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On the throughput gain of device-to-device communications

YoungJu Hwang[a,*], Jihong Park[a], Ki Won Sung[b], Seong-Lyun Kim[a]

[a] *Yonsei University, Department of Electrical and Electronic Engineering, 50 Yonsei-ro, Seodaemun-Gu, Seoul 120-749, Republic of Korea*
[b] *KTH Royal Institute of Technology, Wireless@KTH, Stockholm, Sweden*

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Abstract

In an uplink underlaid device-to-device (D2D) cellular network, this paper considers its two aspects of throughput improvement. The two-fold gain comprises the throughput increase by offloading downlink cellular traffic to D2D communications, *duplexing gain*, and the increase by reusing uplink resources of D2D transmissions, *capacity gain*. Both impacts are investigated by exploiting stochastic geometry. On the basis of the analysis, a throughput optimal D2D operation guideline is provided for different network congestion environments.

Keywords: Device-to-device; OFDMA cellular networks; Underlay spectrum sharing; Duplexing gain; Capacity gain; Densification; Stochastic geometry

1. Introduction

As an effective remedy for the unabated cellular spectrum crunch, device-to-device (D2D) communication has recently attracted much attention [1–3]. Its major improvement in cellular throughput is dyadic: *duplexing gain* and *capacity gain*. First, duplexing gain follows from downlink resource savings via offloading cellular traffic to direct D2D communications of users. Second, capacity gain results from reusing uplink resources via underlaying D2D communications with uplink cellular operations.

The uplink underlaid network protects downlink users from D2D interference, yet in return may incur severe interference at uplink base stations (BSs). To mitigate such an uplink interference problem, D2D communications are only allowed to users outside a certain guard region from each base station.

From the perspectives of guard region size and base station density, the characteristics of both gains are provided in this article by using stochastic geometry. As a consequence, a throughput optimal D2D network design guideline is suggested.

2. System model

2.1. Network model

Consider an uplink cellular network where the BSs are located according to a homogeneous Poisson point process (PPP) with density λ_{BS}. D2D-incapable user equipments (C-UE) and D2D-enabled user equipments (D-UE) are independently distributed according to homogeneous PPPs respectively with the densities λ_C and λ_D. C-UEs associate with the nearest BSs. The associations of D-UEs, on the other hand, depend on their operation mode. In *cellular mode*, they associate with the nearest BSs as in C-UEs. In *D2D mode*, each D-UE associates with its peer UEs for direct communications with the average association distance d.

To specify such a mode selection, define d_{cell} as the nearest BS distance from a D-UE, and d_{th} as the D2D guard region radius at a BS [4]. The transmission mode selection of D-UEs is then given as follows: if $d_{cell} < d_{th}$, a D-UE selects cellular mode; otherwise, it chooses D2D mode. Fig. 1 visualizes the mode selection. For the sake of convenience, cellular users hereafter denote C-UEs and cellular mode D-UEs, and D2D users represent D-UEs in D2D mode.

The uplink spectrum is divided into M orthogonal sub-channels under orthogonal frequency division multiplexing (OFDM). Each cellular user accesses a single sub-channel

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[*] Corresponding author.

E-mail addresses: youngju.hwang@gmail.com (Y. Hwang), jhpark.james@yonsei.ac.kr (J. Park), sungkw@kth.se (K.W. Sung), slkim@yonsei.ac.kr (S.-L. Kim).

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$$\mathsf{F}_C = \exp\left\{-\pi r^2(e^t-1)^{\frac{2}{\alpha}}\left[\frac{p_a(\lambda_{D2D})\lambda_{BS}}{M}\int_{(e^t-1)^{-\frac{\alpha}{2}}}^{\infty}\frac{1}{1+u^{\frac{\alpha}{2}}}\mathrm{d}u + \frac{\lambda_{D2D}}{M}\int_{\frac{(d_{th}/r)^2}{(e^t-1)^{\frac{2}{\alpha}}}}^{\infty}\frac{1}{1+(P/P_D)\,u^{\frac{\alpha}{2}}}\mathrm{d}u\right]\right\} \tag{1}$$

$$\mathsf{F}_{D1} = \exp\left\{-\pi r^2(e^t-1)^{\frac{2}{\alpha}}\left[\frac{p_a(\lambda_{D2D})\lambda_{BS}}{M}\int_{\frac{(1-\eta)^2}{(e^t-1)^{\frac{2}{\alpha}}}}^{\infty}\frac{1}{1+u^{\frac{\alpha}{2}}}\mathrm{d}u + \frac{\lambda_{D2D}}{M}\int_{\frac{(d_{th}/r)^2}{(e^t-1)^{\frac{2}{\alpha}}}}^{\infty}\frac{1}{1+(P/P_D)\,u^{\frac{\alpha}{2}}}\mathrm{d}u\right]\right\} \tag{2}$$

$$\mathsf{F}_{D2} = \exp\left\{-\pi d^2(e^t-1)^{\frac{2}{\alpha}}\left[\frac{p_a(\lambda_{D2D})\lambda_{BS}}{M}\int_0^{\infty}\frac{1}{1+(P/P_D)\,u^{\frac{\alpha}{2}}}\mathrm{d}u + \frac{\lambda_{D2D}}{M}\int_0^{\infty}\frac{1}{1+u^{\frac{\alpha}{2}}}\mathrm{d}u\right]\right\} \tag{3}$$

$$\mathsf{F}_0 = \exp\left\{-\pi r^2(e^t-1)^{\frac{2}{\alpha}}\frac{p_a(\lambda_{cell})\lambda_{BS}}{M}\int_{(e^t-1)^{-\frac{2}{\alpha}}}^{\infty}\frac{1}{1+u^{\frac{\alpha}{2}}}\mathrm{d}u\right\} \tag{4}$$

$$\mathsf{F}_{DL} = \exp\left\{-\pi r^2(e^t-1)^{\frac{2}{\alpha}}\frac{p_a\,(\lambda_{DL})\,\lambda_{BS}}{M}\int_{(e^t-1)^{-\frac{2}{\alpha}}}^{\infty}\frac{1}{1+u^{\frac{\alpha}{2}}}\mathrm{d}u\right\} \tag{5}$$

Box I.

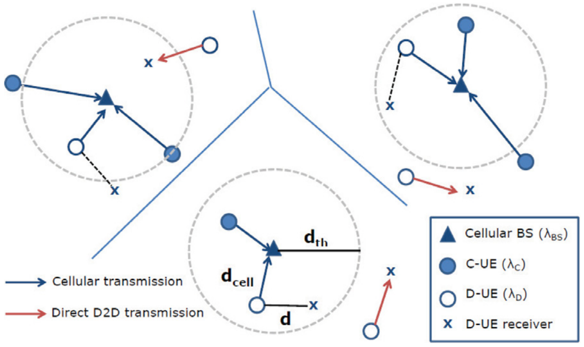

Fig. 1. Illustration of an uplink cellular network underlaid with multiple D2D users. Unlike C-UEs incapable of D2D transmissions, D-UEs are able to associate with either their nearest BSs (if $d_{cell} < d_{th}$) or peer UEs with average association distance d (if $d_{cell} \geq d_{th}$).

allocated by the associated BS. A single D2D user on the other hand accesses a single sub-channel randomly chosen by himself.

2.2. Channel model

Cellular and D2D users transmit signals with powers P and P_D respectively. The transmitted signals then experience distance attenuation with path loss exponent α as well as Rayleigh fading with unity mean. Both transmissions of users share the uplink spectrum as proposed in [2]. It is thus necessary to consider not only inter-cell interference but also intra-cell interference. For simplicity, the given network is assumed to be interference-limited where noise power is negligible compared to interference.

3. Throughput gains in D2D communications

This section defines and formulates duplexing and capacity gains in D2D communications.

3.1. Preliminaries

Let p_a denote the probability that a single BS is turned-on, i.e. having at least a single serving user. Consider a BS-to-user association. Let p_s denote the probability that a single user is assigned to one of M sub-channels in a uniformly random manner. According to [5] with minor modification, such probabilities are given as

$$p_a(\lambda_u) = 1-(1+3.5^{-1}\hat{\lambda})^{-3.5} \tag{6}$$

$$p_s(\lambda_u) = \int_0^{\infty}\left[\sum_{n=0}^{M-1}\frac{(\hat{\lambda}y)^n e^{-\hat{\lambda}y}}{n!}+\sum_{n=M}^{\infty}\frac{M}{n+1}\frac{(\hat{\lambda}y)^n e^{-\hat{\lambda}y}}{n!}\right] \times f_Y(y)\mathrm{d}y \tag{7}$$

where $\hat{\lambda}$ represents λ_{BS} normalized by the associated user density λ_u and $f_Y(y) = \frac{3.5^{4.5}}{\Gamma(4.5)}y^{3.5}e^{-3.5y}$ probability density function (pdf) of the serving area of a single BS, i.e. Voronoi cell area.

Next, consider an uplink D2D underlaid cellular network. For each D-UE, it selects D2D mode with probability $\eta := \mathbb{P}\{d_{cell} \geq d_{th}\} = \exp(-\lambda_{BS}\pi d_{th}{}^2)$. In such a network, τ_C and τ_D respectively denote the per-user throughputs of each C-UE and D-UE, defined as ergodic capacity. Exploiting the approach in [6] with minor modification yields

$$\tau_C = p_s\,(\lambda_{D2D})\int_{t>0}\int_0^{\infty} f_R(r)\mathsf{F}_C\mathrm{d}r\mathrm{d}t \tag{8}$$

$$\tau_D = \int_{t>0}\left[(1-\eta)p_s(\lambda_{D2D})\int_0^{d_{th}} f_{R_D}(r)\mathsf{F}_{D1}\mathrm{d}r + \eta\mathsf{F}_{D2}\right]\mathrm{d}t \tag{9}$$

where $\lambda_{D2D} := \lambda_C + (1-\eta\lambda_D)$, C-UE-to-BS association distance pdf $f_{R_C}(r) = 2\pi\lambda_{BS}re^{-\lambda_{BS}\pi r^2}$, D-UE-to-BS association distance pdf $f_{R_D}(r) = \frac{2\pi\lambda_{BS}re^{-\lambda_{BS}\pi r^2}}{1-e^{-\lambda_{BS}\pi d_{th}{}^2}}$, and F_C and F_{D1} as well as F_{D2} are given in Box I.

In addition, consider a conventional uplink cellular network where the network only consists of C-UEs with density λ_{cell}. For fair comparison, λ_{cell} is set as $\lambda_C + \lambda_D$. The conventional cellular network then provides per-user throughput τ_0 given as

$$\tau_0 = p_s\,(\lambda_{cell})\int_{t>0}\int_0^{\infty}\mathsf{F}_0 f_{R_C}(r)\mathrm{d}r\mathrm{d}t \tag{10}$$

where F_0 is given in Box I.

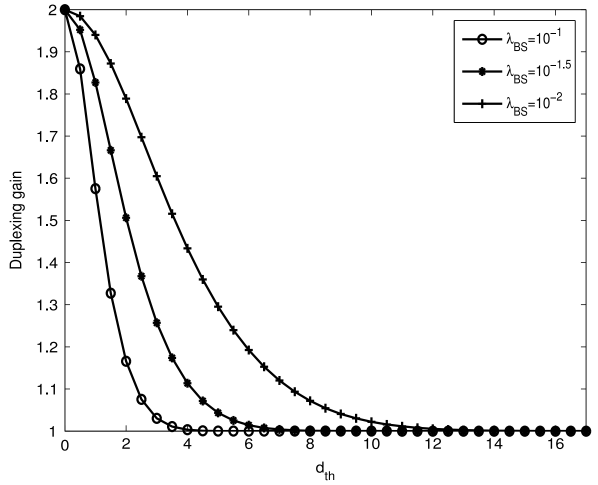

Fig. 2. The duplexing gain as a function of the distance threshold d_{th} for various BS densities λ_{BS}, which determine the distributions of the distance from a UE to its nearest BS in the network.

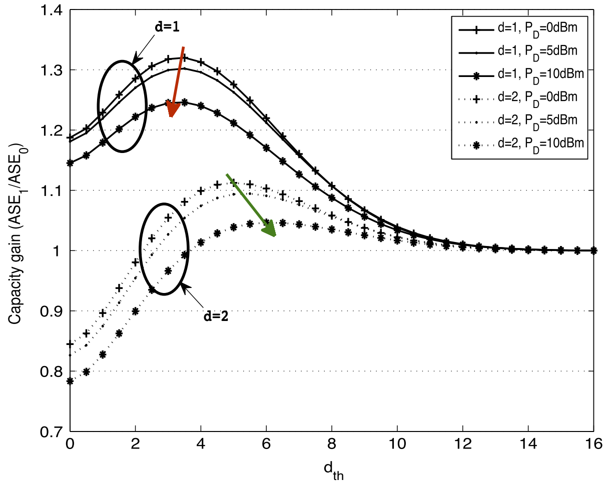

Fig. 3. The capacity gain as a function of the distance threshold d_{th}, for different D2D transmission distance d and transmission power P_D. The red and green arrows represent the tendencies of the capacity gain optimal d_{th} changes: for $d = 1$, the optimal d_{th} decreases with D2D transmission power P_D; for $d = 2$, on the other hand, the optimal d_{th} increases with P_D ($\lambda_{BS} = 10^{-2}$, $\lambda_C = \lambda_D = 10^{-1}$, $d = 5$, $P = 20$ dBm, $M = 16$, and $\alpha = 4$); for interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.

Lastly, consider the downlink operation of an uplink D2D underlaid cellular network with downlink user density λ_{DL}. The value of λ_{DL} is set as λ_C since D2D transmissions are only available via uplink resources. Downlink per-user throughput of the network τ_{DL} is given as

$$\tau_{DL} = p_s(\lambda_{DL}) \int_{t>0} \int_0^\infty \mathsf{F}_{DL} f_{R_C}(r) \mathrm{d}r\mathrm{d}t \tag{11}$$

where F_{DL} is given in Box I.

3.2. Duplexing gain

Define duplexing gain G_{Dup} as follows.

$$G_{\text{Dup}} := \eta\lambda_D\tau_{DL}. \tag{12}$$

This implies how much downlink resource is saved via offloading traffic to uplink D2D transmissions. Such a gain depends on D2D guard zone radius d_{th}. Increase in d_{th} provides higher duplexing gain by allowing more D-UEs to operate in D2D mode. For a given d_{th}, increase in BS density, on the other hand, decreases duplexing gain. This makes more D-UEs associate with BS, and thus the number of D-UEs in cellular mode increases. Fig. 2 visualizes such effects. It shows the maximum duplexing gain is achieved when $d_{th} \to 0$, making all D-UEs be in D2D mode, i.e. $\eta \to 1$. The minimum duplexing gain 1 occurs when $d_{th} \to \infty$.

3.3. Capacity gain

Consider area spectral efficiency (ASE), sum throughput per unit bandwidth and unit area [7]. Capacity gain G_{Cap} is then defined as the ASE ratio of a D2D underlaid network to a conventional cellular network, represented as follows.

$$G_{\text{Cap}} = \frac{\lambda_C\tau_C + \lambda_D\tau_D}{(\lambda_C + \lambda_D)\tau_0}. \tag{13}$$

Capacity gain captures the uplink resource efficiency increased by D2D transmissions. Decrease in D-UE peer distance d and/or increase in D2D transmissions power P_D yield capacity gain improvement. Increase in d_{th}, however, does not always guarantee capacity gain increase. The reason is too much D-UEs in D2D mode may cause severe uplink interference, leading to capacity gain decrease. Fig. 3 captures such effects. As $d_{th} \to \infty$, the entire D-UEs become operating in cellular mode, and thus capacity gain converges to unity.

4. Throughput gain impact on D2D network design

In the preceding section, capacity gain and duplexing gain do not behave identically. To incorporate both impacts simultaneously, we define *total gain* as follows.

$$G = \omega_1 G_{\text{Dup}} + \omega_2 G_{\text{Cap}} \tag{14}$$

where ω_1 and ω_2 are non-negative constants.

Fig. 4 represents total gain behavior. Firstly, we can find that the maximum benefit from D2D communications can be achieved by shrinking D2D link distance as much as possible. Secondly, even in uncoordinated D2D systems (or $d_{th} = 0$), we can see that there exist a definite gain. In addition, downlink resource saving by D2D communications gives a lot of gains to D2D underlaid cellular networks. When sharing the uplink spectrum, D2D transmissions may degrade the uplink resource efficiency (capacity gain) by causing much interference in the network. However, the offloading effect of D2D transmissions (capacity gain) can exceed the loss in uplink, resulting in the overall spectral efficiency improvement. Specifying the total gain optimal ω_1 and ω_2 is an interesting topic, but is deferred to future work.

To investigate how much D2D communication reduces the number of deployed cellular BSs to support a given number of users, we compare the per-user throughput of a D2D underlaid cellular network and that of a conventional cellular-only network.

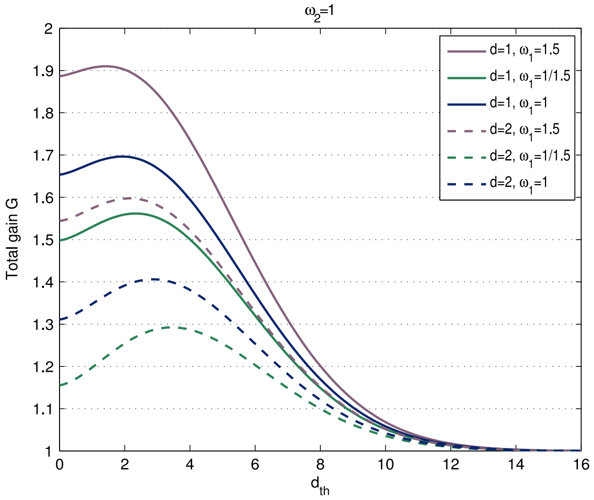

Fig. 4. The total gain of D2D communications with the normalized weighting coefficients of the duplexing gain to that of the capacity gain.

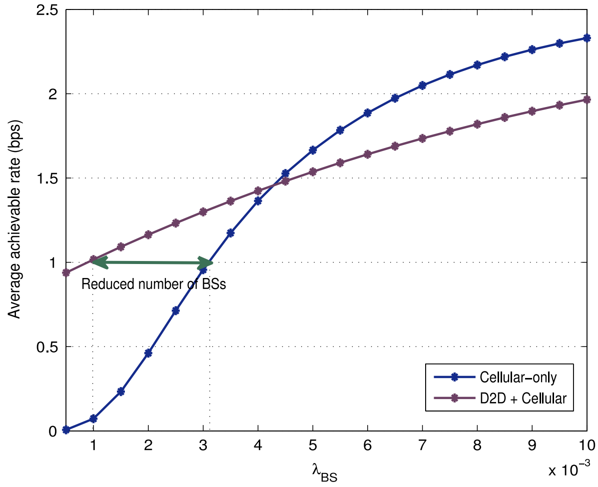

Fig. 5. The average achievable rate of a transmit user as a function of the BS density ($\lambda_{BS} = 10^{-2}$, $\lambda_C = \lambda_D = 10^{-1}$, $d = 5$, $P = 20$ dBm, $P_D = 0.5P$, $M = 16$, $\alpha = 4$).

Fig. 5 firstly shows that the capacity of either cellular-only or D2D underlaid network does not grow proportionally to the number of BSs. It is because many BSs are likely to have no users to serve when BS density increases, as investigated in [5,8]. The result also indicates that D2D underlay is preferable for sufficiently low BS density. Consider, as an example, an ultra-dense cellular networks where average BS density exceeds user density [8]. In such a network, D2D transmissions only incurs unnecessary interference while providing neither shrinking transmission distances nor mitigating multiple user access congestion. Finding the optimal BS density for D2D underlaid cellular networks could therefore be another interesting avenue for future research.

5. Conclusions

This article investigates the throughput of an uplink D2D underlaid cellular network via duplexing and capacity gains. The result indicates that a considerable portion of D2D advantages come from the radio resource saving via its cellular traffic offloading. This can compensate the effect of additional uplink interference due to D2D uplink underlay. Furthermore, the behaviors of duplexing and capacity gains are elucidated, and their aggregate impact on throughput is analyzed in a total gain perspective. In addition, the effect of BS densification on D2D underlaid network throughput is specified, thereby suggesting not only network design guidelines but also promising research problems for future cellular systems.

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References

[1] G. Fodor, E. Dahlman, G. Mildh, S. Parkvall, N. Reider, G. Miklós, Z. Turányi, Design aspects of network assisted device-to-device communications, IEEE Commun. Mag. 50 (3) (2012) 170–177.

[2] K. Doppler, M. Rinne, C. Wijting, C. Ribeiro, K. Hugl, Device-to-device communication as an underlay to LTE-advanced networks, IEEE Commun. Mag. 47 (12) (2009) 42–49.

[3] T. Chen, G. Charbit, S. Hakola, Time-hopping for device-to-device communication in LTE cellular system, in: Proc. IEEE WCNC, 2010.

[4] A. Hassan, J.G. Andrews, The Guard zone in wireless Ad hoc networks, IEEE Trans. Commun. 6 (3) (2007) 897–906.

[5] S.M. Yu, S.-L. Kim, Downlink capacity and base station density in cellular networks, in: Proc. IEEE SpaSWiN, 2013, available at: http://arxiv.org/abs/1109.2992.

[6] J.G. Andrews, F. Baccelli, R.K. Ganti, A tractable approach to coverage and rate in cellular networks, IEEE Trans. Commun. 59 (11) (2011) 3122–3134.

[7] M.S. Alouini, A.J. Goldsmith, Area spectral efficiency of cellular mobile radio systems, IEEE Trans. Veh. Technol. 48 (4) (1999) 1047–1066.

[8] J. Park, S.-L. Kim, J. Zander, Asymptotic behavior of ultra-dense cellular networks and its economic impact, in: Proc. IEEE GLOBECOM, 2014.