Effectiveness of Guard Zone in Mitigating Interference in D2D Underlaid Cellular Networks

Amira Mohamed[1*], Mohamed H. Mousa[2] and Hamed Nassar[3]

[1*] Computer Science Department, Suez Canal University, Ismailia, Egypt.
amira.eleff@ci.suez.edu.eg, Orcid: https://orcid.org/ 0000-0002-0635-4307

[2] Department of Computer Science & Artificial Intelligence, College of Computer Science and Engineering, University of Jeddah, Jeddah, Saudi Arabia. mhmousa@uj.edu.sa,
Orcid: https://orcid.org/ 0000-0002-0733-2919

[3] Computer Science Department, Suez Canal University, Ismailia, Egypt. nassar@ci.suez.edu.eg,
Orcid: https://orcid.org/ 0000-0001-8528-5102

Received: May 29, 2023; Accepted: July 10, 2023; Published: September 30, 2023

Abstract

Device-to-device (D2D) communications, a promising technology, let cellular devices that are close to each other connect with one another directly, by passing the network infrastructure. As such, the technology provides the cellular network with many benefits, such as higher sum data rates, lower latency, extended coverage, higher energy efficiency, added security, higher spectral efficiency, and more useful services like inexpensive file caching. However, it comes with a cost—the interference underlaid D2D users inflict on cellular users at the base station when both use the same uplink frequency, which is the prefered reuse mode. This cost can, however, be reduced using a guard zone—a disk around the base station (BS) where D2D communications are not allowed. This simple and easy to implement approach, which has unfortunately not received enough research attention, is demonstrated in the present article to be highly effective in reducing the interference to cellular users. We leverage for this demonstration the mathematical tool of stochastic geometry. With the assumption that the BSs are distributed as a Poisson point process (PPP), we construct an analytical model to characterize the coverage probability of the cellular user in the presence of D2D nodes. The numerical results obtained, which are validated by rigorous Monte Carlo simulations, confirm that the guard zone approach is highly effective in protecting the cellular user from potential D2D interference.

Keywords: Cellular Network, Inband D2D, Underlay, Caching, Stochastic Geometry.

1 Introduction

A new communications paradigm in cellular networks that is gaining wide use is device to-device (D2D) connections (Kar, U.N., 2020). They paradigm allows transmission between a user equipment (UE) and another UE in close proximity, thus by-passing the cellular network infrastructure. In general, single-hop communications can be used, from a D2D link connecting a transmitter UE and its intended recipient UE, although multihop modes are also possible. As such, D2D offloads traffic of the network

Journal of Wireless Mobile Networks, Ubiquitous Computing, and Dependable Applications (JoWUA), volume: 14, number: 3 (September), pp. 112-124 DOI: *10.58346/JOWUA.2023.I3.021*

*Corresponding author: Computer Science Department, Suez Canal University, Ismailia, Egypt.

infrastructure, resulting in a number of advantages like enhanced throughput, decreased back-haul load, increased spectrum efficiency, increased coverage, improved energy efficiency, low latency, and fairness (Giordani, M., 2020). In addition, D2D creates new possibilities for proximity-based commercial services such as social networking apps, public safety, local data transfer, and data flooding. Other benefits of D2D include content privacy and strong anonymity, as the service provider is not involved for storing the shared information. They also include improving the ability to inexpensively cache popular content in a distributed fashion in order to make this content easier and faster to retrieve later by network users. Further, they include secure communications during natural disasters, such as earthquakes, when network infrastructure is damaged or rendered out of service. For all these benefits, D2D is envisaged to be part of future 5G and 6G cellular network installations (Zhang, Z., 2019).

The idea of direct D2D communications, also referred to as sidelink communications, is not new. As a part of 3GPP Release 12, it was initially launched for LTE (Kar, U.N., 2020). A decade ago, Qualcomm created the FlashLinQ D2D demonstration system and made public the need for the creation of a specific wireless technology to allow D2D on mobile devices. In order to expand coverage and throughput, D2D was initially designed for relaying applications that let mobile devices transmit radio signals in cellular networks (Kang, M., 2020). In December 2012, a consensus was reached on Release 12 of the proximity services feasibility study (ProSe), which enables physically close devices to identify and connect with one another directly. D2D is frequently referred to as LTE Direct due to its capacity to provide direct communication between UEs utilising licenced spectrum and the entire LTE ecosystem (Dahlman, E., 2021). Later LTE releases focused on the vehicle-to-vehicle (V2V) use case and enhanced it further (Peisa, J., 2020). The article (Fodor, G., 2016) discusses the specifics of a conceptual framework for integrating D2D into the current networks.

A basic issue with D2D is how to divide the spectrum between cellular and D2D communications (Jiang, Y., 2015). Based on whether they use the spectrum licensed for the cellular network, Inband and outband D2D communications fall into two broad groups. Inband D2D communications operate on the same spectrum used by the cellular network, whereas outband D2D communications operate on the unlicensed ISM (industrial, scientific, and medical) band. That is, inband D2D modes allow frequency reuse, whereas outband complement cellular resources. Inband D2D communications can be further separated into overlay and underlay modes depending on the spectrum sharing technique. Since D2D and cellular users are given orthogonal (non-overlapping) time and frequency resources in overlay communications, there is no interference between them (Hasan, M., 2015), but spectrum efficiency is degraded. In underlay communications, used in the present article, D2D and cellular users share the same time/frequency resources. That is, the spectrum is split into bands that D2D and cellular users can independently and haphazardly access.

Finally, D2D communication underlaying cellular networks can use the frequencies of either downlinks or uplinks (Ron, D., 2021). Reusing the uplink band, as is the case in the present article, is safer than the downlink, as the uplink transmission covers only a smaller portion of the cell resulting in interference that is more localized (Huynh, T., 2016). Another fundamental D2D issue is how D2D users select their mode of operation. Depending on how far apart the potential D2D transmitter and receiver are from one another, they can choose between sending data directly or using a base station (BS) (Khan, M.I., 2017).

Device discovery can be either centralized or distributed (Ziadi, K., 2022). In the former, the concerned device informs the BS about its intention to connect with a nearby device. Specifically, the device transmits a discovery signal to the BS to find out the neighboring devices (Adnan, M.H., 2020). That is, the BS assists the devices in finding one another after obtaining specific data like power, channel conditions, and the interference control mechanism. In other words, the BS is involved in exchanging the SINR and gain path of each device. Finally, both devices will be permitted by the BS to start a session. In the case of distributed device discovery, the devices independently find one another without using the BS (Gong, L., 2020).

In this article, we characterize the coverage probability of a cellular user in the presence of underlay D2D communications that use the uplink frequency, employing a guard zone around the BS within which D2D communications are not allowed. The guard zone (Lv, S., 2016), in the form of a disk centered at the BS, can extend in the cell as far away from the BS as the administrator desires. When inside the guard zone, the UE can neither initiate nor respond to a D2D pairing request. The UE can discover whether it is inside the guard zone by estimating its distance to the BS and comparing it with the radius of the guard zone. Only if the distance is larger, can the UE engage in a D2D session. It is clear then that the guard zone approach to mitigating interference in underlaid D2D that use uplink frequencies is simple and easy to implement. In fact it can be implemented without any hardware change to the cellular mobile. However, the approach has not received enough research attention to assess its effectiveness, and that is where the present article comes in. Using stochastic geometry as a vehicle, and assuming that the D2D nodes form a Poisson point process (PPP), we characterize the coverage probability of the cellular user in the presence of D2D users operating outside the guard zone. The PPP provides mathematical tractability for modeling the spatial distribution of the D2D nodes, and as such has been used quite frequently to derive compact analytical expressions for the coverage probability and data transmission capacity of cellular and D2D users (Zhu, L., 2022).

The rest of the article is organized as follows. A survey of recent work on D2D underlaid cellular networks is presented in Section 2. The system model is provided in Section 3. Section 4 covers the numerical results obtained both from the derived analytical expression and Monte Carlo simulation, for some sample systems. In Section 5 we provide our concluding remarks.

2 Related Work

Due to its promising viability, D2D has enjoyed in recent years a great body of research which covers the subject from many angles. For example, numerous studies have been carried out to investigate resource allocation in D2D underlay communications, as in (Zhou, Z., 2015) where an energy-efficient resource allocation scheme for D2D communications underlaying LTE networks is considered. This scheme was generalized in (Zhou, Z., 2016) where the authors created the concept of resource allocation using energy-efficient matching in cellular networks with D2D capabilities. In a similar manner, the authors of (Sun, Y., 2022) use a non-cooperative game to examine power control and resource allocation in D2D communications that underlay cellular networks. Throughput maximization is addressed via distributed resource allocation that combines power regulation and spectrum allocation, with the existence and uniqueness of Nash equilibrium established. In (Hakami, V., 2022), a D2D resource allocation scheme with unknown channel state information is presented. Using graph theory, the optimization strategy is described as a weighted bipartite matching problem. Some studies of D2D using downlink sharing have also appeared in the literature, such as (Zeng, R., 2019), where frequency uplink sharing is the preferred mode, as justified earlier.

Power control for D2D enabled cellular networks has also attracted considerable research interest (Yin, R., 2015). It can be defined as the process of optimizing the transmit powers of both the BS (during downlink) and UE (during uplink). This control is, however, easier said than done. Simply, the optimization of transmit power is generally classified as NP-hard with linear constraints (Nadeem, L., 2021). In all cases, the two main categories of power control algorithms are distributed and centralised.

The BS is in charge of power control for centralised algorithms, whereas the UE is in charge of power control for distributed algorithms (Yin, R., 2015). Deep reinforcement learning is used in (Abdallah, A., 2018), in the context of underlaid uplink cellular networks, to optimize the transmit power for both D2D and cellular users.

There are also studies that focus on both resource sharing and power control together. To enhance the security of D2D communication and cellular networks, power control and resource block (RB) assignment are addressed in (Ashtiani, A.F., 2020). The RB assignment scheme is simplified to a 3D matching issue that is solved by a tabu search algorithm. Assignments are addressed to improve security of D2D communication and cellular networks. The improper Gaussian signaling (IGS) for coexisting multiple-input single-output cellular networks with D2D communication is introduced in (Nguyen, H.T., 2021), between cellular users and D2D pairs. Both non-orthogonal and orthogonal frequency sharing are lavishly studied.

A great deal of studies have focused on using D2D for caching and content placement purposes (Prerna, D., 2020). In (Lin, Y., 2022), the study offers a D2D network caching method that performs effectively. By shifting the robot helpers to the best positions determined via partitioned adaptive particle swarm optimization, the authors determine the best caching technique for D2D networks. In order to increase cache hit probability in D2D underlaid networks, a near-optimal content placement approach in cellular D2D networks is studied in (Feng, G., 2020), where the caching problem is formulated as a submodular function maximization problem under a matroid constraint. The solution is given by a greedy algorithm. In (Meng, Y., 2021), cache and energy harvesting in D2D-enabled cellular networks are studied and content delivery strategies are introduced.

D2D communications and non-orthogonal multiple access (NOMA), which allows several users to send and receive signals on the same channel resources (time/frequency) in the coding domain (CD) or power domain (PD), have been studied frequently. This has been effective in increasing network capacity and lightening the load on the conventional cellular network (Kai, C., 2021). In (Yu, S., 2021), in order to address the issue of optimal power allocation for NOMA enabled D2D communications with faulty SIC decoding, a subgradient algorithm is used. In (Uddin, M.B., 2020), NOMA is used in full-duplex (FD) D2D cooperative relaying. In particular, for a transmitter that concurrently transmits the signal of a D2D receiver and relays the signal of a distant NOMA user, the ergodic capacity, outage probability, and diversity order are characterized. In (Huang, B., 2021), a multi-agent reinforcement learning scheme to deal with the limited D2D computing, network and battery capacity constraints is employed, based on cost-aware collaborative task-execution.

One downside of underlaid D2D, which is the subject of the present article, is the interference it causes to the cellular user. Inherently, D2D interference to the cellular uplinks is curtailed by allowing only close neighbors to engage in D2D communications. However, interference management schemes are still needed to mitigate the problem. These schemes fall into three categories: interference cancellation, interference coordination and interference avoidance (Uddin, M.B., 2020), with the latter being the case when a guard zone, such as the one examined in the present article, is used. A guard zone is a good approach to reduce interference to the cellular user (Lv, S., 2016), and it is sad it has not received enough serious research. It is basically a disk around the BS where no UE is allowed to participate in D2D communications, either as a transmitter or as a receiver. That is, when inside the guard zone, the UE can neither initiate nor respond to a D2D pairing request. In (Chu, M., 2021), an analysis for energy harvesting is given in the presence of a guard zone, where underlaid D2D are powered by energy harvested from radio signals of the cellular system. It should be noted, however, that it is technically difficult to use a guard zone in such environment since the original distribution of energy arrival would be changed.

A mathematical branch that has proved useful for modelling and analyzing D2D is stochastic geometry (Zhu, L., 2022). This branch, which is the main tool in the present article, allows modelling the D2D nodes as a PPP, which allows excellent tractability, as is the case in (Mustafa, H.A., 2015). In (Chu, M., 2021), stochastic geometry is used to analyze energy harvesting in underlaid D2D. In (Meng, Y., 2021), cache and energy harvesting in D2D-enabled cellular networks are studied with stochastic geometry used to compute the cache hit probability and successful transmission probability. In (Lin, X., 2014), the authors discuss how D2D users should acquire spectrum and pick between direct communication and using a BS when it comes to overlay and underlay options. In (Ma, Z., 2020), a Poisson hole cluster process is used to perform a performance analysis of D2D underlaying cellular networks. To better capture the idiosyncrasies of hot spots and cell edges, where the majority of mobile UEs exist, a Poisson Hole Process and Thomas Cluster Process are also used. A study of an underlay cellular network that is helped by D2D is provided in (Zhu, L., 2022). An analytical framework for the occurrence of uplink cellular and D2D in the same frequency is provided, with D2D devices assumed a Poisson Cluster Process (PCP) and cellular users assumed a PPP. In the present article, we will also use stochastic geometry to derive an analytical expression for the coverage probability of a cellular user present among D2D devices, with the latter assumed a PPP.

3 System Model

A guard zone, shown in Figure 1, is a disk of a predefined radius $\mathcal{R}_0$ centered at the BS, which is also the center of a cell of radius $\mathcal{R}$. D2D communications are prohibited within the guard zone with the aim to reduce interference at the BS to uplink cellular transmissions, as both D2D and cellular communications are assumed to use the same frequency band. A guard zone approach can be implemented easily by the UE without any hardware change. All the UE has to do before engaging in D2D, by either issuing a D2D pairing request or responding to one, is to estimate its distance to the BS. If that distance is greater than the guard zone radius $\mathcal{R}_0$ the UE can engage; else, it cannot. The ultimate aim is to reduce the interference caused to the cellular user by the D2D users. This interference will be assessed analytically below. We will assess the effectiveness of the guard zone approach in mitigating the D2D interference to the cellular user, by characterizing the coverage probability of the cellular user. The coverage probability is defined as the probability that the signal to interference ratio (SIR) exceeds a desired threshold ξ . Its characterization will be achieved using stochastic geometry, where the D2D nodes are modelled as a PPP.

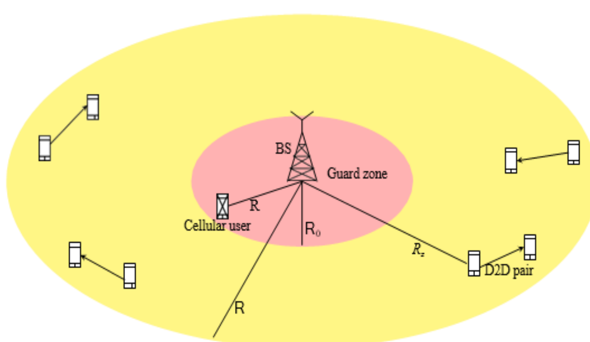

Figure 1: Cell with a Guard Zone Where D2D is not Allowed

The cellular user is located in the cell at some point(R, Θ), where R and Θ are each a uniformly distributed random variable (RV), with $0 < R \leq \mathcal{R}$ and $0 < \Theta \leq 2\pi$. The uniform distribution of Θ implies that.

$$f_{\Theta}(\theta) = \frac{1}{2\pi}. \tag{1}$$

To find the uniform distribution of R, consider a point at distance R = r from the center O of the cell. Then, the cumulative distribution $F_R(r) = \mathbb{P}[R \leq r]$ of R is given by.

$$F_R(r) = \frac{\pi r^2}{\pi \mathcal{R}^2} = \frac{r^2}{\mathcal{R}^2}.$$

Differentiating, we get the distribution of R as

$$f_R(r) = \frac{d}{dr} F_R(r) = \frac{2r}{\mathcal{R}^2}. \tag{2}$$

We can do the same for a D2D node randomly located in the ring $\mathcal{R}_0 < R_D \leq \mathcal{R}$ at a distance R_D away from the BS. Using the same methodology as above, we can get

$$f_{R_z}(r) = \frac{2r}{\Delta\mathcal{R}}. \tag{3}$$

Where $\Delta\mathcal{R} = \mathcal{R}^2 - \mathcal{R}_0^2$.

Let the D2D nodes be modelled as a PPP Φ of density λ. Additionally, consider that Rayleigh fading and distance-dependent path loss are features of the channel model. Further, assume that the transmit power is constant for both the cellular and D2D users, with values p and p_D, respectively. Typically, we set $p_D \ll p$ for two reasons. The first is to further reduce the D2D interference to the cellular user at the BS. The second is to conserve the energy of the D2D nodes since they are paired based on their being in close proximity in the first place. Finally, it is assumed that a radio signal weakens while propagating in the cell with distance in accordance with the known power-law path loss model, with path loss exponent $\alpha > 2$. In other words, the mean received power at distance r away from a transmitter of power p will be $pr^{-\alpha}$. We will incorporate random channel effects by a multiplicative RV G_z for the UE located at point z. The G_z are assumed independent and identically distributed (iid), following an exponential distribution with mean 1. That is, $G \sim exp(1)$ and $G_z \sim exp(1)$. The RV G_z for the cellular user will be denoted by G for simplicity.

With the above in mind, let I_D be a RV denoting the interference at the BS that is caused by all D2D users and harming the uplink signal of a cellular user. This interference I_D is due to every D2D device z in the ring outside the guard zone at distance R_z, $\mathcal{R}_0 < R_z \leq \mathcal{R}$ from the BS, as shown in Figure 1. Based on the above, this interference is given by

$$I_D = \sum_{z \in \Phi} p_D G_z R_z^{-\alpha}, \tag{4}$$

The SIR at the BS is thus given by.

$$\mathrm{SIR} = \frac{pGR^{-\alpha}}{I_D}, \tag{5}$$

Now, the goal is to derive an expression for the uplink coverage probability defined as

$$p_u = \mathbb{P}[\mathrm{SIR} > \xi], \tag{6}$$

where ξ is a positive real number representing some desired SIR threshold.

Using (4) and (5) in (6), the uplink coverage probability can be written as

$$p_u = \mathbb{P}\left[\frac{pGR^{-\alpha}}{I_D} > \xi\right]$$
$$= \mathbb{P}\left[G > \frac{\xi}{p} R^{\alpha} I_D\right]$$
$$\stackrel{(a)}{=} \mathbb{E}_{I_D}\left[\mathbb{P}\left[G > \frac{\xi}{p} R^{\alpha} I_D\right]\right]$$
$$\stackrel{(b)}{=} \mathbb{E}_{I_D}\left[e^{-\frac{\xi}{p} R^{\alpha} I_D}\right]$$
$$= \mathcal{L}_{I_D}\left(\frac{\xi}{p} R^{\alpha}\right) \tag{7}$$

where for any RV A the expectation

$$\mathcal{L}_A(s) = \mathbb{E}[e^{-sA}] = \int_0^{\infty} e^{-st} f_A(t)dt \tag{8}$$

is the Laplace transform of (the distribution of) A. In (a) we utilized the fact that we can write the probability $\mathbb{P}[A > B]$ as $\mathbb{E}_{\mathrm{B}}\big[\mathbb{P}[A > B]\big]$ $\big(\text{or}\mathbb{E}_{\mathrm{A}}\big[\mathbb{P}[A > B]\big]\ \big)$, and in (b) we made use of the fact that $G \sim exp(1)$, i.e. $f_{\mathrm{G}}(\mathrm{r}) = e^{-\mathrm{r}}$. We will now embark on deconditioning (averaging) (*7*) on all the RVs involved.

We start by deconditioning p_u on R, the distance between the cellular user from the BS, which is uniformly distributed between 0 and R, as given by (3) . Although the PPP covers the (infinite) Euclidean plane, we will consider only the D2D nodes in the cell, thus limiting the integral to the cell end, i.e., $r = \mathcal{R}$, getting.

$$p_u = \int_0^{\mathcal{R}} \mathcal{L}_{I_D}\left(\frac{\xi}{p} r^{\alpha}\right) f_R(r)dr$$
$$= \frac{2}{\mathcal{R}^2}\int_0^{\mathcal{R}} \mathcal{L}_{I_D}\left(\frac{\xi}{p} r^{\alpha}\right) rdr \tag{9}$$

Next, we will decondition the Laplace transform $\mathcal{L}_{I_D}$ on the $\mathrm{G_z}$ and Φ, with the latter via the PGFL. From (4) and (8), we get.

$$\mathcal{L}_{I_D}(s) = \mathbb{E}[e^{-sI_D}]$$
$$= \mathbb{E}_{\Phi,G_z}\left[e^{-s\sum_{\mathrm{z}\epsilon\Phi} \mathrm{p_D} G_z R_z^{-\alpha}}\right]$$
$$= \mathbb{E}_{\Phi,G_z}\left[\prod_{\mathrm{z}\epsilon\Phi} e^{-s\,\mathrm{p_D} G_z R_z^{-\alpha}}\right]$$
$$\stackrel{(a)}{=} \mathbb{E}_{\Phi}\left[\prod_{\mathrm{z}\epsilon\Phi} \mathbb{E}_{G_z}\left[e^{-s\,\mathrm{p_D} G_z R_z^{-\alpha}}\right]\right]$$
$$\stackrel{(b)}{=} \mathbb{E}_{\Phi}\left[\prod_{\mathrm{z}\epsilon\Phi\backslash\{\mathrm{b}\}} \mathcal{L}_{G_z}\left(s\,\mathrm{p_D} R_z^{-\alpha}\right)\right]$$
$$\stackrel{(c)}{=} exp\left(-\lambda \int_{\mathbb{R}^2\backslash D(O,\mathcal{R}_0)} f\left(\mathcal{L}_{G_z}\right)\right) \tag{10}$$

Where $f\left(\mathcal{L}_{G_z}\right) = 1 - \mathcal{L}_{G_z}(s\mathrm{p_D}R_z^{-\alpha})$ and $D(O, \mathcal{R}_0)$ is the disk centered at the origin (BS) with radius $\mathcal{R}_0$. We consider this disk an exclusion zone, as the points of the PPP Φ lie outside of it. In (a) we exploited the assumption that the $\mathrm{G_z}$ are independent, and in (b) we used of the definition (8) of the

Laplace transform. In (c), we invoked the PGFL $\mathbb{E}_{\Phi}\left[\Pi_{z\epsilon\Phi} f(R_z)\right]$, with $f(R_z) = \mathcal{L}_{G_z}(spD_z^{-\alpha})$, to decondition on the function $\mathcal{L}_{G_z}(s\mathrm{p_D}R_z^{-\alpha})$ at all the points z of the PPP Φ. Although the points of the PPP exist theoretically everywhere in the Euclidean plane, we will consider as an approximation only those in the ring bounded by the two radii $\mathcal{R}_0$ and R. Using polar coordinates, and using the fact that $f_{G_z}(t) = e^{-t}$ so that $\mathcal{L}_{G_z}(s) = 1/(1+s)$, the Laplace transform on the RHS of (10) yields

$$\mathcal{L}_{G_z}(sp_D R_z^{-\alpha}) = \frac{1}{1+s\mathrm{p_D}R_z^{-\alpha}}$$

Substituting this in (*10*), with the interferer now at a specific point (x,θ), we get

$$\mathcal{L}_{I_D}(\mathrm{s}) = \exp\left(-\lambda \int_{\mathcal{R}_0}^{\mathcal{R}} \int_0^{2\pi} \mathcal{L}_{G_z}(s\mathrm{p_D}R_z^{-\alpha})\, \mathrm{d}\theta x\, dx\right)$$
$$= \exp\left(-2\tilde{\lambda} \int_{\mathcal{R}_0}^{\mathcal{R}} \left(\frac{s\mathrm{p_D}x^{-\alpha}}{1+s\mathrm{p_D}R_z^{-\alpha}}\right) x\, dx\right),$$

Where $\tilde{\lambda} = \lambda\pi$.

Now, we will decondition $\mathcal{L}_{I_D}(\mathrm{s})$ on the R_z which are uniformly distributed as per (3) to get.

$$\mathcal{L}_{I_D}(\mathrm{s}) = \exp\left(-2\tilde{\lambda} \int_{\mathcal{R}_0}^{\mathcal{R}} \left(\int_{\mathcal{R}_0}^{\mathcal{R}} \frac{s\mathrm{p_D}x^{-\alpha}}{1+s\mathrm{p_D}y^{-\alpha}} f_{R_z}(y)\, dy\right) x\, dx\right)$$
$$= \exp\left(-2\tilde{\lambda} \int_{\mathcal{R}_0}^{\mathcal{R}} \left(\int_{\mathcal{R}_0}^{\mathcal{R}} \frac{s\mathrm{p_D}x^{-\alpha}}{1+s\mathrm{p_D}y^{-\alpha}} \frac{2y}{\Delta\mathcal{R}}\, dy\right) x\, dx\right)$$
$$= \exp\left(-\frac{4\tilde{\lambda}}{\Delta\mathcal{R}} \int_{\mathcal{R}_0}^{\mathcal{R}} x^{-\alpha} \left(\int_{\mathcal{R}_0}^{\mathcal{R}} \frac{s\mathrm{p_D}y}{1+s\mathrm{p_D}y^{-\alpha}}\, dy\right) x\, dx\right).$$

From this result, we can write.

$$\mathcal{L}_{I_D}\left(\frac{\xi}{p} r^{\alpha}\right) = \exp\left(-\frac{4\tilde{\lambda}}{\Delta\mathcal{R}} \int_{\mathcal{R}_0}^{\mathcal{R}} \left(\int_{\mathcal{R}_0}^{\mathcal{R}} \frac{\frac{\xi}{p} r^{\alpha}\mathrm{p_D}x^{-\alpha}}{1+\frac{\xi}{p} r^{\alpha} p_D y^{-\alpha}}\, y\, dy\right) x\, dx\right)$$
$$= \exp\left(-\frac{4\tilde{\lambda}}{\Delta\mathcal{R}} \int_{\mathcal{R}_0}^{\mathcal{R}} \left(\int_{\mathcal{R}_0}^{\mathcal{R}} \frac{\frac{\xi}{p}\left(\frac{r}{x}\right)^{\alpha}\mathrm{p_D}}{1+\frac{\xi}{p}\left(\frac{r}{y}\right)^{\alpha}\mathrm{p_D}}\, y\, dy\right) x\, dx\right)$$

Substituting this in (9) we get our final result.

$$p_u = \frac{2}{\mathcal{R}^2} \int_0^{\mathcal{R}} \mathcal{L}_{I_D}\left(\frac{\xi}{p} r^{\alpha}\right) r dr$$
$$= \frac{2}{\mathcal{R}^2} \int_0^{\mathcal{R}} e^{-\frac{4\tilde{\lambda}}{\Delta\mathcal{R}} \int_{\mathcal{R}_0}^{\mathcal{R}} \left(\int_{\mathcal{R}_0}^{\mathcal{R}} \frac{\frac{\xi}{p}\left(\frac{r}{x}\right)^{\alpha} p_D}{1+\frac{\xi}{p}\left(\frac{r}{y}\right)^{\alpha} p_D}\, y\, dy\right) x\, dx} r\, dr$$
$$= \frac{2}{\mathcal{R}^2} \int_0^{\mathcal{R}} e^{-\frac{4\tilde{\lambda}}{\Delta\mathcal{R}} \int_{\mathcal{R}_0}^{\mathcal{R}} \mathfrak{p} x \xi \left(\frac{\mathrm{r}}{x}\right)^{\alpha} \left(\int_{\mathcal{R}_0}^{\mathcal{R}} \frac{\mathrm{y}}{1+\mathfrak{p}\xi\left(\frac{\mathrm{r}}{\mathrm{y}}\right)^{\alpha}}\, dy\right) dx} r\, dr \qquad (11)$$

Where $\mathfrak{p} = p_D/p$. is the D2D to cellular transmit power ratio.

4 Numerical Results

In this section, we will run several experiments to examine the effectiveness of a guard zone on mitigating D2D interference to the cellular user. In particular, we will focus on the effect of the guard zone on the uplink coverage probability p_u of the cellular user in the presence of underlay D2D communications outside the guard zone. Three experiments have been carried out: one to study the specific effect of the D2D node density λ, one to study the specific effect of the cellular and D2D transmit powers p and p_D, respectively, and one to study the specific effect of the desired threshold ξ . The results for these experiments are obtained twice, once from the derived analytical expression (11), and once from a Monte Carlo simulation program written in MATLAB by the authors to validate the results obtained analytically. For each experiment, 5000 simulation runs were used, which were found enough to reach convergence. In all the experiments of this section, the cell radius is set at $\mathcal{R} = 5000$ meters, which is large enough from a practical point of view and also large enough to allow experimenting with a wide range of guard zone radii. We assume that the D2D nodes use time division duplexing, suitable for such data communications applications as caching. In this duplexing mode, the two nodes of a D2D pair alternate between transmission and reception. A practical simulation implication of this is that not all active D2D nodes cause interference, but only half of them—the half that is currently transmitting.

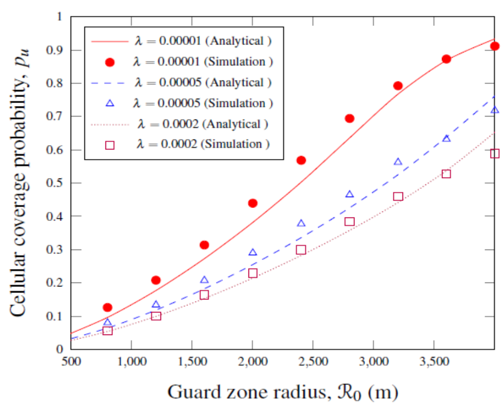

Figure 2: Coverage Probability vs Guard Zone Radius for Three Different λ Values

The output of the first experiment is shown in Figure 2, where the analytical results are displayed as a curve and the simulation results as bullets. For this experiment, the cellular transmit power is set as $p = 100$ mW, the D2D transmit power is set at $p_D = 0.5$ mW , the power loss exponent is set at $\alpha = 8$, and the SIR threshold is set at $\xi = -10\ dB$. The experiment is repeated for three D2D densities, namely $\lambda \epsilon \{0.00001, 0.00005, 0.0002\}$ node/m2. The coverage probability is sketched against the radius $\mathcal{R}_0$ of the guard zone. As can be seen, the coverage probability increases nonlinearly as the radius of the guard zone increases, for any value of λ. This is logical, as the greater the guard zone radius the farther away the D2D communications, hence the lower their interference at the BS to the cellular user. On the other hand, if we stay at a given radius value and focus on the change of the coverage probability against the D2D node density λ, we can see an opposite behavior. Namely, the coverage probability decreases as λ increases. This is also logical, as the greater the D2D node density within the ring outside the guard zone the greater interference to the cellular user, hence the lower the SIR and consequently the coverage probability. We can see that the simulation result agrees reasonably well with the analytical result. The little deviation between the two is due to the approximation adopted in the analysis where we considered as a source of interference only the D2D nodes in the ring $\mathcal{R}_0 < R_z \leq \mathcal{R}$, and integrated accordingly in (11), whereas in theory the PPP exists everywhere in the Euclidean plane.

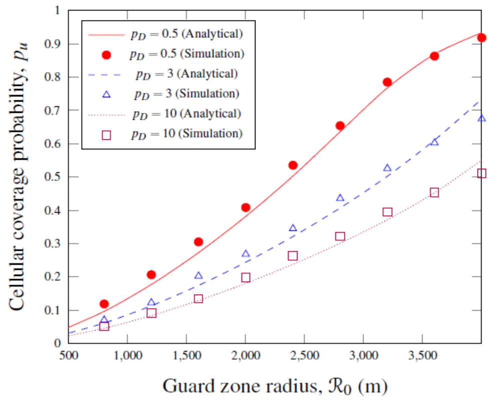

Figure 3: Coverage Probability vs. Guard Zone Radius for Different D2D Transmit Power p_D Values

The output of the second experiment is shown in Figure 3. For this experiment, we set $\lambda = 0.00001$ nodes/m2 and $p = 100$ mW, $\alpha = 8$ and $\xi = -10\ dB$. Here we repeat the experiment three times each with a different D2D transmit power, namely $p_D \in \{0.5, 3, 10\}$ mW. As can be seen, the coverage probability increases nonlinearly as the radius of the guard zone increases, regardless of the value of p_D. This is logical, using the same reasoning in the first experiment. On the other hand, if we consider a fixed radius and focus on the change of the coverage probability against the D2D node density λ, we can see an opposite behavior. Namely, the coverage probability decreases as p_D increases. This is also logical, as the greater the D2D transmit power the greater interference to the cellular user, hence the lower the coverage probability.

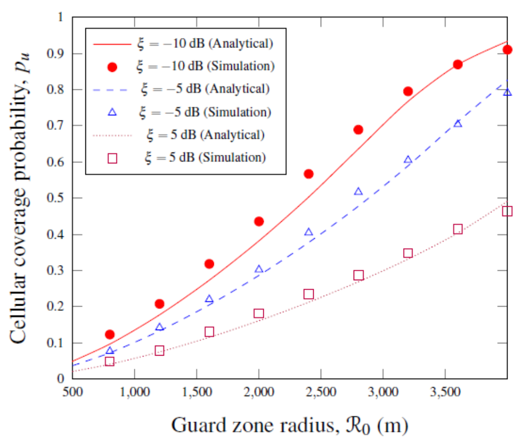

Figure 4: Coverage Probability vs. Guard Zone Radius for Different SIR Threshold ξ Values

Finally, the output of the third experiment is shown in Figure 4. For this experiment, we set $\lambda = 0.00001$ nodes/m2, $p = 100$ mW, $p_D = 0.5$ mW, and $\alpha = 8$. Here we repeat the experiment three times each with a different SIR threshold, namely $\xi \in \{-10, -5, 5\}\ dB$. As in the first two experiments, the coverage probability increases nonlinearly as the radius of the guard zone increases, regardless of the value of ξ . This is logical, as was mentioned in the two previous experiments. On the other hand, if we fix the radius at some value and focus on the change of the coverage probability against the SIR threshold ξ , we can see an opposite behavior. Namely, the coverage probability decreases as ξ increases. This is also logical, as the greater the SIR threshold ξ the higher our coverage benchmark, hence the lower the coverage probability.

5 Conclusions

In this article we have used stochastic geometry to assess the effectiveness of a guard zone approach in mitigating the interference caused by D2D users underlaying a cellular network. We have derived an analytical expression for the coverage probability of a typical cellular user in the presence of D2D users exporting interference from outside the guard zone to the signal of the cellular user at the BS, given that both types of users operate on the same uplink band simultaneously. We have obtained numerical results from the expression and validated them by Monte Carlo simulations, getting a fairly close match between the two. The numerical results attest to the feasibility of the guard zone approach in achieving its intended interference reduction goal. Coupled with its simplicity and ease of implementation, the guard zone seems a viable solution for mitigating D2D interference in cellular networks.

References (APA)

[1] Abdallah, A., Mansour, M.M., & Chehab, A. (2018). Power control and channel allocation for D2D underlaid cellular networks. *IEEE Transactions on Communications*, *66*(7), 3217-3234.

[2] Adnan, M.H., & Ahmad Zukarnain, Z. (2020). Device-to-device communication in 5G environment: Issues, solutions, and challenges. *Symmetry*, *12*(11), 1-22.

[3] Ashtiani, A.F., & Pierre, S. (2020). Power allocation and resource assignment for secure D2D communication underlaying cellular networks: A Tabu search approach. *Computer Networks*, *178*.

[4] Chu, M., Liu, A., Chen, J., Lau, V.K., & Cui, S. (2021). A stochastic geometry analysis for energy-harvesting-based device-to-device communication. *IEEE Internet of Things Journal*, *9*(2), 1591-1607.

[5] Dahlman, E., Mildh, G., Parkvall, S., Persson, P., Wikström, G., & Murai, H. (2021). 5G evolution and beyond. *IEICE Transactions on Communications*, *104*(9), 984-991.

[6] Feng, G., Wang, Y., Li, B., Li, Y., Lv, H., Wang, C., & Wang, H. (2020). A near-optimal content placement in D2D underlaid cellular networks. *Peer-to-Peer Networking and Applications*, *13*(5), 1799-1813.

[7] Fodor, G., Roger, S., Rajatheva, N., Slimane, S.B., Svensson, T., Popovski, P., & Ali, S. (2016). An overview of device-to-device communications technology components in METIS. *IEEE Access*, *4*, 3288-3299.

[8] Giordani, M., Polese, M., Mezzavilla, M., Rangan, S., & Zorzi, M. (2020). Toward 6G networks: Use cases and technologies. *IEEE Communications Magazine*, *58*(3), 55-61.

[9] Gong, L., Zhang, Y., Li, N., Gu, Z. K., Ding, B., & Zhu, C. Y. (2020). Molecular investigation on the displacement characteristics of CH4 by CO2, N2 and their mixture in a composite shale model. *Energies*, *14*(1), 1-13.

[10] Hakami, V., Barghi, H., Mostafavi, S., & Arefinezhad, Z. (2022). A resource allocation scheme for D2D communications with unknown channel state information. *Peer-to-Peer Networking and Applications*, *15*(2), 1189-1213.

[11] Hasan, M., & Hossain, E. (2015). Distributed resource allocation in D2D-enabled multi-tier cellular networks: An auction approach. *In IEEE international conference on communications (ICC)*, 2949-2954.

[12] Huang, B., Liu, X., Wang, S., Pan, L., & Chang, V. (2021). Multi-agent reinforcement learning for cost-aware collaborative task execution in energy-harvesting D2D networks. *Computer Networks*, *195*, 1-23.

[13] Huynh, T., Onuma, T., Kuroda, K., Hasegawa, M., & Hwang, W.J. (2016). Joint downlink and uplink interference management for device-to-device communication underlaying cellular networks. *IEEE Access*, *4*, 4420-4430.

[14] Jiang, Y., Liu, Q., Zheng, F., Gao, X., & You, X. (2015). Energy-efficient joint resource allocation and power control for D2D communications. *IEEE Transactions on Vehicular Technology*, *65*(8), 6119-6127.

[15] Kai, C., Wu, Y., Peng, M., & Huang, W. (2021). Joint uplink and downlink resource allocation for NOMA-enabled D2D communications. *IEEE Wireless Communications Letters*, *10*(6), 1247-1251.

[16] Kang, M. (2020). The Study on the Effect of the Internet and Mobile-Cellular on Trade in Services: Using the Modified Gravity Model. Journal of Internet Services and Information Security (JISIS), 10(4), 90-100.

[17] Kar, U.N., & Sanyal, D.K. (2020). A critical review of 3GPP standardization of device-to-device communication in cellular networks. *SN Computer Science*, *1*(1), 1-18.

[18] Khan, M.I., Alam, M.M., Moullec, Y.L., & Yaacoub, E. (2017). Throughput-aware cooperative reinforcement learning for adaptive resource allocation in device-to-device communication. *Future Internet*, *9*(4), 1-17.

[19] Lin, X., Andrews, J.G., & Ghosh, A. (2014). Spectrum sharing for device-to-device communication in cellular networks. *IEEE Transactions on Wireless Communications*, *13*(12), 6727-6740.

[20] Lin, Y., Song, H., Ke, F., Yan, W., Liu, Z., & Cai, F. (2022). Optimal caching scheme in D2D networks with multiple robot helpers. *Computer Communications*, *181*, 132-142.

[21] Lv, S., Xing, C., Zhang, Z., & Long, K. (2016). Guard zone-based interference management for D2D-aided underlaying cellular networks. *IEEE Transactions on Vehicular Technology*, *66*(6), 5466-5471.

[22] Ma, Z., Nuermaimaiti, N., & Wang, L. (2020). Performance analysis of D2D-aided underlaying cellular networks based on poisson hole cluster process. *Wireless Personal Communications*, *111*, 2369-2389.

[23] Meng, Y., Zhang, Z., & Huang, Y. (2021). Cache-and energy harvesting-enabled d2d cellular network: Modeling, analysis and optimization. *IEEE Transactions on Green Communications and Networking*, *5*(2), 703-713.

[24] Mustafa, H.A., Shakir, M.Z., Imran, M.A., Imran, A., & Tafazolli, R. (2015). Coverage gain and device-to-device user density: Stochastic geometry modeling and analysis. *IEEE Communications Letters*, *19*(10), 1742-1745.

[25] Nadeem, L., Azam, M.A., Amin, Y., Al-Ghamdi, M.A., Chai, K.K., Khan, M.F.N., & Khan, M.A. (2021). Integration of D2D, network slicing, and MEC in 5G cellular networks: Survey and challenges. *IEEE Access*, *9*, 37590-37612.

[26] Nguyen, H.T., Tuan, H.D., Niyato, D., Kim, D.I., & Poor, H.V. (2021). Improper Gaussian signaling for D2D communication coexisting MISO cellular networks. *IEEE Transactions on Wireless Communications*, *20*(8), 5186-5198.

[27] Peisa, J., Persson, P., Parkvall, S., Dahlman, E., Grøvlen, A., Hoymann, C., & Gerstenberger, D. (2020). 5G evolution: 3GPP releases 16 & 17 overview. *Ericsson Technology Review*, *2020*(2), 2-13.

[28] Prerna, D., Tekchandani, R., & Kumar, N. (2020). Device-to-device content caching techniques in 5G: A taxonomy, solutions, and challenges. *Computer Communications*, *153*, 48-84.

[29] Ron, D., & Lee, J. R. (2021). DRL-based sum-rate maximization in D2D communication underlaid uplink cellular networks. *IEEE Transactions on Vehicular Technology*, *70*(10), 11121-11126.

[30] Sun, Y., Chen, Y., Wang, Z., & Liu, Z. (2022). Resource Allocation and Power Control Based on Noncooperative Game for D2D Communications Underlaying Cellular Networks. *Wireless Personal Communications*, *124*(3), 2723-2733.

[31] Uddin, M.B., Kader, M.F., & Shin, S.Y. (2020). Exploiting NOMA in D2D assisted full-duplex cooperative relaying. *Physical Communication*, *38*.

[32] Yin, R., Zhong, C., Yu, G., Zhang, Z., Wong, K.K., & Chen, X. (2015). Joint spectrum and power allocation for D2D communications underlaying cellular networks. *IEEE Transactions on Vehicular Technology*, *65*(4), 2182-2195.

[33] Yu, S., Khan, W.U., Zhang, X., & Liu, J. (2021). Optimal power allocation for NOMA-enabled D2D communication with imperfect SIC decoding. *Physical Communication*, *46*.

[34] Zeng, R., & Tepedelenlioğlu, C. (2019). Multiple device-to-device users underlaying downlink cellular networks with superposition coding. *Physical Communication*, *36*.

[35] Zhang, Z., Xiao, Y., Ma, Z., Xiao, M., Ding, Z., Lei, X., & Fan, P. (2019). 6G wireless networks: Vision, requirements, architecture, and key technologies. *IEEE vehicular technology magazine*, *14*(3), 28-41.

[36] Zhou, Z., Dong, M., Ota, K., Wang, G., & Yang, L.T. (2015). Energy-efficient resource allocation for D2D communications underlaying cloud-RAN-based LTE-A networks. *IEEE Internet of Things Journal*, *3*(3), 428-438.

[37] Zhou, Z., Ota, K., Dong, M., & Xu, C. (2016). Energy-efficient matching for resource allocation in D2D enabled cellular networks. *IEEE Transactions on Vehicular Technology*, *66*(6), 5256-5268.

[38] Zhu, L., & Sun, Y. (2022). Uplink performance analysis in D2D-enabled cellular networks with clustered users. *Wireless Networks*, 1-12.

[39] Ziadi, K., & Asvadi, R. (2022). A Device-to-Device direct discovery algorithm to mitigate the collision caused by hidden users. *Physical Communication*, *52*, 1-12.

Authors Biography

Amira Mohamed is Teacher Assistance in the Computer Science Department, Suez Canal University, Egypt. She received her B.Sc. and M.Sc. in Computer Science from the same University in 2007 and 2016 respectively. Her research interests include IoT, Wireless Networks, Modeling and Simulation.

Mohamed H. Mousa received the B.Sc. degree in computer science and pure mathematics from Ain-Shams University, Egypt, in 1996, the M.Sc. degree from Helwan University, Egypt, in 2001, and the PhD. degree from Claude Bernard University Lyon1, France, in 2007. He is Professor at the Department of Computer Science, Suez Canal University, Egypt, and is currently Associate Professor at the Department of Artificial Intelligence and Computer Science, University of Jeddah, Saudi Arabia. His research interests include high performance computing and GPU computing.

Hamed Nassar is full professor in the Computer Science Department, Suez Canal University, Egypt, since 2004. He obtained his BSc in Electrical Engineering, from Ain Shams University, Egypt, in 1979, and obtained his MSc in Electrical Engineering and PhD in Computer Engineering, from the New Jersey Institute of Technology, USA, in 1985 and 1989, respectively. Prof. Nassar has taught computer science and engineering courses in various universities in USA, Egypt, Saudi Arabia, and Lebanon. He has supervised about 50 MSc and PhD students, and published research articles in reputed international journals and conferences. His research interests include computer networks, wireless communications, cloud computing, machine learning, and mathematical modelling of computer systems, mainly using queueing theory and stochastic geometry.