Throughput Analysis for Full-Duplex Based Device-to-Device Communications

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Abstract. The throughput of Device-to-device (D2D) enabled underlaying cellular networks is analyzed, with either full duplex (FD) or conventional half duplex (HD) transmission mode considered in D2D links. Despite of the severe interference imposed on the cellular users (CUs) by the FD based D2D (FD-D2D) links, the FD-D2D mode always exhibits its superiority in terms of the network throughput due to its reduced large-scale fading as well as low transmit-power essences. Numerical results show that the proposed FD-D2D mechanism is capable of substantially improving the network throughput.

Keywords: Device-to-device · Full duplex · Throughput · Interference

1 Introduction

With the rapid development of wireless communication techniques, the existed cellular networks become more and more insufficient for supporting the customers' exponentially growing data traffic demands [1,2]. In order to successfully relieve the heavy burden of base stations (BSs), Device-to-Device (D2D) communication technique allowing proximity users to communicate directly with each other without relying on the intervention of BS has exhibited several promising advantages in terms of cell throughput [3], spectral efficiency [4], users' end-to-end latency [5], radio coverage [6], power consumption [7] and traffic offloading capabilities [8], etc. Unlike the traditional BS-centric communications, D2D mode possess the characteristics of shorter radio-propagation distance and lower transmit power, thus leading to a higher signal-to-interference-plus-noise ratio (SINR) at the receiver. Up to now, D2D technique has attracted a wide attention in both academia and industry [9,10].

Unlike the conventional half duplex (HD) mode, which has been widely adopted in the existed D2D studies [8,11], the full duplex (FD) mode is capable of supporting concurrent transmission and reception in a single time/frequency

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channel so as to (in theory) improving the attainable spectral efficiency by a factor of two [12–15]. However, FD mode suffers from a performance degradation due to the impact of self-interference (SI) [16], which can be substantially reduced by employing the state-of-the-art SI cancellation techniques [13].

All the above-mentioned issues have motivated us to investigate the combination of D2D communications and FD techniques [11]. However, there still exist several challenges to address in D2D systems. For example, interference management constitutes a major concern of D2D-enabled cellular networks. To implement the practical D2D-based systems, the D2D links can either be allocated a dedicated resource (i.e. be orthogonal to the cellular bandwidth) [17] or be allowed to reuse the cellular's resources [18]. Relative to the former, the same spectrum is shared between the cellular and the D2D systems in the latter scenario, leading to a more efficient resource utilization but also a much more severe interference problem (e.g. cellular-to-D2D interference, D2D-to-D2D interference, etc.). As compared with the HD mode, the FD based D2D (FD-D2D) mode will lead to more serious interference problem. Specifically, the D2D-induced interference may even deteriorate the throughput of the geographically closed D2D pairs.

In light of the fact that the D2D mode is essentially service-oriented and a D2D link is created when and only when a service demand emerges between a pair of D2D-enabled users, the mute duration of the D2D links can still be regarded as the interference-free period of the conventional cellular users (CUs). In this case, it would be critical to complete a given D2D service as quick as possible in order to minimize the impact of D2D-imposed interference. Therefore, an efficient and straightforward way to improve the throughput of CUs might resort to the capability of suppressing the duration of D2D-induced interference. As compared to the HD mode, FD mode is (in theory) capable of doubling the data transmission rate of a given D2D link, corresponding to cut the D2D-imposed interference period by half. For a given block of data to be shared between D2D pairs, FD-D2D is found to be helpful to substantially expedite the completion of D2D services. Although the average interference strength imposed on the CUs by FD-D2D users becomes higher than that induced by the transmissions of HD-mode D2D pairs, the accumulated performance losses observed in the CUs due to the FD-D2D induced interference are still lower than that induced by the latter, because the average transmission time of a given data needed in the latter is almost two times of that of the former. From this point of view, it would be beneficial to improving the throughput of the D2D-aided cellular networks by adopting FD mode rather than HD mode.

In this paper, we investigate the technique of FD-D2D under the scenario of spatially distributed multiple cells by analyzing the network throughput. The main contributions of this paper are reflected as follows. Based on the theory of stochastic geometry, a theoretical framework is established for modelling and analyzing either the cellular/D2D links' data rate and the throughput of the whole network by considering both the FD and HD modes. We analyze the throughput gain brought about by enabling FD-D2D in cellular networks.

Despite of a higher interference than the HD mode may be imposed by employing FD-D2D, the latter still exhibits its superiority in terms of the network throughput due to its short-distance-communication essence and lower power consumption, provided that the SI power can be suppressed to a low enough level[1].

The remainder of this paper is organized as follows. In Sect. 2, the system mode for D2D-aided underlaying cellular networks is described. The theoretical analysis for the transmission rates in both the FD and the HD modes will be presented in Sect. 3, followed by numerical results given by Sect. 4. Finally, Sect. 5 concludes this paper.

Notation: $\mathcal{STP}_{\{\bullet\}}$ denotes the successful transmission probability of a link, $\mathcal{L}\{\bullet\}$ denotes the Laplace transforms of a random variable, $\mathbb{P}\{\bullet\}$ represents the probability of a event, $\mathbb{E}\{\bullet\}$ denotes the expectation, and $R_{\{\bullet\}}$ denotes the throughput of a link.

2 Uplink System Model for FD-D2D Based Underlaying Cellular Networks

In this paper, we consider a cellular system comprising multiple BSs and mobile user equipments (UEs). Without loss of generality, we assume that the BSs are spatially distributed inside a given geographical area according to a homogeneous Poisson point process (PPP) Φ_b of intensity λ_b. Furthermore, both the conventional CUs and the DUs can be served by the system, in which the CUs and DUs are also assumed to be geographically scattered according to independent homogeneous PPPs Φ_c and Φ_d, with intensities of λ_c and λ_d, respectively. We assume that each DU has an opportunity to find a matched DU close to it to constitute a D2D pair, in which the average length of the established D2D links is represented by D_d. In addition, a constant transmit power is assumed in each user, with P_c and P_d denoting the transmit power of CUs and DUs, respectively.

We consider an FD-D2D based underlaid HD cellular network, in which the conventional cellular links are assumed to be operated in HD mode, whereas the D2D links are operated at the FD mode. Furthermore, the uplink recourses are employed for facilitating the D2D communications. Without loss of generality, the general (large-scale) power law propagation model and the (small-scale) Rayleigh fading channels are adopted in both the cellular/D2D links and the interference links. In addition, we assume that all the above-mentioned links in our model are independent and identically distributed (i.i.d.) random variables with $h_{ij} \sim \exp(1), i, j \in \{\Phi_b, \Phi_c, \Phi_d\}$.

In the following, we assume that an orthogonal resource can be assigned to each CU for effectively mitigating the intra-cell interference. The receive SINR of both the conventional cellular links and the D2D links can be expressed as

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[1] According to [13], SI-cancellation capability of up to 110 dB can be attained by employing proper spatial suppression, analog- and digital-domain cancellations.

$$\mathrm{SINR}_c = \frac{P_c h_{cb} d_{cb}^{-\alpha}}{I_{dc} + I_{cc} + \sigma^2}, \tag{1}$$

$$\mathrm{SINR}_d = \frac{P_d h_d D_d^{-\alpha}}{I_{cd} + I_{dd} + I_{SI} + \sigma^2}, \tag{2}$$

respectively, where $I_{dc} = 2\sum_{\Phi_d} P_d h_{d_i b} r_{d_i b}^{-\alpha}$ denotes the interference power imposed on CUs by FD-DUs, $I_{cc} = \sum_{\Phi_c / c_0} P_c h_{c_i b} r_{c_i b}^{-\alpha}$ represents the interference among CUs, $I_{cd} = \sum_{\Phi_c} P_c h_{c_i d} r_{c_i d}^{-\alpha}$ stands for the interference power imposed on DUs by CUs, $I_{dd} = 2\sum_{\Phi_d} P_d h_{d_i d} r_{d_i d}^{-\alpha}$, represents the interference among FD-DUs, $I_{SI} = P_d c_{si}$ denotes the residual SI observed in the FD devices after performing SI cancellation, and c_{si} denotes the SI cancellation coefficient (a larger coefficient corresponds to a higher SI cancellation capability). Furthermore, σ^2 denotes the Additive-White Gaussian Noise (AWGN) covariance.

Note that the average length of D2D links (corresponding to the transmitter-receiver distance) is shorter than that of the cellular and/or interference links. Furthermore, the average interference strength imposed on BSs by the active FD-mode DUs is much higher than that imposed by the HD-mode DUs. It would thus be reasonable to assume that the former is two times of the latter. In other words, the interference induced by an FD-D2D pair comes from both the transmitter and the receiver, resulting in a two-fold interference strength compared to that induced by the HD-mode D2D pair, in which case only one out of the D2D peers is allowed to transmit in each time.

We further define the successful transmission probability (STP) as *the probability that the quality of a randomly chosen link successfully reaches its predetermined target SINR threshold* ε. The STP of a typical cellular or D2D link can thus be define as

$$\mathcal{STP}_c = \Pr\left(\frac{P_c h_{cb} d_{cb}^{-\alpha}}{I_{dc} + I_{cc} + \sigma^2} > \varepsilon\right) \tag{3}$$

and

$$\mathcal{STP}_d = \Pr\left(\frac{P_d h_d D_d^{-\alpha}}{I_{cd} + I_{dd} + I_{SI} + \sigma^2} > \varepsilon\right), \tag{4}$$

respectively.

3 Throughput for FD-D2D Based Underlaying Cellular Networks

In this section, the throughput for D2D based underlaying cellular networks will be analyzed. The SI cancellation is assumed to be already performed (but the residual SI power is always non-zero). The theory of stochastic geometry can be employed for modelling and analyzing the throughput of the proposed system by considering both the FD and HD modes.

According to the tractable analysis of PPP in [19], each CU will always preferentially communicate with the BS having the highest RSS (i.e. the geographically closest BS), leading to the probability density function (PDF) of the random CU-BS distances r as

$$f_r(r) = e^{-\pi \lambda_b r^2} 2\pi \lambda_b r. \tag{5}$$

3.1 STP of a Typical Cellular Links

From the Slivnyaks theorem [20], the statistical property of a typical node located at a specific position holds true for any generic node located at any generic location. Without loss of generality, we assume that the CU of interest is located at the origin of the plane and receives signals from the closest BS. The STP of a typical cellular link in a general FD-D2D underlaying cellular network can be derived as

$$\begin{aligned} \mathcal{STP}_c^f = & \int_0^\infty \mathcal{L}_{I_{cc}}\left(\frac{\varepsilon r^\alpha}{P_c}\right) \mathcal{L}_{I_{dc}}\left(\frac{\varepsilon r^\alpha}{P_c}\right) \\ & \times e^{-\frac{\varepsilon r^\alpha \sigma^2}{P_c}} e^{-\lambda_b \pi r^2} 2\pi \lambda_b r \mathrm{d}r, \end{aligned} \tag{6}$$

where $\mathcal{L}_{I_{cc}}(s)$ and $\mathcal{L}_{I_{dc}}(s)$ denote the Laplace transforms (evaluated at s) of random variables I_{cc} and I_{dc}, respectively, as defined by

$$\mathcal{L}_{I_{cc}}\left(\frac{\varepsilon r^\alpha}{P_c}\right) = \exp\left[\frac{-2\pi\lambda_b r^2 \varepsilon}{\alpha - 2} {}_2F_1\left(1, \frac{\alpha-2}{\alpha}; 2 - \frac{2}{\alpha}; -\varepsilon\right)\right] \tag{7}$$

and

$$\mathcal{L}_{I_{dc}}\left(\frac{\varepsilon r^\alpha}{P_c}\right) = \exp\left[-2^{\frac{2}{\alpha}}\left(\frac{P_d}{P_c}\right)^{\frac{2}{\alpha}} \pi r^2 \lambda_d \varepsilon^{\frac{2}{\alpha}} \frac{1}{\mathrm{sinc}(\frac{2}{\alpha})}\right], \tag{8}$$

respectively, the function ${}_2F_1(a, b; c; z)$ denotes the hypergeometric function, and $\mathrm{sinc}(x) = \dfrac{\sin(\pi x)}{\pi x}$.

3.2 STP of a Typical FD-D2D Links

In the proposed FD-D2D based underlaying cellular networks, a given FD-D2D link also suffers from interference induced by various sources, including the conventional CUs, the neighboring FD-D2D pairs and the residual SI at the FD devices, etc. The STP of a typical FD-D2D link in a general FD-D2D underlaying cellular network is given by

$$\mathcal{STP}_d^f = \mathcal{L}_{I_{cd}}\left(\frac{\varepsilon D_d^\alpha}{P_d}\right) \mathcal{L}_{I_{dd}}\left(\frac{\varepsilon D_d^\alpha}{P_d}\right) e^{-\varepsilon c_{si} D_d^\alpha} e^{-\frac{\varepsilon D_d^\alpha \sigma^2}{P_d}}, \tag{9}$$

where $\mathcal{L}_{I_{cd}}(s)$ and $\mathcal{L}_{I_{dd}}(s)$ denote the Laplace transforms (evaluated at s) of random variables I_{cd} and I_{dd}, respectively, as defined by

$$\mathcal{L}_{I_{cd}}\left(\frac{\varepsilon D_d^\alpha}{P_d}\right) = \exp\left[-\pi\lambda_b D_d^2 \left(\frac{P_c}{P_d}\right)^{\frac{2}{\alpha}} \varepsilon^{\frac{2}{\alpha}} \frac{1}{\mathrm{sinc}(\frac{2}{\alpha})}\right] \tag{10}$$

and

$$\mathcal{L}_{I_{dd}}\left(\frac{\varepsilon D_d^\alpha}{P_d}\right) = \exp\left[-2^{\frac{2}{\alpha}}\pi\lambda_d D_d^2 \varepsilon^{\frac{2}{\alpha}} \frac{1}{\mathrm{sinc}(\frac{2}{\alpha})}\right], \tag{11}$$

respectively.

3.3 Throughput Analysis for the FD-D2D Based Underlaying Cellular Networks

From information theory [21], the average throughput of a typical CU/DU can be defined as

$$R = \mathbb{E}[\log(1+\mathrm{SINR})] = \int_{\varepsilon>0} \frac{\mathbb{P}(\mathrm{SINR} > \varepsilon)}{\varepsilon+1} \mathrm{d}\varepsilon. \tag{12}$$

The throughput of a typical cellular link and FD-D2D link can thus be derived as

$$\begin{aligned} R_c^f &= \int_{\varepsilon>0} \frac{\mathcal{STP}_c^f}{\varepsilon+1} \mathrm{d}\varepsilon \\ &= \int_0^\infty \int_0^\infty \exp\left\{-\pi r^2 \left[\frac{2\lambda_b \varepsilon}{\alpha-2} M + \left(2\frac{P_d}{P_c}\right)^{\frac{2}{\alpha}} \varepsilon^{\frac{2}{\alpha}} N\right]\right\} \\ &\times \exp\left(-\frac{\varepsilon r^\alpha \sigma^2}{P_c} - \lambda_b \pi r^2\right) 2\pi\lambda_b r \mathrm{d}r \frac{1}{\varepsilon+1} \mathrm{d}\varepsilon \end{aligned} \tag{13}$$

and

$$\begin{aligned} R_d^f &= \int_{\varepsilon>0} \frac{\mathcal{STP}_d^f}{\varepsilon+1} \mathrm{d}\varepsilon \\ &= \int_0^\infty \exp\left\{-\frac{\pi D_d^2 \varepsilon^{\frac{2}{\alpha}}}{\mathrm{sinc}(\frac{2}{\alpha})} \left[\lambda_b \left(\frac{P_c}{P_d}\right)^{\frac{2}{\alpha}} + 2^{\frac{2}{\alpha}} \lambda_d\right]\right\} \\ &\times \exp\left(-\varepsilon c_{si} D_d^\alpha - \frac{\varepsilon D_d^\alpha \sigma^2}{P_d}\right) \frac{1}{\varepsilon+1} \mathrm{d}\varepsilon, \end{aligned} \tag{14}$$

respectively.

Note that the impact of thermal noise will no longer dominate the performance degradation of the D2D-aided networks, which should be interference limited. In this case, it would be reasonable to assume that $\sigma^2 \to 0$, thus enabling the throughput of the FD-D2D underlaying cellular networks to be simplified as

$$R^f = \lambda_b R_c^f + 2\lambda_d R_d^f, \tag{15}$$

where

$$R_c^f = \int_0^\infty \frac{1}{\varepsilon+1} \times \frac{1}{\frac{2\varepsilon}{\alpha-2}M + \left(2\frac{P_d}{P_c}\right)^{\frac{2}{\alpha}} \varepsilon^{\frac{2}{\alpha}} \frac{N}{\lambda_b} + 1} \mathrm{d}\varepsilon \tag{16}$$

and

$$R_d^f = \int_0^\infty \frac{1}{\varepsilon+1} \exp\left\{-\frac{\pi D_d^2 \varepsilon^{\frac{2}{\alpha}}}{\mathrm{sinc}(\frac{2}{\alpha})} F - \varepsilon c_{si} D_d^\alpha \right\} \mathrm{d}\varepsilon, \tag{17}$$

respectively, where $F = \left[\lambda_b \left(\frac{P_c}{P_d}\right)^{\frac{2}{\alpha}} + 2^{\frac{2}{\alpha}} \lambda_d\right]$.

For purposes of performance comparison, we also derive the throughput under HD mode, as given by

$$R^h = \lambda_b R_c^h + \lambda_d R_d^h, \tag{18}$$

where

$$R_c^h = \int_0^\infty \frac{1}{\varepsilon+1} \times \frac{1}{\frac{2\varepsilon}{\alpha-2}M + \left(\frac{P_d}{P_c}\right)^{\frac{2}{\alpha}} \varepsilon^{\frac{2}{\alpha}} \frac{N}{\lambda_b} + 1} \mathrm{d}\varepsilon \tag{19}$$

and

$$R_d^h = \int_0^\infty \frac{1}{\varepsilon+1} \times \exp\left\{-\frac{\pi D_d^2 \varepsilon^{\frac{2}{\alpha}}}{\mathrm{sinc}(\frac{2}{\alpha})} \left[\lambda_b \left(\frac{P_c}{P_d}\right)^{\frac{2}{\alpha}} + \lambda_d\right]\right\} \mathrm{d}\varepsilon, \tag{20}$$

respectively. Evidently, the superiority of FD-mode over HD-mode is mainly reflected in the potential factor-2 throughput gain. However, this gain is not attainable in practical designs mainly due to the impact of residual SI as well as the other non-linear distortions [13]. Since the HD mode may occasionally outperform the FD mode in terms of attainable throughput if the residual SI power in the FD devices is high, the latter maintains its advantages only if the SI power can be sufficiently suppressed.

4 Numerical Results

In this section, we evaluate the spectral efficiency gain offered by underlaying cellular networks, which combines the benefits of both the FD mode and D2D communications. The uplink band is shared between the conventional CUs and the D2D links, with i.i.d. Rayleigh fading considered. Furthermore, the path-loss exponent is set to $\alpha = 4$ (i.e. corresponding to the typical urban environment).

In the following simulations, an area of $4000 \times 4000\,\mathrm{m}^2$ square serving 5 BSs and 30 D2D links (deployed according to independent PPP) is considered. Furthermore, an orthogonal resource allocation among CUs is assumed. In addition, the average length of D2D links is assumed to be 50 m, with the transmit powers of CUs and DUs assumed to be 30 dBm and 20 dBm, respectively. Finally, the noise power spectrum density is assumed to be −174 dBm/Hz. The detailed parameter settings are shown in Table 1.

As shown in Fig. 1, the numerical results can well validate the theoretical analysis. In the presence of low SI-cancellation capability (i.e. a relatively higher power of residual SI is imposed on the FD devices), the HD mode based D2D outperforms the FD-D2D mode in terms of the spectral efficiency. However, the FD-D2D mode exhibits its superiority over its FD counterpart if the SI-cancellation capability becomes higher than 85 dB.

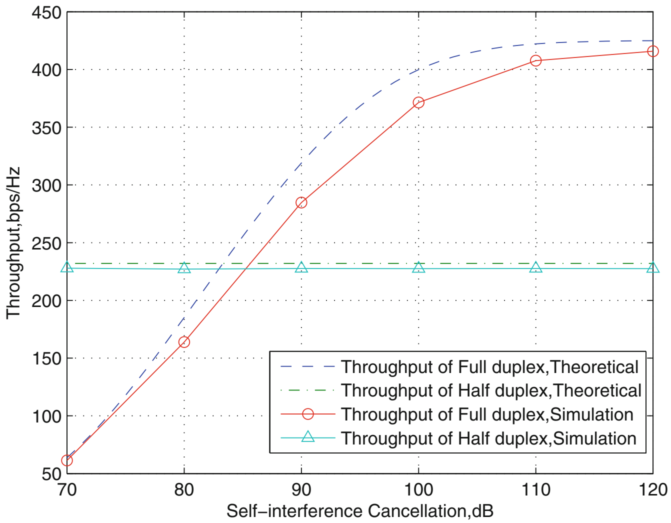

Fig. 1. Performance comparison of HD-D2D and FD-D2D in terms of throughput by considering variant SI cancelation.

Figure 2 illustrates the performance comparison between HD-D2D and FD-D2D modes in terms of spectral efficiency under various number of D2D links. Evidently, the spectral efficiency can be improved as the number of D2D link increases. However, the approach of improving the spectral efficiency by infinitely increasing the number of D2D links is shown to be un-sustainable. As illustrated in Fig. 3, when we shrink the simulation area from $4000 \times 4000\,\mathrm{m}^2$ to $1000 \times 1000\,\mathrm{m}^2$ (i.e. corresponding to magnifying the density of DUs), the spectral efficiency may be eroded by further increasing the D2D numbers once it approaches a critical threshold. We may explain it as follows: In scenarios with sparse D2D distributions, activating more D2D pairs implies contributing more throughput via D2D links. In scenarios with dense D2D distributions, on the other hand, the whole system becomes interference-overloaded, in which case the performance improvement brought about by increasing D2D pairs cannot

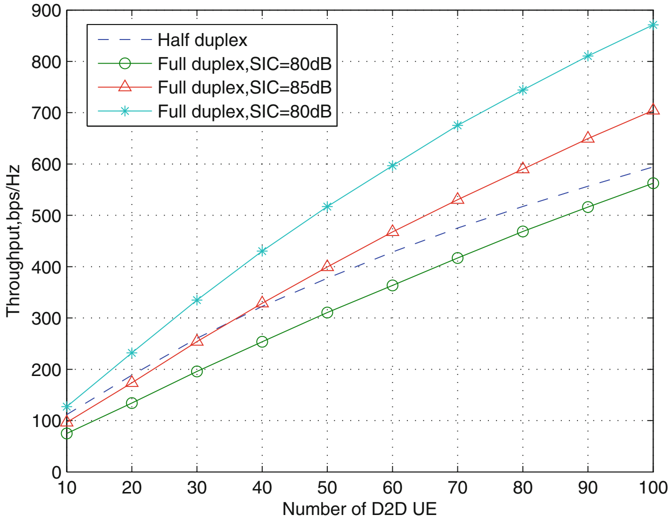

Fig. 2. Performance comparison of HD-D2D and FD-D2D in terms of throughput under different D2D-density settings (sparse scenario is considered).

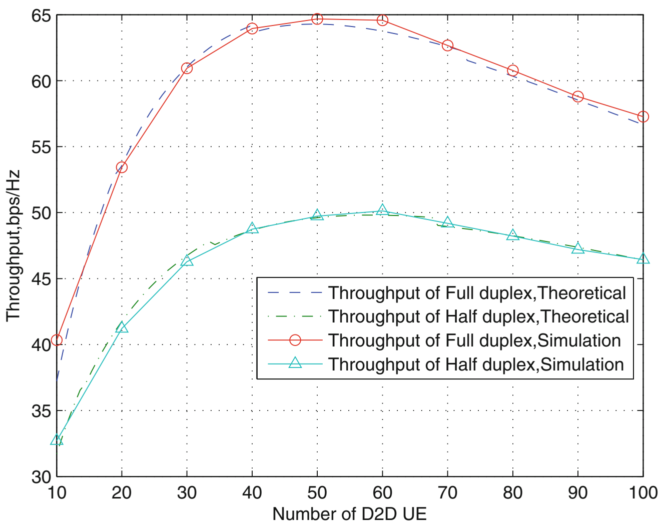

Fig. 3. Performance comparison of HD-D2D and FD-D2D in terms of throughput under different D2D-density settings (dense scenario is considered).

counter-balance the throughput losses induced by the severe interference imposed by D2D links. Furthermore, a further observation in Fig. 2 indicates that the performance gap between the FD-D2D and the HD-D2D modes becomes larger as the number of D2D pairs increases (i.e. the superiority of the FD-D2D mode is enhanced). Anyway, as long as the DU density is below the tolerable threshold, increasing the number of D2D pairs (i.e. corresponding to decreasing the distance between peer DUs) will always enables a better FD mode communication.

Table 1. Default key parameters in the simulation

Parameter	Physical Mean	Value
P_c	Power of CU	30 dBm
P_d	Power of DUs	20 dBm
α	Path loss coefficient	4
D_d	The average distance between a pair of D2D peers	50 m
σ^2	Power level of thermal noise	−174 dBm/Hz
	Simulation area	4000 m × 4000 m
N_b	Number of BS	5
N_d	Number of D2D link	30
k	Cellular Link Protecting Radius Coefficient	0.5–0.7
c_{si}	SI cancellation coefficient	100 dB

5 Conclusions

In this paper, benefits brought about by implementing FD-D2D aided cellular networks in terms of spectral efficiency was analyzed, showing that the FD-D2D communication is capable of improving the sum-rate of the network due to its speciality of short link distance and lower transmit power, despite of a much more severe interference than the HD-D2D mode imposed on it. Furthermore, it was shown that the attainable performance gain in terms of throughput cannot be infinitely increased by simply increasing the number of D2D links, because the CUs may become interference overloaded, in which case the performance gain brought by increasing the number of D2D links cannot counter-balance the throughput loss induced by the severe interference.

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