

On the Performance of Successive Interference Cancellation in D2D-enabled Cellular Networks

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Abstract—Device-to-device (D2D) communication underlying cellular networks is a promising technology to improve network resource utilization. In D2D-enabled cellular networks, the interference among spectrum-sharing links is more severer than that in traditional cellular networks, which motivates the adoption of interference cancellation techniques such as successive interference cancellation (SIC) at the receivers. However, to date, how SIC can affect the performance of D2D-enabled cellular networks is still unknown. In this paper, we present an analytical framework for studying the performance of SIC in large-scale D2D-enabled cellular networks using the tools from stochastic geometry. To facilitate the interference analysis, we propose the approach of stochastic equivalence of the interference, which converts the two-tier interference (interference from both the cellular tier and D2D tier) to an equivalent single-tier interference. Based on the proposed stochastic equivalence models, we derive the general expressions for the successful transmission probabilities of cellular uplinks and D2D links with infinite and finite SIC capabilities respectively. We demonstrate how SIC affects the performance of large-scale D2D-enabled cellular networks by both analytical and numerical results.

I. INTRODUCTION

Recently, there has been a rapid increase in the demand of local area services and proximity services (ProSe) among the highly-capable user equipments (UEs) in cellular networks. In this context, a new technology called device-to-device (D2D) communication, which enables direct communication between UEs that are in proximity, has been proposed and has strongly appealed to both academia [1], [2] and industry [3], [4]. The integration of D2D communication to cellular networks holds the promise of many types of advantages [2]: allowing for high-rate low-delay low-power transmission for proximity services, increasing frequency reuse factor and network capacity, facilitating new types of peer-to-peer services, etc.

However, the introduction of D2D communication also brings a number of technical challenges, such as device discovery, mode selection and interference management. Interference management is a major issue in D2D-enabled cellular networks, since D2D links share the same spectrum resource with regular cellular links and the interference among the spectrum-sharing links severely hampers the performance of the network. To guarantee reliable communications in D2D-enabled cellular networks, extensive research has been undertaken on the topic of interference management. Most proposed schemes can be classified into three categories: (1) *Interference avoidance*: orthogonal time-frequency resource allocation

schemes are adopted to avoid interference between D2D and cellular links [5]; (2) *Interference coordination*: intelligent power control and link scheduling schemes are employed to mitigate the interference between D2D and cellular links [6], [7]; and (3) *Interference cancellation*: advanced signal processing techniques are applied at cellular and/or D2D links to cancel the interfering signals [8], [9]. In this paper, we focus on the topic of *interference cancellation* in D2D-enabled cellular networks.

Interference cancellation (IC) is regarded as a promising technique to reduce interference and improve network capacity. Using interference cancellation techniques, the interfering signals can be regenerated and subsequently canceled from the desired signal [10]. Best known interference cancellation techniques include successive interference cancellation (SIC), parallel interference cancellation (PIC) and iterative interference cancellation (IIC) [11]. The key advantage of SIC compared to other interference cancellation techniques is that the SIC receiver is architecturally similar to traditional non-SIC receivers in terms of hardware complexity and cost [11], as it uses the same decoder to decode the composite signal at different stages and neither complicated decoders nor multiple antennas are required. Furthermore, it is known that SIC can achieve the Shannon capacity region boundaries for both the broadcast and multiple access networks. As such, SIC has been widely studied and recently implemented in commercial wireless systems such as IEEE 802.15.4. However, to date, most analytical results on SIC are for ad hoc and cellular networks. It is still unknown how SIC can improve the performance of large-scale D2D-enabled cellular networks, in which the interference among spectrum-sharing links is more severer than that in traditional ad hoc and cellular networks. In this paper, we present an analytical framework to evaluate how SIC affects the performance of large-scale D2D-enabled cellular networks. The main contributions of this paper are summarized as follows.

(1) We model a large-scale D2D-enabled cellular network without SIC capabilities via stochastic geometry, and derive the general expressions for the successful transmission probabilities of cellular uplinks and D2D links. Furthermore, to simplify the interference analysis in the network, we propose the approach of *stochastic equivalence of the interference*. By this approach, the two-tier interference (interference from the cellular tier and D2D tier) can be represented by an

equivalent single-tier interference that maintains the same stochastic characteristics as the two-tier interference.

(2) Based on the stochastic equivalence models, we derive the general expressions for the successful transmission probabilities of cellular uplinks and D2D links with infinite and finite SIC capabilities respectively. We demonstrate the effect of SIC on the performance of large-scale D2D-enabled cellular networks by analytical and numerical results.

The rest of this paper is organized as follows. Section II presents the related work. Section III describes the system model. Sections IV and V analyze the successful transmission probabilities in D2D-enabled cellular networks without and with SIC respectively and present the numerical results. Section VI concludes the paper. A summary of the notations used in this paper is given in Table I.

II. RELATED WORK

D2D communication. There have been numerous studies on interference management for D2D communications. Xu *et al.* [5] proposed a combinatorial auction approach to allocate orthogonal resources between cellular and D2D users. Kaufman *et al.* [6] presented an opportunistic communication scheme in which the D2D network can communicate as a fully loaded cellular network. Pei and Liang [7] designed a spectrum sharing protocol that enables D2D users to communicate bi-directionally while assisting the two-way communications between the base station and cellular users. Min *et al.* [8] designed an interference cancellation scheme that exploits a retransmission of the interference from the base station. Ma *et al.* [9] proposed two superposition coding-based cooperative relaying schemes to exploit the transmission opportunities for D2D users without deteriorating the performance of cellular users.

Successive interference cancellation. Very recently, there is a growing interest to exploit SIC at the physical layer to improve network performances at upper layers. In [12], Gelal *et al.* proposed a topology control framework for exploiting the benefits of multi-packet reception using SIC in multi-user MIMO networks. In [13], Jiang *et al.* combines SIC and interference avoidance to improve the throughput of a multi-hop network. In [14], Xu *et al.* developed a decentralized power allocation scheme to achieve the maximum throughput for random access systems with SIC receivers. In [15], Lv *et al.* proposed two layered models to characterize the impact of SIC, and presented corresponding link scheduling schemes under these models. In [16], Mollanoori and Ghaderi studied the uplink scheduling problems for networks supporting SIC, and derived the optimal decoding order of the concurrent transmissions.

Stochastic geometry for modeling wireless networks. As a mathematical tool to study random spatial patterns, stochastic geometry can be used to model and analyze the interference, connectivity and coverage in large-scale wireless networks [17]. Most of the literature in the area of modeling networks via stochastic geometry focus on ad hoc [18], [19] and cellular [20], [21] networks. Recently, stochastic geometry has

Table I: Notations used in the paper

Notation	Description
Φ_c	Poisson point process of cellular users (density λ_c)
Φ_d	Poisson point process of D2D transmitters (density λ_d)
Φ_{c-intf}^{eq}	Equivalent Poisson point process of the interferers for cellular links (density λ_{c-intf}^{eq})
Φ_{d-intf}^{eq}	Equivalent Poisson point process of the interference for D2D links (density λ_{d-intf}^{eq})
P_c	Transmission power of cellular users
P_d	Transmission power of D2D users
α	Path loss exponent ($\delta = \frac{2}{\alpha}$)
T	SIR threshold for successful transmission
p_c	Successful transmission prob. of cellular links without SIC
p_d	Successful transmission prob. of D2D links without SIC
p_c^{SIC}, p_c^{N-SIC}	Successful transmission prob. of cellular links with infinite and (finite) N -level SIC
p_d^{SIC}, p_d^{M-SIC}	Successful transmission prob. of D2D links with infinite and (finite) M -level SIC

also been employed to model D2D-enabled cellular networks [22]–[24]. In [22]–[24], the cellular and D2D networks were modeled by independent PPPs, and their SINR distributions were derived without considering interference cancellation techniques. The stochastic geometry-based analysis of SIC has been presented in literature [25]–[29]. In [25], [26], simplified SIC models were given by assuming that the interference greater than a threshold can be completely canceled. Exact SIC models were investigated for ad hoc network in [27], [28] and for cellular networks in [29]. Different from [27]–[29], in this paper, we focus on the analysis of the effect of SIC for D2D-enabled cellular networks. Since the stochastic characteristics of heterogeneous networks (comprising ad hoc users and cellular users) are quite different from those of homogeneous networks (comprising only ad hoc users or cellular users), the analysis of SIC in this paper is more challenging than that in [27]–[29].

III. SYSTEM MODEL

In this section, we elaborate on the network model and describe the SIC scheme.

A. Network Model

We consider a spectrum-sharing D2D-enabled cellular network consisting of both cellular users and D2D users over a large two-dimensional space, and focus on the uplink transmission for cellular users. The cellular users are assumed to be spatially distributed as a homogeneous Poisson point process (PPP) Φ_c with density λ_c , and an independent collection of base stations (BSs) is assumed to be located according to some independent stationary point process Φ_b . We assume that each cellular user is associated with its nearest base station, and each base station has only one active uplink cellular user scheduled. Under such assumptions, each base station can be considered to be uniformly distributed in the Voronoi cell of its associated cellular user, as shown in Fig.1. It is noted that the orthogonal scheduling policy leads to coupling between the locations of cellular users and those of base stations. Nevertheless, it has been shown that the

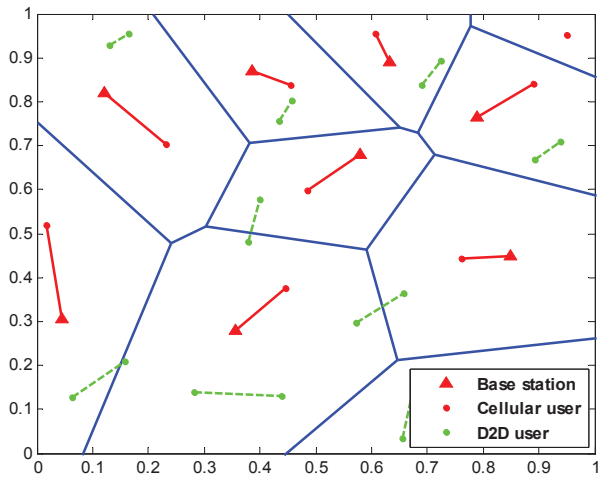


Figure 1: Network model.

dependence introduced by coupling has negligible effects on the performance analysis [21], [29]. Therefore, for analytical tractability, we assume that the point processes of cellular users and base stations are independent.

The D2D transmitters in the network are assumed to be distributed according to a homogeneous PPP Φ_d with density λ_d . For a given D2D transmitter, its associated receiver is assumed to be located at a distance l away with isotropic direction, where l is Rayleigh distributed:

$$f_l(l) = 2\pi\lambda_d l e^{-\pi\lambda_d l^2}. \quad (1)$$

This Rayleigh distribution assumption is of practical interest and is employed in many works [22]–[24]. Other distributions of l can be easily incorporated into the framework.

The transmission powers are assumed to be P_c at uplink cellular users and P_d at D2D transmitters respectively. We adopt a unified channel model that comprises standard path loss and Rayleigh fading for both cellular and D2D links: given transmission power P of the transmitter located at x_i , the received power at the receiver located at x_j can be expressed as $Ph\|x_i - x_j\|^{-\alpha}$, where h is the fading factor following an exponential distribution with unit mean, i.e. $h \sim \exp(1)$, and $\alpha > 2$ is the path loss exponent. In later parts of this paper we use δ to denote $\frac{2}{\alpha}$ for brevity of expressions. In addition, as interference dominates noise in most modern cellular networks, we consider the network to be interference-limited.

B. SIC Technique

SIC is a promising interference cancellation technique that has been widely studied for wireless networks. The basic concept of SIC is to regenerate the interfering signals and subsequently cancel them from the received composite signal, so as to improve the signal-to-interference ratio (SIR) of the desired signal. In this technique, the SIC receiver first decodes the strongest interfering signal by treating other signals as noise. Then it regenerates the analog signal from the decoded signal, and cancels it from the received composite signal. After

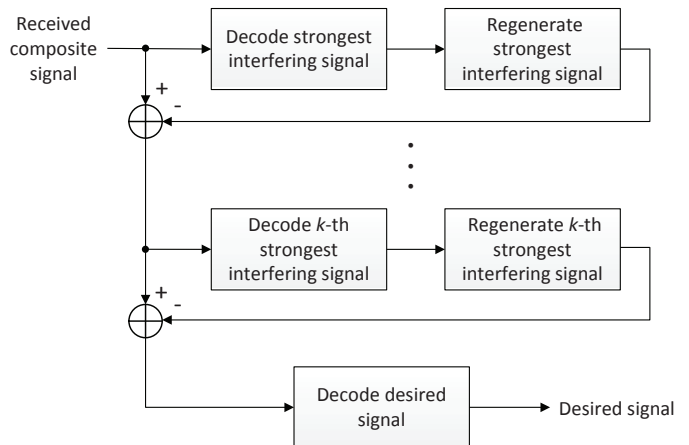


Figure 2: Schematic diagram of SIC process.

this stage, the remaining signal is free from the interference of the strongest interfering signal. Then, the SIC receiver proceeds to decode, regenerate and cancel the second strongest interfering signaling from the remaining signal and so forth, until the desired signal can be decoded. The schematic diagram of SIC process is shown in Fig.2.

In this paper, we assume that the SIC technique is employed at both cellular receivers (BSs) and D2D receivers. For cellular receivers, we consider the cases of infinite and finite SIC capabilities respectively, and study the successful transmission probabilities of cellular links for each case. However, for D2D receivers, due to their limited computational capabilities, we focus only on the case of finite SIC capability.

IV. NETWORK PERFORMANCE WITHOUT SIC

In this section, we consider the scenario that neither the cellular receivers (BSs) nor the D2D receivers have SIC capabilities, and derive the successful transmission probabilities of both cellular and D2D links. We also analyze the stochastic equivalence of interference in the network, which is essential for the SIC analysis in later sections.

A. Successful Transmission Probability of Cellular Links

Without loss of generality, we conduct the analysis on a typical cellular link that comprises a typical BS located at the origin and its associated cellular user located at a random distance r away. Under the nearest-BS association policy, the random variable r can be shown to be Rayleigh distributed and its probability density function (pdf) follows [21]:

$$f_r(r) = 2\pi\lambda_c r e^{-\pi\lambda_c r^2}. \quad (2)$$

Denote the fading factor of the typical cellular link by g_0 , which is i.i.d exponential with $g_0 \sim \exp(1)$. Then, the received SIR of the typical cellular link, i.e., the received SIR at the typical BS, can be expressed as

$$\text{SIR}_c = \frac{P_c g_0 r^{-\alpha}}{I_c}, \quad (3)$$

where

$$I_c = \sum_{x_i \in \Phi_c \setminus \{x_0\}} P_c g_i \|x_i\|^{-\alpha} + \sum_{y_i \in \Phi_d} P_d h_i \|y_i\|^{-\alpha} \quad (4)$$

is the cumulative interference from all other cellular users (except the typical cellular user x_0) that are located at x_i with fading factor g_i and D2D transmitters that are located at y_i with fading factor h_i ¹.

The successful transmission probability of cellular links can be defined as

$$p_c \triangleq \mathbb{P}[\text{SIR}_c > T], \quad (5)$$

where T is the SIR threshold. The expression of p_c is given by the following theorem.

Theorem 1. *The successful transmission probability of cellular links without SIC capability is*

$$p_c = \frac{\lambda_c}{\lambda_c (\mu + 1) + \lambda_d \left(\frac{P_d}{P_c}\right)^\delta \nu}, \quad (6)$$

where

$$\mu = \frac{\delta}{1 - \delta} T \cdot {}_2F_1(1, 1 - \delta; 2 - \delta; -T), \quad (7)$$

$$\nu = T^\delta \Gamma(1 - \delta) \Gamma(1 + \delta), \quad (8)$$

and ${}_2F_1(\cdot)$, $\Gamma(\cdot)$ are respectively the Hypergeometric function and Gamma function.

Proof: Starting from the definitions of p_c , we have

$$\begin{aligned} p_c &\triangleq \mathbb{P}[\text{SIR}_c > T] \\ &= \mathbb{E}_{r, I_c} [\mathbb{P}_{g_0}[\text{SIR}_c > T]] \\ &= \mathbb{E}_{r, I_c} [\mathbb{P}_{g_0}[g_0 > P_c^{-1} T r^\alpha I_c]] \\ &\stackrel{(a)}{=} \mathbb{E}_{r, I_c} [\exp(-P_c^{-1} T r^\alpha I_c)] \\ &\stackrel{(b)}{=} \mathbb{E}_r [\mathcal{L}_{I_c}(P_c^{-1} T r^\alpha)] \\ &= \int_0^\infty \mathcal{L}_{I_c}(P_c^{-1} T r^\alpha) \cdot f_r(r) dr. \end{aligned} \quad (9)$$

(a) follows from the Rayleigh distribution assumption of channel fading. In (b), $\mathcal{L}_{I_c}(\cdot)$ denotes the Laplace transform of I_c . Let $I_c = I_{c-c} + I_{c-d}$, where $I_{c-c} = \sum_{x_i \in \Phi_c \setminus \{x_0\}} P_c g_i \|x_i\|^{-\alpha}$ and $I_{c-d} = \sum_{y_i \in \Phi_d} P_d h_i \|y_i\|^{-\alpha}$ denote the interference from cellular links and D2D links respectively. Then it is straightforward to get

$$\mathcal{L}_{I_c}(s) = \mathcal{L}_{I_{c-c}}(s) \cdot \mathcal{L}_{I_{c-d}}(s). \quad (10)$$

The Laplace transform of I_{c-c} is given by

$$\mathcal{L}_{I_{c-c}}(s) = \mathbb{E} \left[\exp \left(-s \sum_{x_i \in \Phi_c \setminus \{x_0\}} P_c g_i \|x_i\|^{-\alpha} \right) \right]$$

¹To distinguish different links, in this paper we use $g \sim \exp(1)$, $h \sim \exp(1)$ to represent the fading factors of links related to cellular transmitters (cellular users) and D2D transmitters respectively. It is noted that there is no essential distinction between these two symbols.

$$\begin{aligned} &= \mathbb{E}_{\Phi_c} \left[\prod_{x_i \in \Phi_c \setminus \{x_0\}} \mathbb{E}_g \left[\exp \left(-s P_c g_i \|x_i\|^{-\alpha} \right) \right] \right] \\ &\stackrel{(c)}{=} \exp \left(-\lambda_c \int_{\Phi_c \cap \bar{B}(o, r)} \left(1 - \mathbb{E}_g \left[e^{-s P_c g_i \|x_i\|^{-\alpha}} \right] \right) dx_i \right) \\ &= \exp \left(-\lambda_c \int_{\Phi_c \cap \bar{B}(o, r)} \left(1 - \frac{1}{1 + s P_c \|x_i\|^{-\alpha}} \right) dx_i \right) \\ &\stackrel{(d)}{=} \exp \left(-\lambda_c \cdot 2\pi \int_r^\infty \frac{v}{1 + s^{-1} P_c^{-1} v^\alpha} dv \right) \\ &\stackrel{(e)}{=} \exp \left(-\lambda_c \pi \frac{\delta}{1 - \delta} s P_c r^{2-\alpha} {}_2F_1 \left(1, 1 - \delta; 2 - \delta; -\frac{s P_c}{r^\alpha} \right) \right). \end{aligned} \quad (11)$$

(c) follows from the probability generating functional (PGFL) of PPP [30]: $\mathbb{E} \left[\prod_{x \in \Phi} f(x) \right] = \exp \left(-\lambda \int_{\mathbb{R}^2} (1 - f(x)) dx \right)$. (d) follows from the double integral in polar coordinates. (e) follows from the definite integral [31, 3.194.2]: $\int_b^\infty \frac{v}{1 + a v^\alpha} dv = \frac{1}{\alpha} \cdot \frac{b^{2-\alpha}}{a(1-\frac{2}{\alpha})} {}_2F_1 \left(1, 1 - \frac{2}{\alpha}; 2 - \frac{2}{\alpha}; -\frac{1}{ab^\alpha} \right)$. Similarly, we have

$$\begin{aligned} \mathcal{L}_{I_{c-d}}(s) &= \mathbb{E} \left[\exp \left(-s \sum_{y_i \in \Phi_d} P_d h_i \|y_i\|^{-\alpha} \right) \right] \\ &= \exp \left(-\lambda_d \int_{\mathbb{R}^2} \left(1 - \mathbb{E}_h \left[\exp \left(-s P_d h_i \|y_i\|^{-\alpha} \right) \right] \right) dy_i \right) \\ &= \exp \left(-\lambda_d \int_{\mathbb{R}^2} \left(1 - \frac{1}{1 + s P_d \|y_i\|^{-\alpha}} \right) dy_i \right) \\ &= \exp \left(-\lambda_d \cdot 2\pi \int_0^\infty \frac{u}{1 + s^{-1} P_d^{-1} u^\alpha} du \right) \\ &= \exp \left(-\lambda_d \pi (s P_d)^\delta \Gamma(1 - \delta) \Gamma(1 + \delta) \right). \end{aligned} \quad (12)$$

By plugging (11) (12) into (10) and letting $s = P_c^{-1} T r^\alpha$, we get

$$\mathcal{L}_{I_c}(P_c^{-1} T r^\alpha) = \exp \left(-\pi \left[\lambda_c \mu + \lambda_d \left(\frac{P_d}{P_c}\right)^\delta \nu \right] r^2 \right), \quad (13)$$

where $\mu = \frac{\delta}{1 - \delta} T \cdot {}_2F_1(1, 1 - \delta; 2 - \delta; -T)$, $\nu = T^\delta \cdot \Gamma(1 - \delta) \Gamma(1 + \delta)$. Then by plugging (2) (13) into (9), we complete the proof. ■

B. Successful Transmission Probability of D2D Links

We conduct the analysis on a typical D2D link that comprises a typical D2D transmitter located at some point in the network and a typical D2D receiver located at a random distance l away. Shift the coordinates such that the typical D2D receiver is located at the origin², and denote the fading factor of the typical D2D link by h_0 , $h_0 \sim \exp(1)$. Then, the received SIR of the typical D2D link can be expressed as

$$\text{SIR}_d = \frac{P_d h_0 l^{-\alpha}}{I_d}, \quad (14)$$

²It is noted that the translations do not change the distribution of PPP [32].

where

$$I_d = \sum_{y_i \in \Phi_d \setminus \{y_0\}} P_d h_i \|y_i\|^{-\alpha} + \sum_{x_i \in \Phi_c} P_c g_i \|x_i\|^{-\alpha} \quad (15)$$

is the cumulative interference from all other D2D transmitters (except the typical D2D transmitter located at y_0) that are located at y_i with fading factor h_i and cellular users that are located at x_i with fading factor g_i .

The successful transmission probability of D2D links can be defined as

$$p_d \triangleq \mathbb{P}[\text{SIR}_d > T], \quad (16)$$

where T is the SIR threshold. Note that the same SIR threshold T is assumed for cellular and D2D links. The expression of p_d is given by the following theorem.

Theorem 2. *The successful transmission probability of D2D links without SIC capability is*

$$p_d = \frac{\lambda_d}{\lambda_d(\nu + 1) + \lambda_c \left(\frac{P_c}{P_d}\right)^\delta \nu}, \quad (17)$$

where ν is given in (8).

Proof: Starting from the definitions of p_d and SIR_d ,

$$\begin{aligned} p_d &\triangleq \mathbb{P}[\text{SIR}_d > T] \\ &= \mathbb{E}_{l, I_d} [\mathbb{P}_{h_0}[\text{SIR}_d > T]] \\ &= \mathbb{E}_l [\mathcal{L}_{I_d}(P_d^{-1} T l^\alpha)] \\ &= \int_0^\infty \mathcal{L}_{I_d}(P_d^{-1} T l^\alpha) \cdot f_l(l) dl. \end{aligned} \quad (18)$$

Following approaches similar to those in previous proofs and Slivnyak's theorem [30]: $\mathbb{P}^{lx} = \mathbb{P}$, we have

$$\begin{aligned} \mathcal{L}_{I_d}(s) &= \mathbb{E}_{I_d} [\exp(-s I_d)] \\ &= \mathbb{E} \left[\exp \left(-s \sum_{y_i \in \Phi_d \setminus \{y_0\}} P_d h_i \|y_i\|^{-\alpha} \right) \right] \\ &\quad \times \mathbb{E} \left[\exp \left(-s \sum_{x_i \in \Phi_c} P_c g_i \|x_i\|^{-\alpha} \right) \right] \\ &= \exp \left(-\lambda_d \pi (s P_d)^\delta \Gamma(1 - \delta) \Gamma(1 + \delta) \right) \\ &\quad \times \exp \left(-\lambda_c \pi (s P_c)^\delta \Gamma(1 - \delta) \Gamma(1 + \delta) \right). \end{aligned} \quad (19)$$

Therefore,

$$\mathcal{L}_{I_d}(P_d^{-1} T l^\alpha) = \exp \left(-\pi \left[\lambda_d + \lambda_c \left(\frac{P_c}{P_d}\right)^\delta \right] \nu l^2 \right), \quad (20)$$

where ν is given in (8). Then by plugging (1) (20) into (18), we complete the proof. ■

Remark 1. Via the expressions of p_c and p_d shown in Theorem 1 and 2, we can observe that μ , ν represent the effect of the interference from the cellular links and D2D links respectively, and $(P_d/P_c)^\delta$, $(P_c/P_d)^\delta$ can be regarded as the conversion factors of powers.

C. Stochastic Equivalence of Interference

By (4) (15), the cumulative interference at each link is generated by two-tier interferers, i.e., the cellular-tier and D2D-tier interferers. The analysis of such two-tier interference is trivial, as shown in the derivations of Theorem 1 and 2. Therefore, to simplify the analysis and facilitate the performance evaluation of SIC in later sections, we propose an approach to equate the two-tier interference by a single-tier interference that has the same stochastic characteristics (in terms of successful transmission probability) as the two-tier interference.

We first study the stochastic equivalence of the interference for cellular links. By (4), the interferers for the typical cellular link constitute $\Phi_{c-intf} = (\Phi_c \setminus \{x_0\}) \cup \Phi_d$. We represent Φ_{c-intf} by an equivalent PPP $\Phi_{c-intf}^{\text{eq}} \setminus \{x_0\}$ with density $\lambda_{c-intf}^{\text{eq}}$ and transmission power P_c . Then, the equivalent interference at the typical cellular link can be expressed as

$$I_c^{\text{eq}} = \sum_{x_i \in \Phi_{c-intf}^{\text{eq}} \setminus \{x_0\}} P_c g_i \|x_i\|^{-\alpha}, \quad (21)$$

which has the same stochastic characteristics as I_c .

Lemma 1. *The density of the equivalent interferers for cellular links is*

$$\lambda_{c-intf}^{\text{eq}} = \lambda_c + \lambda_d \left(\frac{P_d}{P_c}\right)^\delta \frac{\nu}{\mu}, \quad (22)$$

where μ , ν are given in (7), (8) respectively.

Proof: Considering I_c^{eq} has the same stochastic characteristics as I_c , we have

$$\mathcal{L}_{I_c}(P_c^{-1} T r^\alpha) = \mathcal{L}_{I_c^{\text{eq}}}(P_c^{-1} T r^\alpha). \quad (23)$$

The Laplace transform of I_c^{eq} is obtained as

$$\begin{aligned} \mathcal{L}_{I_c^{\text{eq}}}(s) &= \mathbb{E}_{I_c^{\text{eq}}} [\exp(-s I_c^{\text{eq}})] \\ &= \mathbb{E} \left[\exp \left(-s \sum_{x_i \in \Phi_{c-intf}^{\text{eq}} \setminus \{x_0\}} P_c g_i \|x_i\|^{-\alpha} \right) \right] \\ &= \exp \left(-\lambda_{c-intf}^{\text{eq}} \pi \frac{\delta}{1 - \delta} s P_c r^{2-\alpha} {}_2F_1 \left(1, 1 - \delta; 2 - \delta; -\frac{s P_c}{r^\alpha} \right) \right). \end{aligned} \quad (24)$$

Therefore,

$$\mathcal{L}_{I_c^{\text{eq}}}(P_c^{-1} T r^\alpha) = \exp \left(-\lambda_{c-intf}^{\text{eq}} \pi \mu r^2 \right), \quad (25)$$

where μ is given in (7). Then by plugging (13) (25) into (23), we complete the proof. ■

It is noted that p_c can be obtained as $\int_0^\infty \mathcal{L}_{I_c^{\text{eq}}}(P_c^{-1} T r^\alpha) \cdot f_r(r) dr$, and by (24), we have

$$p_c = \frac{\lambda_c}{\lambda_{c-intf}^{\text{eq}} \mu + \lambda_c}, \quad (26)$$

which is consistent with the result of Theorem 1.

We next study the stochastic equivalence of the interference for D2D links. By (15), the interferers for the typical D2D link constitute $\Phi_{d-intf} = (\Phi_d \setminus \{y_0\}) \cup \Phi_c$. We represent

Φ_{d-intf} by an equivalent PPP $\Phi_{d-intf}^{eq} \setminus \{y_0\}$ with density λ_{d-intf}^{eq} and transmission power P_d . Then, the equivalent interference at the typical D2D link can be expressed as

$$I_d^{eq} = \sum_{y_i \in \Phi_{d-intf}^{eq} \setminus \{y_0\}} P_d h_i \|y_i\|^{-\alpha}. \quad (27)$$

Lemma 2. *The density of the equivalent interferers for D2D links is*

$$\lambda_{d-intf}^{eq} = \lambda_d + \lambda_c \left(\frac{P_c}{P_d} \right)^\delta. \quad (28)$$

Proof: Starting from the Laplace transform of I_d^{eq} ,

$$\begin{aligned} \mathcal{L}_{I_d^{eq}}(s) &= \mathbb{E}_{I_d^{eq}}[\exp(-sI_d^{eq})] \\ &= \mathbb{E} \left[\exp \left(-s \sum_{y_i \in \Phi_{d-intf}^{eq} \setminus \{y_0\}} P_d h_i \|y_i\|^{-\alpha} \right) \right] \\ &= \exp \left(-\lambda_{d-intf}^{eq} \pi (sP_d)^\delta \Gamma(1-\delta) \Gamma(1+\delta) \right). \end{aligned} \quad (29)$$

Therefore,

$$\mathcal{L}_{I_d^{eq}}(P_d^{-1}Tl^\alpha) = \exp \left(-\lambda_{d-intf}^{eq} \pi \nu l^2 \right), \quad (30)$$

where ν is given in (8). Then by letting $\mathcal{L}_{I_d^{eq}}(P_d^{-1}Tl^\alpha) = \mathcal{L}_{I_d}(P_d^{-1}Tl^\alpha)$, we complete the proof. ■

It is noted that p_d can be obtained as $\int_0^\infty \mathcal{L}_{I_d^{eq}}(P_d^{-1}Tl^\alpha) \cdot f_l(l) dl$, and by (30), we have

$$p_d = \frac{\lambda_d}{\lambda_{d-intf}^{eq} \nu + \lambda_d}, \quad (31)$$

which is consistent with the result of Theorem 2.

V. NETWORK PERFORMANCE WITH SIC

In this section, we study how SIC affects the successful transmission probabilities in D2D-enabled cellular networks. The analysis is based on the stochastic equivalence models proposed in section IV.

A. Successful Transmission Probability of Cellular Links

We conduct the analysis on a typical cellular link that comprises a typical SIC-capable BS located at the origin and its associated cellular user located at x_0 , where $\|x_0\| = r$. The equivalent interferers for the typical cellular link are ordered by their received power at the typical BS such that $P_c g_i \|x_i\|^{-\alpha} > P_c g_j \|x_j\|^{-\alpha}, \forall 0 < i < j$. Before deriving the successful transmission probability of the typical cellular link, we first present two lemmas.

Given that n strongest equivalent interferers have been canceled, the received SIR of the typical cellular link, i.e., the received SIR at the typical BS, can be expressed as

$$\text{SIR}_c^{(n)} = \frac{P_c g_0 r^{-\alpha}}{I_c^{eq(n)}}, \quad (32)$$

where

$$I_c^{eq(n)} = \sum_{x_i \in \Phi_{c-intf}^{eq} \setminus \{x_0, x_1, \dots, x_n\}} P_c g_i \|x_i\|^{-\alpha} \quad (33)$$

is the cumulative interference for the typical cellular link. Then, the successful transmission probability of the typical cellular link given that n strongest equivalent interferers have been canceled can be defined as

$$p_c^{(n)} \triangleq \mathbb{P} \left[\text{SIR}_c^{(n)} > T \right]. \quad (34)$$

The expression of $p_c^{(n)}$ is given by the following lemma.

Lemma 3. *Given that n strongest equivalent interferers have been canceled, the successful transmission probability of the typical cellular link is*

$$\begin{aligned} p_c^{(n)} &= \int_0^\infty \int_0^\infty \frac{2 \left(\lambda_{c-intf}^{eq} \pi d_n^2 \right)^n}{d_n \Gamma(n)} e^{-\lambda_{c-intf}^{eq} \pi \xi(r, d_n)} f_r(r) dd_n dr, \end{aligned} \quad (35)$$

where $f_r(r)$ is given in (2) and

$$\xi(r, d_n) = \frac{\delta}{1-\delta} T r^\alpha d_n^{2-\alpha} {}_2F_1 \left(1, 1-\delta; 2-\delta; -\frac{T r^\alpha}{d_n^\alpha} \right) + d_n^2. \quad (36)$$

Proof: Starting from the definitions of $p_c^{(n)}$ and $\text{SIR}_c^{(n)}$,

$$\begin{aligned} p_c^{(n)} &\triangleq \mathbb{P} \left[\text{SIR}_c^{(n)} > T \right] = \mathbb{E}_r \left[\mathcal{L}_{I_c^{eq(n)}}(P_c^{-1}T r^\alpha) \right] \\ &= \int_0^\infty \mathcal{L}_{I_c^{eq(n)}}(P_c^{-1}T r^\alpha) \cdot f_r(r) dr. \end{aligned} \quad (37)$$

The calculation of $\mathcal{L}_{I_c^{eq(n)}}$ requires the distribution of the sum of the order statistics of interfering powers, which is difficult to obtain in the SIC scenario. However, it has been shown that the order statistics of received powers in modern networks are dominated by the distance [29]. Therefore, we can calculate $\mathcal{L}_{I_c^{eq(n)}}$ by relaxing the ordering of interfering powers to that of interfering distances. Denote the distance from n -th equivalent interferer to the origin by d_n , then we have

$$\begin{aligned} \mathcal{L}_{I_c^{eq(n)}}(s) &= \mathbb{E} \left[\exp \left(-s I_c^{eq(n)} \right) \right] \\ &= \mathbb{E}_{d_n, \Phi_{c-intf}^{eq}, g} \left[\prod_{x_i \in \Phi_{c-intf}^{eq} \setminus \{x_0, x_1, \dots, x_n\}} e^{-s P_c g_i \|x_i\|^{-\alpha}} \right] \\ &= \mathbb{E}_{d_n} \left[e^{-\lambda_{c-intf}^{eq} \int_{\Phi_{c-intf}^{eq} \cap \overline{B}(o, d_n)} (1 - \mathbb{E}_g [e^{-s P_c g_i \|x_i\|^{-\alpha}}]) dx_i} \right] \\ &= \int_0^\infty e^{-\lambda_{c-intf}^{eq} \int_{\Phi_{c-intf}^{eq} \cap \overline{B}(o, d_n)} \left(1 - \frac{1}{1+s P_c \|x_i\|^{-\alpha}} \right) dx_i} f_{d_n}(d_n) dd_n \\ &= \int_0^\infty e^{-\lambda_{c-intf}^{eq} \cdot 2\pi \int_{d_n}^\infty \frac{v}{1+s^{-1} P_c^{-1} v^\alpha} dv} \cdot f_{d_n}(d_n) dd_n \\ &= \int_0^\infty e^{-\lambda_{c-intf}^{eq} \pi \frac{\delta}{1-\delta} s P_c d_n^{2-\alpha} {}_2F_1 \left(1, 1-\delta; 2-\delta; -\frac{s P_c}{d_n^\alpha} \right)} f_{d_n}(d_n) dd_n. \end{aligned} \quad (38)$$

From [30], the probability density function of d_n is given by

$$f_{d_n}(d_n) = e^{-\lambda_{c-intf}^{eq} \pi d_n^2} \cdot \frac{2 \left(\lambda_{c-intf}^{eq} \pi d_n^2 \right)^n}{d_n \Gamma(n)}. \quad (39)$$

By plugging (39) into (38) and letting $s = P_c^{-1}Tr^\alpha$, we get

$$\begin{aligned} & \mathcal{L}_{I_c^{\text{eq}(n)}}(P_c^{-1}Tr^\alpha) \\ &= \int_0^\infty e^{-\lambda_{c-intf}^{\text{eq}} \pi \xi(r, d_n)} \cdot \frac{2 \left(\lambda_{c-intf}^{\text{eq}} \pi d_n^2 \right)^n}{d_n \Gamma(n)} dd_n, \end{aligned} \quad (40)$$

where $\xi(r, d_n) = \frac{\delta}{1-\delta} Tr^\alpha d_n^{2-\alpha} {}_2F_1\left(1, 1-\delta; 2-\delta; -\frac{Tr^\alpha}{d_n^\alpha}\right) + d_n^2$. Then by plugging (2)(40) into (37), we complete the proof. \blacksquare

A possible approach for simplifying the expression of $p_c^{(n)}$ is to approximate d_n by a fixed value \tilde{d}_n , which equals the expectation of d_n , i.e.,

$$\tilde{d}_n = \mathbb{E}[d_n] = \frac{\Gamma\left(n + \frac{1}{2}\right)}{\sqrt{\pi} \lambda_{c-intf}^{\text{eq}} \Gamma(n)}. \quad (41)$$

Then, $p_c^{(n)}$ can be approximated by

$$p_c^{(n)} = \int_0^\infty e^{-\lambda_{c-intf}^{\text{eq}} \pi \tilde{\xi}(r, \tilde{d}_n)} \cdot f_r(r) dr, \quad (42)$$

where $f_r(r)$ is given in (2) and

$$\tilde{\xi}(r, \tilde{d}_n) = \frac{\delta}{1-\delta} Tr^\alpha \tilde{d}_n^{2-\alpha} {}_2F_1\left(1, 1-\delta; 2-\delta; -\frac{Tr^\alpha}{\tilde{d}_n^\alpha}\right). \quad (43)$$

Next, we study the probability of canceling n -th strongest equivalent interferer. Given that all $n-1$ stronger equivalent interferers have been canceled, the received SIR of n -th strongest interferer at the typical BS can be expressed as

$$\text{SIR}_{c-intf}^{(n)} = \frac{P_c g_n \|x_n\|^{-\alpha}}{I_{c-intf}^{\text{eq}(n)}}, \quad (44)$$

where

$$I_{c-intf}^{\text{eq}(n)} = \sum_{x_i \in \Phi_{c-intf}^{\text{eq}} \setminus \{x_n, x_1, \dots, x_{n-1}\}} P_c g_i \|x_i\|^{-\alpha} \quad (45)$$

is the cumulative interference for n -th strongest equivalent interferer. Then, the probability of canceling (decoding) n -th strongest equivalent interferer given that all $n-1$ stronger equivalent interferers have been canceled can be defined as

$$p_{c-intf}^{(n)} \triangleq \mathbb{P}\left[\text{SIR}_{c-intf}^{(n)} > T\right]. \quad (46)$$

The expression of $p_{c-intf}^{(n)}$ is given by the following lemma.

Lemma 4. *Given that all $n-1$ stronger equivalent interferers have been canceled, the probability of canceling n -th strongest equivalent interferer for the typical cellular link is*

$$p_{c-intf}^{(n)} = \frac{1}{(\mu + 1)^n}, \quad (47)$$

where μ is given in (7).

Proof: Following the relaxation approach for the order statistics of interfering powers in the proof of Lemma 3, we can rewrite $\text{SIR}_{c-intf}^{(n)}$ as

$$\text{SIR}_{c-intf}^{(n)} = \frac{P_c g_n d_n^{-\alpha}}{I_{c-intf}^{\text{eq}(n)}}. \quad (48)$$

Then, we have

$$\begin{aligned} p_{c-intf}^{(n)} &\triangleq \mathbb{P}\left[\text{SIR}_{c-intf}^{(n)} > T\right] \\ &= \mathbb{E}_{d_n, I_{c-intf}^{\text{eq}(n)}}\left[\exp\left(-P_c^{-1} T d_n^\alpha I_{c-intf}^{\text{eq}(n)}\right)\right] \\ &= \mathbb{E}_{d_n}\left[\mathcal{L}_{I_{c-intf}^{\text{eq}(n)}}\left(P_c^{-1} T d_n^\alpha\right)\right] \\ &= \int_0^\infty \mathcal{L}_{I_{c-intf}^{\text{eq}(n)}}\left(P_c^{-1} T d_n^\alpha\right) \cdot f_{d_n}(d_n) dd_n. \end{aligned} \quad (49)$$

The Laplace transform of $I_{c-intf}^{\text{eq}(n)}$ is obtained as

$$\mathcal{L}_{I_{c-intf}^{\text{eq}(n)}}(s) = e^{-\lambda_{c-intf}^{\text{eq}} \pi \frac{\delta}{1-\delta} s P_c d_n^{2-\alpha} {}_2F_1\left(1, 1-\delta; 2-\delta; -\frac{s P_c}{d_n^\alpha}\right)}. \quad (50)$$

Hence,

$$\mathcal{L}_{I_{c-intf}^{\text{eq}(n)}}\left(P_c^{-1} T d_n^\alpha\right) = \exp\left(-\lambda_{c-intf}^{\text{eq}} \pi \mu d_n^2\right), \quad (51)$$

where μ is given in (7). Then by plugging (39)(51) into (49), we complete the proof. \blacksquare

Based on Lemma 3 and 4, we can derive the successful transmission probability of the typical cellular link.

Theorem 3. *The successful transmission probability of cellular links with infinite SIC capability is*

$$p_c^{\text{SIC}} = p_c + \sum_{n=1}^{\infty} \left(\prod_{i=1}^n p_{c-intf}^{(i)} \right) \left(\prod_{i=0}^{n-1} (1 - p_c^{(i)}) \right) p_c^{(n)}, \quad (52)$$

where $p_c, p_c^{(n)}, p_{c-intf}^{(i)}$ are given in (6), (35), (47) respectively.

Proof: For the typical cellular link, we define the event of its successful transmission without SIC as

$$E_0 : \text{SIR}_c^{(0)} > T, \quad (53)$$

and the event of its successful transmission with n -level ($n \geq 1$) SIC as

$$E_n : \left(\bigcap_{i=1}^n \text{SIR}_{c-intf}^{(i)} > T \right) \cap \left(\bigcap_{i=0}^{n-1} \text{SIR}_c^{(i)} < T \right) \cap \left(\text{SIR}_c^{(n)} > T \right). \quad (54)$$

Using the assumption that the interference to each user is independent, we get

$$\mathbb{P}[E_n] = \begin{cases} p_c^{(0)} = p_c, & n = 0, \\ \left(\prod_{i=1}^n p_{c-intf}^{(i)} \right) \left(\prod_{i=0}^{n-1} (1 - p_c^{(i)}) \right) p_c^{(n)}, & n \geq 1. \end{cases} \quad (55)$$

Therefore, the successful transmission probability of cellular links can be obtained as $p_c^{\text{SIC}} = \sum_{n=0}^{\infty} \mathbb{P}[E_n]$. \blacksquare

Corollary 1. *The successful transmission probability of cellular links with (finite) N -level ($N \geq 1$) SIC capability is*

$$p_c^{N-\text{SIC}} = p_c + \sum_{n=1}^N \left(\prod_{i=1}^n p_{c-intf}^{(i)} \right) \left(\prod_{i=0}^{n-1} (1 - p_c^{(i)}) \right) p_c^{(n)}, \quad (56)$$

where $p_c, p_c^{(n)}, p_{c-intf}^{(i)}$ are given in (6), (35), (47) respectively.

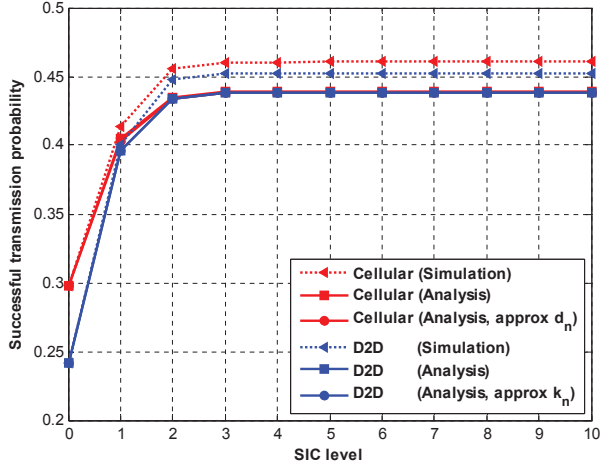


Figure 3: Successful transmission probabilities of cellular and D2D links with SIC.

B. Successful Transmission Probability of D2D Links

We consider a typical D2D link with M -level SIC receivers. The assumption of finite-level SIC receiver is motivated by the limited computational capabilities of D2D users. The derivation of the successful transmission probability of D2D links is quite similar to that of cellular links, and hence we directly present the results and omit their proofs.

Lemma 5. *Given that n strongest equivalent interferers have been canceled, the successful transmission probability of the typical D2D link is*

$$p_d^{(n)} = \int_0^\infty \int_0^\infty \frac{2 \left(\lambda_{d-intf}^{eq} \pi k_n^2 \right)^n}{k_n \Gamma(n)} e^{-\lambda_{d-intf}^{eq} \pi \kappa(l, k_n)} f_l(l) dk_n dl, \quad (57)$$

where $f_l(l)$ is given in (1) and

$$\kappa(l, k_n) = \frac{\delta}{1-\delta} T l^\alpha k_n^{2-\alpha} {}_2F_1 \left(1, 1-\delta; 2-\delta; -\frac{T l^\alpha}{k_n^\alpha} \right) + k_n^2. \quad (58)$$

Lemma 6. *Given that all $n-1$ stronger equivalent interferers have been canceled, the probability of canceling n -th strongest equivalent interferer for the typical D2D link is*

$$p_{d-intf}^{(n)} = \frac{1}{(\mu+1)^n}, \quad (59)$$

where μ is given in (7).

Theorem 4. *The successful transmission probability of D2D links with (finite) M -level ($M \geq 1$) SIC capability is*

$$p_d^{M-SIC} = p_d + \sum_{n=1}^M \left(\prod_{i=1}^n p_{d-intf}^{(i)} \right) \left(\prod_{i=0}^{n-1} (1 - p_d^{(i)}) \right) p_d^{(n)}, \quad (60)$$

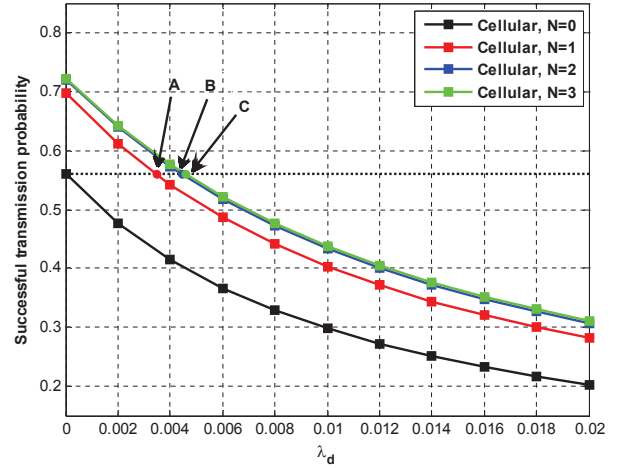


Figure 4: Successful transmission probability of cellular links with SIC vs. density of D2D links.

where $p_d, p_d^{(n)}, p_{d-intf}^{(n)}$ are given in (17), (57), (59) respectively.

C. Discussions and Numerical Results

Now that we have developed expressions for the successful transmission probabilities of cellular and D2D links with SIC capabilities, based on the stochastic equivalence models. It is noted that the derived analytical expressions are not the exact results of corresponding successful transmission probabilities, since approximated models are used in the derivation. We provide some numerical results to compare the analytical results with the actual (simulation) results. The system parameters are set as $\alpha = 4, P_c = P_d = 1, \lambda_c = \lambda_d = 0.01, T = 1$.

Fig.3 shows the successful transmission probabilities with SIC capabilities. As can be observed, there exist gaps between the analytical results of p_c^{N-SIC}, p_d^{M-SIC} and corresponding simulation results. The analytical results can be regarded as lower bounds on the successful transmission probabilities. The analytical results based on approximated d_n (see (41) (42)) and k_n are also plotted in the figure, through which we can find that the results of the approximated analytical expressions closely match those of the exact analytical expressions. Therefore, the approximated analytical expressions can be employed to simplify the calculation of the successful transmission probabilities. In addition, as shown in the figure, 2-level SIC can provide almost 50% performance improvement for the network; however, when the SIC level is larger than 2, SIC cannot further improve the network performance. Considering the hardware cost of multi-level SIC, 1- and 2-level SIC can be adopted in practical networks.

Fig.4 shows the successful transmission probability of cellular links with SIC vs. the density of D2D links. As expected, increasing the density of D2D links leads to a decrease in the successful transmission probability of cellular links. However, from this figure we can observe that SIC can compensate part of the performance loss of cellular links. For example, 1-level

SIC at the cellular receiver can compensate the performance loss generated by D2D interferers of density $\lambda_d = 0.0035$ (see point A), and 2-level SIC corresponds to $\lambda_d = 0.0045$ (see point B).

VI. CONCLUSION

In this paper, we study the performance of SIC in large-scale D2D-enabled cellular networks using the tools from stochastic geometry. We derive the successful transmission probabilities of the network without SIC as the baseline results. To simplify the interference analysis, we propose the approach of stochastic equivalence of the interference, by which the two-tier interference can be represented by an equivalent single-tier interference. Based on the stochastic equivalence models, we derive the successful transmission probabilities of cellular and D2D links with infinite and finite SIC capabilities. The SIC gains are validated by analytical and numerical results.

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