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Guard Zone Based D2D Underlaid Cellular Networks with Two-tier Dependence

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***Abstract*—Device-to-device (D2D) communication is under active investigation and may be a key feature in 5G networks for its great potential in improving network spectral and energy efficiency. Underlaying proximity-based D2D communication links in current cellular networks allows D2D users to opportunistically access the cellular spectrum, thus causing interference not only in the D2D tier but also between D2D and macrocell tiers. In this paper, we consider a D2D underlaid cellular network, in which D2D users reuse macrocell downlink spectrum, imposing guard zones around each active D2D transmitter to avoid nearby interference from both macro base stations (MBSs) and other D2D transmitters. Using spatial models and analytical results from stochastic geometry, we provide bounds and approximations for the D2D and cellular coverage probability, as a means to characterize the performance of D2D underlaid cellular networks with intra-tier and cross-tier dependence. The D2D area spectral efficiency (ASE) is also characterized and an approximate optimal guard zone radius that maximizes a lower bound of D2D network throughput is derived in closed-form. Simulation results validate our theoretical analysis and evince the accuracy of the proposed analytical expressions.**

I. Introduction

Providing connectivity and capacity to a massive amount of devices connected to the cellular networks poses several technical challenges for the network capacity and efficiency. For that, an architectural shift from infrastructure-centric to device-centric networks is envisioned for future 5G systems [1]. In this context, device-to-device (D2D) communication has drawn much attention in both academia and industry as a potential solution for improving both spectral efficiency and energy efficiency, as well as reducing the end-to-end latency, which are key requirements for 5G networks. From a resource utilization point of view, in D2D-enabled cellular networks the spectrum can be either assigned orthogonally to cellular and D2D links or shared among them. Various research works have been carried out on D2D underlaid cellular networks where D2D links opportunistically access spectrum assigned for cellular communication. By allowing D2D users in proximity to establish direct communication links while reusing the cellular network spectrum, the area spectral efficiency can be largely improved. Nevertheless, spectrum sharing may create significant interference between these two types of communication links, especially when one very close interferer can cause an outage to its neighboring links. Among different interference mitigation techniques, setting up guard zones to avoid nearby interference has been proposed and widely discussed in different scenarios. The impact of guard zone in wireless ad hoc networks has been studied in [2]. A cognitive radio network model with inter-tier correlation between primary and secondary users has been considered in [3], with theoretical bounds derived for the interference distribution and outage probability using tools from stochastic geometry. When the primary users are distributed according to a homogeneous Poisson Point Process (PPP), which is a widely used spatial model for large wireless network topology, the distribution of secondary users form a Poisson Hole Process (PHP). Similar analysis for heterogeneous cellular networks with inter-tier correlation can also be found in [4]. D2D integrated cellular networks with cross-tier interference management is studied in [5] and [6]. In [7] a D2D overlaid cellular network with intra-correlation is studied where active D2D transmitters follow a *Matérn Hardcore* (MHC) process, meaning that there exists a minimum distance between two active D2D transmitters. In [8] two-tier dependence is considered by applying guard zones around small cell transmitters with variable size depending on received D2D interference signal power, then using CSMA for remaining potential D2D transmitters to avoid nearby interference in the D2D tier. However, the impact of guard zone in D2D underlaid cellular networks with both intra-tier and inter-tier dependence has not been fully studied.

In this work, we focus on a multi-cell D2D underlaid cellular network with two types of users: macrocell users which connect to the nearest macrocell base station (MBS) and D2D pairs with short transmission distances. A guard zone is applied around each active D2D transmitter, imposing that no MBS or other active D2D transmitter lies therein. As a result, whether a potential D2D link can be active depends on the relative positions of its interferers in both macro and D2D tiers, which creates dependence between tiers (correlation). We use spatial patterns from stochastic geometry for the network modeling and analysis. Thanks to the existing analytical results of previous study in point processes with dependence, we give analytical bounds and approximations of important network performance metrics for our network model, as well as analysis on how the guard zone size affects the overall network throughput.

II. Network Model

We consider a D2D underlaid cellular network where D2D links reuse the spectrum assigned for macrocell downlink communication. The MBSs are distributed in the two-dimensional Euclidean plane $\mathbb{R}^2$ according to a homogeneous spatial PPP Φ_M with intensity λ_M. The macrocell users are located according to some independent stationary point process and are served by the closest base stations. The coverage area of MBS can be presented by a Poisson-Voronoi tessellation (PVT) on the plane $\mathbb{R}^2$. We also assume that all MBSs are fully loaded, meaning that in each Voronoi cell there is always a mobile user being served by its associated MBS. The locations of potential D2D transmitters are modeled by another independent homogeneous PPP Φ_D with intensity λ_D. Each potential D2D transmitter has its intended receiver around it at isotropic directions with fixed distance r.

In order to protect active D2D links from interference caused by nearby transmitters, we impose a guard zone of radius R around each active D2D transmitter so that no MBS or other D2D transmitter lies in it (exclusion region). Although setting up guard zones around receivers can lead to simpler mathematical results and has also been studied in prior work, we consider the case of guard zones around transmitters motivated by the fact that existing carrier sense techniques are based on sensing at the transmitter side [9] [10]. According to this setup a potential D2D transmitter can be active only when the MBSs and other active D2D transmitters are at least R distance away, thus resulting in a cognitive D2D network with each D2D transmitter sensing its neighborhood before transmitting. The distribution of active D2D transmitters is a thinned version of the initial homogeneous PPP, where the thinning procedure involves inter-correlation between the positions of MBSs and D2D transmitters, as well as intra-correlation between the positions of two D2D transmitters. The network topology is shown in Fig. 1. Due to the guard zone setup the distribution of active D2D transmitters is sparser than in the original PPP case.

Lemma 1. *For a two-tier heterogeneous network where the primary transmitters form a homogeneous PPP Φ_1 with intensity λ_1 and the positions of secondary transmitters are constrained by the following conditions:*

- *Based on a homogeneous PPP Φ_2 with intensity λ_2, two secondary transmitters cannot be closer to each other than R;*
- *A secondary transmitter cannot be closer to a primary transmitter than R,*

we have that due to the first condition the resulted distribution of secondary transmitters form a Matérn Type II Hardcore Process (MHC) $\tilde{\Phi}_2$ with intensity $\tilde{\lambda}_2 = \frac{1-\exp\left(-\lambda_2 \pi R^2\right)}{\pi R^2}$ [11]. From the second condition, the probability of a point from the MHC being retained is the probability that for any point from $\tilde{\Phi}_2$, there are no points from Φ_1 within distance R. The resulted intensity of secondary transmitters can be approximated by the intensity of a Poisson Hole Process (PHP) [3], thus given by

$$\begin{aligned} \lambda_s &= \tilde{\lambda}_2 \exp\left(-\lambda_1 \pi R^2\right) \\ &= \exp\left(-\lambda_1 \pi R^2\right) \cdot \frac{1-\exp\left(-\lambda_2 \pi R^2\right)}{\pi R^2}, \end{aligned} \tag{1}$$

when $\lambda_1 < \tilde{\lambda}_2$ holds.

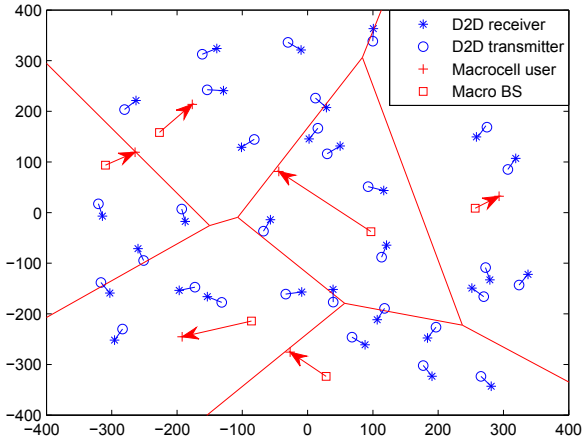


Fig. 1. A snapshot of the D2D underlaid cellular network with guard zones around active D2D transmitters. The red squares represent the MBSs. The red crosses represent cellular users. The blue circles represent active D2D transmitters and the blue stars represent their intended receivers with link length $r = 25$m. The guard zone around each active D2D transmitter is with radius $R = 50$m.

For our cognitive D2D underlaid cellular network model, denoting by Φ_A the point process formed by the set of active D2D transmitters, its intensity is then given as

$$\lambda_A = \exp\left(-\lambda_M \pi R^2\right) \cdot \frac{1-\exp\left(-\lambda_D \pi R^2\right)}{\pi R^2}, \tag{2}$$

when λ_D is sufficiently large compared to λ_M. Fig. 2 shows λ_A as a function of guard zone radius R and is compared with simulation results obtained by setting $\lambda_M = 1.6 \times 10^{-5}$ and $\lambda_D = 8 \times 10^{-4}$. It evinces that (2) provides a very tight approximation of the actual density of our considered D2D underlaid cellular network model with two-tier correlation. The gap between the two curves comes from the fact that the density funtion of MHC of both type I and type II underestimate the real density for such kind of spatial patterns with minimum distance between two points.

Due to the spectrum sharing between macrocell and D2D users, each D2D receiver receives interfering signals from both MBSs and other active D2D transmitters. The background thermal noise is assumed to be negligible compared to the interference, focusing here on the signal-to-interference ratio (SIR) distribution. Our results can be easily extended to take into account the effect of background noise power.

Without loss of generality, considering a typical active D2D receiver located at the origin and at a fixed distance r from

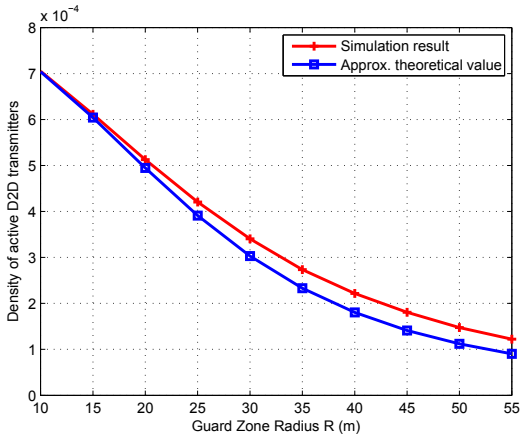


Fig. 2. Density of active D2D transmitters vs. guard zone radius. The red cross points represent the real density values obtained by simulations. The blue square points represent the approximated density calculated by (2) with $\lambda_M = 1.6 \times 10^{-5}$ and $\lambda_D = 8 \times 10^{-4}$.

its associated transmitter D_o, the SIR of the received signal is given by

$$\text{SIR}_D = \frac{P_D h_D r^{-\alpha}}{\sum_{i\in\Phi_M} \frac{P_M}{L} g_i l_i^{-\alpha} + \sum_{j\in\Phi_A\setminus\{D_o\}} \frac{P_D}{L^2} h_j d_j^{-\alpha}}, \quad (3)$$

where P_M and P_D denote the transmit power of MBS and D2D transmitters, respectively. h_D, h_j and g_i denote small-scale power fading from the typical D2D transmitter, the j-th interfering D2D transmitter, and the i-th interfering MBS to the typical D2D receiver, respectively. We assume that all users experience Rayleigh fading, i.e. $h_D, h_j, g_i \sim \exp(1)$. l_i and d_j denote the distance from the i-th MBS and the j-th active D2D transmitter to the typical D2D receiver, respectively. We consider a standard distance-dependent pathloss attenuation, i.e. $r^{-\alpha}$, where $\alpha > 2$ is the pathloss exponent. We consider indoor D2D communication, i.e. interfering signals coming from MBSs and other D2D transmitters experience wall penetration loss with constant attenuation factors L and L^2, respectively.

Similarly, for a typical macrocell user located at the origin with its associated MBS M_o at a random distance l away, the SIR of its received signal is given by

$$\text{SIR}_M = \frac{P_M g_M l^{-\alpha}}{\sum_{i\in\Phi_A} \frac{P_D}{L} h_i d_i^{-\alpha} + \sum_{j\in\Phi_M\setminus\{M_o\}} P_M g_j l_j^{-\alpha}}, \quad (4)$$

where g_M, g_j and h_i denote small-scale fading from the typical MBS, the j-th interfering MBS, and the i-th active D2D transmitter to the typical macrocell receiver, respectively, which also follow exponential distribution with unit mean (Rayleigh fading). d_i and l_j denote the distance from the i-th active D2D transmitter and the j-th MBS to the typical macrocell receiver, respectively.

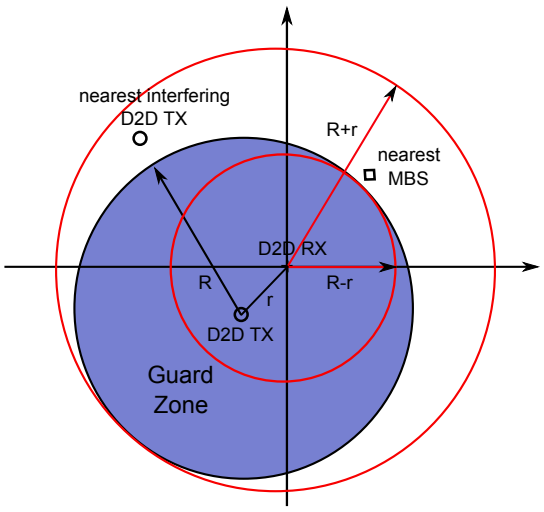


Fig. 3. Guard zone with radius R of a typical active D2D transmitter centered at the origin with its intended receiver being at distance r when $R \geq r$. According to the system model, no MBS or other active D2D transmitter can lie in a circle of radius R centered at the origin, thus the minimum distance from the nearest MBS or D2D transmitter to the typical active D2D receiver is between $R - r$ and $R + r$.

III. Coverage Probability Analysis

A. D2D Link Coverage Probability

For a prescribed D2D target SIR γ_D, the coverage probability of a typical active D2D link in our considered network is given by

$$\begin{aligned} P_{\text{cov}}^D(\gamma_D) &= \mathbb{P}(\text{SIR}_D > \gamma_D) \\ &= \mathbb{P}\left[h_D > \gamma_D r^\alpha \left(\frac{\kappa I_{MD}}{L} + \frac{I_{DD}}{L^2}\right)\right] \\ &= \mathcal{L}_{I_{MD}}\left(\frac{\kappa\gamma_D r^\alpha}{L}\right)\mathcal{L}_{I_{DD}}\left(\frac{\gamma_D r^\alpha}{L^2}\right), \quad (5) \end{aligned}$$

where $I_{MD} = \sum_{i\in\Phi_M} g_i l_i^{-\alpha}$ and $I_{DD} = \sum_{j\in\Phi_A\setminus\{D_o\}} h_j d_j^{-\alpha}$ denote macrocell interference and D2D interference with normalized transmit power $\kappa = P_M/P_D$ is the power ratio between MBS and D2D transmitter; $\mathcal{L}_{I_{MD}}(s) = \mathbb{E}[e^{-sI_{MD}}]$ and $\mathcal{L}_{I_{DD}}(s) = \mathbb{E}[e^{-sI_{DD}}]$ are the Laplace transforms of interference I_{MD} and I_{DD}. The notation of coverage probability in this case is the probability of a random D2D link to achieve SIR higher than the target γ_D.

The Laplace transform of interference in a homogeneous Poisson network is easy to calculate [12]. In a guard zone-based cognitive D2D underlaid cellular network, the received interference to the typical receiver is caused by transmitting nodes distributed outside the guard zone centered at its associated transmitter. In the case where $R \geq r$, there exists a minimum distance between a typical D2D receiver to its nearest interfering transmitter, as shown in Fig. 3. A modified Laplace transform of interference with this minimum distance can be defined as follows [3]:

Definition 1. *Consider an interference model* $I_\Pi = \sum_{x_i\in\Pi} H_i \|x_i\|^{-\alpha}$ *where* Π *is a homogeneous PPP with density*

λ_Π *representing the spatial distribution of the interfering nodes.* $\|x_i\|$ *denotes the Euclidean distance from the* i*-th interfering point to the typical receiver at the origin.* H_i *denotes small-scale power fading of the* i*-th interfering link, which follows exponential distribution with* $\mathbb{E}[H] = 1$*. If* $\|x_i\| \geq r_{min}$ *is valid for every point in* Π*, then we define a modified Laplace transform of* I_Π *as*

$$\begin{aligned}\mathcal{L}_I^1(s,\lambda_\Pi,r_{min}) &= \mathbb{E}_{H,\Pi}\left[\exp\left(-s\sum_{i\in\Pi}H_i\|x_i\|^{-\alpha}\right)\right]\\ &= \exp\left(-2\pi\lambda_\Pi\int_{r_{min}}^{\infty}\left(1-\mathbb{E}_H\left[\exp\left(-sHv^{-\alpha}\right)\right]\right)vdv\right)\\ &= \exp\left(-2\pi\lambda_\Pi\int_{r_{min}}^{\infty}\frac{sv^{-\alpha}}{1+sv^{-\alpha}}vdv\right)\\ &= \exp\left(\frac{-2\pi\lambda_\Pi s}{\alpha-2}r_{min}^{2-\alpha}{}_2F_1\left(1,1-\frac{2}{\alpha};2-\frac{2}{\alpha};-\frac{s}{r_{min}^{\alpha}}\right)\right),\end{aligned} \tag{6}$$

where ${}_2F_1(a,b;c;z)$ *is the hypergeometric function. For* $r_{min} = 0$*, we have the Laplace transform of interference in a Poisson network as*

$$\mathcal{L}_I^0(s,\lambda_\Pi) = \mathcal{L}_I^1(s,\lambda_\Pi,0) = \exp\left(-\frac{\pi\lambda_\Pi s^{2/\alpha}}{\operatorname{sinc}(2/\alpha)}\right). \tag{7}$$

In our network model the minimum distance between the nearest MBS and the typical D2D receiver is bounded by $R-r$ and $R+r$, as shown in Fig. 3, and we can obtain the following two bounds for the Laplace transform of I_{MD}

$$\mathcal{L}_I^1(s,\lambda_M,R-r) \leq \mathcal{L}_{I_{MD}}(s) \leq \mathcal{L}_I^1(s,\lambda_M,R+r). \tag{8}$$

From our analysis in Section II the distribution of active D2D transmitters is resulted from the combination of a MHC and a PHP. For the typical D2D receiver, interference coming from outside the guard zone of its transmitter can be approximately seen as interference in a homogeneous PPP network, with $R-r$ and $R+r$ as boundaries for the minimum distance from the nearest interfering D2D transmitter to the typical receiver, as shown in Fig. 3. Therefore, we have the following bounds for the Laplace transform of I_{DD}

$$\mathcal{L}_I^1(s,\lambda_A,R-r) \leq \mathcal{L}_{I_{DD}}(s) \leq \mathcal{L}_I^1(s,\lambda_A,R+r), \tag{9}$$

with λ_A given in (2). By plugging these bounds into (5) we have the following two bounds for the D2D link coverage probability

$$P_{\text{cov}}^D \geq \mathcal{L}_I^1(\frac{\kappa\gamma_D r^\alpha}{L},\lambda_M,R-r)\mathcal{L}_I^1(\frac{\gamma_D r^\alpha}{L^2},\lambda_A,R-r), \tag{10}$$

$$P_{\text{cov}}^D \leq \mathcal{L}_I^1(\frac{\kappa\gamma_D r^\alpha}{L},\lambda_M,R+r)\mathcal{L}_I^1(\frac{\gamma_D r^\alpha}{L^2},\lambda_A,R+r). \tag{11}$$

An approximation of $\mathcal{L}_{I_{MD}}$ and $\mathcal{L}_{I_{DD}}$ can be obtained by considering the interference field as the entire $\mathbb{R}^2$ except each guard zone, which is an off-center disk for the typical D2D receiver. When $R \geq r$, by using the law of cosines we have

$$\mathcal{L}_{I_{MD}}(s) = \exp\left(-\lambda_M\int_0^{2\pi}\int_{d_1(\varphi)}^{\infty}\frac{v\mathrm{d}v\mathrm{d}\varphi}{1+s^{-1}v^\alpha}\right), \tag{12}$$

$$\mathcal{L}_{I_{DD}}(s) = \exp\left(-\lambda_A\int_0^{2\pi}\int_{d_1(\varphi)}^{\infty}\frac{v\mathrm{d}v\mathrm{d}\varphi}{1+s^{-1}v^\alpha}\right), \tag{13}$$

where $d_1(\varphi) = r\cos\varphi + \sqrt{R^2 - r^2\sin^2\varphi}$.

Similarly, when $R < r$ we have the approximate Laplace transform of interference as

$$\mathcal{L}_{I_{MD}}(s) = \exp\left\{-\lambda_M\left(\frac{\pi s^{\frac{2}{\alpha}}}{\operatorname{sinc}(\frac{2}{\alpha})} - \int_{-\theta}^{\theta}\int_{d_0(\varphi)}^{d_1(\varphi)}\frac{v\mathrm{d}v\mathrm{d}\varphi}{1+s^{-1}v^\alpha}\right)\right\}, \tag{14}$$

$$\mathcal{L}_{I_{DD}}(s) = \exp\left\{-\lambda_A\left(\frac{\pi s^{\frac{2}{\alpha}}}{\operatorname{sinc}(\frac{2}{\alpha})} - \int_{-\theta}^{\theta}\int_{d_0(\varphi)}^{d_1(\varphi)}\frac{v\mathrm{d}v\mathrm{d}\varphi}{1+s^{-1}v^\alpha}\right)\right\}, \tag{15}$$

where $d_0(\varphi) = r\cos\varphi - \sqrt{R^2 - r^2\sin^2\varphi}$ and $\theta = \arcsin\frac{R}{r}$. Putting them into (5) we get the approximation of D2D link coverage probability P_{cov}^D for the case with $R \geq r$ and with $R < r$ respectively.

B. Macrocell Coverage Probability

For an arbitrary served macrocell user, since it connects to the nearest MBS, we have the pdf of the cellular link length r_M given by [13]

$$f_{r_M}(l) = e^{-\lambda_M\pi l^2}2\pi\lambda_M l. \tag{16}$$

Similar to the analysis of D2D link, considering a typical macrocell user located at the origin, we have the macrocell coverage probability as

$$\begin{aligned}P_{\text{cov}}^M(\gamma_M) = \int_0^\infty e^{-\lambda_M\pi l^2}2\pi\lambda_M l\cdot\mathcal{L}_{I_{MM}}(\gamma_M l^\alpha)\\ \times\mathcal{L}_{I_{DM}}\left(\frac{\gamma_M l^\alpha}{\kappa L}\right)\mathrm{d}l,\end{aligned} \tag{17}$$

where γ_M is the target SIR for successful macrocell communication, $I_{MM} = \sum_{j\in\Phi_M\setminus\{M_o\}}g_j l_j^{-\alpha}$ and $I_{DM} = \sum_{i\in\Phi_A}h_i d_i^{-\alpha}$ denote the interference from other MBSs and from active D2D transmitters with normalized transmit powers.

Since the positions of MBSs follow a PPP and each macrocell user connects to the nearest MBS, the nearest interfering MBS is at least at distance r away. The Laplace transform of I_{MM} can be written as

$$\mathcal{L}_{I_{MM}}(s) = \mathcal{L}_I^1(s,\lambda_M,l). \tag{18}$$

As for the interference coming from active D2D transmitters, since the guard zone is around each transmitter and the cellular link length is a random variable in $[0,\infty)$, the minimum distance constraint between a typical macrocell receiver and the nearest active D2D transmitter does not apply. I_{DM} can be approximated by using the Laplace transform of interference in a Poisson network, thus given by

$$\mathcal{L}_{I_{DM}}(s) \simeq \mathcal{L}_I^0(s,\lambda_A) = \exp\left(-\frac{\pi\lambda_A s^{2/\alpha}}{\operatorname{sinc}(2/\alpha)}\right). \tag{19}$$

Then the macrocell coverage probability becomes

$$\begin{aligned}P_{\text{cov}}^M = \int_0^\infty e^{-\lambda_M\pi l^2}2\pi\lambda_M l\cdot\mathcal{L}_I^1(\gamma_M l^\alpha,\lambda_M,l)\\ \times\mathcal{L}_I^0(\frac{\gamma_M l^\alpha}{\kappa L},\lambda_A)\mathrm{d}l.\end{aligned} \tag{20}$$

IV. Impact of Guard Zone on Network Throughput

In this section we analyze how the guard zone in our D2D underlaid cellular network with intra-tier and cross-tier dependence affects the D2D network throughput. We also give approximate expression for the optimal guard zone radius by maximizing a lower bound on the D2D throughput.

The area spectral efficiency (ASE), often referred to as network throughput, is a measure of spatial reuse and gives the spectral efficiency (maximum average data rate per Hz) per unit area. For the considered network model, the ASE of D2D network can be written as

$$\begin{aligned}\mathcal{T}(\gamma_D) &= \lambda_A P_{\text{cov}}^D(\gamma_D)\log_2(1+\gamma_D)\\ &= \lambda_A \mathcal{L}_{I_{MD}}\left(\frac{\kappa\gamma_D r^\alpha}{L}\right)\mathcal{L}_{I_{DD}}\left(\frac{\gamma_D r^\alpha}{L^2}\right)\log_2(1+\gamma_D),\end{aligned} \tag{21}$$

with $\lambda_A = \exp\left(-\lambda_M \pi R^2\right)\cdot\frac{1-\exp\left(-\lambda_D \pi R^2\right)}{\pi R^2}$, $\mathcal{L}_{I_{MD}}$ and $\mathcal{L}_{I_{DD}}$ are approximated by (12) and (13) for $R \geq r$, and by (14) and (15) for $R < r$.

Due to the complex mathematical derivation, it is impossible to obtain a closed-form solution for the optimal guard zone radius $R^\star$ by maximizing the ASE given in (21). However the D2D coverage probability can be lower bounded by the case with Poisson distributed interference given by

$$\begin{aligned}P_{\text{cov}}^D &> P_{\text{LB}}^D\\ &= \exp\left(-\frac{\pi\lambda_M r^2\kappa_1^{2/\alpha}}{\text{sinc}\,(2/\alpha)}\right)\exp\left(-\frac{\pi\lambda_A r^2\kappa_2^{2/\alpha}}{\text{sinc}\,(2/\alpha)}\right),\end{aligned} \tag{22}$$

where $\kappa_1 = \frac{\gamma_D\cdot P_M}{P_D L}$ and $\kappa_2 = \frac{\gamma_D}{L^2}$. Then we have a lower bound for the ASE as

$$\begin{aligned}\mathcal{T}_{LB} = \lambda_A \log_2(1+\gamma_D)\exp\left(-\frac{\pi\lambda_M r^2\kappa_1^{2/\alpha}}{\text{sinc}\,(2/\alpha)}\right)\\ \times\exp\left(-\frac{\pi\lambda_A r^2\kappa_2^{2/\alpha}}{\text{sinc}\,(2/\alpha)}\right),\end{aligned} \tag{23}$$

which is not a concave function of λ_A. Nevertheless, we can still have a stationary point λ_A^* (maximizer) by using the first order optimality condition, which gives

$$\begin{aligned}\lambda_A^* &= \arg\max_{\lambda_A}\mathcal{T}_{LB}\\ &= \frac{\text{sinc}\,(2/\alpha)\cdot L^{4/\alpha}}{\pi r^2\gamma_D^{2/\alpha}}.\end{aligned} \tag{24}$$

Using (2), we get the optimal guard zone radius R^* as the solution of

$$\exp\left(-\lambda_M\pi R^2\right)\cdot\frac{1-\exp\left(-\lambda_D\pi R^2\right)}{\pi R^2} = \frac{\text{sinc}\,(2/\alpha)\cdot L^{4/\alpha}}{\pi r^2\gamma_D^{2/\alpha}}. \tag{25}$$

When λ_M is small enough we have $\exp\left(-\lambda_M\pi R^2\right) \simeq 1$, which gives

$$e^{-\lambda_D\pi R^2} + \frac{\text{sinc}\,(2/\alpha)\cdot L^{4/\alpha}}{r^2\gamma_D^{2/\alpha}}R^2 - 1 = 0. \tag{26}$$

Denoting $\mu = \frac{\text{sinc}(2/\alpha)\cdot L^{4/\alpha}}{r^2\gamma_D^{2/\alpha}}$ and using the Lambert W function we have the solution to (26) as

$$R^* = \sqrt{\frac{W\left(-\frac{\pi\lambda_D}{\mu}e^{-\frac{\pi\lambda_D}{\mu}}\right)}{\pi\lambda_D} + \frac{1}{\mu}}, \tag{27}$$

which can be seen as an approximate value for the optimal guard zone radius.

V. Simulation Results

In this section, we validate the theoretical bounds and approximations of the coverage probability for our guard zone-based D2D underlaid cellular network via simulation results. The area spectral efficiency of the D2D network is also numerically evaluated to validate our analysis of how the guard zone radius affects network throughput.

A. Simulation Setup

In our simulations, MBSs and potential D2D transmitters are dropped in a two-dimensional square of surface 600×600 m^2 according to homogeneous PPP with intensity $\lambda_M = 1.6\times10^{-5}$ and $\lambda_D = 8\times10^{-4}$. Potential D2D receivers are distributed at isotropic directions around their transmitters with fixed distance $r = 25$ m. Each MBS serves one macrocell user at a time in its coverage according to the geographically closest MBS association. A guard zone is imposed around each D2D transmitter with radius R. The transmit power of MBS and active D2D transmitter are set as $P_M = 1$W and $P_D = 0.05$W. Rayleigh fading model is adopted for both cellular and D2D links with $\mathbb{E}[h] = 1$. The pathloss exponent is $\alpha = 4$ and the wall penetration loss factor is $L = 5$ dB.

B. Coverage Probability of D2D and Cellular Links

Fig. 4 illustrates the bounds and approximations for the D2D link coverage as a function of the target SIR γ_D for $R = 50$ m and $R = 15$ m, representing the case when $R \geq r$ and $R < r$ respectively. The simulated values are obtained by averaging over 10000 realizations. We see that compared to the simulated curve, the D2D coverage probability given in (5) with Laplace transform of interference as in (12)-(15) provides a sufficiently tight approximation.

Fig. 5 shows the cellular coverage probability given in (20) as a function of the target SIR γ_M and is compared to the simulated performance. We observe that macrocell users suffer from much higher interference than the D2D users due to the larger range usually used for cellular links as compared to the short-distance D2D links. Therefore, the transmitter-based guard zone does not prevent cellular receiver from its nearby interference.

C. Area Spectral Efficiency of D2D Underlaid Networks

Fig. 6 plots the ASE of D2D underlaid network vs. the guard zone radius R with target SIR $\gamma_D = 5$ dB and 10 dB, respectively. The ASE is obtained by (21) with the Laplace transform of interference as given in (12)-(15). From (27) we have an approximate optimal value of $R = 16.6$m for $\gamma_D = 5$

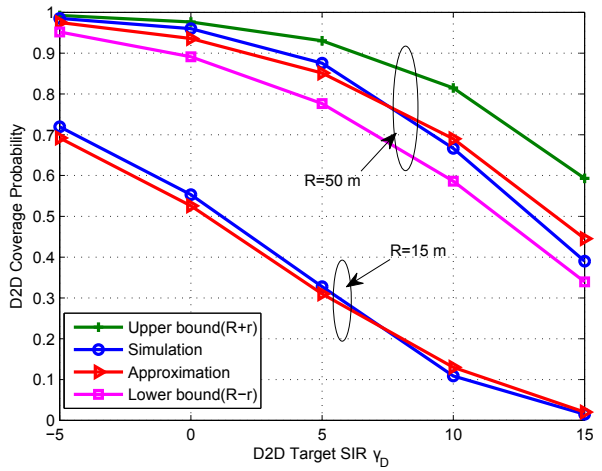


Fig. 4. Theoretical lower bound, upper bound and proposed approximations for the D2D coverage probability.

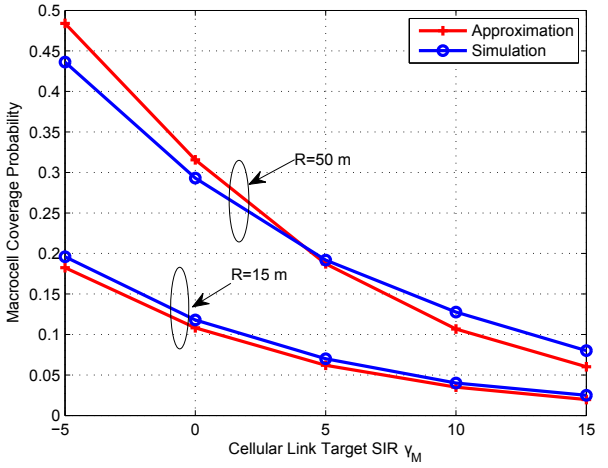


Fig. 5. Comparison between approximated values and simulation results for the macrocell coverage probability.

dB and $R = 29.7$m for $\gamma_D = 10$ dB. From Fig. 6 we have the optimal radius as $R = 20$m for $\gamma_D = 5$ dB and $R = 30$m for $\gamma_D = 10$ dB, evincing that (27) provides a very good approximation of the optimal guard zone radius.

VI. Conclusions

In this paper, we studied a guard zone-based D2D underlaid cellular network with intra-tier and cross-tier dependence, where a D2D transmitter can be active only when no macro BSs or other active D2D transmitters lie in its guard zone. We derived analytical bounds as well as approximation for the coverage probability of both cellular and D2D links, which have been proven to be very accurate. We evaluated the D2D area spectral efficiency as a function of the guard zone radius and provided the approximate optimal radius that maximizes the network throughput.

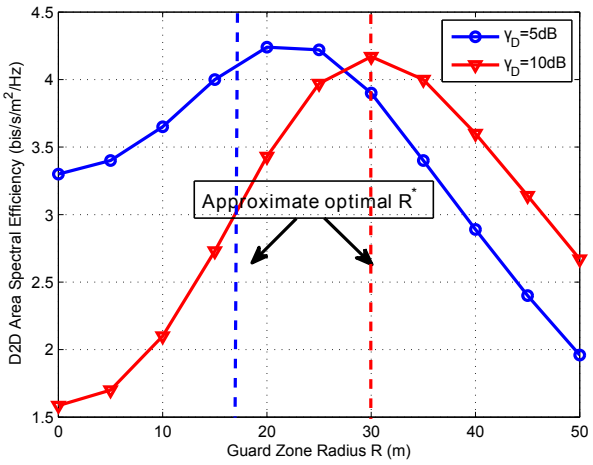


Fig. 6. Area spectral efficiency of D2D network vs. guard zone radius with target SIR $\gamma_D = 5$ dB and 10 dB.

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