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On the throughput gain of device-to-device communications

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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.

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

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

$$\mathsf{F}_{D2} = \exp\left\{-\pi d^2 (e^t-1)^{\frac{2}{\alpha}} \left[\frac{p_a(\lambda_{D2D})\lambda_{BS}}{M}\int_{0}^{\infty}\frac{1}{1+(P/P_D)\,u^{\frac{\alpha}{2}}}\mathrm{d}u + \frac{\lambda_{D2D}}{M}\int_{0}^{\infty}\frac{1}{1+u^{\frac{\alpha}{2}}}\mathrm{d}u\right]\right\} \quad (3)$$

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

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

Box I.

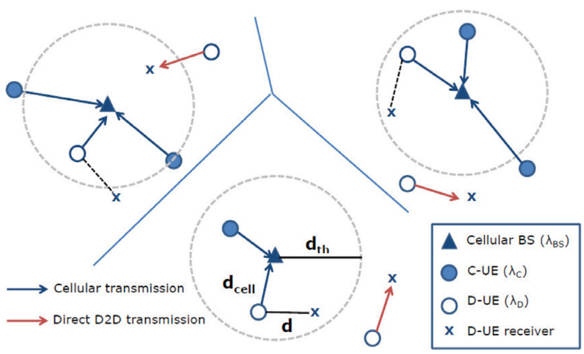

Fig. 1. Illustration of an uplink cellular network underlaid with multiple D2D users. Unlike C-UEs incapable of D2D transmissions, D-UEs are able to associate with either their nearest BSs (if $d_{cell} < d_{th}$) or peer UEs with average association distance d (if $d_{cell} \geq d_{th}$).

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

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

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

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

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

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

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

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

where F_0 is given in Box I.