Downlink Goodput Analysis for Massive MIMO Networks with Underlaid D2D

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***Abstract*—The performance of downlink massive multiple-input-multiple-output networks with co-channel device-to-device communications is investigated in this paper. Specifically, we consider a cellular network with sufficient number of antennas at the base station and typical hexagonal cell coverage, where the cell users and device-to-device transmitters are randomly and uniformly distributed. To obtain the analytical expressions of system-level performance, the asymptotic signal-to-interference ratios for both downlink and device-to-device links are first obtained, which depend on the pathloss and small-scale fading of the interference channels. Since these information may not be available at the service base station or device-to-device transmitters, there exists a chance of packet outage. Therefore, we continue to derive the closed-form approximation of the average goodput, which measures the average number of information bits successfully delivered to the receiver. Hence, the system design trade-off between downlink and co-channel device-to-device communications can be investigated analytically. Moreover, the performance region in which the co-channel device-to-device communications could lead to better overall spectral efficiency can be obtained. Finally, it is shown by simulations that the analytical results matches the actual performance very well.**

I. Introduction

Massive multiple-input multiple-output (MIMO) is an efficient technique to boost the spectral efficiency. However, as elaborated in the existing literature, the issue of pilot contamination [1], which refers to the undiminished inter-cell interference caused by pilot reuse, may severely degrade its performance. Although there have been significant research efforts devoted to address the pilot contamination issue [2], [3], most of the works handle the inter-cell interference from the conventional cellular network point of view, instead of novel network topologies.

Recently, the deployment of wireless cache nodes in cellular networks has drawn significant research attentions [4], [5], where the device-to-device (D2D) links has to be introduced into cellular network. The co-channel deployment of D2D communications and cellular networks was studied in some literature [6], [7], where it is shown that the D2D transmission reusing the cellular spectrum may cause severe interference. To alleviate the interference, D2D underlay massive MIMO cellular networks has been proposed by exploiting spatial degrees of freedom at the base station (BS). For example, in [8], the authors proposed a pilot reuse strategy for D2D receivers and a novel interference-aided minimum mean square error (MMSE) detector to suppress the D2D-to-cellular interference. In [9], a novel revised graph coloring-based pilot allocation (RGCPA) algorithm was proposed for pilot allocation, and an iterative scheme was adopted to minimize the transmission power of D2D links. In order to evaluate the overall effect of D2D links on cellular network, a system-level performance analysis is necessary. The interplay between massive MIMO uplink transmission and co-channel D2D transmission has been studied in [10]. However, the conclusion of its analysis cannot be directly applied in downlink. Moreover, the authors assume that the antenna number at the BS is infinity, which is not practical[1]. As a result, performance analysis of massive MIMO downlink transmission with co-channel D2D links is still open.

In this paper, we would like to shed some light on the above issue by analysing the performance trade-off between massive MIMO downlink and co-channel D2D transmissions. Specifically, we consider a massive MIMO network with typical hexagonal cell structure and random distribution users and D2D links. The D2D links may refer to the direct transmission from wireless cache nodes to cell users, which off-load the traffic from service BSs. In the analysis, we first obtain the asymptotic expressions of downlink and D2D signal-to-interference ratios (SIRs) for sufficiently large (but finite) number of antennas at the BS. These expressions depend on the pathloss and small-scale fading of interference channels, which may be unknown to the service BS or D2D transmitters. For example, the interference to downlink users comes from neighbouring BSs and nearby D2D transmitters, and the channel condition of those interference is not easy to obtain at the service BS. When the randomness of user locations and small-scale fading are considered, it is possible that the transmission data rate is greater than the channel capacity, leading to the *packet outage*. Hence We use the average goodput [11], which measures the average number of bits successfully delivered to the receiver, as performance metric. We derive the approximated expressions of the downlink and D2D goodput, based on which the performance trade-off between massive MIMO downlink and D2D can be evaluated. It is shown by numerical simulations that the analytical results

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[1] In massive MIMO systems, the typical number of antennas at the BS is up to a few hundred, which is large but not infinity.

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matches the actual performance very well.

II. System Model

A. Network Model

We consider a typical cellular network with C hexagonal cells where the radius of each cell is R, as illustrated in Figure. 1. Each cell consists of a base station equipped with M antennas, K active single-antenna downlink users and D active D2D transmitters. BSs and D2D transmitters transmit with constant powers P_b and P_d, respectively. The D2D links may refer to the data delivery between the downlink users and wireless cache nodes. For example, the desired data of downlink users is found in one cache node nearby, and then a direct D2D communication link is established. Since the focus of this paper is on the physical-layer SIR and throughput analysis, the establishment of D2D links is outside the scope of this work. Since massive MIMO technology is considered, M is sufficiently large, e.g., a few hundred. The downlink users and D2D transmitters are uniformly and independently distributed. Without loss of generality, we investigate the performance of the first cell while other cells are all interfering cells. The j-th downlink user of the i-th cell is referred to as the (i, j)-th downlink user.

The massive MIMO network is working in time-division duplex (TDD) mode. Thus it is assumed that the downlink channel of downlink users is estimated from their uplink pilot transmission within the same coherent fading block. Moreover, in order to improve the overall spectrum efficiency, we consider the co-channel deployment of D2D and downlink transmission, i.e., the D2D transmitters use the same spectrum as the cellular network. Note that the coexistence issue of massive MIMO uplink and D2D communications has been investigated in [10], the focus of this paper is put on sharing the downlink transmission opportunities with D2D links. All D2D transmitters and receivers are equipped with single antenna. The k-th D2D link (transmitter or receiver) of the i-th cell is referred to as the (i, k)-th D2D link (transmitter or receiver). The notations of downlink and D2D transmissions are summarized below.

- $\mathbf{h}_{l,k}^i, \mathbf{v}_{l,j}^i \in \mathcal{C}^{1\times M}$ represent the downlink channel vectors from the i-th BS to the k-th downlink user and j-th D2D receiver in the l-th cell, respectively. Each component of $\mathbf{h}_{l,k}^i$ and $\mathbf{v}_{l,j}^i$ is complex Gaussian with mean zero and variance $\rho_{l,k}^i$ and $\rho_{l,j}^i$ respectively. $\rho_{l,k}^i = \left(s_{l,k}^i\right)^{-\sigma}$ and $\rho_{l,j}^i = \left(s_{l,j}^i\right)^{-\sigma}$ are the pathloss from the i-th BS to the (l, k)-th downlink user and (l, j)-th D2D receiver, where $s_{l,k}^i$ and $s_{l,j}^i$ are the distances from the i-th BS to the (l, k)-th downlink user and (l, j)-th D2D receiver. σ is the pathloss exponent between BSs and users. $\mathbf{H}_i^l \in \mathcal{C}^{K\times M}$ and $\mathbf{V}_i^l \in \mathcal{C}^{K\times M}$ are the aggregation of $\mathbf{h}_{l,j}^i$ and $\mathbf{v}_{l,j}^i$ within one cell.
- $g_{l,j}^{i,m}, u_{l,k}^{i,m}$ represents the downlink channel vector from the (i, m)-th D2D transmitters to the j-th D2D receiver and k-th downlink user in the l-th cell, respectively. $g_{l,j}^{i,m}$ and $u_{l,k}^{i,m}$ are complex Gaussian with mean zero and variance $\rho_{l,j}^{i,m}$ and $\rho_{l,k}^{i,m}$, respectively. $\rho_{l,j}^{i,m} = \left(d_{l,j}^{i,m}\right)^{-\kappa}$ and $\rho_{l,k}^{i,m} = \left(d_{l,k}^{i,m}\right)^{-\kappa}$ are the pathloss from the (i, m)-th D2D transmitter to the (l, j)-th D2D receiver and (l, k)-th downlink user, where $d_{l,j}^{i,m}$ and $d_{l,k}^{i,m}$ are the distances from the (i, m)-th D2D transmitter to the (l, j)-th D2D receiver and (l, k)-th downlink user. κ is the pathloss exponent between users. $\mathbf{G}_i^l \in \mathcal{C}^{K\times D}$ and $\mathbf{U}_i^l \in \mathcal{C}^{K\times D}$ are aggregation of $g_{l,j}^{i,m}$ and $u_{l,j}^{i,m}$.
- $\mathbf{x}_{l,k}^p$ is the pilot sequence of the (l, k)-th downlink user. We have $\left|\mathbf{x}_{l,k}^p(\mathbf{x}_{l,m}^p)^H\right| = 0, \forall k \neq m$ and $\left|\mathbf{x}_{l,k}^p(\mathbf{x}_{i,j}^p)^H/L_p\right| = \frac{P_u}{\sqrt{L_p}}, \forall i \neq l$, where P_u is the transmission power of each mobile user and L_p represents the pilot length in the uplink. $\mathbf{X}_l^p$ is the aggregation of pilot sequences from active downlink users in the l-th cell. .

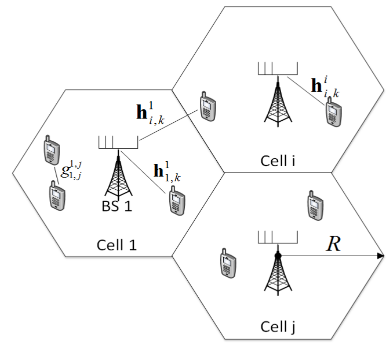

Fig. 1. Illustration of hexagonal cellular network with radius R, where Cell 1 is the target cell.

Remark 1. *The coexistence SIR analysis of massive MIMO uplink transmission and D2D transmission in [10] cannot be applied in downlink scenario, as the source of interference is completely different. In this paper, we also propose a new analytical framework to evaluate the asymptotic goodput performance with sufficiently large (but finite) number of antennas at BS M. Note that the approach introduced in [10] is for infinite M, which may not be accurate when M is only a few hundred. Moreover, we use Gaussian approximation to obtain a simple closed-form expression of the cumulative distribution function (CDF) of SIR, based on which we also derive the average goodput as the performance metric so that the potential packet outage can be counted. These results cannot be obtained with the approach in [10].*

B. Channel Model

Since D2D links share the downlink transmission opportunities, they are silent in the uplink subframe. Thus in the channel estimation phase (as illustrated in Fig. 2), the received signal of the i-th BS is given by

$$\mathbf{Y}_i^p = \left(\mathbf{H}_i^i\right)^H \mathbf{X}_i^p + \sum_{\forall l\neq i} \left(\mathbf{H}_l^i\right)^H \mathbf{X}_l^p.$$