Performance Improvement for Device-to-Device (D2D) Users in Underlay Cellular Communication Networks

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Abstract

This study focuses on the performance of device-to-device (D2D) communications in underlay cellular networks by analyzing key metrics such as successful transmission probability, coverage probability, and throughput. Under the homogeneous Poisson point process (PPP) spatial distribution of full-duplex (FD)-D2D users in cellular networks, stochastic geometry tools are used to derive approximate expressions for D2D users' coverage probability and throughput. In comparison to the conventional half-duplex (HD) communication mode, when the self-interference cancellation factor β reaches -95 dB, there is a substantial improvement in the throughput of FD-D2D users, nearly doubling their gain. Additionally, experimental results demonstrate that the Newton iterative algorithm can be used to optimize the targeted signal-to-interference-plus-noise-ratio (SINR) threshold of users within the range of (10, 20) dB.

Keywords: Device-to-device communications, full duplex, Newton iterative, stochastic geometry

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1. Introduction

Device-to-device (D2D) communication technology enables users in close proximity to communicate directly without relying on base station forwarding. This approach offers several potential advantages, including significantly enhanced throughput [1-5], increased spectrum efficiency [6], reduced end-to-end latency between nodes [7], expanded wireless coverage [8], saved energy consumption of users [9], and offloaded local communication loads from the base station [10]. As a result, D2D communication has garnered widespread attention in academia and industry [11-13] and holds broad potential for application in the field of wireless sensor networks [14-15].

Currently, D2D communication can be categorized into two models based on the methods used to reuse spectrum resources in heterogeneous cellular networks: overlay and underlay models. Overlay D2D communication allocates an exclusive spectrum to D2D users, thereby avoiding interference between D2D and cellular links but at the cost of low spectrum utilization [16]. On the other hand, underlay D2D communication allows D2D links to reuse cellular users' spectrum resources while ensuring that interference with cellular users remains below a specified threshold [17]. The implementation of D2D communication in underlay cellular communication networks significantly enhances spectrum utilization, albeit at the cost of introducing additional interference for cellular users. Furthermore, within the realm of 5G technology, in-band full-duplex (FD) communication plays a pivotal role in improving spectrum utilization efficiency [18-22]. The introduction of full-duplex (FD) networks complicates the interference of users within D2D networks [18]. However, as D2D communication is service-driven, only activated links can interfere with other communications. A sleep mode D2D link can be considered interference-free for both cellular users and other D2D nodes, making it essential to expedite the completion of D2D communication services to minimize the impact time. Compared to half-duplex (HD) mode D2D users, FD mode users theoretically double the data rate of the D2D link and significantly reduce interference time [19-22]. There are limited preliminary studies focusing on the integration of D2D communication and FD technology [23-25]. For instance, prior research has addressed and resolved the issue of maximizing throughput in FD-D2D communication by implementing resource sharing and power control [23]. Effective interference suppression for FD links can significantly enhance the capacity of FD-assisted cellular networks [24]. Additionally, power allocation for FD relay nodes could enhance the capacity of D2D-based underlay cellular networks [25].

However, if the objective function of network optimization is set to pursue total network rate maximization, severe load imbalance will occur: limited resources will inevitably be occupied by D2D links, resulting in severe degradation of cellular link performance [26, 27]. To date, previous studies have not investigated the activation probability and optimal targeted signal-to-interference-plus-noise-ratio (SINR) threshold for users in D2D underlay communication networks, considering complicated cross-tier and intra-tier interference scenarios. In this paper, we studied FD and HD-D2D communications in underlay cellular networks, taking into account the activation probability and optimal targeted SINR threshold. The Newton iterative algorithm is applied to adjust the targeted SINR threshold, which is beneficial for enhancing D2D users' throughput. The main contributions of this paper are outlined as follows:

1) We investigate the performance of FD and HD-D2D users in underlay cellular networks and derive approximate expressions for metrics such as successful transmission probability, coverage probability, and throughput.

2) We analyze the impacts of cross-tier interference on D2D users and self-interference during FD mode in underlay cellular networks. As a result, when the self-interference cancellation factor β reaches −95 dB, the throughput of FD-D2D users substantially improves, nearly double that of HD users.
3) We propose a Newton iterative algorithm to optimize the targeted SINR threshold, which falls within the range of (10, 20) dB, thereby improving the performance of D2D users in underlay cellular communication networks.

The structure of this paper is as follows: Section 2 introduces the system model of the D2D communications network; Section 3 presents the approximate expressions of successful transmission probability, coverage probability, and throughput; Section 4 offers the numerical results; and finally, Section 5 concludes this paper.

Notation: $\Pr(.)$ denotes the probability. $\mathbb{E}(\cdot)$ signifies the mathematical expectation. $\mathcal{L}_X(\cdot)$ represents the Laplace transform of random variable *X*.

2. System Model

Here, we consider D2D communication networks, which consist of a base station (BS) with a coverage radius of *R*, a co-spectrum cellular user (CU) *c*, and multiple D2D pairs, as shown in **Fig. 1**.

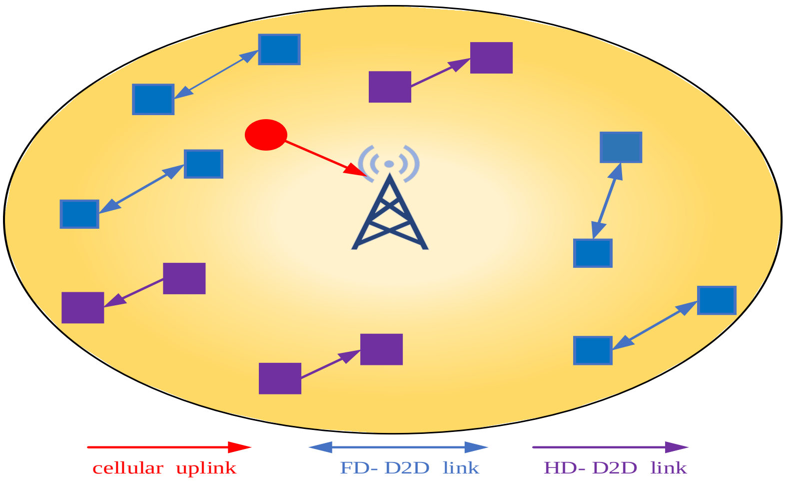

Fig. 1. System model

In this system model, D2D users operate in FD/HD mode within underlay cellular networks. D2D users can only communicate with each other when the interference to the CU is controlled to the threshold level. The spatial distribution of D2D users is assumed to be uniformly distributed within the BS coverage following a homogeneous Poisson point process (PPP) Φ_d with spatial density λ_d, a fixed distance d_k and channel gain h_k between D2D pairs. The channel between nodes i and j is denoted by $h_{i,j} = \exp(1)$ with distannce $d_{i,j}$, where $i, j \in \{\Phi_d, c\}$. Additionally, other system parameters are defined as shown in **Table 1**.

Four scenarios are considered: 1) activation of both FD-D2D users and a co-spectrum CU; 2) activation of both HD-D2D users and a co-spectrum CU; 3) activation of only FD-D2D users; and 4) activation of only HD-D2D users.

Table 1. System parameters

symbol	definition	symbol	definition
P_c	The transmit power of CU	P_k	The transmit power of D2D users
α	Path loss exponent	γ	The targeted SINR threshold
$\mathbb{P}_c$	The activation probability of CU[1]	β	Self-interference cancellation coefficient

2.1 Activation of both D2D Users and a Co-spectrum CU

In this section, both FD and HD users experience interference generated by the co-spectrum CU sharing the same channel. The received SINR for both FD and HD users can be represented as

$$\mathrm{SINR}_d^{(\mathrm{FD})} = \frac{P_k h_k d_k^{-\alpha}}{I_c + I_d^{(\mathrm{FD})} + I_{RSI} + \sigma^2}, \tag{1}$$

and

$$\mathrm{SINR}_d^{(\mathrm{HD})} = \frac{P_k h_k d_k^{-\alpha}}{I_c + I_d^{(\mathrm{HD})} + \sigma^2}, \tag{2}$$

respectively. In particular, $I_c = P_c h_{c,k} d_{c,k}^{-\alpha}$, is utilized to depict the cross-tier interference experienced by D2D users due to their co-spectrum CU. Notably, $I_d^{(\mathrm{FD})} = 2\sum_{j\in\Phi_d\backslash k} P_j h_{j,k} d_{j,k}^{-\alpha}$ represents the intra-tier interference for FD users, while $I_d^{(\mathrm{HD})} = \sum_{j\in\Phi_d\backslash k} P_j h_{j,k} d_{j,k}^{-\alpha}$ represents it for HD users. Additionally, σ^2 signifies the additive white Gaussian noise (AWGN) power at each user.

2.2 Activation of D2D Users Only

In this scenario, the interference generated by the CU does not affect FD or HD users. As a result, the received SINR for both FD and HD users can be expressed as

$$\mathrm{SINR}_d^{(\mathrm{NF})} = \frac{P_k h_k d_k^{-\alpha}}{I_d^{(\mathrm{FD})} + I_{RSI} + \sigma^2}, \tag{3}$$

and

$$\mathrm{SINR}_d^{(\mathrm{NH})} = \frac{P_k h_k d_k^{-\alpha}}{I_d^{(\mathrm{HD})} + \sigma^2}, \tag{4}$$

respectively.

3. Approximate Expression Analysis

3.1 Successful Transmission Probability

The successful transmission probability analysis for the D2D link is assumed under the condition of $\sigma^2 = 0$. Therefore, the received signal-to-interference ratio (SIR) is used instead of the SINR.

[1] Each user determines their activation probability based on their workload [28]

3.1.1 Activation of both D2D Users and a Co-spectrum CU

When both D2D Users and co-spectrum CUs are activated, the successful transmission probability of FD- D2D users is expressed as

$$\begin{aligned} S_d^{fc} &= \mathcal{L}_{I_d^{(\mathrm{FD})}}(s)\mathcal{L}_{I_c}(s)\exp\left(-\beta\gamma d_k^{\alpha}\right) \\ &\approx \frac{\exp\left(-\frac{2\pi\lambda_d}{\mathrm{sinc}(2/\alpha)}d_k^2\gamma^{\frac{2}{\alpha}}-\beta\gamma d_k^{\alpha}\right)}{1+\left(\frac{\gamma P_c}{P_k}\right)^{2/\alpha}d_k^2\left(\frac{128R}{45\pi}\right)^{-2}}. \end{aligned} \tag{5}$$

The detailed calculation process is provided in Appendix I.

Similarly, the successful transmission probability of HD-D2D users can be derived as

$$\begin{aligned} S_d^{hc} &= \Pr\left(SIR_d^{(\mathrm{HD})}\geq\gamma\right) \\ &= \mathcal{L}_{I_d^{(\mathrm{HD})}}(s)\mathcal{L}_{I_c}(s) \\ &\approx \frac{\exp\left(-\frac{\pi\lambda_d}{\mathrm{sinc}(2/\alpha)}d_k^2\gamma^{\frac{2}{\alpha}}\right)}{1+\left(\frac{\gamma P_c}{P_k}\right)^{2/\alpha}d_k^2\left(\frac{128R}{45\pi}\right)^{-2}}. \end{aligned} \tag{6}$$

3.1.2 Activation of D2D Users Only

In this scenario, the successful transmission probability of FD-D2D users can also be formulated as

$$\begin{aligned} S_d^{Nf} &= \Pr\left(SIR_d^{(\mathrm{NF})}\geq\gamma\right) \\ &= \mathcal{L}_{I_d^{\mathrm{FD}}}(s)\exp\left(-\beta\gamma d_k^{\alpha}\right) \\ &\approx \exp\left(-\frac{2\pi\lambda_d}{\mathrm{sinc}(2/\alpha)}d_k^2\gamma^{\frac{2}{\alpha}}-\beta\gamma d_k^{\alpha}\right). \end{aligned} \tag{7}$$

Likewise, the successful transmission probability for HD-D2D users can be expressed as

$$\begin{aligned} S_d^{Nh} &= \Pr\left(SIR_d^{(\mathrm{NH})}\geq\gamma\right) \\ &= \mathcal{L}_{I_d^{\mathrm{HD}}}(s) \\ &\approx \exp\left(-\frac{\pi\lambda_d}{\mathrm{sinc}(2/\alpha)}d_k^2\gamma^{\frac{2}{\alpha}}\right). \end{aligned} \tag{8}$$

3.2 Coverage Probability

The coverage probability for D2D users indicates that the SINR exceeds a specified targeted threshold γ. Consequently, the coverage probability for FD-D2D users can be expressed as

$$S_d^f = \mathbb{P}_c S_d^{fc} + (1-\mathbb{P}_c)S_d^{Nf}. \tag{9}$$

Similarly, the coverage probability for HD-D2D users can be formulated as

$$S_d^h = \mathbb{P}_c S_d^{hc} + (1-\mathbb{P}_c)S_d^{Nh}. \tag{10}$$

3.3 Throughput

Here, the throughput of the FD-D2D users can be determined as

$$T_d^f = 2\mathbb{P}_f \lambda_d S_d^f \log(1+\gamma), \tag{11}$$

where $\mathbb{P}_f$ denotes the active probability of FD-D2D users.

Additionally, the throughput for HD-D2D users can be expressed as

$$T_d^h = \mathbb{P}_h \lambda_d S_d^h \log(1+\gamma), \tag{12}$$

where $\mathbb{P}_h$ denotes the activation probability of the HD-D2D users.

The optimal parameters can be determined by maximizing the throughput using the approximate expressions in (11) and (12). Additionally, the cost function can be expressed as

$$\begin{aligned} &\max_{\mathbb{P}_C, \beta, \gamma} \left(T_d^f\right) \\ &\text{s.t.} 0 \le \mathbb{P}_c \le 1, \end{aligned} \tag{13}$$

and

$$\begin{aligned} &\max_{\mathbb{P}_C, \beta, \gamma} \left(T_d^h\right) \\ &\text{s.t.} 0 \le \mathbb{P}_c \le 1. \end{aligned} \tag{14}$$

The nonlinear optimization problem defined in (13) and (14), which aims to maximize the throughput of D2D communications, cannot be straightforwardly resolved. Eestablishing the convexity of the objective function presented in (13) and (14) is challenging. Consequently, the Newton iterative algorithm is proposed as a solution for solving the problem outlined in (13) and (14) according to the following iterative equation:

$$\gamma_{n+1} = \gamma_n - \frac{f(\gamma)}{f^{'}(\gamma)}, n \in \mathbb{Z} \tag{15}$$

where $f(\gamma) = \frac{\partial T_d^f}{\partial \gamma} / f(\gamma) = \frac{\partial T_d^h}{\partial \gamma}$, $f^{'}(\gamma) = \frac{\partial^2 T_d^f}{\partial \gamma^2} / f^{'}(\gamma) = \frac{\partial^2 T_d^h}{\partial \gamma^2}$, and $\gamma_0 \in \mathbb{R}$.

The algorithm solution process is described in **Table 2**.

Table 2. Newton iterative algorithm solution process

Input: $f(\gamma)$, $f^{'}(\gamma)$, γ_0, iteration number: $N \in \mathbb{N}^+$, error threshold: $\varepsilon \in \mathbb{R}^+$

Preconditions: $f(\gamma) \in \mathbb{C}^2$ and γ_0 is sufficiently close to a root of $f(\gamma)$

Postconditions: $|f(\gamma)| < \varepsilon$ or $k = N$

1 $\gamma \leftarrow \gamma_0$
2 for $k = 0 : N$ **do**
3 $u \leftarrow f(\gamma)$
4 **if** $|u| < \varepsilon$ **then break**
5 $\gamma \leftarrow \gamma - \frac{u}{f^{'}(\gamma)}$
6 end

Output： $\gamma_{opt}^f \leftarrow \gamma$, / $\gamma_{opt}^h \leftarrow \gamma$; maximum throughput : $T_d^f(\gamma_{opt}^f)$, / $T_d^h(\gamma_{opt}^h)$.

4. Numerical Results

In this section, the performances of both the FD and HD-D2D communication networks are evaluated, taking into account crucial parameters such as the activation probability $\mathbb{P}_c$, D2D user density λ_d, and targeted SINR threshold γ.

The accuracy of the theoretical coverage probability is validated through Monte Carlo simulations, as shown in **Fig. 2**. The coverage probability of D2D links linearly decreases with increasing activation probability $\mathbb{P}_c$, with a more pronounced decrease occurring at a higher SINR threshold γ. This suggests a trade-off between the throughput and coverage probability. Specifically, the coverage probability meeting the SINR threshold of FD users may decrease with the introduction of self-interference, potentially causing the HD network to surpass the FD network in terms of coverage probability.

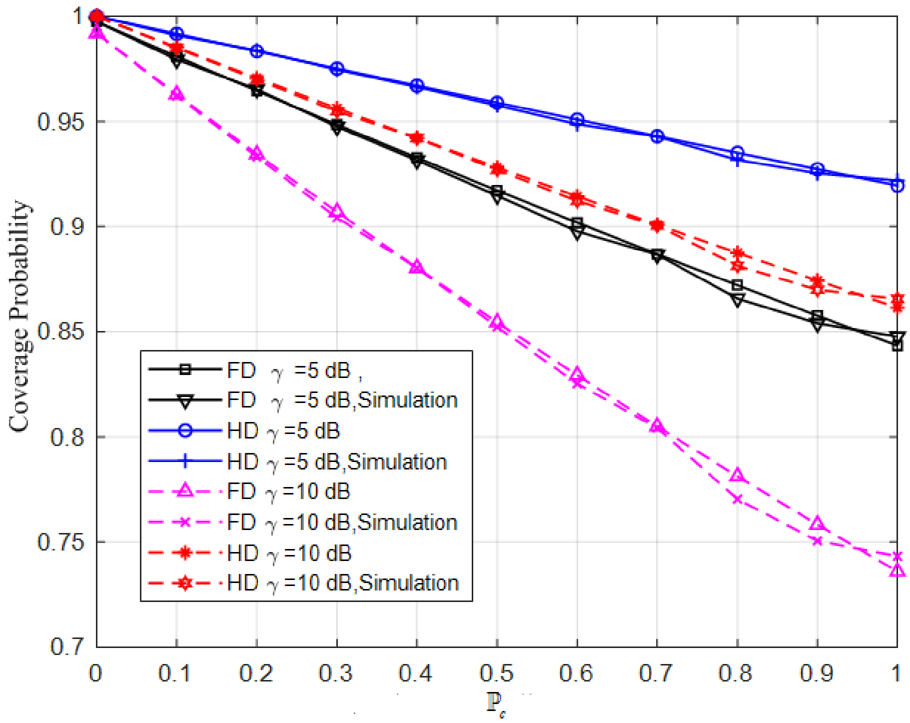

Fig. 2. Coverage probability vs $\mathbb{P}_c$ for different values of γ

The impact of the targeted SINR threshold γ on D2D user throughput is analyzed in **Fig. 3**. The results indicate that for a D2D user density of $\lambda_d = 4\times10^{-5}$, increasing the targeted SINR threshold to 12 dB leads to a gradual increase in FD and HD-D2D communication throughput before reaching a peak and then decreasing. Additionally, for a D2D user density of $\lambda_d = 10^{-5}$, raising the targeted SINR threshold γ to 18 dB results in a gradual increase in FD and HD-D2D throughput up to a peak followed by a decrease. Notably, higher-density D2D traffic peaks at lower SINR thresholds than lower-density traffic due to quicker saturation. The results demonstrate that the FD network outperforms the HD network in terms of throughput. Furthermore, as shown in **Fig. 3**, the trend of D2D throughput demonstrates an initial increase followed by a decrease with the continuous adjustment of the targeted SINR threshold, indicating a continuous function. The optimal targeted SINR threshold within (10,

20) dB can be successfully found.

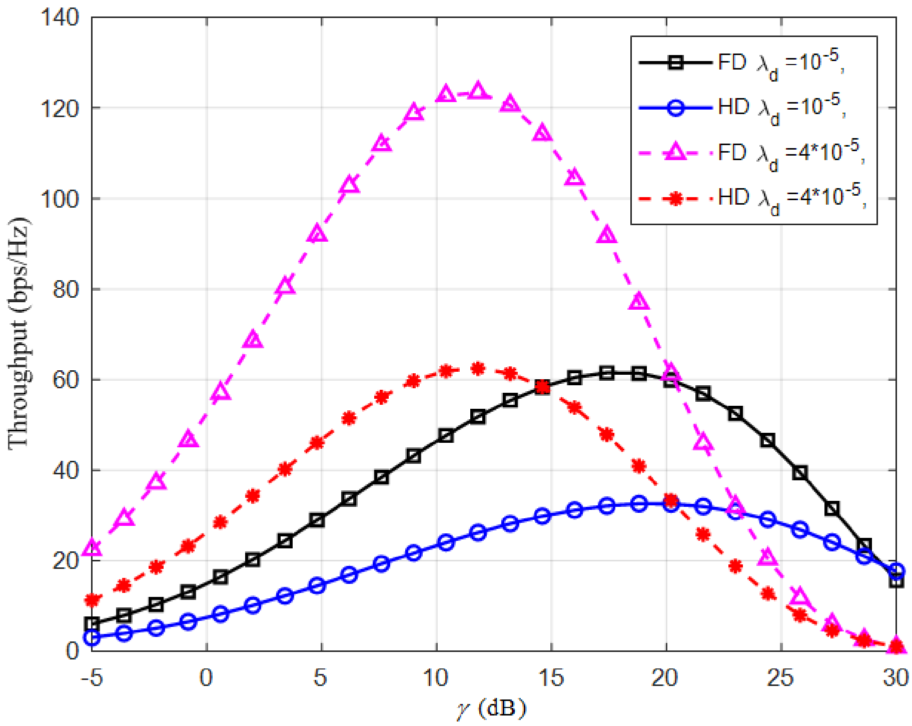

Fig. 3. D2D throughput vs targeted SINR threshold γ for different values of λ_d

Here, the determination of the maximum system throughput involves utilizing the Newton iterative method. **Fig. 4** shows that the maximum throughput of D2D users is influenced by the self-interference cancellation factor β. In scenarios where HD-D2D operates without self-interference, there is no impact on the system's maximum throughput, which remains constant regardless of β. Conversely, in FD mode at $\beta < -95$ dB and with D2D users exhibiting strong self-interference cancellation capabilities, there is limited impact from D2D communication's self-interference, resulting in stable maximum throughput. However, at $\beta > -95$ dB, there is a sharp decrease in the maximum throughput of D2D users. Additionally, the maximum system throughput for a D2D network increases with increasing user density. If FD users achieve perfect self-interference cancellation, their maximum throughput surpasses that of HD users. In larger networks with higher densities and more complex topologies, the D2D user throughput of the proposed system increases as the number of active D2D users increases.

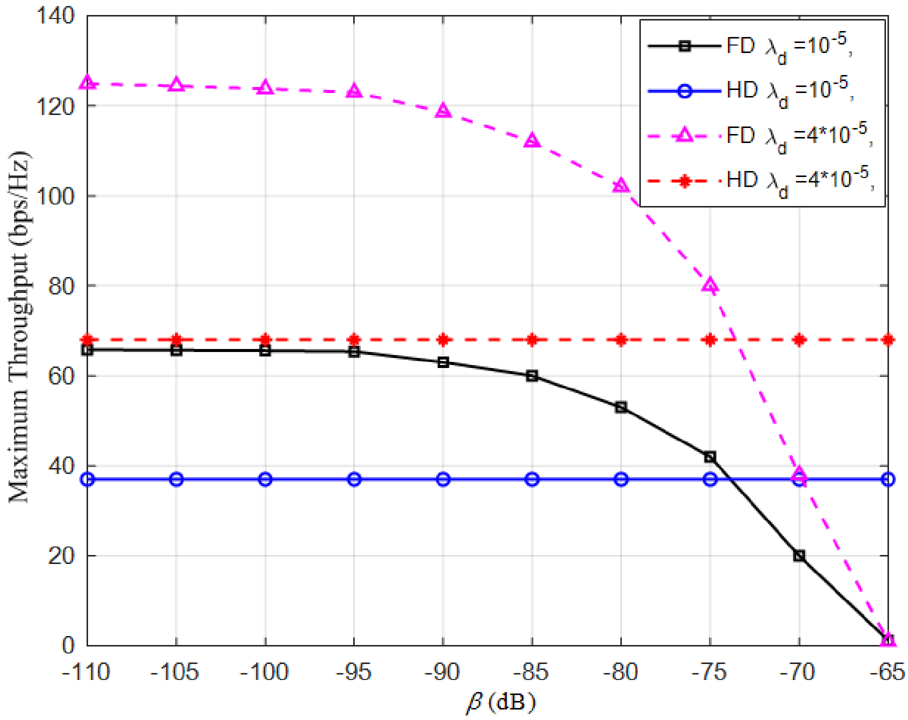

Fig. 4. Maximum throughput of D2D users vs β for different values of λ_d

5. Conclusion

The study investigated the performance of FD and HD-D2D users within cellular networks. Stochastic geometry methods were employed to derive the successful transmission probability, coverage probability, and throughput. The analysis revealed that utilizing FD-D2D users could improve throughput performance compared to using HD users, despite the potential occurrence of self-interference. Furthermore, adjusting the targeted SINR threshold via the Newton iterative algorithm offered a superior balanced solution for throughput and additional interference. In addition, the optimal targeted SINR threshold was in the range of (10, 20) dB. It is important to note that the performance of the CU was not considered in this analysis, and future work will focus on complex heterogeneous networks with unmanned aerial vehicles (UVAs) enabled.

Appendix I

Successful Transmission Probability of FD-D2D users

The successful transmission probability of FD-D2D users can be derived as

$$\begin{aligned} S_d^{fc} &= \Pr\left(\mathrm{SIR}_d^{(\mathrm{FD})} \geq \gamma\right) \\ &= \Pr\left(h_k \geq \frac{I_c + I_d^{(\mathrm{FD})} + I_{RSI}}{P_k d_k^{-\alpha}} \cdot \gamma\right) \\ &= \mathcal{L}_{I_d^{(\mathrm{FD})}}(s)\mathcal{L}_{I_c}(s)\exp\left(-\beta\gamma d_k^{\alpha}\right), \end{aligned} \tag{16}$$

where $s=\gamma d_k^{\alpha}/P_k$.

Furthermore, by using $\mathbb{E}\left(\left[\prod_{\Phi} f(x)\right]\right)=\exp\left(-\lambda_d\int_{\mathbb{R}^2}[1-f(x)]dx\right)$ and $\int_{\mathbb{R}^2} f(x)dx=2\pi\int_0^{\infty}xf(x)dx$, the Laplace transforms of I_d can be derived as

$$\begin{aligned}\mathcal{L}_{I_d^{(\mathrm{FD})}}(s)&=2\mathbb{E}\left[\exp\left(-sP_k\sum_{\Phi}h_k d_k^{-\alpha}\right)\right]\\&=2\mathbb{E}\left[\prod_{\Phi}\frac{1}{1+sP_k d_k^{-\alpha}}\right]\\&=\exp\left\{-4\pi\lambda_d\int_0^{\infty}\left(1-\frac{1}{1+sP_k x^{-\alpha}}\right)xdx\right\}\\&=\exp\left(-\frac{2\pi\lambda_d}{\mathrm{sinc}(2/\alpha)}P_k^{\frac{2}{\alpha}}s^{\frac{2}{\alpha}}\right)\end{aligned}\tag{17}$$

Similarly, the Laplace transform of I_c can be expressed as

$$\begin{aligned}\mathcal{L}_{I_c}(s)&=\mathbb{E}\left[\exp\left(-sP_c h_{c,k}d_{c,k}^{-\alpha}\right)\right]\\&=\mathbb{E}_{d_{c,k}}\left[\frac{1}{1+sP_c d_{c,k}^{-\alpha}}\right]\\&\approx\frac{1}{1+\left(sP_c\right)^{2/\alpha}\mathbb{E}\left(d_{c,k}^{-2}\right)}\\&=\frac{1}{1+\left(\frac{\gamma d_k^{\alpha}}{P_k}P_c\right)^{2/\alpha}\left(\frac{128R}{45\pi}\right)^{-2}},\end{aligned}\tag{18}$$

where $\mathbb{E}\left(d_{c,k}\right)=\frac{128R}{45\pi}$ [29, 30].

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