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, \textit{duplexing gain}, and the increase by reusing uplink resources of D2D transmissions, \textit{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: \textit{duplexing gain} and \textit{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 $\lambda_{\text{BS}}$. D2D-incapable user equipments (C-UE) and D2D-enabled user equipments (D-UE) are independently distributed according to homogeneous PPPs respectively with the densities $\lambda_{\text{C}}$ and $\lambda_{\text{D}}$. C-UEs associate with the nearest BSs. The associations of D-UEs, on the other hand, depend on their operation mode. In \textit{cellular mode}, they associate with the nearest BSs as in C-UEs. In \textit{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 $d_{\text{cell}}$ as the nearest BS distance from a D-UE, and $d_{\text{th}}$ as the D2D guard region radius at a BS [4]. The transmission mode selection of D-UEs is then given as follows: if $d_{\text{cell}} < d_{\text{th}}$, 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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users. Unlike C-UEs incapable of D2D transmissions, D-UEs are able to associate not only inter-cell interference but also intra-cell 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

$$p_a(\lambda_u) = 1 - (1 + 3.5^{-1} \lambda_c)^{-3.5}$$

$$p_s(\lambda_u) = \int_0^\infty \sum_{n=0}^{\infty} \frac{M-1}{n!} (\hat{\lambda} y)^n e^{-\hat{\lambda} y} + \sum_{n=M}^{\infty} \frac{M}{n+1} \frac{M}{n!}$$

$$\times f_Y(y) dy$$

where $\hat{\lambda}$ represents $\lambda_{BS}$ normalized by the associated user density $\lambda_u$ and $f_Y(y) = \frac{3.5^{3.5/4} e^{-3.5 y}}{3.5^{3.5}}$ 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 $\eta \lambda_u$. The conventional BS-D2D association distance pdf $f_{R_C}(r) = 2\pi \lambda_{BS} r e^{-\lambda_{BS} \pi r^2}$, D-UE to BS association distance pdf $f_{R_D}(r) = 2\pi \lambda_{BS} e^{-\lambda_{BS} \pi r^2}$, and $F_C$ and $F_D$ as well as $F_{DL}$ are given in Box I.

In addition, consider a conventional uplink cellular network where the network only consists of C-UEs with density $\lambda_{cell}$. For fair comparison, $\lambda_{cell}$ is set as $\lambda_c + \eta \lambda_u$. The conventional cellular network then provides per-user throughput $\tau_0$ given as

$$\tau_0 = p_s(\lambda_{cell}) \int_{r>0} \int_0^\infty F_0 f_{R_C}(r) d\tau dr$$

where $F_0$ is given in Box I.
Define duplexing gain $G_{\text{Dup}}$ as follows.

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

(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 $G_{\text{Cap}}$ is then defined as the ASE ratio of a D2D underlaid network to a conventional cellular network, represented as follows.

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

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.

$$G = \omega_1 G_{\text{Dup}} + \omega_2 G_{\text{Cap}} \quad \text{(14)}$$

where $\omega_1$ and $\omega_2$ 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 $\omega_1$ and $\omega_2$ 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, $P_D = 0.5P$, $M = 16$, $\alpha = 4$).

**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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