha_{\mathrm{BL}}}}{\mathrm{P_0}\left(\mathrm{A_{BL}}\mathrm{r}^{-\alpha^{\mathrm{BL}}}\right)^{1-\varepsilon}}\right)\right.\\&\quad\lambda_{tu}^L(v)dv\\&\quad-\int_{t_{LoS}}^\infty\left(1-\exp\left(\mathrm{i}\omega\frac{\mathrm{P_d}\mathrm{A_{BN}}\mathrm{v}^{-\alpha_{\mathrm{BN}}}}{\mathrm{P_0}\left(\mathrm{A_{BL}}\mathrm{r}^{-\alpha^{\mathrm{BL}}}\right)^{1-\varepsilon}}\right)\right)\lambda_{tu}^{NL}(v)dv\Bigg\}\end{aligned} \tag{47}$$

and $\mathcal{L}_{\mathrm{n}}(\omega)=\exp\left(\mathrm{iw}\frac{\sigma^2}{\mathrm{P_0}\left(\mathrm{A_{BL}}\mathrm{r}^{-\alpha^{\mathrm{BL}}}\right)^{1-\varepsilon}}\right)$ which is the cellular interference , D2D interference and noise part in characteristic function.

Finally, note that the value of $p_c^{\mathrm{cov}}(\lambda,\gamma)$ in Eq. (21) should be calculated by taking the expectation with $f_{\overline{R_{LCU}}}(r)$ and $f_{\overline{R_{NLCU}}}(r)$, which is given as follow

$$\begin{aligned}f_{\overline{R_{LCU}}}(r)&=\left(\frac{d}{dr}\left\{1-\exp\left[-\Lambda^L([0,r])\right]\cdot\exp\left[-\Lambda^{NL}([0,\overline{r_1}])\right]\right\}\right)\\&=\exp\left[-\Lambda^L([0,r])\right]\exp\left[-\Lambda^{NL}([0,\overline{r_1}])\right]\\&\quad\times\Pr^{\mathrm{L}}(r)\lambda_B^L(r)/q\end{aligned} \tag{48}$$

where the typical UE should guarantee that there is no NLoS BS in $\overline{r_1}$ when the signal is LoS. Given that the typical BS is connected to a NLoS UE, the conditional coverage probability T^{N} can be derived in a similar way as the above. In this way, the coverage probability is obtained by $T_c^{\mathrm{L}}+T_c^{\mathrm{NL}}$. Which concludes our proof.

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APPENDIX C:PROOF OF THEOREM 3

The typical D2D receiver selects the equivalent nearest UE as a potential transmitter. If the potential D2D transmitter is operating in a cellular mode, D2D RU must search for another transmitter. We approximately consider that the second neighbor can be found as the transmitter under this situation both for LoS/NLoS links. The approximate cumulative distribution function (CDF) of $\overline{R}_d^{LoS}$ can be written as

$$\begin{aligned}
&\Pr\left[\overline{R}_d^{LoS} < R\right] \\
&\approx \int_{R+t_L}^{\infty} \left(\int_0^R f_{R_d^L}(\overline{R}_d) d\overline{R}_d\right) f_{r_1^L}(r_1) dr_1 \\
&+ \int_{t_L}^{R+t_L} \left(\int_0^{r_1-t_L} f_{R_d}(\overline{R}_d) d\overline{R}_d\right. \\
&+ \int_{r_1-t_L}^{R} (1-P_c^L)\cdot f_{R_d^L}(\overline{R}_d) d\overline{R}_d \\
&+ \left.\int_{r_1-t_L}^{R} P_c^L \cdot f_{R_{d_2}^L}\left(\overline{R}_d\right) d\overline{R}_d\right) f_{r_1^L}(r_1) dr_1 \\
&+ \int_{R+t_{NL}}^{\infty} \left(\int_0^R f_{R_d^L}(\overline{R}_d) d\overline{R}_d\right) f_{r_1^{NLoS}}(r_1) dr_1 \\
&+ \int_{t_{NL}}^{R+t_{NL}} \left(\int_0^{r_1-t} f_{R_d^L}(\overline{R}_d) d\overline{R}_d\right. \\
&+ \int_{r_1-t_{NL}}^{R} (1-P_c^L)\cdot f_{R_d^L}(\overline{R}_d) d\overline{R}_d \\
&+ \left.\int_{r_1-t_{NL}}^{R} P_c^L \cdot f_{R_{d_2}^L}\left(\overline{R}_d\right) d\overline{R}_d\right) f_{r_1^{NL}}(r_1) dr_1,
\end{aligned} \tag{49}$$

where r_1 is the equivalent distance from TU to the strongest LoS/NLoS BS, P_c^L and $P_c^{NL}$is the probability of a D2D receiver be a CU with LoS and NLoS.

$$\begin{aligned}
f_{r_1^L}(r) &= \exp\left[-\Lambda^L([0,r])\right] \\
&\times \exp\left[-\Lambda^{NL}([0,\overline{r_1}])\right] \\
&\times \mathrm{Pr}_{\mathrm{B}}^{\mathrm{L}}(r)\,\lambda_B^L(r)/(1-q)
\end{aligned} \tag{50}$$

and

$$\begin{aligned}
f_{r_1^{NL}}(r) &= \exp\left[-\Lambda^{NL}([0,r])\right] \\
&\times \exp\left[-\Lambda^{L}([0,\overline{r_1}])\right] \\
&\times \mathrm{Pr}_{\mathrm{B}}^{\mathrm{NL}}(r)\,\lambda_B^{NL}(r)/(1-q)
\end{aligned} \tag{51}$$

According to [8], if there is no difference between CUs and D2D UEs, the pdf of the distance for a tier of PPP LoS UEs is

$$\begin{aligned}
f_{R_d^L}(r) &= \exp\left(-\int_0^{\overline{r_1}} \mathrm{Pr}_{\mathrm{D}}^{\mathrm{NL}}(u)\,\lambda_u^{NL}(u)du\right) \\
&\times \exp\left(-\int_0^{r} \mathrm{Pr}_{\mathrm{D}}^{\mathrm{L}}(u)\,\lambda_u^{L}(u)du\right) \\
&\times \mathrm{Pr}_{\mathrm{D}}^{\mathrm{L}}(r)\,\lambda_u^L(r)
\end{aligned} \tag{52}$$

and if there is no difference between CUs and D2D UEs, the pdf of the distance for a tier of PPP NLoS UEs is

$$\begin{aligned}
f_{R_d^{NL}}(r) &= \exp\left(-\int_0^{\overline{r_2}} \mathrm{Pr}_{\mathrm{D}}^{\mathrm{L}}(u)\,\lambda_u^{L}(u)du\right) \\
&\times \exp\left(-\int_0^{r} \mathrm{Pr}_{\mathrm{D}}^{\mathrm{NL}}(u)\,\lambda_u^{NL}(u)du\right) \\
&\times \mathrm{Pr}_{\mathrm{D}}^{\mathrm{NL}}(r)\,\lambda_u^{NL}(r),
\end{aligned} \tag{53}$$

where

$$\begin{aligned}
&\lambda_u^L(r) \\
&= \frac{d}{dt}\left(\mathbb{E}_{\mathcal{H_D}}\left[2\pi(1-q)\lambda_u \int_0^{t(\mathcal{H_D})^{\frac{1}{\alpha_{DL}}}} \mathrm{Pr}_{\mathrm{D}}^{\mathrm{L}}(r) r dr\right]\right)
\end{aligned} \tag{54}$$

and

$$\begin{aligned}
&\lambda_u^{NL}(r) \\
&= \frac{d}{dt}\left(\mathbb{E}_{\mathcal{H_D}}\left[2\pi(1-q)\lambda_u \int_0^{t(\mathcal{H_D})^{\frac{1}{\alpha_{DN}}}} \mathrm{Pr}_{\mathrm{D}}^{\mathrm{NL}}(r) r dr\right]\right).
\end{aligned} \tag{55}$$

According to [31] , the second neighbor point is distributed as

$$\begin{aligned}
f_{R_{d_2}^L}(r) &= 2\pi^2 r^3 \lambda_u^L(t)^2 \\
&\times \exp\left[-\mathbb{E}_{\mathcal{H_D}}\left[2\pi\lambda_u \int_0^{r(\mathcal{H_D})^{\frac{1}{\alpha_{DL}}}} \mathrm{Pr}_{\mathrm{D}}^{\mathrm{L}} r dr\right]\right]
\end{aligned} \tag{56}$$

and

$$\begin{aligned}
f_{R_{d_2}^{NL}}(r) &= 2\pi^2 r^3 \lambda_u^{NL}(t)^2 \\
&\times \exp\left[-\mathbb{E}_{\mathcal{H_D}}\left[2\pi\lambda_u \int_0^{r(\mathcal{H_D})^{\frac{1}{\alpha_{DN}}}} \mathrm{Pr}_{\mathrm{D}}^{\mathrm{NL}} r dr\right]\right].
\end{aligned} \tag{57}$$

similarity, the cdf of the distance of NLoS D2D signal can be written as

$$\begin{aligned}
&\Pr\left[\overline{R}_d^{NL} < R\right] \\
&\approx \int_{R+t_L}^{\infty} \left(\int_0^R f_{R_d^{NL}}(\overline{R}_d) d\overline{R}_d\right) f_{r_1^L}(r_1) dr_1 \\
&+ \int_{t_L}^{R+t_L} \left(\int_0^{r_1-t_L} f_{R_d^{NL}}(\overline{R}_d) d\overline{R}_d\right. \\
&+ \int_{r_1-t_L}^{R} (1-P_c^{NL})\cdot f_{R_d^{NL}}(\overline{R}_d) d\overline{R}_d
\end{aligned}$$

$$
\begin{aligned}
&+\int_{r_1-t_L}^{R} P_c^{NL}\cdot f_{R_{d_2}^{NL}}\left(\overline{R}_d\right)d\overline{R}_d \Bigg) f_{r_1^L}(r_1)dr_1\\
&+\int_{R+t_{NL}}^{\infty}\left(\int_0^R f_{R_d^{NL}}(\overline{R}_d)d\overline{R}_d\right) f_{r_1^{NL}}(r_1)dr_1\\
&+\int_{t_{NL}}^{R+t_{NL}}\Bigg(\int_0^{r_1-t} f_{R_d^{NL}}(\overline{R}_d)d\overline{R}_d\\
&+\int_{r_1-t_{NL}}^{R}(1-P_c^{NL})\cdot f_{R_d^{NL}}(\overline{R}_d)d\overline{R}_d\\
&+\int_{r_1-t_{NL}}^{R} P_c^{NL}\cdot f_{R_{d_2}^{NL}}\left(\overline{R}_d\right)d\overline{R}_d \Bigg) f_{r_1^{NL}}(r_1)dr_1, \qquad (58)
\end{aligned}
$$

the pdf of $\overline{R_d}^{L(NL)}$ can be written as

$$
f_{\overline{R_d}^{L(NL)}}(r)=\frac{\partial \Pr\left[R_d^{L(NL)}>r\right]}{\partial \overline{R_d}}, \qquad (59)
$$

where P_c is the probability of the potential D2D receiver operating in the cellular mode, and it can be calculated as

$$
P_c^{L/NL}=\arccos\left(\frac{\overline{R}_d+r_1^2-t_{L/NL}^2}{2\overline{R}_d r_1}\right)/\pi, \qquad (60)
$$

which concludes our proof.

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