Underlaid FD D2D Communications in MU-MIMO Systems via Joint Beamforming and Power Allocation

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Abstract

This paper studies the benefits of incorporating underlaid full-duplex (FD) D2D communications into multi-user multiple-input-multiple-output (MU-MIMO) cellular systems in terms of achievable network throughput. The focus is joint beamforming and power allocation design for average sum-rate (per cell) maximization while considering the effects of interference to both cellular and D2D transmission. The problem formulation leads to a nonconvex vector-variable optimization problem, where we develop an efficient solution using a fractional programming (FP) based approach. Numerical results show that, at sufficiently high self-interference cancellation (SIC) levels, the FD D2D transmission provides a significant sum-rate improvement as compared to the half-duplex (HD) counterpart and pure cellular systems in absence of D2D transmission.

Index Terms

Device-to-device communications, cellular networks, full-duplex, multi-user MIMO, optimization.

I. INTRODUCTION

In recent years, device-to-device (D2D) communications has emerged as an innovative technology for future cellular networks [1]. Instead of traversing through base-station (BS), D2D communications enables the cellular users to communicate directly with each others, thereby reducing network congestion, shortening packet delay, enhancing spectral efficiency, and enabling location-based applications. However, incorporating the D2D feature would give rise to many challenges and risks to existing cellular systems. In particular, interference is a fundamental limiting factor in the underlaid D2D cellular networks. When the cellular time-frequency resources are
fully reused by D2D transmission, cellular links experience the interference from both intercell and D2D transmission, while D2D links have to combat the interference caused by not only cellular transmission but also other co-channel D2D links. Thus, interference management is essential to ensure a harmonious co-existence of D2D and cellular networking.

In cellular systems, the employment of multi-user-multiple-input-multiple-output (MU-MIMO) equipped BSs in conjunction with coordinated resource allocation between cellular and D2D transmitters is an appealing solution to address this challenge. With a sufficiently large number of antennas and intelligent beamformer design, the BS is capable of forming very narrow beams aiming toward the intended cellular receivers, thereby resulting in extremely low interference to co-channeled cellular/D2D users. Meanwhile, implementing resource allocation strategies at D2D transmitters allow to effectively mitigate the interference caused by the D2D transmission at both cellular and D2D receivers. In this paper, we shall develop a joint beamforming and power allocation algorithm in MU-MIMO muti-cell systems being underlaid by D2D transmission for network throughput maximization, while ensuring the quality of service (QoS) for both cellular and D2D transmission. Our focus is the downlink whose time-frequency resources are fully reused by the D2D transmission.

In existing research, there has been considerable interest in designing the precoding/beamforming and/or power allocation techniques for underlaid D2D cellular networks. Assuming a single-cell setting without out-of-cell interference, Mirza et al. focused on joint beamforming and power allocation to optimize the transmit powers at both cellular and D2D users [2]. Interestingly, numerical results in [2] showed that the solution of joint beamforming and power allocation converged to that of power control with fixed beamforming schemes (zero-forcing (ZF), regularized ZF, and hybrid ZF and maximum ratio transmission (MRT)). Power control at both cellular and D2D users with fixed beamformers (ZF and MRT) was investigated in [3] for multi-cell massive MIMO systems with underlaid D2D in order to maximize the minimum spectral efficiency (SE) and the product of SINRs. For single-cell massive MIMO cellular system being underlaid by D2D users, Chen et al. in [4] proposed a simple rate adaptation method based on stochastic geometry approach to minimize the interference to cellular users. Also, in the single-cell setting, [5] studied a joint pilot design and power control problem to minimize the D2D data transmit power. Rate adaptation based on a stochastic geometry approach was extended for the multi-cell setting in [6]. For underlaid D2D systems in absent of cellular transmission, Shen et al. adopted the matrix fractional programming techniques, solving the coordinated joint
scheduling, power control, and beamforming so as to optimize the network sum-rate \cite{7}. In this system, each D2D link was equipped with single-user (SU) MIMO transmission, and the mappings between the transmitters and the corresponding receivers were one-to-one.

In prior works, D2D studies have developed and evaluated under the consideration of half-duplex (HD) D2D communications, where a D2D user can either transmit or receive on a single channel, but not simultaneously. Given a number of encouraging FD designs, the integration of FD in D2D communications is an attractive solution for the development of new architectures and algorithms in cellular networks. As the FD D2D nodes use a single carrier frequency in both transmitting and receiving signals, FD D2D not only enhances the spectrum efficiency but it also alleviate the frequency resource demand for underlaid D2D transmission. Recently, the power control problems were investigated for underlaid FD D2D cellular networks in \cite{8}–\cite{10}. Under this line of works, single antenna transmission was adopted at both D2D and cellular users.

This paper focuses on exploring impact of incorporating underlaid FD D2D transmission into existing multi-cell networks where BSs are equipped with MU-MIMO transmission. Our objective is to design a joint beamforming and power allocation algorithm so as to alleviate the interference between cellular and D2D transmission and optimize the overall network sum-rate. The proposed algorithm is based on the fractional programming (FP) approach, which is developed to solve general nonconvex optimization problem in which the objective function is in form of the sum-functions-of-ratio. In wireless communications systems, FP has recently been employed extensively to solve the energy and spectral efficient optimization problems (e.g., \cite{7}, \cite{11}–\cite{13} and the references therein). The FP-based algorithm takes advantage of the fractional structure of the nonconvex optimization problem by directly looking at the objective function decomposition. The form of the original objective function naturally lends itself to this choice of fractional decomposition. More specifically, the FP-based algorithm approximates the nonconvex optimization problem by applying a quadratic transformation to the fractional argument terms of the objective function to ensure that the transformed objective function is concave. The FP-based algorithm is operated in a centralized manner and requires full knowledge of channel state information (CSI) at the central controllers.

Based on the developed FP-based algorithm, the benefits of incorporating underlaid FD D2D networking into MU-MIMO cellular systems are investigated. In particular, we shall study the average network sum-rates per cell under the impact of important network parameters including
SIC levels and number of active D2D links in each cell. We adopt the network sum-rates (over a cell) of HD D2D cellular systems and pure cellular systems (in absence of D2D transmission), both also employing the FP-based algorithm, as the benchmarks to characterize the benefits offered by the FD D2D transmission. For completeness, we consider two scenarios in which D2D users are either located inside or outside of the buildings in urban area. An interesting observation is that adopting the FP-based algorithm to FD D2D cellular systems significantly improves the achievable network throughput (over a cell) and vastly outperforms that achieved by the HD D2D counterpart and pure cellular systems, but only under sufficiently high SIC levels. Based on the numerical results, a comparison with the scenario in which omni direction transmission is employed at the cellular link is also made to demonstrate the advantage of ULA-equipped BS.

Notation: In this work, we use lower case, e.g., \( x \), to denote scalars, bold lower case, e.g., \( \mathbf{v} \), to denote vectors, and bold upper case, e.g., \( \mathbf{V} \), to denote matrices. We use \( \mathbb{R}_+ \) to denote the set of nonnegative real numbers, and \( \mathbb{C} \) to denote the set of complex numbers. \( \text{Re}(\cdot) \) refers to the real part of a complex number, while the overline of a complex number, e.g., \( \bar{v} \) refers to the complex conjugate of \( v \). Finally, \( (\cdot)^H \) refers to the vector/matrix conjugate transpose, and \( |\cdot|^2 \), e.g., \( |v|^2 \) refers to its Euclidean norm.

II. SYSTEM MODEL AND PROBLEM FORMULATION

A. System Model

As illustrated in Fig. 1, we consider a hybrid network including cellular downlinks and D2D links operating in half-duplex (HD) and full-duplex (FD) modes, respectively. The network consists of \( B \) base-stations (BSs) located in multiple hexagonal cells. We assume that both multiple cellular and D2D transceivers are randomly located within the cell region. The associated receiver with a D2D transceiver is located at a fixed distance away with isotropic direction. This paper considers single antenna transmission at all cellular/D2D users, while each multiple-input multiple-output (MIMO) BS is equipped with \( A \) antennas. Each BS is capable of serving \( M \) cellular users simultaneously in a time-frequency slot (\( A \geq M \)). In addition, the downlink spectrum-time resource is fully reused by multiple underlaid FD D2D links, and the universal frequency reuse scheme (UFR) is employed. The sets of cellular users served by the BS \( b \) are denoted as \( C_b, b = 1, \ldots, B \). Meanwhile, let \( \mathcal{D} \) be the collection of all D2D transceivers in the network. As a result, \( N = |\mathcal{D}|/(2B) \) is the number of D2D links per cell.
Fig. 1. A underlaid D2D cellular network with multi-cell setting (black circle: BS, red triangle: cellular user, green square: D2D transceiver).

The transmit power vector of D2D users in the same time-frequency slot is defined as \( \mathbf{P} = [P_1, \ldots, P_{2D}] \in \mathbb{R}^{2BN}_+ \), where \( P_n \) denotes the transmit power at D2D transceiver \( n \).

The path-loss \( L \) is computed as \( L = Cr^{-\alpha} \) where \( r \) is the distance, \( \alpha > 2 \) is the path-loss exponent, and \( C \) denotes the reference path-loss determined by the carrier frequency and reference distance. Furthermore, the system uses the time division multiplexing (TDD); we assume channel reciprocity, i.e., the downlink channel is Hermitian transpose of the uplink channel.

Given the system model, the received signals at cellular user \( m \) in cell \( b \) is given by

\[
y^{(c)}_{bm} = L^{(cc)}_{b,bm} \mathbf{h}^{(cc)}_{b,bm} \mathbf{v}^{(c)}_{bm} x^{(c)}_{bm} + \sum_{j \in C_b \setminus \{m\}} L^{(cc)}_{b,bm} \mathbf{h}^{(cc)}_{b,bm} \mathbf{v}^{(c)}_{bj} x^{(c)}_{bj} + \sum_{i \neq b} \sum_{j \in C_i} L^{(cc)}_{i,bm} \mathbf{h}^{(cc)}_{i,bm} \mathbf{v}^{(c)}_{ij} x^{(c)}_{ij} \]

\[
+ \sum_{j \in D} L^{(dc)}_{j,bm} \mathbf{h}^{(dc)}_{j,bm} x^{(d)}_{j} + z^{(c)}_{bm}, \tag{1}
\]

where \( \mathbf{h}^{(cc)}_{l,uv} \in \mathbb{C}^M \) (\( L_{l,uv} \in \mathbb{R}_+ \)), \( l \in \{m, i\} \) and \( uv \in \{bm, mj, ij\} \), denotes the channel fading vector (path-loss) from for cellular user \( v \) in cell \( u \) to the BS \( l \). Correspondingly, \( \mathbf{v}^{(c)}_{uv} \in \mathbb{C}^M \), \( uv \in \{bm, mj, ij\} \), is the downlink precoding/beamforming vector for cellular user \( v \) in cell \( u \); and it satisfies \( |\mathbf{v}_{uv}|^2 = 1 \). We use \( h^{(dc)}_{j,bm} \in \mathbb{C} \) (\( L^{(dc)}_{j,bm} \in \mathbb{R}_+ \)) to denote the channel (path-loss) from D2D transceiver \( j \) to cellular user \( m \) in cell \( b \). Further, \( x^{(c)}_{bm} \) and \( x^{(d)}_{j} \) refer to the signal sent by BS \( b \)
and D2D transceiver $j$ to cellular user $m$, respectively, while $x_{uv}^{(c)}$, $uv \in \{bm, bj, ij\}$ denotes the interfering signal from BS $u$ that is intended to transmit to the cellular user $v$. In addition, we assume that all transmitted signals are normalized so that $|x_{uv}^{(c)}|^2 = |x_j^{(d)}|^2 = 1$, $\forall u, v \in C$, $\forall j \in V$. $h_{jk}^{(dc)}$ refers to the channel fading gain from D2D transceiver $k$ in cell $j$; and $z_{bm}^{(c)} \in C$ is the thermal noise at cellular user $m$ in cell $k$, and it is distributed as $z_{bm}^{(c)} \sim \mathcal{CN}(0, \sigma_c^2)$.

Considering a typical D2D link constituted by two D2D transceivers $n$ and $n'$ which can communicate simultaneously in both directions in a spectrum-time slot. Using a similar approach, the received signal at D2D transceiver $n \in D$ is given by

$$ y_n^{(d)} = \sqrt{p_n} L_{n',n}^{(dd)} h_{n',n}^{(dd)} x_n^{(d)} + \sum_{b=1}^{B} \sum_{m \in C_b} L_{b,n}^{(cd)} (h_{b,n}^{(cd)})^H v_{bm} x_{bm}^{(c)} + \sum_{j \notin \mathcal{D}(n,n')} \sqrt{p_j} L_{j,n}^{(dd)} h_{j,n}^{(dd)} x_j^{(d)} + s_n + z_n^{(d)}, $$

(2)

where $x_u^{(d)}$, $u \in \{n, j\}$ denote the signal sent by the D2D transceiver $u \in \mathcal{D}$, and $h_{b,n}^{(cd)} \in \mathbb{C}^M$ ($L_{b,n}^{(cd)} \in \mathbb{R}_+$) denotes the vector channel (path-loss) from D2D transceiver $n$ to the BS $b$. In addition, $h_{j,n}^{(dd)} \in \mathbb{C}$ ($L_{j,n}^{(dd)} \in \mathbb{R}_+$) denotes the channel (path-loss) from D2D transceiver $j$ to the D2D transceiver $n$. Here, $s_n$ is the residual self-interference (SI) caused by imperfect cancellation of FD operation. We adopt an SI model in which the residual interference is reflected in the self-interference-to-power-ratio (SIPR) so that $|s_n|^2 = \beta P_n$ given by [14], [15] with $P_n$ being the instantaneous transmit power at the D2D transceiver $n$. $z_n^{(d)}$ is the thermal noise at D2D transceiver $n$ and it is also distributed as $z_n^{(d)} \sim \mathcal{CN}(0, \sigma_d^2)$, $\forall i \in \mathcal{D}$ with $\sigma_d^2$ being the noise power at the D2D receiver. From (2), the received signal at other D2D transceiver $n'$ can be obtained by replacing the index $n$ with $n'$ and vice versa, but we omit its derivation here for the sake of a concise presentation. In this paper, as D2D and cellular transmission operate in downlink, we can assume that the D2D and cellular receivers have identical noise powers, denoted as $\sigma^2 \triangleq \sigma_d^2 = \sigma_c^2$.

This work assumes linear uniform array antennas being employed at each BS. We model the channel vector $h^{(c)}$ from D2D/cellular users to BS as [16] $h^{(c)} = [A \ 0_{M \times M-P}] \times \hat{h}^{(c)}$, where $\hat{h}^{(c)}$ denotes the fast fading channel vector. Each vector element is independent and identically distributed (i.i.d.) and follows the Rayleigh distribution with zero mean and unit variance, i.e., $\mathcal{CN}(0, 1)$. Additionally, $0_{A \times A-P}$ is the $A \times A-P$ zero matrix. Here, $P$ represents the fixed number
of angular dimensions. The steering matrix $A = [a(\phi_1), \ldots, a(\phi_P)] \in \mathbb{C}^{N \times P}$ is composed of the steering vector $a(\phi)$ defined as

$$a(\phi) = \frac{1}{\sqrt{P}} [1, e^{-i2\pi w \sin(\phi)}, \ldots, e^{-i2\pi w (N-1) \sin(\phi)}],$$

where $w$ is the antenna spacing in multiples of the wavelength and $\phi_p = -\pi/2 + (p-1)\pi/P$, $p = 1, \ldots, P$, are uniformly distributed angles of transmission.

Before processing further, to avoid cumbersome equations with many denotations in our subsequent derivations, we define the overall channel power gains as

$$g_{j,bm}^{(dc)} \triangleq L_{j,bm}^{(dc)} h_{j,bm}^{(dc)},$$

$$g_{u,n}^{(dd)} \triangleq L_{u,n}^{(dd)} h_{u,n}^{(dd)}, \quad u \in \{n', j\},$$

$$\left(\mathbf{g}_{b,n}^{(cd)}\right)^H \triangleq L_{b,n}^{(cd)} \mathbf{h}_{b,n}^{(cd)},$$

$$\left(\mathbf{g}_{l,uv}^{(cc)}\right)^H \triangleq L_{l,uv}^{(cc)} \mathbf{h}_{l,uv}^{(cc)}, \quad l \in \{b, n\}, \quad uv \in \{bm, bj, nj\}.$$

**B. Problem Formulation**

Given the system model, we now define the desired performance metrics, including SINR and sum-rate of cellular/D2D links, and correspondingly formulate the optimization problem. From the received signal in (1), the signal-to-interference-plus-noise (SINR) at the cellular receiver $m$ in cell $b$ can be written as

$$\text{SINR}_{bm}^{(c)} = \frac{\left| \left(\mathbf{g}_{b,bm}^{(cc)}\right)^H \mathbf{v}_{bm} \right|^2}{I_{bm}^{(c)} + \sigma^2},$$

where the term $I_{bm}^{(c)}$ represents the aggregate interference power caused by both cellular and D2D transmission, and it is given by

$$I_{bm}^{(c)} = \sum_{j \in C_b \setminus \{m\}} \left| \left(\mathbf{g}_{b,bm}^{(cc)}\right)^H \mathbf{v}_{bj} \right|^2 + \sum_{i \neq b} \sum_{j \in C_i} \left| \left(\mathbf{g}_{i,bm}^{(cc)}\right)^H \mathbf{v}_{ij} \right|^2 + \sum_{j \in D} P_j \left| g_{j,bm}^{(dc)} \right|^2.$$

Treating the interference as noise, the achievable rate of cellular link $m$ in cell $b$ can be computed by invoking the Shannon’s capacity formula as

$$R_{bm}^{(c)} = \log_2 \left( 1 + \text{SINR}_{bm}^{(c)} \right).$$
Meanwhile, for a FD D2D link constituted by D2D transceivers \( n \) and \( n' \), the received SINR of D2D the transceiver \( n \) can be written from (2) as

\[
\text{SINR}^{(d)}_{n} = \frac{p_n |g_{n',n}^{(dd)}|^2}{I^{(d)}_n + \beta P_n + \sigma^2},
\]

(6)

where

\[
I^{(d)}_n \triangleq \sum_{b=1}^{B} \sum_{j \in C_b} \left| \left( g_{b,n}^{(cd)} \right)^{H} v_{bj} \right|^2 + \sum_{j \in D \setminus \{n\}} P_j |g_{j,n}^{(dd)}|^2
\]

(7)
denotes the aggregate interference power caused by other D2D and cellular transmission. Likewise, the received SINR at D2D the transceiver \( n' \), denoted as \( \text{SINR}^{(d)}_{n'} \) can be obtained by replacing the index \( n \) with \( n' \) in (6) and (7) and vise versa. As a result, the achievable rate of corresponding FD D2D link is given by

\[
R^{(d)}_n = \log_2 \left( 1 + \text{SINR}^{(d)}_{n} \right) + \log_2 \left( 1 + \text{SINR}^{(d)}_{n'} \right).
\]

(8)

This work uses the average network sum-rate of both cellular and D2D links over a cell as the optimization objective under the constraints on the target (minimum required) SINR at both cellular and D2D transmission and maximum transmit power of D2D transmitters and BSs, denoted as \( P_d \) and \( P_c \), respectively. Without generality, we can assume that D2D (cellular) users have equal target SINR \( \gamma_d \) (\( \gamma_c \)). The optimization problem therefore can be mathematically formulated as

\[
\max_{P, v_{bm}} R \triangleq \frac{1}{B} \sum_{b=1}^{B} \sum_{k \in C_b} R^{(c)}_{bm} + \frac{1}{B} \sum_{n \in D} R^{(d)}_{n}
\]

(9a)

s.t. \( \text{SINR}^{(c)}_{bm} \geq \gamma_c, b = 1, \ldots, B, m \in C_b \),

(9b)

\( \text{SINR}^{(d)}_{n} \geq \gamma_d, \forall n \in D \),

(9c)

\( \sum_{m \in C_b} |v_{bm}|^2 \leq P_c, b = 1, \ldots, B \),

(9d)

\( P_n \leq P_d, \forall n \in D \).

(9e)

III. JOINT BEAMFORMING AND POWER ALLOCATION ALGORITHM

In this section, we focus on addressing the optimal solution of (9a-e). The problem (9a-e) involves a continuous nonconvex optimization, and it is not possible to directly obtain the globally optimal solution. To overcome this issue, we propose to apply fractional programming
(FP) approach [13] to transform (9a-e) into a sequence of convex problems in which each problem can be solved effectively by standard convex optimization techniques. More specifically, the FP-based approach exploits the fractional structure of the objective function so that we can develop a sequential convex programming algorithm that approximately locates the globally optimal point with a low complexity. Such an approach is possible when the objective function exhibits a sum-ratio form of \( \sum_n f \left( \frac{A_n(x)}{B_n(x)} \right) \). Additionally, \( f(-) \) is a non-decreasing and concave function, while the functions \( A_n(x) : \mathbb{C}^u \rightarrow \mathbb{R} \) and \( B_n(x) : \mathbb{C}^u \rightarrow \mathbb{R} \), \( u \geq 1 \), are convex and concave w.r.t. \( x \), respectively.

Let first consider the case in which the numerator function \( A_n(-) \) can be represented by a quadratic form \( A_n(x) = a_n^2(x) \) with \( a_n(x) : \mathbb{C}^u \rightarrow \mathbb{R} \) being a multidimensional and real-value function. By adopting the quadratic transform of \( A_n/B_n \) to \( 2q_n a_n - q_n^2/B_n \) [13], the optimization problem

\[
\max_x \sum_n f \left( \frac{A_n(x)}{B_n(x)} \right) \tag{10}
\]

s.t. \( x \in \mathcal{X} \),

where \( \mathcal{X} \) represents the nonempty convex set of constraints, is equivalent to [13]

\[
\max_{x,q_n} \sum_n f \left( 2q_n a_n(x) - q_n^2/B_n(x) \right) \tag{11}
\]

s.t. \( x \in \mathcal{X} \).

In (11), \( q_n \in \mathbb{R} \) refers to an auxiliary variable, and it is optimized when \( x \) is held fixed as \( q_n^* = a_n(x)/B_n \).

For alternative cases in which the numerator of \( f \) is represented by an expanded multiplication \( A_n(x) = a_n(x) \bar{a}_n(x) \) with \( a_n(x) : \mathbb{C}^u \rightarrow \mathbb{C} \) being a multidimensional and complex-valued function, the problem (10) is now equivalent to [13]

\[
\max_{x,q_n} \sum_n f \left( 2\text{Re}\{q_n a_n(x)\} - \bar{q}_n B_n(x) q_n \right) \tag{12}
\]

s.t. \( x \in \mathcal{X} \),

where the auxiliary variables \( q_n \in \mathbb{C} \) are also optimized at \( q_n^* = a_n(x)/B_n(x) \).

The argument function of each outer function \( f \) is now convex w.r.t. \( x \) and \( q_n \) and the transformed optimization problem (11) becomes convex. As a result, the global optimal solution
can be achieved by solving a sequence of convex optimization subproblems that find the optimal $x$ and $q_n$ in an iterative fashion. The detailed procedure is given as follows.

Following (11) and (12), the optimization problem (9) can be transformed to

$$\max_{P, v_{bm}, q_{bm}, q_d} f_{FR} = \frac{1}{B} \sum_{b=1}^{B} \sum_{m \in C_b} f_{bm}^{(c)} + \frac{1}{B} \sum_{n \in D} f_{dn}^{(d)}$$

(13)

s.t. (9) - (9e).

In the objective function of (13), using $\left| \left( \mathbf{g}_{bm}^{(cc)} \right)^H \mathbf{v}_{bm} \right|^2 = \left( \mathbf{g}_{bm}^{(cc)} \right)^H \mathbf{v}_{bm} \left( \mathbf{v}_{bm} \right)^H \mathbf{g}_{bm}^{(cc)}$, the component $f_{bm}^{(c)}$ can be expressed from (12) as follows

$$f_{bm}^{(c)} = \log_2 \left( 1 + 2 \text{Re} \left( \left( \mathbf{g}_{bm}^{(cc)} \right)^H \mathbf{v}_{bm} \right) - \bar{q}_{bm}^{(c)} \left( f_{bm}^{(c)} + \sigma^2 \right) q_{bm}^{(c)} \right).$$

(14)

Meanwhile, the component $f_{dn}^{(d)}$ is provided from (11) by

$$f_{dn}^{(d)} = \log_2 \left( 1 + 2 q_{dn}^{(d)} \sqrt{P_n} \left| g_{dn}^{(dd)} \right| - 2 \left( q_{dn}^{(d)} \right)^2 \left( f_{dn}^{(d)} + \beta p_n + \sigma^2 \right) \right).$$

(15)

From (14) and (15), we observe that, as the logarithmic function $\log_2(\cdot)$ is nondecreasing and concave, the optimization problem (13) is a convex problem of $v_{bm}$ and $P$ when the auxiliary variables $q_{bm}^{(c)} \in \mathbb{C}$ and $q_{dn}^{(d)} \in \mathbb{R}^+$ are held fixed. It follows that, the optimal $q_{bm}^{(c)}$ and $q_{dn}^{(d)}$ that maximizes the objective function (13) for fixed $v_{bm}$ and $P$ are given by

$$q_{bm}^{(c)} = \left( \mathbf{g}_{bm}^{(cc)} \right)^H \mathbf{v}_{bm} \left( f_{bm}^{(c)} + \sigma^2 \right)^{-1},$$

(16)

$$q_{dn}^{(d)} = \sqrt{P_n} \left| g_{dn}^{(dd)} \right| \left( f_{dn}^{(d)} + \beta p_n + \sigma^2 \right)^{-1}.$$  

(17)

The convex optimization problem (13) allows to develop an iterative algorithm in order to solve (9) as follows. The iterative algorithm generates a sequence $v_{bm}$ and $P$ to improve the optimal solutions. From the first feasible solution $v_{bm}$ and $P$ that is randomly generated, at each iteration, we compute the optimal values of $q_{bm}^{(c)}$ and $q_{dn}^{(d)}$ and subsequently locate the optimal solution of the convex program (13), which can be solved effectively by using standard convex programming techniques. Because the constraint set (9b) - (9e) is convex, the sequence $v_{bm}$ and $P$ always converges [13]. We can set to stop the iterative algorithm when the objective function $f_{FR}$ converges, i.e., its absolute improvement is less than a desired (pre-selected) threshold $\epsilon$. For convenience, the iterative joint beamforming and power allocation algorithm based on FR programing is summarized in Algorithm 2.
Algorithm 1 Iterative FP-based algorithm

1: Initiate a feasible solution of $v_{bm}$ and $P$ and choose $\epsilon$.

2: \textbf{repeat}

3: Compute $q_{bm}^{(c)}$ and $q_{n}^{(d)}$ given by (16) and (17).

4: Solve the convex program (13) to obtain optimal $v_{bm}^*$, $P^*$, and $f_{FR}^*$.

5: \textbf{until} $f_{FR}$ converges, i.e., $|f_{FR} - f_{FR}^*| \leq \epsilon$

IV. ILLUSTRATIVE RESULTS

In this section, numerical results are presented to compare the achievable network sum-rates (per cell) of both cellular and D2D links, provided by FP-based algorithm developed in previous section, for the FD D2D, HD D2D, and pure MU-MIMO cellular systems (in absence of D2D transmission). The behaviors of such sum-rates under the effect of various networking parameters such as SIC level, D2D link distance, and number of active D2D links per cell are also illustrated.

Our Monte Carlo simulations are performed as follows. We consider a multi-cell network consisting of three hexagonal-cells as shown in Fig. 1. The cellular users and D2D transceivers are dropped randomly within the cell region. Each D2D transceiver is located uniformly in the circle where the radius equals a fixed D2D link distance $r$ and the corresponding D2D transceiver is located at the origin. The pathloss parameters correspond to a carrier frequency of 2 GHz, while the channel fast fading are generated independently according to complex Gaussian distribution with unit variance. With regards to the steering matrix $A$, we select the number of angular dimension $P = N/2$ and the antenna spacing $w = 0.3$ (wavelength) provided in [16].

In FP-based algorithm, the rate improvement threshold of iterative algorithm is chosen as $\epsilon$.

In our simulations, we assume that cellular users are located outside of the buildings (i.e., outdoor) and in the urban macrocells. In addition, we consider two D2D-related propagation scenarios in which the D2D users are located either outside or inside of the buildings in urban areas (i.e., outdoor and indoor, respectively). We denote these two scenarios as outdoor and indoor D2D transmission, respectively. For outdoor D2D transmission, we adopt the 3GPP macrocell propagation model (urban area) is adopted [17], [18]. For indoor D2D transmission, we consider the setting where the D2D transceivers are located inside indoor RRH/Hotzone [17], [19]. Unless stated otherwise, the network parameters used in both outdoor and indoor D2D transmission scenarios are provided in Tables [1].
### TABLE I

**COMMON SIMULATION PARAMETERS OF OUTDOOR AND INDOOR D2D**

| Parameter                                      | Value                  |
|------------------------------------------------|------------------------|
| Carrier frequency                              | 2 GHz                  |
| Channel bandwidth                              | 10 MHz                 |
| Cell area                                       | $\pi \times 500^2$ m$^2$ |
| Number of cells                                | 3                      |
| Number of antennas at BS A                     | 16                     |
| Number of angular dimension $P$ [16]            | 8                      |
| Antenna spacing $\omega$ [16]                  | 0.3 wavelength         |
| Number of cellular users per cell $M$           | 4                      |
| Number of D2D links per cell $N$               | $[10, 40]$             |
| D2D link distance $r$ [17]                     | $\{20, 50\}$ m        |
| Total BS Tx power $P_t$ [18]                   | 46 dBm                 |
| Max. D2D Tx power $P_d$                        | 23 dBm                 |
| Noise PSD                                      | $-174$ dB/Hz           |
| Receiver noise figure                          | 9 dB                   |
| Self-interference-to-Tx-signal power ratio $\beta$ | $[-120, -60]$ dB     |
| Target SINR $\gamma_c = \gamma_d$             | 0 dB                   |
| Improvement threshold $\epsilon$               | $10^{-5}$ dB           |

### A. Outdoor D2D Transmission

In this section, the illustrative results of outdoor D2D transmission scenario will be represented. The path-loss parameters for outdoor D2D transmission scenarios are provided in Tables II. We should note that, for a concise representation, we denote UE as either cellular user (CU) or D2D user.

### TABLE II

**PATH-LOSS PARAMETERS OF OUTDOOR D2D TRANSMISSION**

| Path-loss of BS-UE (D2D or CU) channels [17], [18] | $15.3 + 37.6 \log(r)$, $r$ in m |
|-----------------------------------------------------|---------------------------------|
| Path-loss of UE-UE channels [17], [18]              | $15.3 + 37.6 \log(r)$, $r$ in m |

For FD and HD D2D performance comparison, we first establish the FD-to-HD network sum-rate ratio and plot it versus SIPR $\beta$ in dB in Fig. 2. The numbers of cellular and D2D links per cell are chosen as $M = 4$ and $N = \{14, 30\}$ links/cell, respectively. In addition, the D2D link distance is $r = 50$ m. The obtained results show that FD D2D can offer better sum-rate...
than HD D2D with SICR $\beta \leq -95$ dB. For $\beta \leq -100$ dB, the FD-to-HD D2D sum-rate ratios seem to get stable around 1.45 and 1.30 for $N = 14$ and $N = 30$ links/cell, respectively. For the obtained results, we observe that, for outdoor D2D transmission scenario, the SIC level of 100 dB is sufficient to provide the best sum-rate ratio.

In Fig. 3, we plot network sum-rate (per cell) for different D2D link distances.

In Fig. 3 we plot network sum-rate (over a cell) of D2D links for both FD and HD D2D
transmission versus maximum D2D link distance for $N = 14$ links/cell and $\beta = -100$ dB. The obtained results demonstrate a significant D2D link sum-rate achieved, especially with FD D2D at short distances. As the D2D link distance increases, the achieved network sum-rate exponentially reduces. Interestingly, we observe that, as the D2D link distance exceeds 70 m, the sum-rate performances of FD and HD D2D are almost identical. This result indicates that, with sufficiently large D2D link distances, FD D2D is no longer beneficial in terms of spectral efficiency gain as compared to HD D2D operated in the same outdoor environment. This is because when the D2D link distance increases, D2D transceivers, in average, are located closer, thus causing more interference to each other.

![Achievable network sum-rate versus number of D2D links (per cell) when D2D links operate in FD and HD modes.](image)

In Fig. 4 we plot the achieved network sum-rate versus the number of D2D links over a cell under the consideration of FD and HD D2D. Moreover, to demonstrate the advantage of ULA-equipped BSs, we also compare the network sum-rates between the cases of beamforming and omni direction transmission at BSs. In the simulations for Fig. 4 we assume the D2D link distance as $r = 50$ m, while the numbers of D2D links (per cell) are from $N = 10$ to $N = 40$ links/cells. In addition, the SIC level is chosen as $\beta = -100$ dB. It can be seen that the network sum-rate for both FD and HD D2D increases as the number of D2D links $D$ increases. However, such increase in sum-rate gets compressed when $D$ exceeds a certain threshold. For instance, the sum-rate of FD D2D gets stable at $N = 20$ links/cell. Meanwhile, for HD D2D, the sum-rate gets stable at $N = 30$ links/cell. At $N = 30$ links/cell, the network sum-rates (over all cell) for
FD and HD D2D are 53.40 and 30.16 bits/s/Hz, respectively. This results implies that, when $D \geq 30$ links/cell, the FD-to-HD sum-rate ratio is fixed around 1.77. This can be explained that the number of D2D links satisfying the SINR constraints will get stable at sufficiently high number of active D2D links. We also observe that the network sum-rates offered by ULA-equipped BSs significantly outperforms those achieved by omni direction transmission at BSs in both FD and HD D2D. For instance, at $N = 40$ links/cells, the ULA-equipped BSs provide 1.83 and 1.60 times better in terms of network sum-rate as compared to omni transmission for FD and HD D2D respectively. These gains seem to get compressed with increasing number of D2D links since the number of D2D links satisfying the target SINRs becomes stable.

![Fig. 5. Spectral efficiency gain versus number of D2D links (per cell) when D2D links operate in FD and HD modes.](image)

By defining the spectral efficiency gain as the ratio of the network sum-rate (provided in Fig. 4) to the achievable sum-rate of only cellular links (operating alone without D2D links in the same environmental conditions), Fig. 5 plots the resulting spectral efficiency gain versus the number of active D2D link over a cell. Given the D2D link distance $r = 50$ m and SIC level $\beta = -100$ dB, the results in Fig. 5 indicate that, over the wide D2D link density range from 10 to 40 links/cell, the spectral efficiency gain linearly increases with the D2D link number for the cases of FD and HD D2D to a sufficient high number of active D2D links. For example, at D2D link number of 20 links/cell, FD D2D offers a spectral efficiency gain of 2.61 as compared to pure cellular transmission. Meanwhile, HD D2D offers a spectral efficiency gain of 2.00 at the D2D link number of 30 links/cell. Similar to the observation in Fig. 4 for number of active FD
(HD) beyond 20 (30) links/cell, the increase in spectral efficiency gain will eventually become stable.

B. Indoor D2D Transmission

In this section, we provide the numerical results for the indoor D2D transmission scenario in which D2D users are located inside of the building, while cellular users (CU) are located outside in urban macrocell environment. As aforementioned, D2D transceivers are located inside indoor RRH/Hotzone [17], [19]. The direct D2D transmission is assumed to be inside the same building as the indoor RRH/Hotzone, while the transmission from a D2D transmitter to cellular users or interfered D2D receivers is assumed to be outside the same building as the indoor hotzone. The path-loss, penetration loss, and lognormal shadowing parameters for indoor D2D transmission scenario are provided in Tables III whereby the indoor RRH/Hotzone-related parameters are given in [19 Table A.2.1.1.5].

| TABLE III |
| --- |
| **PATH-LOSS AND SHADOWING PARAMETERS OF INDOOR D2D TRANSMISSION** |

| Channel Type                      | Path-loss                      | Lognormal Shadowing $\sigma$ |
|-----------------------------------|--------------------------------|-------------------------------|
| BS-CU channels [18]               | $15.3 + 37.6 \log(r)$, $r$ in m | 7 dB                          |
| BS-D2D channels [19]              | $2.7 + 42.8 \log(r)$, $r$ in m | 20 dB                         |
| Direct D2D channels [19]          | $17.5 + 43.3 \log(r)$, $r$ in m| 4 dB                          |
| D2D-UE channels [19]              | $\max\{17.5 + 43.3 \log(r), 2.7 + 42.8 \log(r)\}$, $r$ in m | 20 dB                         |
|                                   | Penetration loss                | 10 dB                         |

Similar to the case of outdoor D2D transmission, in Fig. 6 we first demonstrate the FD-to-HD network sum-rate ratio versus SIPR $\beta$ in dB so as to compare FD and HD D2D sum-rate performances. The numbers of cellular and D2D links per cell are chosen as $M = 4$ and $N = \{14, 30\}$, respectively. In addition, the D2D link distance is chosen as $r = \{20, 50\}$ m for $N = 30$ links/cell. The results show that FD D2D can offer better sum-rate than HD D2D with SIPR $\beta \leq -100$ dB. We also observe that, for indoor D2D transmission, FD D2D can offer
significant sum-rate improvement (as compared to HD D2D) when $\beta \leq -120$ dB. Further, as $\beta \leq -120$ dB and D2D link distance $r = 20$ m, the FD-to-HD D2D sum-rate ratios seem to get stable around 1.85 and 1.90 for $N = 14$ and $N = 30$ D2D links/cell, respectively. When the D2D link distance increases to $r = 50$ m, the FD-to-HD D2D sum-rate ratio reduces to 1.6 for $\beta \leq -120$ dB. The results in Fig. 6 also indicate that the SIC of 120 dB is sufficient to achieve the best FD-to-HD D2D sum-rate ratio for indoor D2D transmission.

![Achievable network sum-rate versus number of D2D links (per cell).](image)
In Fig. 7 we plot the network sum-rate (over a cell) versus number of D2D links per cell for D2D link distance $r = 20\, m$ and SIPR $\beta = -120\, dB$. The range of D2D link numbers is chosen as $N \in [10, 40]$. Similar to the case of outdoor D2D transmission, to demonstrate the benefit of ULA-equipped BSs, we also compare the network sum-rates between the cases of beamforming and omni direction transmission at BSs. The obtained results show a significant D2D link sum-rate achieved, especially with FD D2D. As the number of D2D link increases, the achieved network sum-rate linearly increases. Interestingly, the increase in difference between FD and HD D2D sum-rates shows the increase in FD-to-HD sum-rate ratio. For example, at $N = 10$ and $N = 40$ links/cell, the achievable network throughput (per cell) for FD D2D are $173.13$ and $461.47$ bits/s/Hz, respectively, while the throughput of HD D2D are $100.10$ and $235.77$ bits/s/Hz, repectively. These results imply that, at $N = 10$ and $N = 40$ links/cell, FD D2D achieves a spectral efficiency gains of $1.73$ and $1.95$, as compared to the HD D2D operated in the same indoor D2D environment. However, as shown in the case of outdoor D2D transmission, such FD-to-HD sum-rate ratio will eventually get stable because the increase in number of cellular/D2D links that satisfying the target SINR constraints will get compressed. Fig. 7 also shows a significant network sum-rates achieved by ULA-equipped BSs as compared to the omni transmission. For instance, at $N = 40$ links/cell, ULA-equipped BSs offer $1.74$ and $1.52$ times better (in terms of network sum-rate) than omni transmission for FD and HD D2D services, respectively. Similar to outdoor D2D transmission, as the number of D2D links increases further, these gains will eventually compressed since the number of D2D links satisfying the target SINRs becomes stable.

Fig. 8 illustrates the resulting spectral efficiency gain versus the number of D2D links over a cell for D2D link distance $r = 20\, m$ and SIPR $\beta = -120\, dB$. Recall that the spectral efficiency gain is computed as the ratio of the network sum-rate to the achievable sum-rates of cellular links. We observe that, over various number of D2D links ranging from $N = 10$ to $N = 40$ links/cell, the spectral efficiency gain linearly increases with the number of D2D links for both cases of HD D2D and FD D2D. With better SIC of $120\, dB$, FD D2D offers a substantial improvement in the spectral efficiency gain as compared to HD D2D. For example, in Fig. 8 for a D2D link density of $40$ links/cell, HD D2D achieves a spectral spectrum gain of $12.0$ while FD D2D can offer $23.6$. Similar to the behavior of achievable network sum-rate illustrated in Fig. 7 as the number of D2D links increases further, the spectral efficiency gain of FD D2D will get stable beyond a sufficient number of D2D links.
V. CONCLUDING REMARKS

In this paper, we have focused on multi-cell multi-user multiple-input-multiple-output (MU-MIMO) cellular networks being underlaid by full-duplex (FD) device-to-device (D2D) transmission. Specifically, we proposed a joint beamforming and power allocation scheme that maximizes the network sum-rate while protecting the D2D and cellular link. To deal with the non-convexity of the problem, a fractional programing (FP)-based method was developed to transform the problem into a sequence of convex subproblems, which can be solved efficiently. For both indoor and outdoor D2D transmission, simulation results revealed that significant performance gains in term of spectral efficiency can be achieved in the considered FD network, especially in the indoor D2D scenario, as compared to the half-duplex (HD) D2D counterpart and pure cellular transmission (in absent of D2D) with sufficient self-interference cancellation levels.

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