JOURNAL OF SOUTHERN COMMUNICATION ENGINEERING
ISLAMIC AZAD UNIVERSITY BUSHEHR BRANCH

E-ISSN: 2980-9231
https://jce.bushehr.iau.ir

https://doi.org/10.30495/jce.2022.1962935.1166

Vol. 12/ No. 46/Winter 2023

Research Article

Millimeter-Wave Underlay D2D Communications: Channel Assignment, Transmission Mode Selection and Power Control for Full-CSI and Limited-CSI Scenarios

Nima Reisi, Assistant Professor [1*]

[1]Department of Electrical Engineering, Islamic Azad University, Central Tehran Branch, Tehran, Iran,
n.raeisi@iauctb.ic.ir

Correspondence
Nima Reisi, Assistant Professor of Electrical Engineering, Islamic Azad University, Central Tehran Branch, Tehran, Iran,
n.raeisi@iauctb.ic.ir

Received: 10 July 2022
Revised: 30 August 2022
Accepted: 20 September 2022

Abstract

In this paper, we study relay-assisted underlay Device-to-Device (D2D) communication operating at millimeter-wave (mmWave) band in which half-duplex/full-duplex (HD/FD) relays may assist D2D users to improve transmission quality and coverage range. We aim to jointly select D2D transmission mode, assign one or more cellular resource blocks (RBs) to each D2D user and control the powers of users to maximize the aggregate data rate of the network. We focus on the main features of mmWave communication including larger bandwidth, directive antenna arrays utilization, and severe path loss and shadowing. As the optimization problem is mixed-integer-non-linear programming, two heuristic algorithms are proposed, assuming full Channel Side Information (CSI) and limited CSI at Base Station, respectively. Simulation results show the superiority of utilizing FD relays, especially for non-line-of-sight links, which is the dominant propagation mechanism in mmWave band. Furthermore, mode selection may imropves the performance in the case of large residual-self-interference. The limited CSI algorithm has considerably lower complexity. Moreover, when the number of RBs far exceeds the number of D2D users, the gap between two algorithms vanishes.

Keywords: D2D communication, Full-Duplex Relay, Millimeter-wave, 5G Cellular Networks, Resource Allocation

Highlights

- Joint D2D mode selection, channel assignment and power control in order to maximize the aggregate data rate.
- Realistic modeling of mm Wave channel including both LOS and NLOS links.
- Proposing two heuristic algorithms for full-CSI and limited-CSI scenarios.

Citation: N. Reisi, "Millimeter-Wave Underlay D2D Communications: Channel Assignment, Transmission mode Selection and Power Control for Full-CSI and Limited-CSI Scenarios," *Journal of southern Communication Engineering*, vol. 12, no. 46, pp. 1–18, 2023, doi:10.30495/jce.2022.1962935.1166.

1- Introduction

Device-to-Device (D2D) communication is a technique for direct communication between proximity users within a cellular network without involving the Base Station (BS), proposed for constantly-growing local services and emergency conditions. D2D communication is proved to be a vital technique for improving spectral efficiency and decreasing latency in current and succeeding generation of cellular systems [1-4]. Resource allocation and interference management are the most important concerns in D2D networks, especially in underlay D2D communications. The coexistence of cellular and D2D users in microwave spectrum bands has been investigated in many researches and different centralized and distributed power allocation algorithms are proposed [5-10]. A good survey on the existing algorithms related to interference management (avoidance, coordination, and cancellation) in D2D networks can be found in [11].

Relays-assisted D2D communication is suggested to increase D2D communication range and improve quality of service (QoS) [12]. FD relaying, in which simultaneous transmission and reception of on a common frequency band is possible, is proved to improve energy and spectrum efficiency compared to HD relaying [13-16].

On the other hand, millimeter wave (mmWave) communication is one of the key enabling technologies to meet the vast data demand growth [16-18]. Due to extremely low wavelengths of mmWave signals, using antenna arrays is possible in order to enable high-gain beamforming to overcome path-loss and shadowing effects [17-20]. Recently, D2D communication in mmWave band has gained considerable attention [21]. The propagation characteristics of mmWave communication and its impacts on Fifth Generation (5G) of cellular networks are discussed in [22]. Moreover, a resource sharing algorithm is proposed which allows non-interfering D2D links to operate concurrently.

In existing research on achievable aggregate-rate of underlay D2D transmission, two different approaches are proposed based on the geometry of the network: some papers assume the positions of D2D/cellular users are deterministic [23-24], while others use stochastic geometry to model the randomness of the network [6]. Alternately, rate analysis can be studied assuming instantaneous or statistical CSI availability which results in ergodic capacity and capacity with outage, respectively.

In [25], a resource allocation algorithm for D2D communications underlaying cellular network in the E-band is proposed to maximize the achievable sum rate of cellular and dense D2D network while alleviating the interference caused by D2D links. Nevertheless, a D2D pair can only reshare the resource blocks of a particular cellular user. Furthermore, the necessity of utilizing relay-based communication in Non-Line-of-Sight (NLOS) conditions is ignored.

It is proven that utilizing HD/FD relays in microwave D2D networks can improve system capacity and coverage [26]. However, the literature on utilizing FD relays in mmWave networks in the context of D2D communication is limited.

In [27], a multi-hop approach is investigated to improve the connectivity of the mmWave network. Nevertheless, the side-effects of multi-hop relaying like overhead increase and delay are not considered. In [28], it is shown that D2D relaying can help to increase the connectivity and coverage range of mmWave cellular systems and an algorithm is proposed for relay selection in a two-hop decode-and-forward mmWave cellular system. The authors in [29] propose a relay-assisted mmWave cellular network in which an idle user can act as a relay to forward the BS signal to a destination user once there is an outage on the direct cellular link. All these papers [27-29] consider only HD relaying. In [30], a full-duplex relay-based D2D network communicating in mmWave band is considered and an efficient algorithm is proposed for relay selection and power allocation when the D2D network works in dedicated mode with no interference on cellular users. In [31], using deep learning, a D2D mmWave communication framework for mode selection is considered in which the D2D transmitter select the mode to transmit the data directly or through the BS as a relay.

Contribution

To the best of the author’s knowledge, the problem of uplink resource allocation for D2D users with HD/FD relaying, underlaying the cellular network in mmWave band has been not considered in any popular research yet. In this paper, a D2D network in the mmWave frequency band undelaying the uplink of a cellular system is analysed. Based on their distance or the Line-of-Sight (LOS) probability of the direct link, D2D users can establish connection directly, or by the help of relays, operating either in HD or FD mode. Resource management and power control for this framework are considered to achieve maximum aggregate rate of cellular and D2D network.

It is necessary to mention that joint resource allocation and D2D mode selection for D2D underlaid cellular networks by decoupling the "power control" and "mode selection/channel assignment" phases has been studied in some papers. Authors in [32] consider joint relay selection and resource allocation for D2D underlaid cellular networks with focus on HD relays and microwave band, while in [33], D2D mode selection - between direct transmission and HD relaying -, power allocation and channel assignment is studied.

The main features that distinct our work from others are as follows: (1) to increase the D2D rate, each D2D link is allowed to reshare the spectrum of more than one cellular link; (2) to effectively manage the trade-off between

complexity and performance, two heuristic solutions are proposed for both full and limited CSI cases. In both algorithms, a low complexity power control technique - which is an extension to previously proposed algorithm in [32-33] - and two greedy algorithms for mode selection and channel assignment are proposed.
We point out that both proposed algorithms are backward compatible and can be applied to microwave band. Our concentration on mmWave band is characterized by utilizing highly-directive antennas, the high probability of NLOS links for D2D pairs -which emphasizes the importance of utilizing relays in D2D communication-, and the possibility of allocating more than one resource block (RB) to a D2D link, to increase the achievable rate.
A comparison among main features of recent works in the field of D2D communication in mmWave band are summerized in Table 1.

Table 1. Main features of recent works in the field of D2D communication in mmWave band

Ref	**Relay**	**Method**	**Resource Blocks**	**CSI**
[25]	-----	Rate Analysis	D2D pair can only reshare the resource blocks of one cellular user	Full CSI
[27]	HD	Stochastic Geometry	Dedicated resource blocks for D2D transmissions	-----
[28]	HD	Rate Analysis	Dedicated resource blocks for D2D transmissions	Full CSI
[29]	HD	Rate Analysis	D2D pair can reshare the resource blocks of cellular users	statistical CSI
[30]	FD	Stochastic Geometry	Dedicated resource blocks for D2D transmissions	-----
[31]	HD	Rate Analysis	Dedicated resource blocks for D2D transmissions	Full CSI
Our	Direct HD/FD	Rate Analysis	D2D pair can reshare the resource blocks of more than on cellular user	Full CSI Limited CSI

The remainder of this paper is as follows. System and channel models are presented in section 2. Problem formulation is presented in section 3 in which the analytical expression for D2D links, cellular users, and aggregate rate of the network are derived. In sections 4, the proposed algorithms for joint mode selection, power control, and channel assignment are presented for full and limited CSI cases. Simulation results and discussions are available in section 5. Finally, the paper is concluded in section 6.

2- System and Channel Model

2-1- System Model

We consider resource allocation for a relay-based D2D communication underlaying the 5G cellular network operating at mmWave frequency band. Due to blockage and shadowing effects, the relays may assist D2D users with poor direct link quality. The relays are operating according to decode-and-forward (DaF) protocol and can operate in both HD and FD modes.
Comparing to downlink (DL) spectrum band, the uplink (UL) spectrum is underutilized in the frequency division duplexing (FDD) based cellular systems. Hence, UL resources are preferred to be shared among cellular and D2D users [34].
In the single-cell scenario, we assume that cellular users (CUs) occupy all the available RBs. To reduce the interference, each RB is permitted to be reused by at most one D2D link. To fully exploit the spectrum resources and to satisfy the high data-rate demands of D2D users, each D2D link can occupy more than one RB, conditioned on minimum QoS demands of cellular users and maximum possible D2D bandwidth.
More specifically, as depicted in Figure 1, the BS serves N cellular users denoted as $C = \{1,2,\ldots,N\}$ and control the communication of $M < N$ D2D links denoted as $U = \{1,2,\ldots,M\}$, where a D2D link is consisted of a source (S), destination (D), and relay (R). The relays can operate in HD or FD mode with residual self-interference (RSI) in FD mode is denoted by h_{rsi}. The RSI value is assumed to be near the receiver noise floor utilizing analogue and digital mitigation methods [35, 36]. Without loss of generality, we assume that the number of RBs is equal to the number of CUs, and i'th RB is allocated to i'th CU. Hence, CU and RB may be used interchangeably throughout the paper.
We highlight that although relay selection can be also considered as a part of resource allocation problem, we assume that a dedicated relay is assigned to each D2D pair, according to the minimum average Euclidean distance of relays from D2D pairs, for instance.

2-2- Channel Model

The channel gain between any two nodes x and y, considering the effects of antenna gains, shadowing, and path-loss is modelled as

$$h_{xy} = \frac{G_{xy}}{L\left(d_{xy}\right)} \tag{1}$$

where $G_{xy} = G_t(\theta_t)\, G_r(\theta_r)$ and $L(d_{xy})$ are the product of transmitting and receiving antenna gains, and path-loss function, respectively.

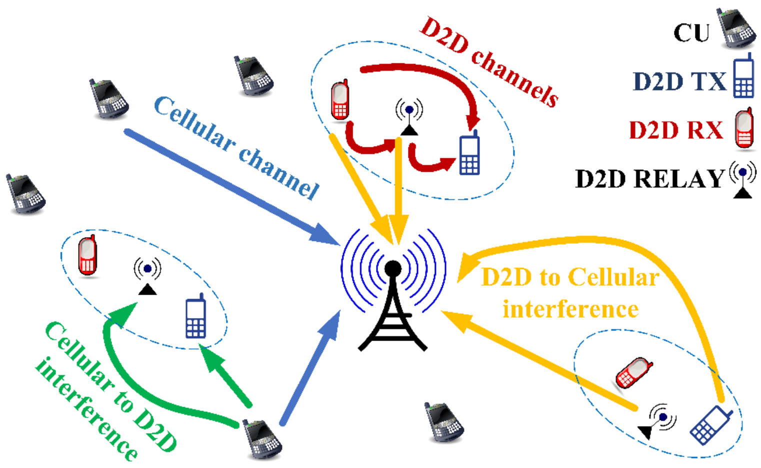

Figure 1. A typical D2D communication underlaying cellular network.

A sectored antenna model with constant high-gain G_{ml} and low gain G_{sl} in the main and side lobes, respectively is deployed at both BS and mobile stations to perform directional beamforming [37]:

$$G_{t/r}\left(\theta_{t/r}\right)=\begin{cases} G_{t/r,ml}, & \left|\theta_{t/r}\right|\le \frac{\theta_{hpbw}}{2} \\ G_{t/r,sl}, & otherwise \end{cases} \qquad (2)$$

θ_t and r_t are the angles of departure-from-transmitter and arrival-to-receiver, respectively, and θ_{hpbw} is the half-power-beam-width (HPBW) for the transmitting and receiving antennas.
To model LOS-NLOS links, we utilize the model presented in [38] where the probability of LOS occurrence between two nodes with distance d is modeled as $p(d) = e^{-\beta d}$, where $1/\beta$ is the average LOS range of the cellular network. The path-loss model, in dB, is written as

$$L(d)=L(d_0)+\left[\mathrm{I}\left(p(d)\right)\right]\left[10\alpha_{LOS}\log_{10}d+\chi_{\sigma,LOS}\right]+\left[1-\mathrm{I}\left(p(d)\right)\right]\left[10\alpha_{NLOS}\log_{10}d+\chi_{\sigma,NLOS}\right], \quad d\ge d_0 \qquad (3)$$

Where $L(d_0)$ is the path-loss at reference distance d_0, $I(x)$ is a Bernoulli random variable with parameter x, α_{LOS} and α_{NLOS} are the LOS and NLOS power loss exponents (PLE) and $\chi_{\sigma,LOS}$ and $\chi_{\sigma,NLOS}$ are zero mean Gaussian random variables with variances σ^2_{LOS} and σ^2_{NLOS} in dB to model the shadowing and blockage effects [37, 39].
For D2D links, it is assumed that $S\rightarrow D$ links are in NLOS conditions ($I(p(d)=0)$, $S\rightarrow D$, and $R\rightarrow D$ links experience LOS ($I(p(d)=1)$, while other links, including desired and interference links, encounter combined LOS-NLOS conditions.
The transmitted powers are declared as P_{ci}, P_{sj}, and P_{rj} for i'th CU, j'th D2D source, and j'th D2D relay, respectively. The channel gains between different node are defined in Table 2.

Table 2. Channel Gains Definitions

Symbol	Channel gain between
$h^i_{c_ib}$	i'th CU and BS
$h^i_{s_jr_j}$	j'th D2D source and relay on i'th RB
$h^i_{r_jd_j}$	j'th D2D relay and destination on i'th RB
$h^i_{c_ir_j}$	i'th CU and j'th D2D relay
$h^i_{c_id_j}$	i'th CU and j'th D2D destination
$h^i_{s_jb}$	j'th D2D source and BS on i'th RB
$h^j_{r_jb}$	i'th D2D relay and BS on i'th RB

3- Problem Formulation

3-1- Cellular Network Data Rate

Consider the case where all uplink cellular RBs are occupied. Assuming each RB may be shared by at most one D2D link, either in direct transmission (DT), half-duplex transmission (HT), or full-duplex transmission (FT) mode, the uplink rate of the single-cell system normalized by channel bandwidth *B*, can be formulated as (4)

$$R_{cell}=\sum_{i\in C}\left(1-\sum_{j\in U}\rho_{ij}\right)R_{c_i,0}+\sum_{i\in C}\left(\sum_{j\in U}\rho_{ij}\left\{\left(1-\mathfrak{I}_{ij}\right)R_{c_i,j}^{DT}+\left(\mathfrak{I}_{ij}\right)\left[\xi_{ij}R_{c_i,j}^{HT}+\left(1-\xi_{ij}\right)R_{c_i,j}^{FT}\right]\right\}\right) \quad (4)$$

where ρ_{ij}, the reuse indicator of i'th RB by j'th D2D link is a binary variable equal to one if j'th D2D link uses the i'th RB and zero, otherwise, with the following properties: $\rho_{ij}\in\{0,1\}$, $\sum_{j\in U}\rho_{ij}\leq 1$. $\mathfrak{I}_{ij}\in\{0,1\}$ indicates whether j'th D2D source-destination communicates directly ($\mathfrak{I}_{ij}=0$) or by the help of relay ($\mathfrak{I}_{ij}=1$), $\zeta_{ij}\in\{0,1\}$ is a binary indicator for HD/FD relay selection ($\zeta_{ij}=0$ for HT mode and 1 for FT mode). The achievable rate of i'th CU in different modes are as follows

$$R_{c_i,0}=\log_2\left(1+\gamma_{c_i,0}\right)=\log_2\left(1+\frac{P_{c_i}^{\max}h_{c_ib}^i}{N_0}\right) \quad (5)$$

$$R_{c_i,j}^{DT}=\log_2\left(1+\gamma_{c_i,j}^{DT}\right)=\log_2\left(1+\frac{P_{c_i}h_{c_ib}^i}{N_0+P_{s_j}h_{s_jb}^i}\right) \quad (6)$$

$$R_{c_i,j}^{HT}=\frac{1}{2}\log_2\left(1+\gamma_{c_i,j}^{HT_1}\right)+\frac{1}{2}\log_2\left(1+\gamma_{c_i,j}^{HT_2}\right)=\frac{1}{2}\log_2\left(1+\frac{P_{c_i}h_{c_ib}^i}{N_0+P_{s_j}h_{s_jb}^i}\right)+\frac{1}{2}\log_2\left(1+\frac{P_{c_i}h_{c_ib}^i}{N_0+P_{r_j}h_{r_jb}^i}\right) \quad (7)$$

$$R_{c_i,j}^{FT}=\log_2\left(1+\gamma_{c_i,j}^{FT}\right)=\log_2\left(1+\frac{P_{c_i}h_{c_ib}^i}{N_0+P_{s_j}h_{s_jb}^i+P_{r_j}h_{r_jb}^i}\right) \quad (8)$$

where N_0 is the noise variance and $P_{ci}^{\max}$ is the maximum allowable power of i'th CU, $R_{ci,0}$ denotes the i'th CU rate when its RB is not reused by any D2D link, and $R_{ci,j}^{DT}$, $R_{ci,j}^{HT}$, and $R_{ci,j}^{FT}$ are the rates of the i'th CU when its RB is reused by j'th D2D link in DT, HT, and FT modes, respectively. Note that when a relay operates in HT mode, the rate should be calculated over two successive time intervals corresponding to $S\rightarrow R$ and $R\rightarrow D$ transmission phases, while in FT mode, receiving and transmitting of a relay occurs concurrently.

3-2- D2D Network Data Rate

Assuming that the i'th RB is reused by the j'th D2D link, the D2D achievable rates for different modes over this RB are:

$$\begin{aligned}R_{u_j,i}^{DT}&=\log_2\left(1+\gamma_{sd_j,i}^{DT}\right)\\R_{u_j,i}^{HT}&=\frac{1}{2}\log_2\left(1+\min\left[\gamma_{sr_j,i}^{HT_1},\gamma_{rd_j,i}^{HT_2}\right]\right).\\R_{u_j,i}^{FT}&=\log_2\left(1+\min\left[\gamma_{sr_j,i}^{FT},\gamma_{rd_j,i}^{FT}\right]\right)\end{aligned} \quad (9)$$

where:

$$\gamma_{sd_j,i}^{DT_1}=\frac{P_{s_j}h_{s_jd_j}^i}{N_0+P_{c_i}h_{c_id_j}^i} \quad (10\text{-a})$$

$$\gamma_{sr_j,i}^{HT_1}=\frac{P_{s_j}h_{s_jr_j}^i}{N_0+P_{c_i}h_{c_ir_j}^i} \quad (10\text{-b})$$

$$\gamma_{rd_j,i}^{HT_2}=\frac{P_{r_j}h_{r_jd_j}^{j}}{N_0+P_{c_i}h_{c_id_j}^{i}} \tag{10-c}$$

$$\gamma_{sr_j,i}^{FT}=\frac{P_{s_j}h_{s_jr_j}^{i}}{N_0+P_{r_j}h_{rsi}+P_{c_i}h_{c_ir_j}^{i}} \tag{10-d}$$

$$\gamma_{rd_j,i}^{FT}=\frac{P_{r_j}h_{r_jd_j}^{i}}{N_0+P_{c_i}h_{c_id_j}^{i}} \tag{10-e}$$

and the D2D network rate can be written as (11)

$$R_{d2d}=\sum_{i\in C}\sum_{j\in U}\left(\rho_{ij}\right)\left(1-\mathfrak{T}_{ij}\right)R_{u_j,i}^{DT}+\left(\rho_{ij}\right)\left(\mathfrak{T}_{ij}\right)\left(\left[\xi_{ij}R_{u_j,i}^{HT}+\left(1-\xi_{ij}\right)R_{u_j,i}^{FT}\right]\right) \tag{11}$$

3-3- Optimization Problem

Our goal is to maximize the aggregate rate according to the QoS requirements of cellular links, i.e., their minimum required signal-to-noise-and-interference-ratio (SINR) values and under different power constraints (maximum transmitted powers of CUs and D2D users), and the fact that each cellular channel can be reused by at most one D2D link but each D2D link can reshare at most L RBs, where $L\times B$ is the maximum bandwidth of a D2D transmission. Hence, the optimization problem can be written as

$$\max_{\rho_{ij},\mathfrak{T}_{ij},\ \xi_{ij},P_{c_i},\ P_{s_j},\ P_{r_j}} R_{agg}=R_{cell}+R_{d2d} \tag{12}$$

Subject to:

$$\begin{aligned}
&(c_1)\ \ \gamma_{i,j,0}^{C},\gamma_{c_i,j}^{DT},\gamma_{c_i,j}^{FT}\geq\gamma_{c_i}^{\min},\ \ \forall i\in C\\
&(c_2)\ \ \gamma_{c_i,j}^{HT_1},\gamma_{c_i,j}^{HT_2}\geq\frac{1}{2}\gamma_{c_i}^{\min},\ \ \forall i\in C\\
&(c_3)\ \ P_{c_i}\leq P_{c_i}^{\max},\ \ \forall i\in C\\
&(c_4)\ \ P_{s_j}\leq P_{s_j}^{\max}\ ,P_{r_j}\leq P_{r_j}^{\max},\ \ \forall j\in U\\
&(c_5)\ \ \sum_{j\in U}\rho_{ij}\leq 1,\forall i\in C\\
&(c_6)\ \ \sum_{i\in C}\rho_{ij}\leq L,\forall j\in U\\
&(c_7)\ \ \rho_{ij}\in\{0,1\},\ \ \mathfrak{T}_{ij}\in\{0,1\},\ \ \xi_{ij}\in\{0,1\}
\end{aligned} \tag{13}$$

Constraints (c_1) and (c_2) illustrate the minimum SINR requirements of cellular links, (c_3) and (c_4) denote the power constraints, while (c_5) ensures that each RB can be reused by at most one D2D link and (c_6) limits the D2D transmission bandwidth.

The optimization problem (12) with constraints (13) is a mixed-integer non-linear programming (MINLP) which is NP-hard. To solve the problem, two heuristic algorithms are utilized. In the first algorithm, we assume that CSI of all links is available at BS. Since full CSI availability is not practical, a second algorithm is proposed in which, the locations of all users are known, and the CSI of a subset of links can be acquired by BS.

4- Proposed Algorithms

4-1- Full-CSI algorithm

Let us assume that the instantaneous CSI of all direct and interference links on different frequency bands (RBs) are available at BS. Similar to [33] and [32], the optimization problem can be solved heuristically using a two-phase algorithm: In the first phase, called Power Control (PC), we will find all D2D candidates which can reuse each RB according to power and SINR constraints, either in DT, HT, or FT mode. Then, in the second phase, denoted by Mode-Selection and Channel Assignment (MSCA), the best RBs to share with D2D links and transmission mode of each D2D link are assigned, using a greedy algorithm.

Phase I: PC

In PC sub-problem, the aim is to conclude which D2D users -in DT, HT, or FT mode - can reuse each of RBs. Hence, we maximize the sum-rate $R_{i,j}$ for all cellular-D2D pairs, subject to power and SINR constraints. If the problem is not feasible in any of modes, we conclude that the i'th RB cannot be shared by the j'th D2D. Otherwise, j'th D2D is selected as a candidate to share i'th RB.

The optimization problem can be solved through bearing in mind the following facts:

To save the transmit power for D2D transmission in HT/FT mode, the source-to-relay and relay-to-destination rates must be equal [40], hence, $\gamma_{srj,i}^{FT} = \gamma_{rdj,i}^{FT}$ and $\gamma_{srj,i}^{HT1} = \gamma_{rdj,i}^{HT2}$ for FT and HT modes, respectively.

When optimal powers are allocated, at least one of the users (CU, D2D transmitter, or D2D relay in HT/FT modes) will transmit at its maximum allowable power [34]. Hence, for optimal power allocation of i 'th cellular link which is reused by j'th D2D pair, we will consider three events: (I) $P_{ci} = P_{ci}^{\max}$, (II) $P_{sj} = P_{sj}^{\max}$, and (III) $P_{rj} = P_{rj}^{\max}$. The first two events should be evaluated for all modes, while the latter is only applicable for HT and FT modes.

<u>Direct-Transmission (DT)</u>

The optimization problem for DT mode is written as:

$$\left(\tilde{P}_{c_i},\ \tilde{P}_{s_j}\right)_{\text{opt}} = \underset{P_{c_i},\ P_{s_j}}{\operatorname{argmax}} \left(1+\frac{P_{c_i} h^i_{c_i b}}{N_0 + P_{s_j} h^i_{s_j b}}\right) \times \left(1+\frac{P_{s_j} h^i_{s_j d_j}}{N_0 + P_{c_i} h^i_{c_i d_j}}\right) \tag{14}$$

For the first and second events, denoted by DT-I and DT-II, we assume that $P_{ci} = P_{ci}^{\max}$ and $P_{sj} = P_{sj}^{\max}$, respectively, and the goal is to find the optimum values of P_{sj} and P_{ci}, respectively. The constraints are the minimum QoS requirement for i'th cellular user and maximum allowable power values ($P_{ci}^{\max}$ for DT-I and $P_{sj}^{\max}$ for DT-II). These constraints are as (15) and (16), for DT-I and DT-II, respectively.

$$P_{s_j} \le \min\left(P^{\max}_{s_j}, \frac{P^{\max}_{c_i} h^i_{c_i b} - \gamma^{\min}_{c_i} N_0}{\gamma^{\min}_{c_i} h^i_{s_j b}}\right) \tag{15}$$

$$\frac{\left(N_0 + P^{\max}_{s_j} h^i_{s_j b}\right)\gamma^{\min}_{c_i}}{h^i_{c_i b}} \le P_{c_i} \le P^{\max}_{c_i} \tag{16}$$

The optimization problem is a non-linear fractional programming (NFP) problem which can be solved by Dinkelbach's algorithm [41]: Introducing an axillary variable y, the fractional problem max {A(x)/B(x)} is reformulated as max {A(x) – yB(x)} and iteratively updated by y[n+1]={A(x[n]}/{B(x[n]} , where n is the iteration index [42]. However, the problem can be solved more efficiently.

For DT-I, setting $P_{ci} = P_{ci}^{\max}$, the objective function in (14) will have the following form:

$$\left(\frac{ax^2 + bx + c}{b'x + c'}\right),\ \ x = P_{s_j} \tag{17}$$

where the numerator of its derivative is a quadratic function with at most two real positive roots, named $P_{sj,1}$ and $P_{sj,2}$ which are maxima, minima, or saddle points of the objective function. If the constraint (15) can be met, i.e., the upper limit is greater than the lower limit, to calculate optimum power pair ($P_{ci}^{\max}$, $\tilde{P}_{sj}^{DT\text{-}I}$) and the achievable rate $\tilde{R}_{i,j}^{I}$, it is sufficed to check 4 points, at most: the lower limit P_{sj}^{low}, the upper limit P_{sj}^{up}, and the critical points $P_{sj,1}$ and $P_{sj,2}$.

The same procedure can be utilized for DT-II to calculate optimum power pair ($\tilde{P}_{ci}^{DT\text{-}I}$,$P_{sj}^{\max}$) and achievable rate $\tilde{R}_{i,j}^{II}$, which is omitted here.

The feasible set for i'th RB link in DT mode contains all D2D users which can reshare the RB as well with decision variables equals to sum-rates $\tilde{R}_{i,j} = \max(\tilde{R}_{i,j}^{I}, \tilde{R}_{i,j}^{II})$, ∀j϶U.

<u>Half-Duplex-Transmission (HT)</u>

The optimization problem for HT mode has the following form

$$\left(\hat{P}_{c_i},\hat{P}_{s_j},\hat{P}_{r_j}\right)_{\text{opt}}=\underset{P_{c_i},P_{s_j},P_{r_j}}{\arg\max}\left(1+\frac{P_{c_i}h^i_{c_ib}}{N_0+P_{s_j}h^i_{s_jb}}\right)\times\left(1+\frac{P_{c_i}h^i_{c_ib}}{N_0+P_{r_j}h^i_{r_jb}}\right)\times\left(1+\frac{P_{r_j}h^i_{r_jd_j}}{N_0+P_{c_i}h^i_{c_id_j}}\right) \tag{18}$$

where the first and second terms are related to cellular network rate, while the third term is related to D2D network and written according to the equality of SINRs of $S\rightarrow R$ and $R\rightarrow D$ links.

For each event (HT-I, HT-II, and HT-III), the constraints contain the equality of the SINR values of $S_j\rightarrow R_j$ and $R_j\rightarrow Dj$ links, the minimum QoS requirement for cellular users, and maximum allowable power values. After some straightforward manipulations, the constraints can be obtained as (19), (20), and (21), for HT-I, HT-II, and HT-III, respectively. Constraint (c'_1) in each mode is in accordance with the equality of $S_j\rightarrow R_j$ and $R_j\rightarrow Dj$ SINR values, while constraints (c'_2) and (c'_3) encompass QoS and power budget.

$$\begin{aligned}
&(c'_1)\;\; P_{r_j}=\frac{h^{SR}_j\left(N_0+P^{\max}_{c_i}h^i_{c_id_j}\right)}{h^i_{r_jd_j}\left(N_0+P^{\max}_{c_i}h^{CR}_{ij}\right)}P_{s_j}\\
&(c'_2)\;\; P_{s_j}\le\min\left(P^{\max}_{s_j},\frac{h^i_{c_ib}P^{\max}_{c_i}-0.5\gamma^{\min}_{c_i}N0}{0.5\gamma^{\min}_{c_i}h^i_{s_jb}}\right)\\
&(c'_3)\;\; P_{r_j}\le\min\left(P^{\max}_{r_j},\frac{h^i_{c_ib}P^{\max}_{c_i}-0.5\gamma^{\min}_{c_i}N0}{0.5\gamma^{\min}_{c_i}h^i_{r_jb}}\right)
\end{aligned} \tag{19}$$

$$\begin{aligned}
&(c'_1)\;\; P_{r_j}=\frac{h^i_{s_jr_j}P^{\max}_{s_j}\left(N_0+h^i_{c_id_j}P_{c_i}\right)}{h^i_{r_jd_j}\left(N_0+h^i_{c_ir_j}P_{c_i}\right)}\\
&(c'_2)\;\; \frac{0.5\gamma^{\min}_{c_i}\left(N_0+h^i_{s_jb}P^{\max}_{s_j}\right)}{h^i_{c_ib}}<P_{c_i}\le P^{\max}_{c_j}\\
&(c'_3)\;\; P_{r_j}\le\min\left(P^{\max}_{r_j},\frac{h^i_{c_ib}P^{\max}_{c_i}-0.5\gamma^{\min}_{c_i}N0}{0.5\gamma^{\min}_{c_i}h^i_{r_jb}}\right)
\end{aligned} \tag{20}$$

$$\begin{aligned}
&(c'_1)\;\; P_{s_j}=\frac{P^{\max}_{r_j}h^i_{r_jd_j}\left(N_0+h^{CR}_{ij}P_{c_i}\right)}{h^{SR}_j\left(N_0+h^i_{c_id_j}P_{c_i}\right)}\\
&(c'_2)\;\; \frac{0.5\gamma^{\min}_{c_i}\left(N_0+P^{\max}_{r_j}h^i_{r_jb}\right)}{h^i_{c_ib}}<P_{c_i}\le P^{\max}_{c_i}\\
&(c'_3)\;\; P_{s_j}\le\min\left(P^{\max}_{s_j},\frac{h^i_{c_ib}P_{c_i}-0.5\gamma^{\min}_{c_i}N_0}{0.5\gamma^{\min}_{c_i}h^i_{s_jb}}\right)
\end{aligned} \tag{21}$$

Similar to DT mode, the optimization problem can be solved with reduced complexity compared with Dinkelbach's algorithm.

For HT-I, inserting constraint (c'_1) in (18), the optimization problem becomes a NFP problem over P_{sj} which has the following form:

$$\left(\frac{ax^3+bx^2+cx+d}{a'x^2+b'x+c'}\right),\;\; x=P_{s_j} \tag{22}$$

The numerator of the derivative of the expression (22) is a quartic polynomial with four roots. However, it can be shown that at most two of them named $P_{sj,1}$ and $P_{sj,2}$ may be real and positive. For each root which lies in constraint (c'_2), the corresponding values for P_{rj} are calculated as $P_{rj,1}$ and $P_{rj,2}$, using equality constraint (c'_1). Assuming that these points are in the range of constraint (c'_3), there are at most four points to be checked to find the maximum value of (17) as $\hat{R}_{i,j}^{I}$.

For HT-II, letting $P_{sj} = P_{sj}^{\max}$, inserting constraint (c'_1) of (20) in (18), and computing the derivative of (18) with respect to P_{ci}, its numerator is a quintic polynomial. However, at most two of its roots are real and positive. Hence, at most four points should be checked for HT-II event to calculated the power control values and $\hat{R}_{i,j}^{II}$. With a similar procedure, it can be shown that at most four points should be checked for HT-III event to calculate $\hat{R}_{i,j}^{III}$. The feasible set of i'th RB in HT, contains D2D users which can use this RBs with decision variables $\hat{R}_{i,j} = \max(\hat{R}_{i,j}^{I}, \hat{R}_{i,j}^{II}, \hat{R}_{i,j}^{III}), \forall j\epsilon U$.

<u>Full-Duplex-Transmission (FT)</u>

The optimization problem in the FT mode can be written as the following:

$$\left(\bar{P}_{c_i}, \bar{P}_{s_j}, \bar{P}_{r_j}\right)_{\text{opt}} = \underset{P_{c_i}, P_{s_j}, P_{r_j}}{\operatorname{argmax}} \left(1 + \frac{P_{r_j} h^i_{r_j d_j}}{N_0 + P_{c_i} h^i_{c_i d_j}}\right)\left(1 + \frac{P_{c_i} h^i_{c_i b}}{N_0 + P_{s_j} h^i_{s_j b} + P_{r_j} h^i_{r_j b}}\right) \tag{23}$$

Taking similar procedure like HT mode, the constraints for each event (FT-I, FT-II, and FT-III) can be written as (24), (25), and (26), respectively.

$$\begin{aligned}
&(c'_1)\ \ P_{s_j} = \frac{\left(h^i_{r_j d_j} h_{rsi}\right)\left(P_{r_j}\right)^2 + \left(N_0 + P^{\max}_{c_i} h^i_{c_i r_j}\right)\left(h^i_{r_j d_j} P_{r_j}\right)}{h^i_{s_j r_j}\left(N_0 + P^{\max}_{c_i} h^i_{c_i d_j} h^{SR}_j\right)} \\
&(c'_2)\ P_{r_j} \le P^{\max}_{r_j} \\
&(c'_3)\ P_{s_j} \le \min\left(P^{\max}_{s_j}, \frac{P^{\max}_{c_i} h^i_{c_i b} - \gamma^{\min}_{c_i}\left(N_0 - h^i_{r_j b} P_{r_j}\right)}{\gamma^{\min}_{c_i} h^i_{s_j b}}\right)
\end{aligned} \tag{24}$$

$$\begin{aligned}
&(c'_1)\ \ P_{c_i} = \frac{\left(h^i_{r_j d_j} h_{rsi}\right)\left(P_{r_j}\right)^2 + \left(h^i_{r_j d_j} N_0 P_{r_j}\right) - \left(P^{\max}_{s_j} h^i_{s_j r_j} N_0\right)}{\left(h^i_{c_i d_j} P^{\max}_{s_j} h^{SR}_j\right) - \left(h^i_{r_j d_j} h^i_{c_i r_j} P_{r_j}\right)} \\
&(c'_2)\ P_{c_i} \le P^{\max}_{c_i} \\
&(c'_3)\ P_{r_j} \le \min\left(P^{\max}_{r_j}, \frac{\left(h^i_{c_i b} P_{c_i}\right) - \left(N_0 + P^{\max}_{s_j} h^i_{s_j b}\right)\gamma^{\min}_{c_i}}{\gamma^{\min}_{c_i} h^i_{r_j c_i}}\right)
\end{aligned} \tag{25}$$

$$\begin{aligned}
&(c'_1)\,P_{s_j} = \frac{\left(P^{\max}_{r_j} h^i_{r_j d_j} h^i_{c_i r_j}\right)\left(P_{c_i}\right) + \left(N_0 + P^{\max}_{r_j} h_{rsi}\right) P^{\max}_{r_j} h^i_{r_j d_j}}{\left(h^i_{s_j r_j} h^i_{c_i d_j}\right)\left(P_{c_i}\right) + \left(h^i_{s_j r_j} N_0\right)} \\
&(c'_2)\ 0 < P_{s_j} \le P^{\max}_{s_j} \\
&(c'_3)\ \ \frac{\gamma^{\min}_{c_i} h^i_{s_j b} P_{s_j} + \left(N_0 + P^{\max}_{r_j} h^i_{r_j b}\right)\gamma^{\min}_{c_i}}{h^i_{c_i b}} < P_{c_i} \le P^{\max}_{c_i}
\end{aligned} \tag{26}$$

The optimization problem can be solved similar to the proposed algorithms for DT and HT modes to identify $\bar{R}_{i,j} = \max(\bar{R}_{i,j}^{I}, \bar{R}_{i,j}^{II}, \bar{R}_{i,j}^{III})$. It can be shown that for each event, the objective function derivative has four roots, two of which can be real and positive. Consequently, at most four points must be checked to find the maximum value of the optimization problem (23).

Finally, j'th D2D pair can reuse the RB of i'th cellular channel if *j* is at least in one of feasible sets.

The maximum number of points which will be checked for each mode is as follows: 8 points for DT mode, 12 points for HT mode, and 12 points for FT mode. Consequently, the achievable sum-rate may be calculated for at most 32 points to allocate optimized powers for j'th D2D pair and i'th cellular user which has considerably lower complexity compared to existing algorithms like the one in [32].

Phase II: MSCA

In MSCA sub-problem, using the results of PC phase, the RBs are assigned to D2D users so that the aggregate rate is maximized:

$$\max_{\rho_{ij}} \sum_{i\in C}\left[\left(1-\sum_{j\in U}\rho_{ij}\right)R_{c_i,0}+\sum_{j\in U}\rho_{ij}R_{i,j}\right] \tag{27}$$

subject to:

$$\sum_{j\in U}\rho_{ij}\le 1 \qquad \sum_{i\in C}\rho_{ij}\le L \tag{28}$$

To write the above optimization problem, we only consider SINR of $S \to R$ link according to equality of $S \to R$ and $R \to D$ SINR values for HT and FT modes ($\Im ij = 1$).

To solve the above binary linear programming (BLP) problem, an iterative algorithm is proposed with the following features:

- Fair RB assignment among different D2D links is guaranteed;
- A D2D link utilizes the same transmission mode for all assigned RBs.

The algorithm has several rounds and each round consists of at most M iterations. In each iteration of different rounds, at most one RB is assigned to each D2D link which results in maximum sum-rate. The transmission mode of D2D links (mode selection) is concluded in the first round. The algorithm works as Table. 3.

4-2- Limited-CSI algorithm

Assuming full CSI at BS is impractical because of its huge feedback overhead. With limited-feedback capacity, the CSI of a limited number of channels can be acquired at BS.

In the second proposed algorithm, it is assumed that the channel gains between CUs and BS along with the location of all cellular and D2D nodes are known at BS. Hence, BS can estimate the channel gains of CU-BS channels and the variances of the channel gains between all other nodes. This information will be used to select transmission mode and to allocate RBs to D2D users, prior to power allocation.

Table 3. MSCA with full-CSI

First round: 1. *Let* $\Phi=\{1,2,...,M\}$ *and* $\rho=\{1,2,...,N\}$ *as the set of D2D links and available RBs, respectively;* 2. *The cellular-D2D pair with maximum non-zero sum-rate is selected from* $R_{i,j}=[\tilde{R}_{i,j},\hat{R}_{i,j},\bar{R}_{i,j}; i\in\rho, j\in\Phi]$ *;* 3. *The selected RB and D2D link are omitted from the available RBs set ρ and D2D set* Φ *, respectively;* 4. *Transmission mode of the selected D2D link is fixed for the rest of the algorithm, i.e, any other RB that may be assigned to this link in the next rounds would only communicate according to the selected mode;* 5. *Reconstruct* $R_{i,j}$ *by forcing the sum-rates of the selected D2D link and remaining RBs to zero, except for the selected transmission mode. This will preserve the transmission mode of the selected D2D link in the next iterations;* 6. *Continue from (2) until* $\Phi=\varnothing$ *, or the remaining D2D links cannot reshare any RB.* **Second round**: 1. *Reconstruct* $\Phi=\{1,2,...,M\}$ *as the set of D2D links;* 2. *The cellular-D2D pair with maximum non-zero sum-rate is selected from* $R_{i,j}$ *;* 3. *The selected RB and D2D link are omitted from the available RBs set* ρ *and D2D set* Φ *, respectively;* 4. *Continue from the beginning until* $\Phi=\varnothing$ *, or the remaining D2D links cannot reshare any RB.* **Next rounds (Third to at most *L*'th round):** *The algorithm continues until all D2D users reach their maximum transmission bandwidth, or the remaining RBs cannot be assign to any D2D link. This guarantees fair RB assignment among all D2D links.*

Assuming that i'th RB is allocated to the j'th D2D link, the BS collects the required CSI in order to control transmitted powers of i'th CU, and j'th D2D transmitter and relay, if HT or FT modes are selected. It is obvious that the required amount of CSI is less compared with full CSI.

The procedure is similar to the first algorithm except that MSCA phase is performed prior to PC phase. In MSCA phase, instead of achievable sum-rates, the product of estimated channel variances ratios is used to select transmission modes, and assign RBs to D2D links. In other words, instead of $R_{i,j} = [\tilde{R}_{i,j}, \hat{R}_{i,j}, \bar{R}_{i,j}]$, the decision metric $\Psi = [\Psi_{i,j}^{DT}, \Psi_{i,j}^{HT}, \Psi_{i,j}^{FT}; i \in \rho, j \in \Phi]$ is used, in which:

$$\Psi_{ij}^{DT}=\left(\frac{h_{c_i b}^{i}}{\hat{h}_{s_j b}^{i}}\right)\left(\frac{\hat{h}_{s_j d_j}^{i}}{\hat{h}_{c_i d_j}^{i}}\right) \tag{29-a}$$

$$\Psi_{ij}^{HT} = \left(\frac{h_{c_i b}^{i}}{\sqrt{\hat{h}_{s_j r_j}^{i} \hat{h}_{r_j d_j}^{i}}} \right) \left(\min \left[\sqrt{\frac{\hat{h}_{s_j r_j}^{i}}{\hat{h}_{c_i r_j}^{i}}}, \sqrt{\frac{\hat{h}_{r_j d_j}^{i}}{\hat{h}_{c_i d_j}^{i}}} \right] \right) \tag{29-b}$$

$$\Psi_{ij}^{FT} = \left(\frac{h_{c_i b}^{i}}{\hat{h}_{s_j b}^{i} + \hat{h}_{r_j b}^{i}} \right) \left(\min \left[\frac{\hat{h}_{s_j r_j}^{i}}{\hat{h}_{c_i r_j}^{i}}, \frac{\hat{h}_{r_j d_j}^{i}}{\hat{h}_{c_i d_j}^{i}} \right] \right) \tag{29-c}$$

where

$$\hat{h}_{xy}^{i} = \begin{cases} \left(d_{xy}\right)^{\alpha_{los}}, & if d_{xy} \le R_B \\ \left(d_{xy}\right)^{\alpha_{nlos}}, & if d_{xy} > R_B \end{cases} \tag{30}$$

and R_B is the radius of the LOS ball model in which the LOS probability function is modeled by a simple step function [37].

Once the channel assignment and mode selection are performed, the BS allocates the power control values according to acquired CSI, in order to maximize sum-rate of CU-D2D pairs with common RBs.

5- Simulation Results and Discussion

To evaluate the performance of the proposed algorithms, we simulate a mmWave single-cell scenario at frequency band of 28 *GHz* which is one of the promising spectrum bands to be utilized in 5G [16]. Each cellular RB has bandwidth of 200 *MHz*. The BS location is at the center of the cell with radius r_{cell} = 500 *m*. All cellular users are uniformly distributed in the cell. D2D transmitters and receivers are also distributed in the cell considering that TX-RX distance is between $r_d^{\min}$ and $r_d^{\max}$. Finally, each relay is randomly dropped in a circle with radius r_{Relay} = 10 *m* whose center is equal to half-distance of TX-RX. Other simulation parameters, if fixed, are tabulated in Table 4.

Table 4. Simulation parameters (when fixed)

Parameter	Value
CU Max transmit power	$P_{c_i}^{\max} = 40\ [dBm]$
D2D Max transmit power	$P_{s/r}^{j,\max} = 15\ [dBm]$
Min SINR of CU	$\gamma_{c_i}^{\min} = 10\ [dB]$
RSI	$h_{rsi} = -100\ [dB]$
LOS path-loss	$\sigma = 3.6\ [dB],\ \alpha = 2.1$
NLOS path-loss	$\sigma = 9.7\ [dB],\ \alpha = 3.4$
Noise spectral density	$N_0 = -174\ [dBm/Hz]$
Average LOS range	$1/\beta = 141.4$
Antenna HPBW	$\theta_{t/r}^{hpbw} = 10.9\ [^o]$
Antenna main-lobe gain	$G_{t/r,ml} = 24.5\ [dB]$
Antenna side-lobe gain	$G_{t/r,sl} = -5\ [dB]$

5-1- Performance evaluation under full CSI

In Figure 2, the aggregate data rate in terms of maximum allowable transmit power of D2D transmitters and relays, is compared for three cases of direct transmission, half-duplex relaying, and full-duplex relaying, under full CSI assumption. The number of RBs is assumed to be 25, while 10 D2D links compete to reshare the RBs and D2D link may reuse at most three RBs ($L=3$). As expected, FD relaying notably outperforms other methods, in terms of aggregate rate. As a case in point, when the maximum D2D power is 18 *dBm*, FD relying results in 750 *bps* rate, while the rate for HD relaying and direct transmission is about 530 *bps*. Moreover, when the maximum allowable power of D2D users is small, utilizing HD relaying has better performance than direct transmission. On the other hand, for larger values of D2D powers -more than 18 *dBm* in this simulation set-, direct transmission of D2D relays is preferred, due to the sufficiency of power for direct transmission.

The effect of mode selection on the achievable aggregate rate is investigated in Figure 3, for the same parameters used in the previous simulation. Surprisingly, utilizing FD relaying without mode selection results in higher aggregate rate. This is because of the fact that the transmission mode of a D2D link is selected according to the maximum D2D-cellular rate and would be fixed when resharing other cellular RBs. Hence, if at the first round of MSCA phase, the selected mode for a typical D2D link is DT or HT, no FD relaying can be utilized for other RBs used by this D2D link. However, the gap between two curves is ignorable. It is expected that for higher values of RSI for FD relays, the mode selection improves the performance slightly.

The maximum achievable aggregate rates in terms of RSI of FD relays are depicted in Figure 4. As expected, FD relaying improves the achievable rate. The major limiting factor in employing FD relay is the RSI: the aggregate rate decreases with the increase in RSI. However, due to advanced analogue and digital SI cancellation techniques, having RSI even less than -100 *dB* is possible and it has lost its previous importance. Moreover, when the RSI becomes larger (more than -80 *dBm* for this simulation set), mode selection can improve the performance but still most D2D links communicate through FD relaying.

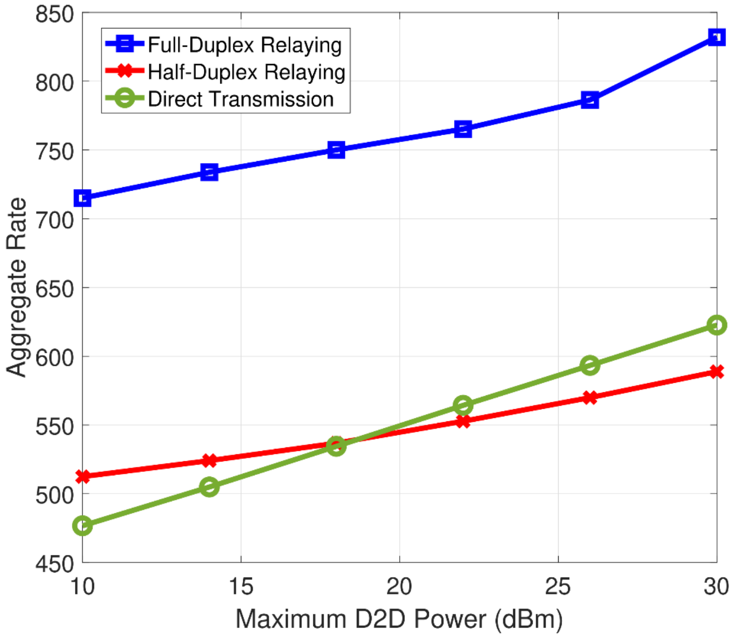

Figure 2. Achievable aggregate rate without mode selection versus maximum allowable power $P_{\max}^{S/R}$ under full CSI assumption for D2D users for $N = 25$ and $M = 10$.

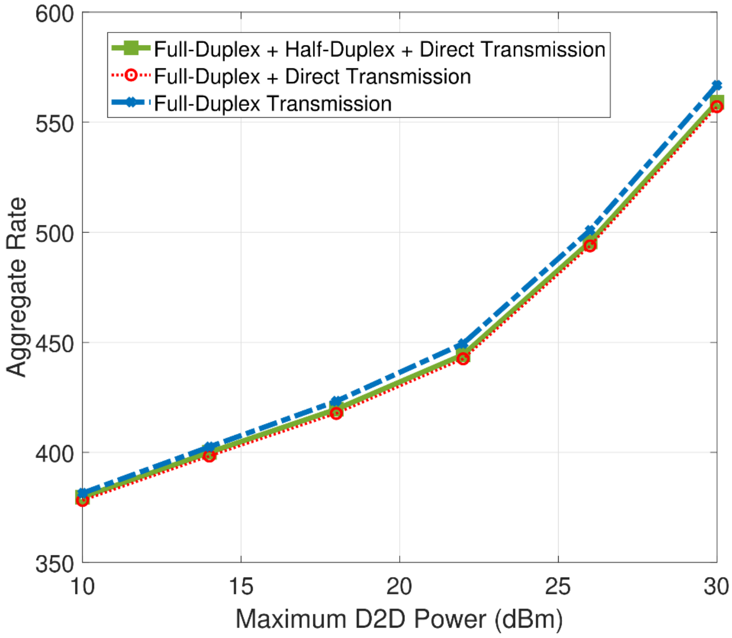

Figure 3. Achievable aggregate rate with mode selection versus maximum allowable power $P_{\max}^{S/R}$ under full CSI assumption for D2D users for $N = 25$ and $M = 10$.

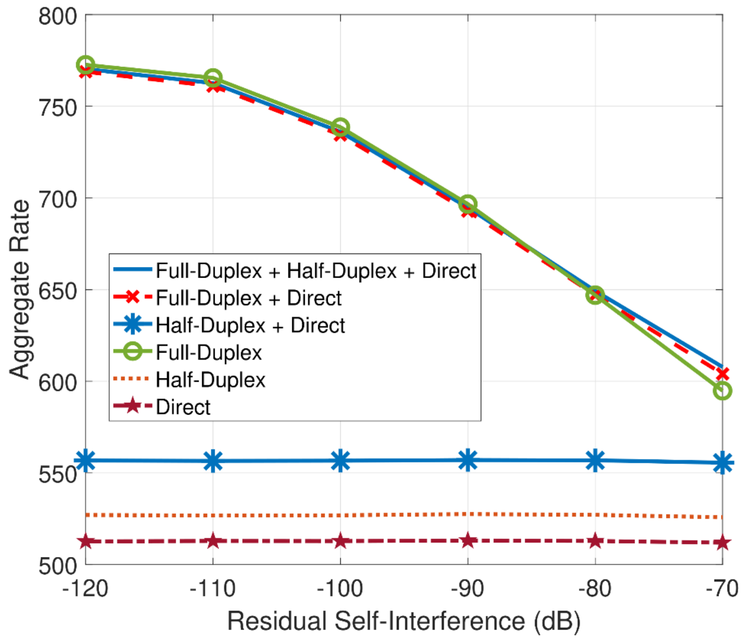

Figure 4. Residual self-inteference of FD relays effect on the achievable aggregate rate for $N = 25$ and $M = 10$, when full CSI is available at BS.

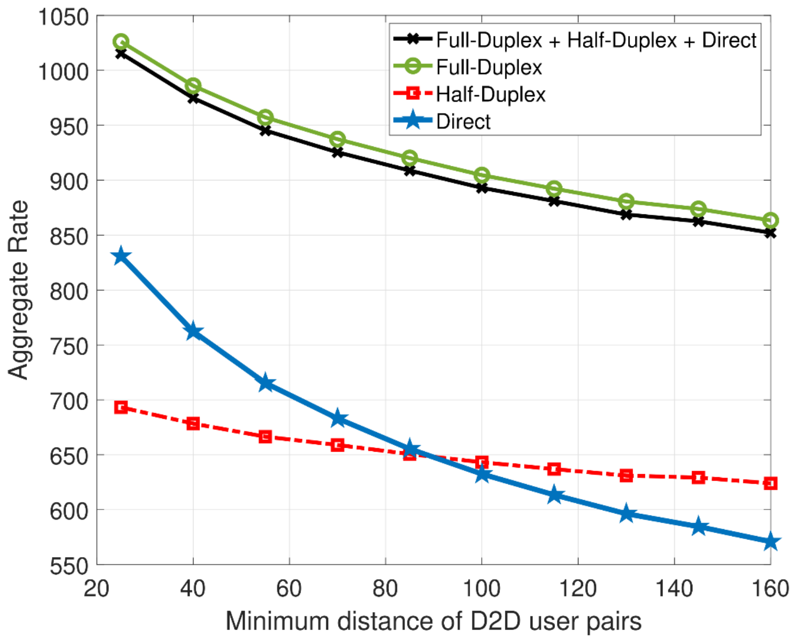

Figure 5. The effect of average distance of D2D pairs on aggregate rate of the network for $N = 30$ and $M = 10$ ($\boldsymbol{r_{D,max}}$ is selected two times larger than $\boldsymbol{r_{D,min}}$).

The sequel of decreasing the average distance of D2D user-pairs on the performance of the proposed algorithm is presented in Figure 5. In this simulation set, $r_{D,max}$ is assumed to be two times larger than $r_{D,min}$ and $r_{D,min}$ is changed between 25 *m* to 160 *m*. As it can be seen, when the average distance between D2D users is small (less than 90 *m* in this simulation set), direct transmission is more likely to happen. However, increasing the average distance causes more relay-assisted transmission, while FD relying is preferred compared with HD relaying because of its higher transmission rate.

5-2- Performance evaluation under limited CSI

As full CSI assumption is impractical, we proposed a second algorithm to work with mutual distances of users along with CSI of selected users. In Figure 6, limited CSI algorithm performance is compared with full CSI algorithm, when FD relaying is utilized. The comparison is performed for different values of average D2D pairs distances and different values of RSI. As expected, the achievable aggregate-rate decrease compared with the full CSI case, due to sub-optimal channel assignment. Despite the decrease in aggregate-rate, the required bandwidth to acquire the CSI decreases considerably. Consequently, selection of the appropriate algorithm is a performance-complexity trade-off.

Finally, In Figure 7, for $M = 10$ D2D links and constant value of $L=3$, the effect of increasing the number of RBs from 20 to 80 on D2D sum-rate is evaluated. It is seen that for full CSI, increasing the number of RBs from 30 to 40 results in rate improvement. However, when there exists much more RBs than required for D2D users, no further improvement is achieved. On the other hand, by increasing the number of RBs, the limited CSI algorithm's performance reaches the full CSI algorithm (aggregate rate for full-CSI and limited-CSI are the same when the number of RBs is 60 or more). Moreover, as it has been concluded from previous simulation results, FD relaying is the dominant transmission mode in all cases.

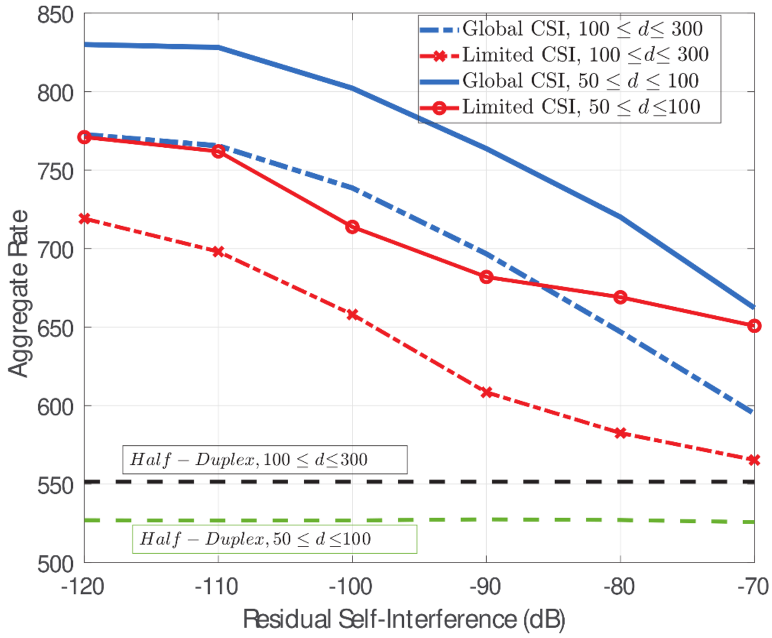

Figure 6. Comparison of the full CSI and limited CSI algorithms.

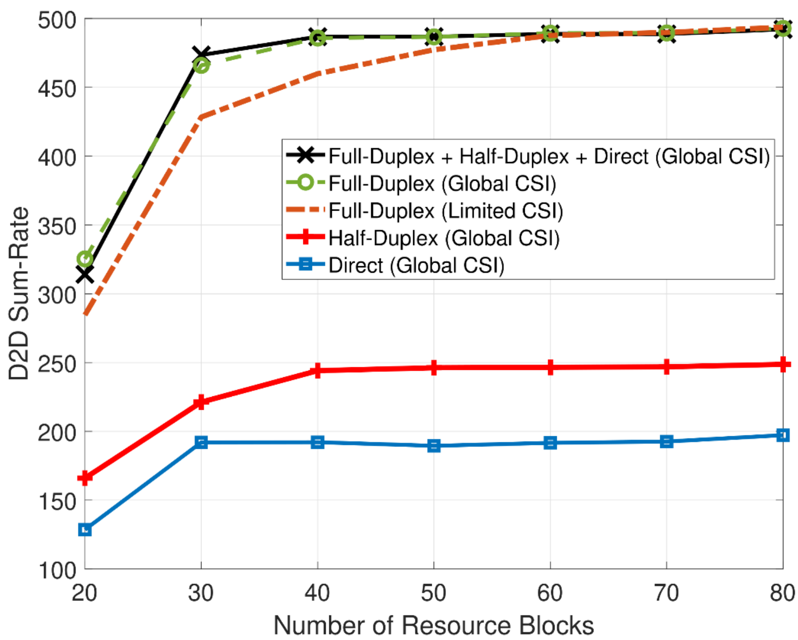

Figure 7.The effect of increasing the number of resource blocks N on D2D sum-rate for M D2D links.

6- Conclusion

The paper presents a D2D network framework underlaid the uplink of a cellular system operating in mmWave spectrum band. Relays operating in HD or FD modes can assist D2D users in the case of blockage. Our aim is to maximize the aggregate rate of cellular and D2D systems subject to different QoS requirements and power budgets of users, when D2D links allow to use different RBs simultaneously but each RB may be reused by only one D2D link. The main features of mmWave communication including larger available bandwidth, antenna beamforming, and NLOS propagation mechanism are took into account and two heuristic algorithms are proposed for power control, mode selection, and channel assignment for full and limited CSI cases. The limited CSI algorithm is more practical since only the location of users and CSI of a limited number of channels is required. The decrease in required feedback bandwidth for CSI is reached at the expense of performance loss in terms of data rate. We observe that the complexity of power control phase is reasonably low and a limited number of points shall be checked to find the optimum power values in each mode. Furthermore, the greedy algorithms proposed for MSCA phases are easy to trace and implement. Simulation results admit that utilizing FD relays in mmWave band is critical which is mainly because of the existence of NLOS paths in mmWave communication. The limiting factor in utilizing FD relaying is the residual self-interference which may be reduced significantly using existing algorithms.

References

[1] A.Asadi, Q. Wang, and V. Mancuso, "A survey on device-to-device communication in cellular networks," *IEEE Communications Surveys & Tutorials*, vol. 16, no. 4, pp. 1801–1819, 2014, doi: 10.1109/COMST.2014.2319555.

[2] J. Liu, N. Kato, J. Ma, and N. Kadowaki, "Device-to-device communication in lte-advanced networks: A survey," *IEEE Communications Surveys & Tutorials*, vol. 17, no. 4, pp. 1923–1940, 2014, doi: 10.1109/COMST.2014.2375934.

[3] P. Mach, Z. Becvar, and T. Vanek, "In-band device-to-device communication in ofdma cellular networks: A survey and challenges," *IEEE Communications Surveys & Tutorials*, vol. 17, no. 4, pp. 1885–1922, 2015, doi: 10.1109/COMST.2015.2447036.

[4] H. A. U. Mustafa, M. A. Imran, M. Z. Shakir, A. Imran, and R. Tafazolli, "Separation framework: An enabler for cooperative and d2d communication for future 5g networks," *IEEE Communications Surveys & Tutorials*, vol. 18, no. 1, pp. 419–445, 2015, doi: 10.1109/COMST.2015.2459596.

[5] H. ElSawy, E. Hossain, and M.-S. Alouini, "Analytical modeling of mode selection and power control for underlay d2d communication in cellular networks," *IEEE Transactions on Communications*, vol. 62, no. 11, pp. 4147–4161, 2014, doi: 10.1109/TCOMM.2014.2363849.

[6] N. Lee, X. Lin, J. G. Andrews, and R. W. Heath, "Power control ford2d underlaid cellular networks: Modeling, algorithms, and analysis," *IEEE Journal on Selected Areas in Communications*, vol. 33, no. 1, pp. 1–13, 2014, doi: 10.1109/JSAC.2014.2369612.

[7] P. Sun, K. G. Shin, H. Zhang, and L. He, "Transmit power control for d2d-underlaid cellular networks based on statistical features," *IEEE Transactions on Vehicular Technology*, vol. 66, no. 5, pp. 4110–4119, 2016, doiI: 10.1109/TVT.2016.2620523.

[8] Y. J. Chun, S. L. Cotton, H. S. Dhillon, A. Ghrayeb, and M. O. Hasna, "A stochastic geometric analysis of device-to-device communications operating over generalized fading channels," *IEEE Transactions on Wireless Communications*, vol. 16, no. 7, pp. 4151–4165, 2017, doi: 10.1109/TWC.2017.2689759.

[9] X. Li, R. Shankaran, M. A. Orgun, G. Fang, and Y. Xu, "Resource allocation for underlay d2d communication with proportional fairness," *IEEE Transactions on Vehicular Technology*, vol. 67, no. 7, pp. 6244– 6258, 2018, doi: 10.1109/TVT.2018.2817613.

[10] A. Abdallah, M. M. Mansour, and A. Chehab, "Power control and channel allocation for d2d underlaid cellular networks," *IEEE Transactions on Communications*, vol. 66, no. 7, pp. 3217–3234, 2018, doi: 10.1109/TCOMM.2018.2812731.

[11] R. I. Ansari, C. Chrysostomou, S. A. Hassan, M. Guizani, S. Mumtaz, J. Rodriguez, and J. J. Rodrigues, "5g d2d networks: Techniques, challenges, and future prospects," *IEEE Systems Journal*, vol. 12, no. 4, pp. 3970–3984, 2017, doi: 10.1109/JSYST.2017.2773633.

[12] A. Al-Hourani, S. Kandeepan, and E. Hossain, "Relay-assisted deviceto-device communication: A stochastic analysis of energy saving," *IEEE Transactions on Mobile Computing*, vol. 15, no. 12, pp. 3129–3141, 2016, doi: 10.1109/TMC.2016.2519343.

[13] G. Liu, F. R. Yu, H. Ji, V. C. Leung, and X. Li, "In-band full-duplex relaying: A survey, research issues and challenges," *IEEE Communications Surveys & Tutorials*, vol. 17, no. 2, pp. 500–524, 2015, doi: 10.1109/COMST.2015.2394324.

[14] G. Zhang, K. Yang, P. Liu, and J. Wei, "Power allocation for fullduplex relaying-based d2d communication underlaying cellular networks," *IEEE Transactions on Vehicular Technology*, vol. 64, no. 10, pp. 4911–4916, 2014, doi: 10.1109/TVT.2014.2373053.

[15] A. Memarinejad, M. Mohammadi, and M. B. Tavakoli, "Outage Performance Analysis of Multi-Antenna FullDuplex NOMA Cellular Systems," *Journal of Southern Communication Engineering*, vol. 12, no. 45, pp. 2–18, 2022 (in Persian).

[16] T. S. Rappaport, G. R. MacCartney, M. K. Samimi, and S. Sun, "Wideband millimeter-wave propagation measurements and channel models for future wireless communication system design," *IEEE transactions on Communications*, vol. 63, no. 9, pp. 3029–3056, 2015, doi: 10.1109/TCOMM.2015.2434384.

[17] W. Roh, J.-Y. Seol, J. Park, B. Lee, J. Lee, Y. Kim, J. Cho, K. Cheun, and F. Aryanfar, "Millimeter-wave beamforming as an enabling technology for 5g cellular communications: Theoretical feasibility and prototype results," *IEEE communications magazine*, vol. 52, no. 2, pp. 106–113, 2014, doi: 10.1109/MCOM.2014.6736750.

[18] A. N. Uwaechia and N. M. Mahyuddin, "A comprehensive survey on millimeter wave communications for fifth-generation wireless networks: Feasibility and challenges," *IEEE Access*, vol. 8, pp. 62 367–62 414, 2020, doi: 10.1109/ACCESS.2020.2984204.

[19] O. El Ayach, S. Rajagopal, S. Abu-Surra, Z. Pi, and R. W. Heath, "Spatially sparse precoding in millimeter wave mimo systems," *IEEE Transactions on wireless communications*, vol. 13, no. 3, pp. 1499–1513, 2014, doi: 10.1109/TWC.2014.011714.130846.

[20] W. Roh, J.-Y. Seol, J. Park, B. Lee, J. Lee, Y. Kim, J. Cho, K. Cheun, and F. Aryanfar, "Millimeter-wave beamforming as an enabling technology for 5g cellular communications: Theoretical feasibility and prototype results," *IEEE communications magazine*, vol. 52, no. 2, pp. 106–113,2014, doi: 10.1109/MCOM.2014.6736750.

[21] Y. Niu, C. Gao, Y. Li, L. Su, D. Jin, and A. V. Vasilakos, "Exploiting device-to-device communications in joint scheduling of access and backhaul for mmwave small cells," *IEEE Journal on Selected Areas in Communications*, vol. 33, no. 10, pp. 2052–2069, 2015, doi: 10.1109/JSAC.2015.2435273.

[22] J. Qiao, X. S. Shen, J. W. Mark, Q. Shen, Y. He, and L. Lei, "Enabling device-to-device communications in millimeter-wave 5g cellular networks," *IEEE Communications Magazine*, vol. 53, no. 1, pp. 209– 215, 2015, doi: 10.1109/MCOM.2015.7010536.

[23] S. Ali and A. Ahmad, "Resource allocation, interference management, and mode selection in device-to-device communication: a survey," *Transactions on Emerging Telecommunications Technologies*, vol. 28, no. 7, p. e3148, 2017, doi: 10.1002/ett.3148.

[24] F. A. Orakzai, M. Iqbal, M. Naeem, and A. Ahmad, "Energy efficient joint radio resource management in d2d assisted cellular communication," *Telecommunication Systems*, vol. 69, no. 4, pp. 505–517, 2018, doi:10.1007/s11235-018-0451-3.

[25] Z. Guizani and N. Hamdi, "mmwave e-band d2d communications for 5g-underlay networks: Effect of

power allocation on d2d and cellular users throughputs," *in IEEE Symposium on Computers and Communication (ISCC)*, 2016, pp. 114–118, doi: 10.1109/ISCC.2016.7543724.

[26] K. Vanganuru, S. Ferrante, and G. Sternberg, "System capacity and coverage of a cellular network with d2d mobile relays," i*n MILCOM IEEE Military Communications Conference*, 2012, pp. 1–6, doi: 10.1109/MILCOM.2012.6415659.

[27] X. Lin and J. G. Andrews, "Connectivity of millimeter wave networks with multi-hop relaying," *IEEE Wireless Communications Letters*, vol. 4, no. 2, pp. 209–212, 2015, doi: 10.1109/LWC.2015.2397884.

[28] N. Wei, X. Lin, and Z. Zhang, "Optimal relay probing in millimeterwave cellular systems with device-to-device relaying," *IEEE Transactions on Vehicular Technology*, vol. 65, no. 12, pp. 10 218–10 222, 2016, doi: 10.1109/TVT.2016.2552239.

[29] S. Wu, R. Atat, N. Mastronarde, and L. Liu, "Coverage analysis of d2d relay-assisted millimeter-wave cellular networks," in *IEEE wireless communications and networking conference (WCNC)*, 2017, pp. 1–6, doi: 10.1109/WCNC.2017.7925803.

[30] B. Ma, H. Shah-Mansouri, and V. W. Wong, "Full-duplex relaying for d2d communication in millimeter wave-based 5g networks," *IEEE Transactions on Wireless Communications*, vol. 17, no. 7, pp. 4417–4431, 2018, doi: 10.1109/TWC.2018.2825318.

[31] A. Abdelreheem, A. S. Mubarak, O. A. Omer, H. Esmaiel, and U. S. Mohamed, "Improved d2d millimeter wave communications for 5g networks using deep learning," in *IEEE 2nd International Conference on Computer and Information Sciences (ICCIS)*, 2020, pp. 1–5, doi: 10.1109/ICCIS49240.2020.9257634.

[32] T. D. Hoang, L. B. Le, and T. Le-Ngoc, "Joint mode selection and resource allocation for relay-based d2d communications," *IEEE Communications Letters*, vol. 21, no. 2, pp. 398–401, 2016, doi: 10.1109/LCOMM.2016.2617863.

[33] M. Liu, L. Zhang, and P. R. Gautam, "Joint relay selection and resource allocation for relay-assisted d2d underlay communications," in *IEEE 22nd International Symposium on Wireless Personal Multimedia Communications (WPMC)*, 2019, pp. 1–6, doi: 10.1109/WPMC48795.2019.9096172.

[34] D. Feng, L. Lu, Y. Yuan-Wu, G. Y. Li, G. Feng, and S. Li, "Device-todevice communications underlaying cellular networks," *IEEE Transactions on communications*, vol. 61, no. 8, pp. 3541–3551, 2013, 10.1109/TCOMM.2013.071013.120787.

[35] C. Motz, T. Paireder, H. Pretl, and M. Huemer, "A survey on selfinterference cancellation in mobile lte-a/5g fdd transceivers," *IEEE Transactions on Circuits and Systems II: Express Briefs*, vol. 68, no. 3, pp. 823–829, 2021, doi: 10.1109/TCSII.2021.3051101.

[36] C. D. Nwankwo, L. Zhang, A. Quddus, M. A. Imran, and R. Tafazolli, "A survey of self-interference management techniques for single frequency full duplex systems," *IEEE Access*, vol. 6, pp. 30 242–30 268, 2017, doi: 10.1109/ACCESS.2017.2774143.

[37] T. Bai and R. W. Heath, "Coverage and rate analysis for millimeter-wave cellular networks," *IEEE Transactions on Wireless Communications*, vol. 14, no. 2, pp. 1100–1114, 2014, doi: 10.1109/TWC.2014.2364267.

[38] T. Bai, R. Vaze, and R. W. Heath, "Analysis of blockage effects on urban cellular networks," *IEEE* Transactions on Wireless Communications, vol. 13, no. 9, pp. 5070–5083, 2014, doi: 10.1109/TWC.2014.2331971.

[39] G. R. MacCartney, J. Zhang, S. Nie, and T. S. Rappaport, "Path loss models for 5g millimeter wave propagation channels in urban microcells," in *IEEE global communications conference (GLOBECOM).*, 2013, pp. 3948–3953, doi: 10.1109/GLOCOM.2013.6831690.

[40] T. Riihonen, S. Werner, and R. Wichman, "Mitigation of loopback selfinterference in full-duplex mimo relays," *IEEE transactions on signal processing*, vol. 59, no. 12, pp. 5983–5993, 2011, doi:

0.1109/TSP.2011.2164910.

[41] W. Dinkelbach, “On nonlinear fractional programming,” *Management science*, vol. 13, no. 7, pp. 492–498, 1967.

[42] K. Shen and W. Yu, “Fractional programming for communication systems—part i: Power control and beamforming,” *IEEE Transactions on Signal Processing*, vol. 66, no. 10, pp. 2616–2630, 2018, doi: 10.1109/TSP.2018.2812733.