Interference Mitigation Scheme for Device-to-Device MIMO Communications Underlaying a Cellular Network

Yujin Nam[1], Jaewoo So[1] and Jinsung Kim[2]
[1] Department of Electronic Engineering, Sogang University
Seoul 04107, Republic of Korea
[e-mail: {hydralisk, jwso}@sogang.ac.kr]
[2] Research and Development Laboratory, Encored Technologies
Seoul 06109, Republic of Korea
[e-mail: kjs@encoredtech.com]
*Corresponding author: Jaewoo So

Received September 5, 2016; revised November 15, 2016; accepted December 17, 2016; published April 30, 2017

Abstract

This paper proposes a new interference mitigation scheme for device-to-device (D2D) communications underlaying a cellular network. The object of the proposed scheme is to determine the number of data streams, a precoding matrix, and a decoding matrix of D2D networks so as to maximize the system capacity given the number of data streams of a cellular network while satisfying the constraint of the inter-system interference from D2D networks to the cellular network. Unlike existing interference mitigation schemes based on the interference alignment technique, the proposed scheme operates properly regardless of the number of data streams of a cellular network and moreover it does not require changing the precoding and decoding matrices of a cellular network. The simulation results demonstrate that the proposed scheme significantly increases the system capacity by mitigating the intra- and inter- system interference.

Keywords: Device-to-device communications, heterogeneous network, interference mitigation, interference alignment, MIMO

https://doi.org/10.3837/tiis.2017.04.002 **ISSN : 1976-7277**

1. Introduction

Device-to-device (D2D) communications have drawn considerable attention due to the advantage of providing higher data rates for local services. Moreover, D2D communications have been included as a key feature, referred to as proximity service (ProSe), in 3GPP Release 12 [1]. When the spectrum resources are shared in D2D networks underlaying a cellular network, D2D communications cause *inter-system interference* to a cellular network, and vice versa. The D2D communications also cause *intra-system interference* among D2D pairs. The intra- and inter- system interference severely deteriorates the capacity of the cellular network and the D2D networks. Reducing the intra- and inter- system interference is thus crucial [2], [3].

Many researchers have endeavored to increase the capacity of cellular networks and D2D networks in D2D communications underlaying a cellular network. The authors of [4-8] adjusted the precoding and/or decoding matrices of a cellular network as well as the D2D networks in order to mitigate the inter-system interference between the cellular network and the D2D networks. However, they considered only inter-system interference without taking the channel environment between a base station (BS) and a cellular user (CU) in the cellular network into consideration, resulting in performance degradation of the cellular network.

The authors of [9] and [10] determined the precoding matrices of the D2D networks without changing the precoding and decoding matrices of the cellular network in order to maximize the capacity or minimize the mean square error (MSE) of the D2D networks. However, they failed to find the decoding matrices of the D2D networks. The authors of [11] and [12] adjusted the precoding and decoding matrices of the D2D networks in order to mitigate the inter-system interference from the D2D networks to the cellular network. However, the authors of [11] did not consider the intra-system interference in the D2D networks, and the authors of [12] did not consider the inter-system interference from the cellular network to the D2D networks. The authors of [13-15] changed the precoding and decoding matrices of the D2D networks in order to minimize the intra-system interference in the D2D networks while satisfying the constraint of the inter-system interference from the D2D networks to the cellular network. However, the proposed schemes of [13-15] failed to increase the capacity of the D2D networks under high intra-system interference environments in the D2D networks.

Some researchers have used an interference alignment (IA) technique in order to reduce the intra- and inter- system interference [16-19]. The IA technique is a recent development to eliminate the effective interference in multiple interference channels by aligning multiple interference signals in a signal subspace with dimensions smaller than the number of interferers. The authors of [16] adjusted the precoding and decoding matrices in order to reduce the inter-system interference from the D2D networks to the cellular network while eliminating the intra-system interference in the cellular network by using the IA technique. However, the authors of [16] failed to reduce the intra-system interference in the D2D networks. The authors of [17] adjusted the inter-system interference to the cellular network by controlling the transmission powers of the D2D transmitters (DTs) while eliminating the intra-system interference in the D2D networks. However, the power control-based interference mitigation scheme of [17] degrades the performance of the D2D networks because of the decrease of the transmission power of the DTs. The authors of [18] and [19] adopted IA techniques to eliminate the intra- and inter- system interference for D2D multiple-input multiple-output (MIMO) communications underlaying a cellular network.

However, because the IA technique in the symmetric D2D networks underlaying a cellular network is feasible only if $d_0 \leq M - (K+1)d/2$, where d_0 is the number of data streams in a cellular network, M is the number of antennas of each D2D device, K is the number of D2D pairs, and d is the number of data streams of each D2D pair [18], where the IA technique could be not applied to the case where a cellular network has an arbitrary number of data streams.

This paper proposes an interference mitigation scheme that increases the capacity of D2D networks while satisfying an interference constraint to a cellular network by adjusting the precoding matrices of the DTs and the decoding matrices of the D2D receivers (DRs). In addition, this paper mitigates the inter-system interference from the DTs to the CU and vice versa by adjusting the number of data streams of the D2D pairs. The contribution of this paper is twofold: First, the proposed scheme is valid regardless of the number of data streams of a cellular network; i.e., the proposed scheme can be applied to a heterogeneous network that does not satisfy the IA feasibility condition of [18]. Second, the proposed scheme significantly increases the system capacity by mitigating the intra- and inter- system interference.

The following notations are used throughout the paper. We use lower-case bold symbols for vectors and upper-case bold fonts to denote matrices. For any general matrix $\mathbf{X}$, $tr(\mathbf{X})$, $\mathbf{X}^{-1}$, $\mathbf{X}^H$, and $\|\mathbf{X}\|_F$ denote the trace, inverse, Hermitian transpose, and Frobenius norm of the matrix $\mathbf{X}$.

The remainder of this paper is organized as follows: Section II gives a description of the system model. Section III proposes the interference mitigation scheme on the basis of the IA technique by adjusting the precoding matrices, the decoding matrices, and the number of data streams for the D2D pairs. Section IV shows the simulation results and finally Section V concludes this paper.

2. System Model

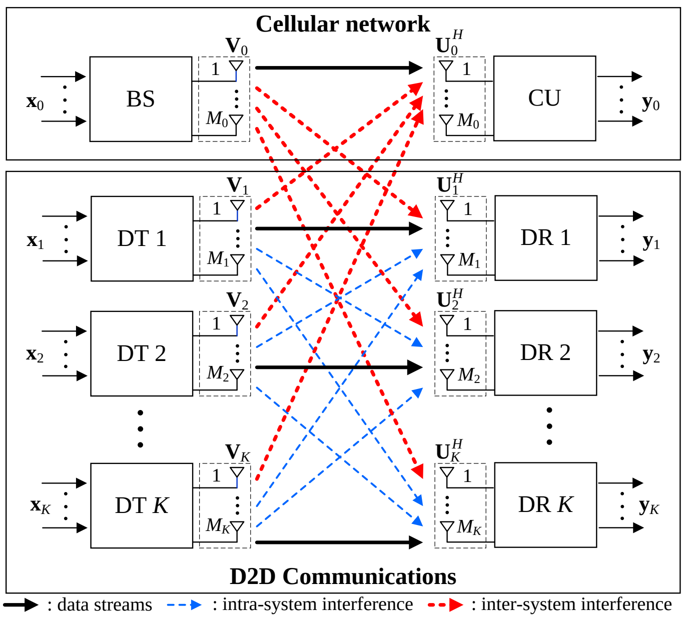

Fig. 1. System model

The D2D MIMO networks underlaying a cellular network are considered, where there is one cellular downlink (i.e., one BS and one CU) and $K \geq 3$ D2D pairs, as shown in **Fig. 1**. The i^{th} transmitter is targeting the i^{th} receiver only. We denote the cellular link by the index 0 while the k^{th} D2D pair is denoted by the index k, where $k \in \{1, 2, \cdots, K\}$. The BS and the CU are all equipped with M_0 antennas. The DT and the DR of the k^{th} D2D pair are all equipped with M_k antennas. The D2D pairs share the same downlink spectrum resource with the cellular network.

In the cellular network, a CU is assumed to obtain d_0 independent data streams from the BS. In the k^{th} D2D pair, the DR obtains d_k independent data streams from its corresponding DT. Let some symbols be defined as shown in **Table 1**.

Table 1. Symbols

Symbol	Description
d_0	A number of independent data streams from the BS to the CU in the cellular network.
d_k	A number of independent data streams in the k^{th} D2D pair of the D2D networks.
M_0	A number of antennas at the BS and the CU.
M_k	A number of antennas at the DT and the DR of the k^{th} D2D pair, where $k \in \{1, 2, \cdots, K\}$.
$\mathbf{V}_k$	A precoding matrix of link k, where $k \in \{0, 1, 2, \cdots, K\}$ and $\mathbf{V}_k \in \mathbb{C}^{M_k \times d_k}$.
$\mathbf{U}_k^H$	A decoding matrix of link k, where $k \in \{0, 1, 2, \cdots, K\}$ and $\mathbf{U}_k^H \in \mathbb{C}^{d_k \times M_k}$.
$p_{0,0}$	The received power at the CU from the BS.
$p_{0,k}$	The received power at the CU from the k^{th} DT, where $k \in \{1, 2, \cdots, K\}$.
$p_{k,k}$	The received power at the k^{th} DR from the k^{th} DT, where $k \in \{1, 2, \cdots, K\}$.
$\mathbf{H}_{0,0}$	The channel matrix containing the channel coefficients between the CU and the BS, where $\mathbf{H}_{0,0} \in \mathbb{C}^{M_0 \times M_0}$.
$\mathbf{H}_{0,k}$	The channel matrix containing the channel coefficients between the CU and the k^{th} DT, where $\mathbf{H}_{0,k} \in \mathbb{C}^{M_0 \times M_k}$ and $k \in \{1, 2, \cdots, K\}$.
$\mathbf{H}_{k,0}$	The channel matrix containing the channel coefficients between the k^{th} DR and the BS, where $\mathbf{H}_{k,0} \in \mathbb{C}^{M_k \times M_0}$ and $k \in \{1, 2, \cdots, K\}$.
$\mathbf{H}_{k,k}$	The channel matrix containing the channel coefficients between the k^{th} DR and the k^{th} DT, where $\mathbf{H}_{k,k} \in \mathbb{C}^{M_k \times M_k}$ and $k \in \{1, 2, \cdots, K\}$.
$\mathbf{G}_{0,k}$	An effective inter-system channel matrix containing the channel coefficients at the CU from the k^{th} DT, where $\mathbf{G}_{0,k} \equiv \sqrt{p_{0,k}} \mathbf{U}_0^H \mathbf{H}_{0,k}$ and $k \in \{1, 2, \cdots, K\}$.
$\mathbf{G}_{k,0}$	An effective inter-system channel matrix containing the channel coefficients at the k^{th} DR from the BS, where $\mathbf{G}_{k,0} \equiv \sqrt{p_{k,0}} \mathbf{H}_{k,0} \mathbf{V}_0$ and $k \in \{1, 2, \cdots, K\}$.

Let $\mathbf{x}_0 \in \mathbb{C}^{d_0 \times 1}$ denotes the transmitted symbol from the BS and let $\mathbf{x}_k \in \mathbb{C}^{d_k \times 1}$ denotes the transmitted symbol from the k^{th} DT. The d_0-dimensional received signal at the CU and the d_k-dimensional received signal at the k^{th} DR can then be expressed as follows:

$$\mathbf{y}_0 = \underbrace{\sqrt{p_{0,0}}\mathbf{U}_0^H\mathbf{H}_{0,0}\mathbf{V}_0\mathbf{x}_0}_{\text{signal}} + \underbrace{\sum_{k=1}^{K}\underbrace{\sqrt{p_{0,k}}\mathbf{U}_0^H\mathbf{H}_{0,k}}_{\equiv\mathbf{G}_{0,k}}\mathbf{V}_k\mathbf{x}_k}_{\text{inter-system interference}} + \mathbf{n}_0, \quad (1)$$

$$\mathbf{y}_k = \underbrace{\sqrt{p_{k,k}}\mathbf{U}_k^H\mathbf{H}_{k,k}\mathbf{V}_k\mathbf{x}_k}_{\text{signal}} + \underbrace{\sqrt{p_{k,0}}\mathbf{U}_k^H\mathbf{H}_{k,0}\mathbf{V}_0\mathbf{x}_0}_{\text{inter-system interference}} + \underbrace{\sum_{i=1,i\neq k}^{K}\sqrt{p_{k,i}}\mathbf{U}_k^H\mathbf{H}_{k,i}\mathbf{V}_i\mathbf{x}_i}_{\text{intra-system interference}} + \mathbf{n}_k, \quad (2)$$

where $\mathbf{n}_0 \in \mathbb{C}^{d_0\times 1}$ denotes the noise vector as the Gaussian noise at the CU and $\mathbf{n}_k \in \mathbb{C}^{d_k\times 1}$ denotes the noise vector as the Gaussian noise at the k^{th} DR.

All DTs are assumed to broadcast pilot signals. By measuring the received pilot signals from DTs, each DR estimates the channel matrix, $\mathbf{H}_{i,j}$, and the CU estimates the effective inter-system channel matrix, $\mathbf{G}_{0,k}$. The BS is assumed to broadcast a pilot signal and each DR estimates the effective inter-system channel matrix, $\mathbf{G}_{k,0}$. The BS informs D2D devices about $\mathbf{G}_{0,k}$ by using the specific control channel, e.g., a physical sidelink control channel (PSCCH) of the 3GPP ProSe standard [20]. Moreover, the channel matrix of $\mathbf{H}_{i,j}$ is shared in the D2D devices. Hence, D2D devices can obtain the following channel state information, which is an assumption similar to [17-19], [21].

- The k^{th} DT is assumed to obtain the information about ($\mathbf{H}_{i,j}$, $\mathbf{G}_{0,k}$), where $i, j \in \{1, 2, \cdots, K\}$.
- The k^{th} DR is assumed to obtain the information about ($\mathbf{H}_{i,j}$, $\mathbf{G}_{0,k}$, $\mathbf{G}_{k,0}$), where $i, j \in \{1, 2, \cdots, K\}$.

3. Proposed Interference Mitigation Scheme

3.1 Problem Formulation

In D2D networks underlaying a cellular network, the objective of the D2D networks is to maximize the sum capacity of D2D pairs while satisfying the inter-system interference constraint. Hence, given the number of data streams, d_0, in the cellular network, for $k \in \{1, 2, \cdots, K\}$, the optimization problem can be expressed as follows:

$$\max_{\mathbf{V}_k,\mathbf{U}_k^H,d_k} \sum_{k=1}^{K}\sum_{l=1}^{d_k}\log_2\left(1+\frac{\frac{p_{k,k}}{d_k}\left\|\mathbf{u}_{k,l}^H\mathbf{H}_{k,k}\mathbf{v}_{k,l}\right\|_F^2}{\underbrace{\frac{p_{k,0}}{d_0}\left\|\mathbf{u}_{k,l}^H\mathbf{H}_{k,0}\mathbf{V}_0\right\|_F^2}_{\text{inter-system interference}} + \underbrace{\sum_{j=1,j\neq k}^{K}\frac{p_{k,j}}{d_j}\left\|\mathbf{u}_{k,l}^H\mathbf{H}_{k,j}\mathbf{V}_j\right\|_F^2}_{\text{intra-system interference}} + \underbrace{\sum_{m=1,m\neq l}^{d_k}\frac{p_{k,k}}{d_k}\left\|\mathbf{u}_{k,l}^H\mathbf{H}_{k,k}\mathbf{v}_{k,m}\right\|_F^2}_{\text{inter-stream interference}} + n_k}\right) \quad (3)$$

$$\text{s.t.} \quad \mathbf{V}_k^H\mathbf{V}_k = \mathbf{I}_{d_k},$$

$$\sum_{l=1}^{d_0}\frac{p_{0,k}}{d_k}\left\|\mathbf{u}_{0,l}^H\mathbf{H}_{0,k}\mathbf{V}_k\right\|_F^2 < \gamma_{th,k},$$

where $\mathbf{u}_{k,l}^H$ denotes the l^{th} row vector of the $\mathbf{U}_k^H$, i.e., $\mathbf{U}_k^H = \left[\mathbf{u}_{k,1}\ \mathbf{u}_{k,2}\ \cdots\ \mathbf{u}_{k,d_k}\right]^H$, $\mathbf{v}_{k,l}$ denotes the l^{th} column vector of the $\mathbf{V}_k$, i.e., $\mathbf{V}_k = \left[\mathbf{v}_{k,1}\ \mathbf{v}_{k,2}\ \cdots\ \mathbf{v}_{k,d_k}\right]$, n_k denotes the noise power at the k^{th} DR, $\mathbf{I}_{d_k}$ denotes the $d_k \times d_k$ identity matrix, and $\gamma_{th,k}$ is the inter-system interference constraint at the k^{th} D2D pair.

By applying IA conditions to the optimization problem of (3), we can simplify (3) as follows:

$$\max_{\mathbf{V}_k, \mathbf{U}_k^H, d_k} \sum_{k=1}^{K}\sum_{l=1}^{d_k} \log_2\left(1+\frac{\frac{p_{k,k}}{d_k}\left\|\mathbf{u}_{k,l}^H\mathbf{H}_{k,k}\mathbf{v}_{k,l}\right\|_F^2}{\underbrace{\frac{p_{k,0}}{d_0}\left\|\mathbf{u}_{k,l}^H\mathbf{H}_{k,0}\mathbf{V}_0\right\|_F^2}_{\text{inter-system interference}} + \underbrace{\sum_{m=1,m\neq l}^{d_k}\frac{p_{k,k}}{d_k}\left\|\mathbf{u}_{k,l}^H\mathbf{H}_{k,k}\mathbf{v}_{k,m}\right\|_F^2}_{\text{inter-stream interference}} + n_k}\right) \tag{4}$$

$$\begin{aligned}
\text{s.t.}\quad & \mathbf{V}_k^H\mathbf{V}_k = \mathbf{I}_{d_k}, \\
& \sum_{l=1}^{d_0}\frac{p_{0,k}}{d_k}\left\|\mathbf{u}_{0,l}^H\mathbf{H}_{0,k}\mathbf{V}_k\right\|_F^2 < \gamma_{th,k}, \\
& rank\left\{\mathbf{U}_k^H\mathbf{H}_{k,k}\mathbf{V}_k\right\} = d_k, \\
& \mathbf{U}_i^H\mathbf{H}_{i,k}\mathbf{V}_k = \mathbf{0}_{d_i\times d_k} \quad \forall i = 1,\cdots,K,\ i\neq k, \\
& \mathbf{U}_k^H\mathbf{H}_{k,j}\mathbf{V}_j = \mathbf{0}_{d_k\times d_j} \quad \forall j = 1,\cdots,K,\ j\neq k,
\end{aligned}$$

where $\mathbf{0}_{q\times r}$ denotes a $q\times r$ matrix of all zeros and $rank\{\mathbf{X}\}$ denotes the rank of the matrix $\mathbf{X}$. However, the optimization problem of (4) is an NP-hard problem that is computationally difficult to solve because the optimization problem of (4) is a 3-dimensional matching problem [22]. Hence, to reduce the computational complexity and make the optimization problem tractable, we sequentially determine the parameters, the precoding matrices ($\mathbf{V}_k$), the decoding matrices ($\mathbf{U}_k^H$), and the number of data streams (d_k) for D2D pairs, where $k\in\{1,2,\cdots,K\}$.

3.2 Base Precoding and Decoding Matrices, ($\tilde{\mathbf{V}}_k$, $\tilde{\mathbf{U}}_k^H$), for Intra-system Interference Elimination

Let $\tilde{\mathbf{V}}_k$ be a base precoding matrix and $\tilde{\mathbf{U}}_k^H$ be a base decoding matrix for the k^{th} D2D pair. The base precoding and decoding matrices, ($\tilde{\mathbf{V}}_k$, $\tilde{\mathbf{U}}_k^H$), are determined based on the IA technique that eliminates the intra-system interference in the D2D networks, where we do not consider the inter-system interference and $k\in\{1,2,\cdots,K\}$.

This paper proposes two different IA algorithms to eliminate the intra-system interference: one is a non-iterative IA algorithm and the other is an iterative IA algorithm. While the non-iterative IA algorithm does not generate interference leakage, the iterative IA algorithm generates interference leakage. Also, the complexity of the non-iterative IA algorithm is lower than that of the iterative IA algorithm. However, the D2D pairs can use the non-iterative IA algorithm only when the condition of the non-iterative IA algorithm, that is the number of D2D pairs is three and the number of antennas at each D2D pair is identical, is satisfied.

Therefore, for the specific case when the number of D2D pairs is three (K = 3) and the number of antennas at each D2D pair is identical, we can find the matrices of ($\tilde{\mathbf{V}}_k, \tilde{\mathbf{U}}_k^H$) by using the non-iterative IA algorithm [23], [24]. Otherwise, we can find the matrices of ($\tilde{\mathbf{V}}_k, \tilde{\mathbf{U}}_k^H$) by using the iterative IA algorithm [25].

A. Finding ($\tilde{\mathbf{V}}_k, \tilde{\mathbf{U}}_k^H$) based on the Non-iterative IA algorithm

If the number of D2D pairs is three (K = 3) and the number of antennas at each D2D pair is identical, the base precoding matrix for the k^{th} D2D pair is given by [23]

$$\tilde{\mathbf{V}}_1 = \begin{bmatrix} \mathbf{e}_1 & \mathbf{e}_2 & \cdots & \mathbf{e}_{M_k/2} \end{bmatrix}, \tag{5}$$

$$\tilde{\mathbf{V}}_2 = \mathbf{H}_{3,2}^{-1}\mathbf{H}_{3,1}\tilde{\mathbf{V}}_1, \tag{6}$$

$$\tilde{\mathbf{V}}_3 = \mathbf{H}_{2,3}^{-1}\mathbf{H}_{2,1}\tilde{\mathbf{V}}_1, \tag{7}$$

where $\mathbf{e}_1, \mathbf{e}_2, \cdots, \mathbf{e}_{M_k/2}$ are the eigenvectors of $\mathbf{E} = \mathbf{H}_{3,1}^{-1}\mathbf{H}_{3,2}\mathbf{H}_{1,2}^{-1}\mathbf{H}_{1,3}\mathbf{H}_{2,3}^{-1}\mathbf{H}_{2,1}$. The base decoding matrix for the k^{th} D2D pair is given by [24]

$$\tilde{\mathbf{U}}_1^H = \begin{bmatrix} \mathbf{I}_{\lfloor M_k/2 \rfloor} & \mathbf{0}_{\lfloor M_k/2 \rfloor} \end{bmatrix} \begin{bmatrix} \mathbf{H}_{1,1}\tilde{\mathbf{V}}_1 & \mathbf{H}_{1,2}\tilde{\mathbf{V}}_2 \end{bmatrix}^{-1} \tag{8}$$

$$\tilde{\mathbf{U}}_2^H = \begin{bmatrix} \mathbf{I}_{\lfloor M_k/2 \rfloor} & \mathbf{0}_{\lfloor M_k/2 \rfloor} \end{bmatrix} \begin{bmatrix} \mathbf{H}_{2,2}\tilde{\mathbf{V}}_2 & \mathbf{H}_{2,3}\tilde{\mathbf{V}}_3 \end{bmatrix}^{-1} \tag{9}$$

$$\tilde{\mathbf{U}}_3^H = \begin{bmatrix} \mathbf{I}_{\lfloor M_k/2 \rfloor} & \mathbf{0}_{\lfloor M_k/2 \rfloor} \end{bmatrix} \begin{bmatrix} \mathbf{H}_{3,3}\tilde{\mathbf{V}}_3 & \mathbf{H}_{3,1}\tilde{\mathbf{V}}_1 \end{bmatrix}^{-1} \tag{10}$$

where $\lfloor x \rfloor$ denotes the largest integer less than or equal to x and $\mathbf{0}_q$ denotes a $q \times q$ matrix of all zeros.

If the DTs decide the precoding matrix by using the non-iterative IA algorithm, the precoding matrices of the D2D pairs satisfy the three interference aligning constraints in [23] described as

$$\text{span}\left(\mathbf{H}_{1,2}\tilde{\mathbf{V}}_2\right) = \text{span}\left(\mathbf{H}_{1,3}\tilde{\mathbf{V}}_3\right) \tag{11}$$

$$\mathbf{H}_{2,1}\tilde{\mathbf{V}}_1 = \mathbf{H}_{2,3}\tilde{\mathbf{V}}_3 \tag{12}$$

$$\mathbf{H}_{3,1}\tilde{\mathbf{V}}_1 = \mathbf{H}_{3,2}\tilde{\mathbf{V}}_2 \tag{13}$$

The received signal at the k^{th} DR is given by

$$\mathbf{y}_k = \mathbf{U}_k^H \sum_{l=1}^{3} \mathbf{H}_{k,l}\mathbf{V}_l\mathbf{x}_l + \mathbf{U}_k^H\mathbf{n}_k \tag{14}$$

We can divide (14) into the intended signal and the intra-system interference signal. Equation

(14) then can be expressed as follows:

$$\mathbf{y}_k = \underbrace{\mathbf{U}_k^H \mathbf{H}_{k,k} \mathbf{V}_k \mathbf{x}_k}_{\text{intentded signal}} + \underbrace{\mathbf{U}_k^H \sum_{l=1, l \neq k}^{3} \mathbf{H}_{k,l} \mathbf{V}_l \mathbf{x}_l}_{\text{intra-system interference signal}} + \mathbf{U}_k^H \mathbf{n}_k . \tag{15}$$

By applying the decoding matrix of the k^{th} DT and the three interference aligning constraints in [23] to (15), Eq. (15) can be expressed as follows:

$$\begin{aligned} \mathbf{y}_k &= \underbrace{\left[\mathbf{I}_{\lfloor M_k/2 \rfloor} \quad \mathbf{0}_{\lfloor M_k/2 \rfloor} \right] \left[\mathbf{H}_{k,k} \tilde{\mathbf{V}}_k \quad \mathbf{H}_{k,l} \tilde{\mathbf{V}}_l \right]^{-1} \mathbf{H}_{k,k} \mathbf{V}_k \mathbf{x}_k}_{\text{intentded signal}} \\ &+ \underbrace{\sum_{l=1, l \neq k}^{3} \left[\mathbf{I}_{\lfloor M_k/2 \rfloor} \quad \mathbf{0}_{\lfloor M_k/2 \rfloor} \right] \left[\mathbf{H}_{k,k} \tilde{\mathbf{V}}_k \quad \mathbf{H}_{k,l} \tilde{\mathbf{V}}_l \right]^{-1} \mathbf{H}_{k,l} \mathbf{V}_l \mathbf{x}_l}_{\text{intra-system interference signal}} + \mathbf{U}_k^H \mathbf{n}_k \end{aligned} . \tag{16}$$

Because of $\left[\mathbf{H}_k \mathbf{V}_k \quad \mathbf{H}_l \mathbf{V}_l \right]^{-1} \mathbf{H}_k \mathbf{V}_k = \begin{bmatrix} \mathbf{I} \\ \mathbf{0} \end{bmatrix}$ and $\left[\mathbf{H}_k \mathbf{V}_k \quad \mathbf{H}_l \mathbf{V}_l \right]^{-1} \mathbf{H}_l \mathbf{V}_l = \begin{bmatrix} \mathbf{0} \\ \mathbf{I} \end{bmatrix}$, Eq. (16) can be simplified as follows:

$$\begin{aligned} \mathbf{y}_k &= \underbrace{\left[\mathbf{I}_{\lfloor M_k/2 \rfloor} \quad \mathbf{0}_{\lfloor M_k/2 \rfloor} \right] \begin{bmatrix} \mathbf{I}_{\lfloor M_k/2 \rfloor} \\ \mathbf{0}_{\lfloor M_k/2 \rfloor} \end{bmatrix} \mathbf{x}_k}_{\text{intentded signal}} + \underbrace{\left[\mathbf{I}_{\lfloor M_k/2 \rfloor} \quad \mathbf{0}_{\lfloor M_k/2 \rfloor} \right] \begin{bmatrix} \mathbf{0}_{\lfloor M_k/2 \rfloor} \\ \mathbf{I}_{\lfloor M_k/2 \rfloor} \end{bmatrix} \sum_{l=1, l \neq k}^{3} \mathbf{x}_l}_{\text{intra-system interference signal}} + \mathbf{U}_k^H \mathbf{n}_k \\ &= \mathbf{I}_{\lfloor M_k/2 \rfloor} \mathbf{x}_k + \mathbf{U}_k^H \mathbf{n}_k \end{aligned} \tag{17}$$

Therefore, the non-iterative IA algorithm eliminates the intra-system interference signal and decodes the intended signal successfully.

B. Finding ($\tilde{\mathbf{V}}_k$, $\tilde{\mathbf{U}}_k^H$) based on the Iterative IA algorithm

If the number of D2D pairs is more than three ($K > 3$), in the iterative IA algorithm, we iteratively find the precoding and decoding matrices, as shown in **Algorithm 1**. The iterative IA algorithm uses the minimal interference leakage IA algorithm that minimizes the interference leakage in D2D networks by alternating the forward and reverse directions until the interference leakage converges [5], [25].

Algorithm 1. Iterative IA algorithm to find the base precoding and decoding matrices

1: Set $\tilde{\mathbf{V}}_k^{[0]} \in \mathbb{C}^{M_k \times \tilde{d}_k}$, $\tilde{\mathbf{V}}_k^{[0]H} \tilde{\mathbf{V}}_k^{[0]} = \mathbf{I}_{\tilde{d}_k}$ as arbitrary precoding matrix where $k \in \{1, 2, \cdots, K\}$

2: Set $\tilde{\mathbf{U}}_k^{[0]H} \in \mathbb{C}^{\tilde{d}_k \times M_k}$, $\tilde{\mathbf{U}}_k^{[0]H} \tilde{\mathbf{U}}_k^{[0]} = \mathbf{I}_{\tilde{d}_k}$ as arbitrary decoding matrix where $k \in \{1, 2, \cdots, K\}$

3: $\tilde{I}^{[0]} = \sum_{k=1}^{K} \sum_{j=1, j \neq k}^{K} \frac{p_{k,j}}{\tilde{d}_j} tr\left(\tilde{\mathbf{U}}_k^{[0]H} \mathbf{H}_{k,j} \tilde{\mathbf{V}}_j^{[0]} \tilde{\mathbf{V}}_j^{[0]H} \mathbf{H}_{k,j}^H \tilde{\mathbf{U}}_k^{[0]} \right)$ // calculate the total interference

---

Set $t = 0$

do

$t = t + 1$

$\mathbf{Q}_k^{[t]} = \sum_{j=1, j\neq k}^{K} \frac{p_{k,j}}{\tilde{d}_j} \mathbf{H}_{k,j} \mathbf{V}_j^{[t-1]} \mathbf{V}_j^{[t-1]H} \mathbf{H}_{k,j}^H, \ k \in \{1, 2, \cdots, K\}$ // forward direction

$\tilde{\mathbf{U}}_k^{[t]} = u_{\tilde{d}_k}\left(\mathbf{Q}_k^{[t]}\right), \ k \in \{1, 2, \cdots, K\}$ // eigenvalue decomposition of $\mathbf{Q}_k^{[t]}$

$\bar{\mathbf{Q}}_k^{[t]} = \sum_{j=1, j\neq k}^{K} \frac{p_{j,k}}{\tilde{d}_k} \mathbf{H}_{j,k}^H \mathbf{U}_j^{[t]} \mathbf{U}_j^{[t]H} \mathbf{H}_{j,k}, \ k \in \{1, 2, \cdots, K\}$ // reverse direction

$\tilde{\mathbf{V}}_k^{[t]} = u_{\tilde{d}_k}\left(\bar{\mathbf{Q}}_k^{[t]}\right), \ k \in \{1, 2, \cdots, K\}$ // eigenvalue decomposition of $\bar{\mathbf{Q}}_k^{[t]}$

$\tilde{I}^{[t]} = \sum_{k=1}^{K} \sum_{j=1, j\neq k}^{K} \frac{p_{k,j}}{\tilde{d}_j} tr\left(\tilde{\mathbf{U}}_k^{[t]H} \mathbf{H}_{k,j} \tilde{\mathbf{V}}_j^{[t]} \tilde{\mathbf{V}}_j^{[t]H} \mathbf{H}_{k,j}^H \tilde{\mathbf{U}}_k^{[t]}\right)$ // calculate the total interference

while $\tilde{I}^{[t-1]} - \tilde{I}^{[t]} > \varepsilon$

return $\tilde{\mathbf{V}}_k = \tilde{\mathbf{V}}_k^{[t]}, \ \tilde{\mathbf{U}}_k^H = \tilde{\mathbf{U}}_k^{[t]H}$

In **Algorithm 1**, $\tilde{\mathbf{V}}_k^{[t]}$ is the base precoding matrix of the k^{th} DT at the t^{th} iteration, $\tilde{\mathbf{U}}_k^{[t]H}$ is the base decoding matrix of the k^{th} DR at the t^{th} iteration, $\tilde{d}_k = \left\lfloor 2M_k / (K+1) \right\rfloor$ is the number of data streams for the base precoding and decoding matrices of the k^{th} D2D pair, $u_n(\mathbf{X})$ is the matrix containing n eigenvectors corresponding to n smallest eigenvalues of matrix $\mathbf{X}$, and ε is the convergence threshold of the iterative IA algorithm. The iterative IA algorithm reduces the value of weighted leakage interference (WLI) where the WLI is given by

$$\tilde{I}^{[t]} = \sum_{k=1}^{K} \sum_{j=1, j\neq k}^{K} \frac{p_{k,j}}{\tilde{d}_j} tr\left(\tilde{\mathbf{U}}_k^{[t]H} \mathbf{H}_{k,j} \tilde{\mathbf{V}}_j^{[t]} \tilde{\mathbf{V}}_j^{[t]H} \mathbf{H}_{k,j}^H \tilde{\mathbf{U}}_k^{[t]}\right) \tag{18}$$

in Algorithm 1. Since the WLI is bounded below by zero, this implies that the algorithm must converge. Given the value of $\tilde{\mathbf{V}}_k$, $\tilde{\mathbf{U}}_k$ computed in the forward direction minimizes the value of WLI over all possible choices of $\tilde{\mathbf{U}}_k$. As with the forward direction, given the value of $\tilde{\mathbf{U}}_k$, $\tilde{\mathbf{V}}_k$ computed in the reverse direction minimizes the value of WLI over all possible choices of $\tilde{\mathbf{V}}_k$. Since the value of WLI is monotonically reduced after each iteration, the convergence of the algorithm is guaranteed, although the convergence to global minimum is not guaranteed. The detailed procedure for convergence proof is provided in [26].

3.3 Precoding Matrix ($\mathbf{V}_k$) of D2D Pairs

Each DT finds the precoding matrix that mitigates both the intra-system interference and the inter-system interference (the D2D networks to the cellular network) on the basis of the base precoding matrix, $\tilde{\mathbf{V}}_k$. In the D2D networks underlaying a cellular network, to mitigate the inter-system interference from the D2D networks to the cellular network, we set $\mathbf{V}_k = \tilde{\mathbf{V}}_k \mathbf{C}_k$, where $\mathbf{C}_k$ is a matrix for the linear span of $\tilde{\mathbf{V}}_k$ to minimize the inter-system interference to the cellular network. The optimal matrix, $\mathbf{C}_k^*$, that minimizes the inter-system interference is given by

$$\mathbf{C}_k^* = \arg\min_{\mathbf{C}_k} \left\| \mathbf{G}_{0,k} \tilde{\mathbf{V}}_k \mathbf{C}_k \right\|_F^2 \quad \text{for } k \in \{1, 2, \cdots, K\} \tag{19}$$
$$\text{s.t.} \quad \left\| \tilde{\mathbf{V}}_k \mathbf{c}_{k,l} \right\|_F^2 = 1, \quad \forall l \in \{1, \cdots, d_k\},$$

where $\mathbf{c}_{k,l}$ is the l^{th} column vector of the $\mathbf{C}_k$ and d_k is an arbitrary number of data streams for the k^{th} D2D pair, where $d_k \le \lfloor 2M_k / (K+1) \rfloor$. Equation (11) can be simplified as follows:

$$\mathbf{C}_k^* = \arg\min_{\mathbf{C}_k} \; tr\left(\mathbf{C}_k^H \mathbf{Q} \mathbf{C}_k \right) \tag{20}$$
$$\text{s.t.} \quad \mathbf{c}_{k,l}^H \mathbf{R} \mathbf{c}_{k,l} = 1, \quad \forall l \in \{1, \cdots, d_k\}.$$

In (12), $\mathbf{Q}$ and $\mathbf{R}$ are respectively expressed as follows:

$$\mathbf{Q} = \tilde{\mathbf{V}}_k^H \mathbf{G}_{0,k}^H \mathbf{G}_{0,k} \tilde{\mathbf{V}}_k, \tag{21}$$

$$\mathbf{R} = \tilde{\mathbf{V}}_k^H \tilde{\mathbf{V}}_k. \tag{22}$$

With the number of data streams of the k^{th} D2D pair being d_k, the optimal solution of (12) is given by [27]

$$\mathbf{C}_k^*(d_k) = normc\left(u_{d_k}\left(\mathbf{R}^{-1} \mathbf{Q} \right) \right). \tag{23}$$

where $u_n(\mathbf{X})$ is the matrix containing n eigenvectors corresponding to n smallest eigenvalues of matrix $\mathbf{X}$ and $normc(\mathbf{X})$ normalizes the columns of matrix $\mathbf{X}$ to a length of 1.

Consequently, the optimal precoding matrix of the k^{th} DT is given by

$$\mathbf{V}_k(d_k) = \tilde{\mathbf{V}}_k \mathbf{C}_k^*(d_k), \quad \text{for } k \in \{1, 2, \cdots, K\}. \tag{24}$$

3.4 Decoding Matrix ($\mathbf{U}_k$) of D2D Pairs

Each DR finds the decoding matrix that mitigates both the intra-system interference and the inter-system interference (the cellular network to the D2D networks) on the basis of the base decoding matrix, $\tilde{\mathbf{U}}_k^H$. To mitigate the inter-system interference from the cellular network to the D2D networks, we find the optimal matrix, $\mathbf{B}_k^*$, that minimizes the inter-system interference, as follows:

$$\mathbf{B}_k^* = \arg\min_{\mathbf{B}_k} \left\| \mathbf{B}_k \tilde{\mathbf{U}}_k^H \mathbf{G}_{k,0} \right\|_F^2. \tag{25}$$

With the number of data streams of the k^{th} D2D pair being d_k, the optimal solution of (17) is given by [27]

$$\mathbf{B}_k^*(d_k) = u_{d_k}\left(\tilde{\mathbf{U}}_k^H \mathbf{G}_{k,0} \mathbf{G}_{k,0}^H \tilde{\mathbf{U}}_k \right). \tag{26}$$

Finally, to eliminate the inter-stream interference in the k^{th} D2D pair, we determine the zero-forcing (ZF) matrix as follows:

$$\mathbf{A}_k(d_k) = \left(\mathbf{B}_k^*(d_k)\tilde{\mathbf{U}}_k^H \mathbf{H}_{k,k} \mathbf{V}_k(d_k)\right)^{-1}, \tag{27}$$

where d_k is the number of data streams of the k^{th} D2D pair. Consequently, for $k \in \{1, 2, \cdots, K\}$, the optimal decoding matrix of the k^{th} DR is given by

$$\mathbf{U}_k(d_k)^H = normc\left(\mathbf{A}_k(d_k)\mathbf{B}_k^*(d_k)\tilde{\mathbf{U}}_k^H\right). \tag{28}$$

3.5 Number of Data Streams for D2D Pairs

We determine the optimal number of data streams for D2D pairs in order to maximize the capacity of each D2D pair while satisfying the inter-system interference constraint to the cellular network. The procedure to find the optimal number of data streams for the k^{th} D2D pair is summarized in **Algorithm 2** and **Algorithm 3**.

Algorithm 2 finds the maximum number of data streams for the k^{th} D2D pair, $d_{k,\max}$, that satisfies the inter-system interference constraint while iteratively increasing the value of d_k. In **Algorithm 2**, $d_{k,\min}$ denotes the minimum number of data streams at the k^{th} D2D pair; $I_k(d_k)$ denotes the inter-system interference from the k^{th} DT with d_k data streams to the CU; and $\mathbf{g}_{k,l}$ denotes the l^{th} row vector of $\mathbf{G}_{0,k}$.

Algorithm 2. `findStreamMax`(k): find the maximum number of data streams for the k^{th} D2D pair

---

1: Set $d_{k,\min} = \max\left(\left\lfloor \frac{2M_k}{K+1} \right\rfloor - d_0, 1\right)$
2: **for** $d_k = d_{k,\min}$ **to** $\left\lfloor \frac{2M_k}{K+1} \right\rfloor$ **do**
3: Compute $\mathbf{V}_k(d_k)$ from (16)
4: Compute $I_k(d_k) = \sum_{l=1}^{d_0} \frac{\left\| g_{k,l}\mathbf{V}_k(d_k) \right\|_F^2}{d_k}$
5: **if** $I_k(d_k) \geq \gamma_{th,k}$ **then**
6: **break**
7: **end if**
8: **end for**
9: **return** $d_{k,\max} = d_k - 1$

Algorithm 3 finds the optimal number of data streams for the k^{th} D2D pair, d_k^*, that maximizes the SINR_k of each D2D pair while iteratively increasing the value of d_k up to $d_{k,\max}$, where $\bar{n}_k$ denotes the average noise power at the k^{th} DR. Notice that as the number of d_k increases, the spatial multiplexing gain increases but the inter-system interference also increases.

Algorithm 3. `findStreamOpt`(k): find the optimal number of data streams for the k^{th} D2D pair

```
Set d_{k,min} = max( ⌊2M_k/(K+1)⌋ − d_0, 1 )
Set d_{k,max} = findStreamMax(k)
Set SINR_k(d_k - 1) = 0
for d_k = d_{k,min} to d_{k,max} do
    Compute U_k^H(d_k) from (20)
    Compute SINR_k(d_k) = sum_{l=1}^{d_k} ( ||u_{k,l}(d_k)^H H_{k,k} V_k(d_k)||_F^2 / d_k ) / { ||u_{k,l}(d_k)^H G_{k,0}||_F^2 / d_0 + n̄_k }
    if SINR_k(d_k) ≤ SINR_k(d_k - 1) then
        break
    end if
end while
return d_k^* = d_k − 1
```

$$d_{k,\min} = \max\left(\left\lfloor \frac{2M_k}{K+1} \right\rfloor - d_0, 1\right)$$

$$\mathrm{SINR}_k(d_k) = \sum_{l=1}^{d_k} \frac{\left\| \mathbf{u}_{k,l}(d_k)^H \mathbf{H}_{k,k} \mathbf{V}_k(d_k) \right\|_F^2}{d_k} \Bigg/ \left\{ \frac{\left\| \mathbf{u}_{k,l}(d_k)^H \mathbf{G}_{k,0} \right\|_F^2}{d_0} + \bar{n}_k \right\}$$

Because the minimum value of $d_{k,\min}$ is 1, the maximum iterations of **Algorithm 2** and **Algorithm 3** are identically equal to $\lfloor 2M_k/(K+1) \rfloor$, where K is the number of D2D pairs and M_k is the number of antennas at the k^{th} D2D pair.

Algorithm 3 also can use the inter-system interference leakage (IL) criterion. To use the inter-system IL criterion in **Algorithm 3**, the **Algorithm 3** needs the inter-system IL constraint. The DRs compute the inter-system IL from the BS to the DRs according to the number of data streams for the D2D pairs by using

$$\mathrm{IL}_k(d_k) = \sum_{l=1}^{d_k} \frac{\left\| \mathbf{u}_{k,l}(d_k)^H \mathbf{G}_{k,0} \right\|_F^2}{d_0}. \tag{29}$$

Then, the D2D pairs find the maximum number of all possible data streams that satisfy the inter-system IL constraint.

If **Algorithm 3** uses the inter-system IL criterion, the D2D pairs can find the optimal number of data streams that satisfies the inter-system IL constraint but the D2D pairs cannot maximize the capacity of the D2D pairs because the D2D pairs do not consider the received signal power of data streams. Consequently, the average capacity of the cellular network on the basis of the inter-system IL criterion is similar to the average capacity of the cellular network on the basis of the SINR criterion. However, the average capacity of the D2D pairs on the basis of the inter-system IL criterion is lower than the average capacity of the D2D pairs on the basis of the SINR criterion.

3.6 Capacity Analysis

The capacity of the cellular network can be expressed as follows:

$$C_{Cell} = \sum_{l=1}^{d_0} \log_2 \left(1 + \frac{\frac{p_{0,0}}{d_0} \left\| \mathbf{u}_{0,l}^H \mathbf{H}_{0,0} \mathbf{V}_0 \right\|_F^2}{\sum_{k=1}^{K} \frac{p_{0,k}}{d_k} \left\| \mathbf{u}_{0,l}^H \mathbf{H}_{0,k} \mathbf{V}_k \right\|_F^2 + n_0} \right), \tag{30}$$

where d_0 is the number of data streams, $p_{0,0}$ is the received power at the CU from the BS, $\mathbf{u}_{0,l}^H$ denotes the l^{th} row vector of the decoding matrix of the CU, $\mathbf{U}_0^H$, and n_0 denotes the noise power at the CU.

If D2D pairs use the non-iterative IA algorithm, the intra-system interference and the inter-stream interference do not exist. Therefore, if D2D pairs use the non-iterative IA algorithm, the sum capacity of the D2D pairs is given by

$$C_{D2D} = \sum_{k=1}^{3} \sum_{l=1}^{d_k} \log_2 \left(1 + \frac{\frac{p_{k,k}}{d_k} \left\| \mathbf{u}_{k,l}^H \mathbf{H}_{k,k} \mathbf{V}_k \right\|_F^2}{\frac{p_{k,0}}{d_0} \left\| \mathbf{u}_{k,l}^H \mathbf{H}_{k,0} \mathbf{V}_0 \right\|_F^2 + n_k} \right), \tag{31}$$

where $\mathbf{u}_{k,l}^H$ denotes the l^{th} row vector of the decoding matrix of the k^{th} DR, $\mathbf{U}_k^H$, and n_k denotes the noise power at the k^{th} DR.

Whereas if D2D pairs use the iterative IA algorithm, the intra-system interference exists because of the interference leakage in the D2D networks. Therefore, if D2D pairs use the iterative IA algorithm, the sum capacity of the D2D pairs is given by

$$C_{D2D} = \sum_{k=1}^{K} \sum_{l=1}^{d_k} \log_2 \left(1 + \frac{\frac{p_{k,k}}{d_k} \left\| \mathbf{u}_{k,l}^H \mathbf{H}_{k,k} \mathbf{V}_k \right\|_F^2}{\frac{p_{k,0}}{d_0} \left\| \mathbf{u}_{k,l}^H \mathbf{H}_{k,0} \mathbf{V}_0 \right\|_F^2 + \underbrace{\sum_{j=1, j \neq k}^{K} \frac{p_{k,j}}{d_j} \left\| \mathbf{u}_{k.l}^H \mathbf{H}_{k,j} \mathbf{V}_j \right\|_F^2}_{\text{intra-system interference leakage}} + n_k} \right). \tag{32}$$

Therefore, the average capacity of the cellular network on the basis of the iterative IA algorithm is similar to the average capacity of the cellular network on the basis of the non-iterative IA algorithm. However, the average capacity of the D2D pairs on the basis of the iterative IA algorithm is lower than the average capacity of the D2D pairs on the basis of the non-iterative IA algorithm because of the interference leakage in the D2D networks.

4. Simulation Results

We compare the performance of the proposed interference mitigation scheme with the following two schemes: an intra-system IA scheme, where the IA technique is used without consideration of the inter-system interference, and a power control (PC)-based IA scheme of [17], where the inter-system interference is controlled by using the power control and the intra-system interference is controlled by using the IA technique. Moreover, we additionally compare the performance of the minimum mean square error (MMSE) based scheme of [13], where the intra-system interference and the inter-system interference are minimized by optimizing the parameters of ($\mathbf{V}_k$, $\mathbf{U}_k^H$) in the D2D networks, as the value of d_0 increases.

In the simulation, we consider symmetric K pair D2D networks where the k^{th} DT and the k^{th} DR are equipped with M_k antennas. In a cellular network, a BS and a CU are equipped with M_0 = 8 antennas for long term evolution-advanced (LTE-Advanced) or M_0 = 16 antennas for LTE-Advanced Pro [28], [29]. The cellular network is assumed to use the MIMO technique on the basis of the singular value decomposition (SVD) among many MIMO techniques because the SVD-MIMO technique can decompose the MIMO channel matrix into parallel single-input single-output subchannels. Therefore, the BS easily can select the subchannels that maximize the capacity of the cellular network with the given number of data streams [30]. The SVD-MIMO technique is optionally used in LTE systems.

When the channel matrix between the BS and the CU is $\mathbf{H}_{0,0}$, the SVD of the channel matrix is given by $\mathbf{H}_{0,0} = \mathbf{U}_0 \mathbf{\Lambda} \mathbf{V}_0^H$, where $\mathbf{U}_0$ and $\mathbf{V}_0$ are unitary matrices and $\mathbf{\Lambda}$ is a diagonal matrix with non-negative real numbers. Then, the precoding and decoding matrices of the cellular network on the basis of the SVD-MIMO technique are respectively $\mathbf{V}_0$ and $\mathbf{U}_0^H$. Therefore, the effective channel matrix in the cellular network on the basis of the SVD-MIMO technique is the diagonal matrix $\mathbf{\Lambda}$ because the $\mathbf{U}_0$ and the $\mathbf{V}_0$ are unitary matrices [31]. Consequently, the cellular network easily can adjust the number of data streams by selecting as many columns of $\mathbf{V}_0$ and rows of $\mathbf{U}_0^H$ as the number of data streams.

We assume that the inter-system interference constraint at each D2D pair is identical to $\gamma_{th,k} = \gamma_{th}/K$, where γ_{th} is the total inter-system interference constraint from the D2D networks to the cellular network. The parameters used in the simulation are summarized in **Table 2**.

Table 2. Simulation parameters

Item	Value
Number of D2D pairs, K	3~7
Number of antennas of each DT and each DR, M_k	4~16
Number of antennas of a BS and a CU, M_0	8, 16 [28], [29]
Transmission power of a BS, p_0	43 dBm [32]
Transmission power of the k^{th} DT, p_k	23 dBm [33], [34]
Total inter-system interference constraint, γ_{th}	-90 dBm
Pathloss model for a cellular link	128.1+37.6$\log_{10}(d$[km]) [35]
Pathloss model for D2D links	148 + 40$\log_{10}(d$[km]) [35]
Distance between a BS and a CU, $L_{0,0}$	2 km [32]
Distance between a BS and the k^{th} DR, $L_{k,0}$	1.5 km~2.5 km

Distance between the k^{th} DT and a CU, $L_{0,k}$	200 m~300 m
Distance between DTs and DRs	50 m [33]
Channel model for a cellular link	Rayleigh with unit power
Channel model for a D2D link	Rician with K = 0 dB [33]
Center frequency	2 GHz [35]
Bandwidth	10 MHz [32]
Noise model	Gaussian noise with zero mean [32]
Noise spectral density	-174 dBm/Hz
Convergence threshold for iterative IA algorithm	10^{-15}

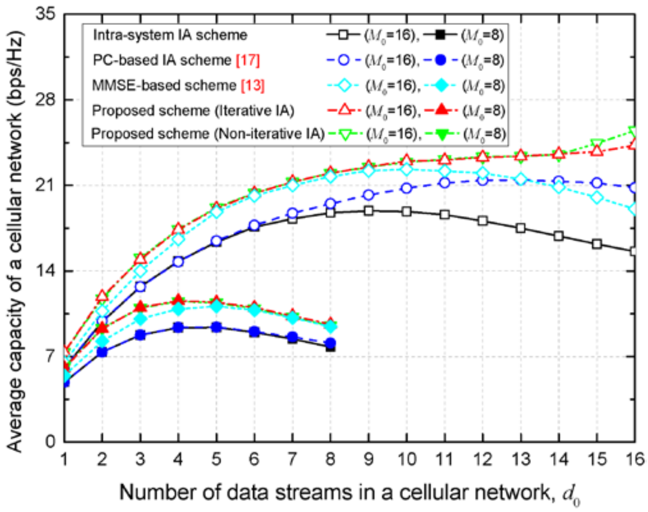

Fig. 2. Average capacity of a cellular network vs. the number of data streams in a cellular network

Fig. 2 shows the average capacity of a cellular network as the number of data streams (d_0) in the cellular network increases when K = 3, M_k = 8, $L_{k,0}$ = 2 km, and $L_{0,k}$ = 250 m. As the value of d_0 increases, the average capacity of the cellular network increases owing to the spatial multiplexing gain if the inter-system interference caused by the D2D networks does not excessively increase. In the intra-system IA scheme, the average capacity of the cellular network declines after a certain value, d_0 = 7 and d_0 = 5 when M_0 = 16 and M_0 = 8 respectively, in our simulation environment, because it does not control the inter-system interference. In the MMSE-based scheme, the average capacity of the cellular network declines after a certain value, d_0 = 11 and d_0 = 5 when M_0 = 16 and M_0 = 8 respectively, in our simulation environment because the inter-system interference from the DTs to the CU of the MMSE-based scheme is lower than that of the intra-system IA scheme as a result of optimizing the parameters of ($\mathbf{V}_k$, $\mathbf{U}_k^H$). In the PC-based IA scheme, the average capacity of the cellular network also declines after a certain large value, d_0 = 13 and d_0 = 5 when M_0 = 16 and M_0 = 8 respectively, in our simulation environment, although it controls the total inter-system interference by reducing the transmission power of DTs, because the signal-to-interference-plus-noise ratio (SINR) per data stream in the cellular network is too small for a large value of d_0. However, in the proposed scheme, the average capacity of the cellular network increases as the value of d_0 increases when the value of M_0 = 16 because it dynamically controls the inter-system interference by optimizing the parameters of ($\mathbf{V}_k$, $\mathbf{U}_k^H$, d_k) in the D2D networks, where $k \in \{1, 2, \cdots, K\}$. Moreover, the proposed scheme outperforms the other scheme thanks to the optimization of parameters of ($\mathbf{V}_k$, $\mathbf{U}_k^H$, d_k). In the proposed scheme, the average capacity of a cellular network steeply increases after d_0 = 14 when the value of M_0 is 16, because the D2D transmissions are restrained to satisfy the inter-system interference constraint. On the other hand, unlike when the value of M_0 is 16, the average capacity of a cellular network declines after d_0 = 4 when the value of M_0 is 8. Also, the average capacity of the cellular network when the value of M_0 is 8 does not increase even if the BS uses the maximum number of data streams because the D2D transmissions are not restrained by optimizing the parameters of ($\mathbf{V}_k$, $\mathbf{U}_k^H$, d_k) when the value of d_0 is lower than 14 regardless of the value of M_0. The average capacity of the cellular network when the value of M_0 is 8, is surely lower than the average capacity of the cellular network when the value of M_0 is 16.

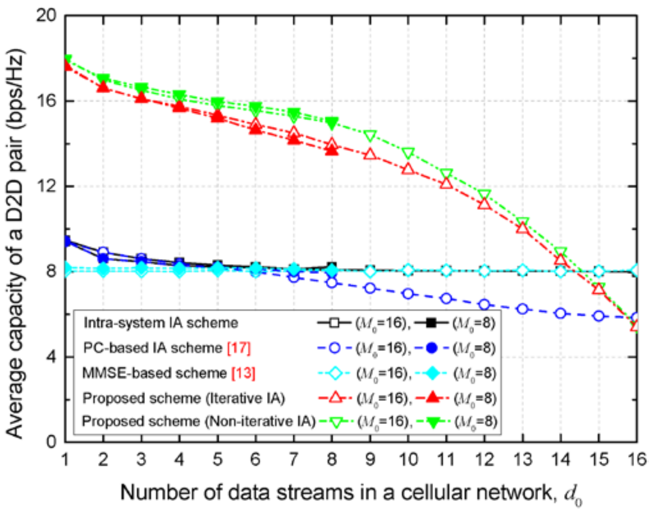

Fig. 3. Average capacity of a D2D pair vs. the number of data streams in a cellular network

Fig. 3 shows the average capacity of a D2D pair as the number of data streams (d_0) in the cellular network increases when K = 3, M_k = 8, $L_{k,0}$ = 2 km, and $L_{0,k}$ = 250 m. In the intra-system IA scheme, the average capacity of a D2D pair is almost unchanged regardless of the value of d_0 because d_0 does not control the inter-system interference. In the MMSE-based scheme, the average capacity of the D2D pair is maintained regardless of the value of d_0 because the inter-system interference and the intra-system interference are controlled by optimizing the value of ($\mathbf{V}_k$, $\mathbf{U}_k^H$). However, if the distance between the DTs and the DRs in the other D2D pair decreases, the average capacity of the D2D pair decreases because the MMSE-based scheme does not eliminate the intra-system interference. In the PC-based IA scheme, the average capacity of a D2D pair declines after d_0 = 5 because the DTs begin to control the transmission power when d_0 = 5 in our simulation environment in order to restrain the inter-system interference to the cellular network. In the proposed scheme, the average capacity of the D2D networks declines according to the increase of d_0 because the number of data streams in the D2D networks decreases with the value of d_0 in order to reduce the inter-system interference caused by the D2D networks. In particular, when the value of M_0 is 16, a higher value of d_0 results in higher inter-system interference, and therefore the average capacity of the D2D networks steeply declines when the value of d_0 is high because the number of data streams of a D2D pair is rapidly restrained. However, the average capacity of a D2D pair is significantly higher in the proposed scheme than in other schemes because the proposed scheme dynamically mitigates the inter-system interference. However, when the value of M_0 is 8, the average capacity of the D2D pair of the proposed scheme does not sharply decrease even if the BS uses the maximum number of data streams because the D2D transmissions are not restrained by optimizing the parameters of ($\mathbf{V}_k$, $\mathbf{U}_k^H$, d_k).

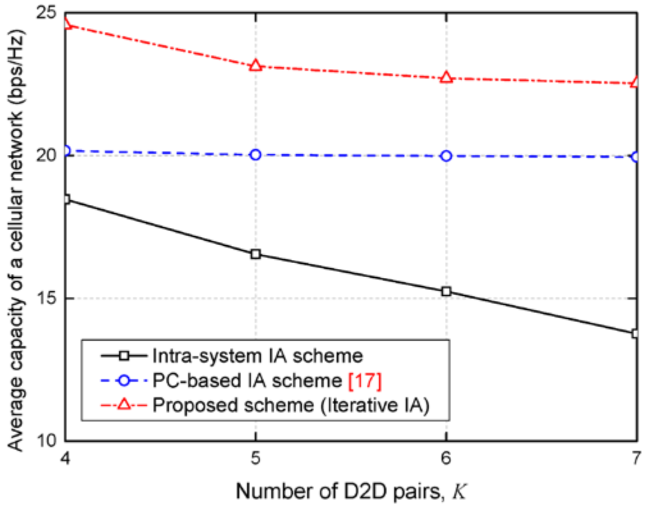

Fig. 4. Average capacity of a cellular network vs. the number of D2D pairs

Fig. 4 shows the average capacity of the cellular network as the number of D2D pairs (K) increases when M_0 = 16, M_k = 16, $L_{k,0}$ = 1 km, $L_{0,k}$ = 250 m, d_0 = 10, and $d_{k,\max}$ = 4. As the value of K increases, the inter-system interference increases due to the increase of the DTs, and therefore the capacity of the cellular network exponentially decreases with the value of K if we do not control the inter-system interference. Hence, in the intra-system IA scheme, the average capacity of the cellular network decreases with the value of K because it does not control the inter-system interference. In the proposed scheme, the inter-system interference is controlled by adjusting the discrete number of data streams of D2D pairs whereas in the PC-based IA scheme, the inter-system interference is controlled by adjusting the continuous value of the transmission power of each DT. Hence, in the PC-based IA scheme, the average capacity of the cellular network is maintained regardless of the number of K because the total inter-system interference is controlled to be the inter-system interference constraint, γ_{th}. However, in the proposed scheme, the average capacity of the cellular network slowly declines and approaches a certain value as the value of K increases because the total inter-system interference is controlled to be less than or equal to the inter-system interference constraint, γ_{th}, by changing the parameters ($\mathbf{V}_k$, $\mathbf{U}_k^H$, d_k). Above all, the proposed scheme outperforms the other schemes in terms of the average capacity of the cellular network.

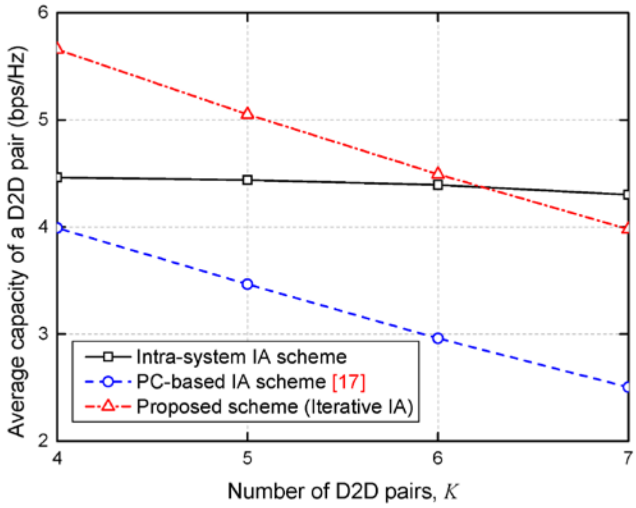

Fig. 5. Average capacity of a D2D pair vs. the number of D2D pairs

Fig. 5 shows the average capacity of a D2D pair as the number of D2D pairs (K) increases when $M_0 = 16$, $M_k = 16$, $L_{k,0} = 1$ km, $L_{0,k} = 250$ m, $d_0 = 10$, and $d_{k,\max} = 4$. In the intra-system IA scheme, the average capacity of a D2D pair is unchanged regardless of the number of K because the D2D pair does not control the inter-system interference. In the PC-based IA scheme and in the proposed scheme, the average capacity of a D2D pair linearly decreases as the value of K increases because the PC-based IA scheme reduces the transmission power of DTs and the proposed scheme reduces the number of data streams of each D2D pair in order to restrain the inter-system interference.

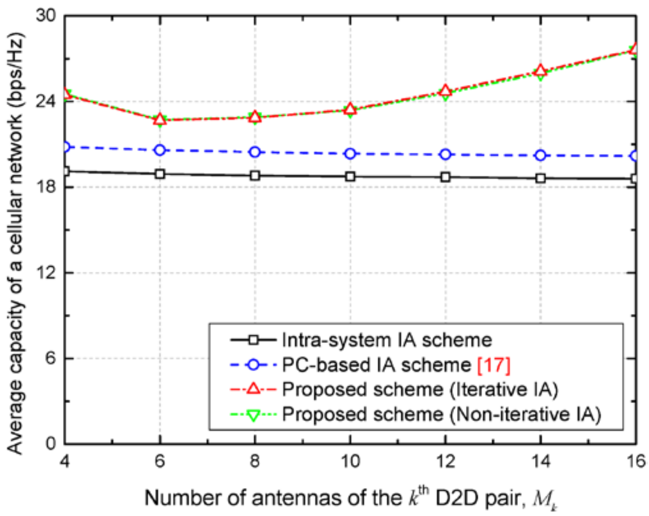

Fig. 6. Average capacity of a cellular network vs. the number of antennas of the k^{th} D2D pair

Fig. 6 shows the average capacity of a cellular network as the number of antennas of the k^{th} D2D pair (M_k) increases when $K = 3$, $M_0 = 16$, $L_{k,0} = 2$ km, $L_{0,k} = 250$ m, and $d_0 = 10$. As the value of M_k increases, the number of data streams that interfere with the CU increases but the inter-system interference power per data stream decreases. Therefore, the inter-system interference from the DTs to the CU remains at a constant level regardless of the value of M_k in our simulation environment. Consequently, in the intra-system IA scheme and the PC-based IA scheme, the average capacity of the cellular network is almost unchanged regardless of the value of M_k. However, in the proposed scheme, the average capacity of the cellular network decreases until a certain value, $M_k = 6$, because the ratio of the number of data streams to the number of antennas of the D2D pair increases. However, if the value of M_k is larger than 6, the average capacity of the cellular network increases because the ratio of the number of data streams to the number of antennas of the D2D pair decreases to satisfy the inter-system interference constraint.

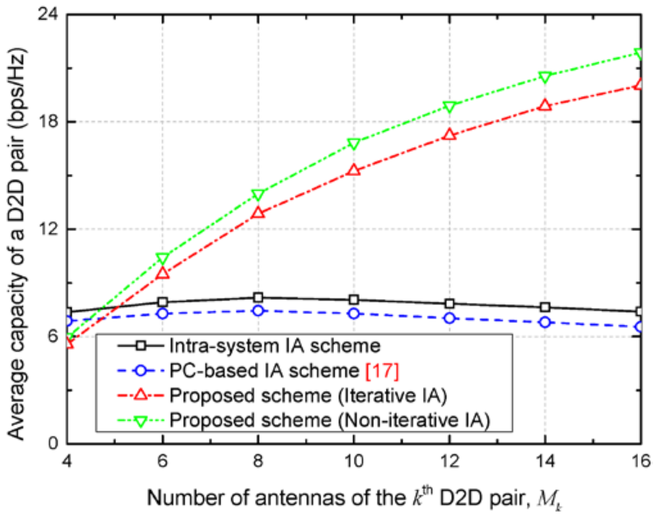

Fig. 7. Average capacity of a D2D pair vs. the number of antennas of the k^{th} D2D pair

Fig. 7 shows the average capacity of a D2D pair as the number of antennas of the k^{th} D2D pair (M_k) increases when $K = 3$, $M_0 = 16$, $L_{k,0} = 2$ km, $L_{0,k} = 250$ m, and $d_0 = 10$. As the value of M_k increases, the spatial multiplexing gain increases but the total inter-system interference from the BS increases and the SNR per data stream in the D2D pair decreases. Consequently, in the intra-system IA scheme and the PC-based IA scheme, the average capacity of the D2D pair is almost unchanged regardless of the value of M_k. However, in the proposed scheme, as the value of M_k increases, the average capacity of the D2D pair also increases by spatial multiplexing gain because the DRs minimize the inter-system interference from the BS by optimizing the parameters of ($\mathbf{V}_k$, $\mathbf{U}_k^H$, d_k). However, when the value of M_k is lower than 4, the average capacity of the D2D pair in the proposed scheme is lower than that in the previous schemes because the partial D2D transmissions are restrained to satisfy the inter-system interference constraint.

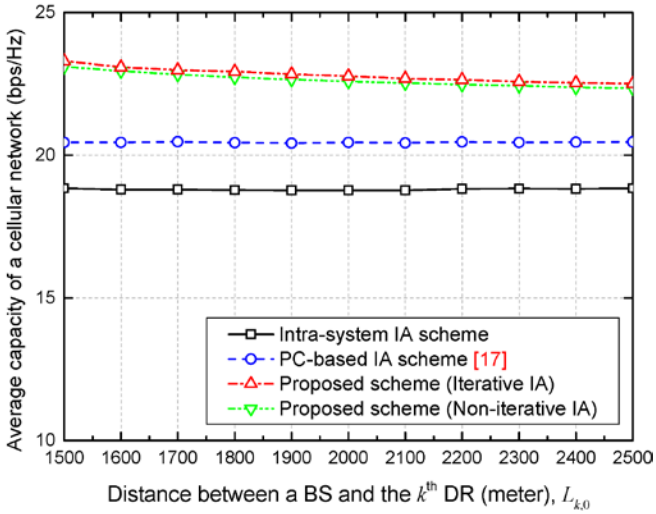

Fig. 8. Average capacity of a cellular network vs. the distance between a BS and the k^{th} DR

Fig. 8 shows the average capacity of a cellular network as the distance between a BS and the k^{th} DR ($L_{k,0}$) increases when K = 3, M_0 = 16, M_k = 8, $L_{0,k}$ = 250 m, and d_0 = 10. The average capacity of the cellular network is not related to the value of $L_{k,0}$ because the inter-system interference from the DTs to the CU does not change even if the value of $L_{k,0}$ changes. Consequently, the average capacity of the cellular network of all schemes is almost unchanged regardless of the value of $L_{k,0}$.

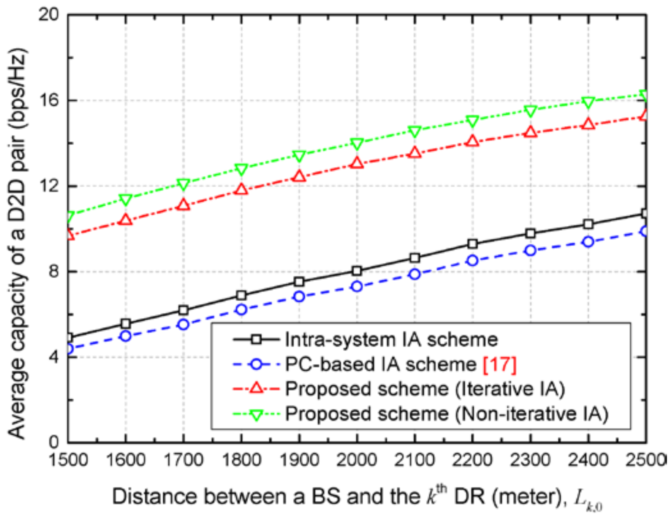

Fig. 9. Average capacity of a D2D pair vs. the distance between a BS and the k^{th} DR

Fig. 9 shows the average capacity of a D2D pair as the distance between a BS and the k^{th} DR ($L_{k,0}$) increases when K = 3, M_0 = 16, M_k = 8, $L_{0,k}$ = 250 m, and d_0 = 10. As the value of $L_{k,0}$ increases, the average capacity of the D2D pair increases because the inter-system interference from the BS to the DRs decreases. Consequently, as the value of $L_{k,0}$ increases, the average capacity of the D2D pair of all schemes increases.

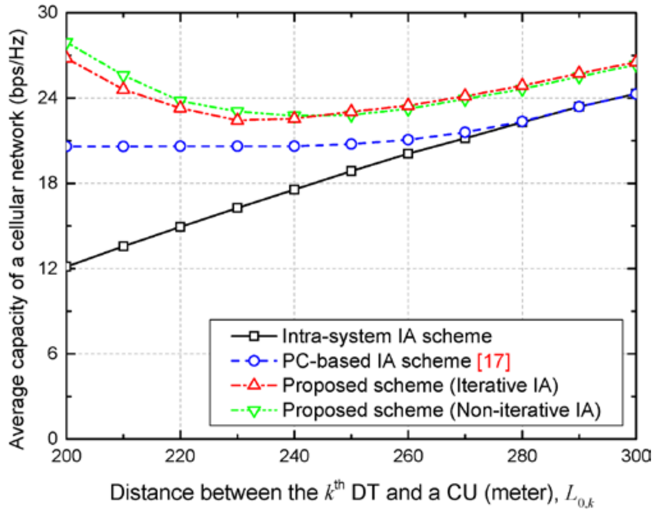

Fig. 10. Average capacity of a cellular network vs. the distance between the k^{th} DT and a CU

Fig. 10 shows the average capacity of a cellular network as the distance between the k^{th} DT and a CU ($L_{0,k}$) increases when K = 3, M_0 = 16, M_k = 8, $L_{k,0}$ = 2 km, and d_0 = 10. In the intra-system IA scheme, as the value of $L_{0,k}$ increases, the average capacity of the cellular network increases because the inter-system interference from the DTs to the CU decreases with the value of $L_{0,k}$. However, in the PC-based IA scheme, the average capacity of the cellular network is maintained until a certain value, $L_{0,k}$ = 260 m, because the DT controls the transmission power to satisfy the inter-system interference constraint. However, if the value of $L_{0,k}$ is higher than 260 m, the average capacity of the cellular network increases as the value of $L_{0,k}$ increases because the DT can satisfy the inter-system interference constraint even if it uses the full transmission power. In the proposed scheme, as the value of $L_{0,k}$ increases, the DT increases the number of data streams because it can satisfy the inter-system interference constraint even if it increase the number of data streams. Therefore, in the proposed scheme, the average capacity of the cellular network decreases until a certain value, $L_{0,k}$ = 240 m. However, if the value of $L_{0,k}$ is higher than 240 m, the average capacity of the cellular network increases as the value of $L_{0,k}$ increases because the DT can satisfy the inter-system interference constraint even if it uses all data streams.

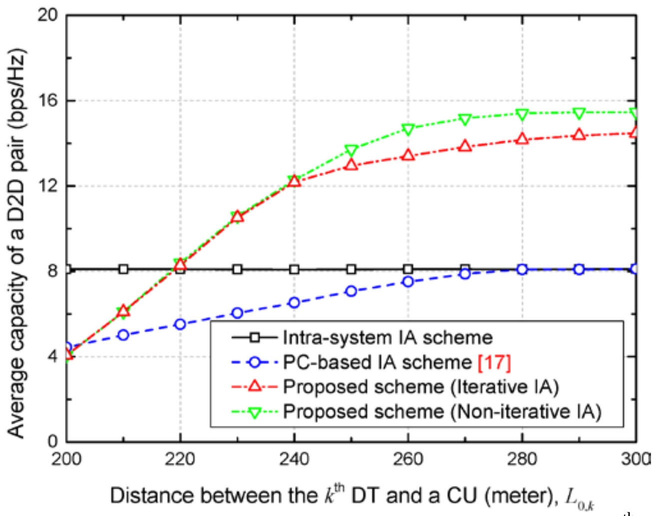

Fig. 11. Average capacity of a D2D pair vs. the distance between the k^{th} DT and a CU

Fig. 11 shows the average capacity of a D2D pair as the distance between the k^{th} DT and a CU ($L_{0,k}$) increases when $K = 3$, $M_0 = 16$, $M_k = 8$, $L_{k,0} = 2$ km, and $d_0 = 10$. In the intra-system IA scheme, the average capacity of the D2D pair is maintained regardless of the value of $L_{0,k}$. In the PC-based IA scheme, the average capacity of the D2D pair increases until a certain value, $L_{0,k} = 260$ m, because the DT increases the transmission power as the value of $L_{0,k}$ increases. However, if the value of $L_{0,k}$ is higher than 260 m, the average capacity of the D2D pair is maintained because the DT does not control the transmission power. In the proposed scheme, as the value of $L_{0,k}$ increases, the DT increases the number of data streams because it can satisfy the inter-system interference constraint even if it increases the number of data streams. However, if the value of $L_{0,k}$ is higher than 260 m, the average capacity of the D2D pair slowly rises and approaches a certain value as the value of $L_{0,k}$ increases because the maximum number of data streams for the D2D pair are limited as $M_k/2$.

5. Conclusion

This paper proposed an interference mitigation scheme for D2D communications underlaying a cellular network and developed an optimization problem that maximizes the capacity of D2D networks while satisfying the inter-system interference constraint. This paper presented how to determine the optimal parameters of the precoding matrix ($\mathbf{V}_k$), the decoding matrix ($\mathbf{U}_k^H$), and the number of data streams (d_k) for each D2D pair. The proposed scheme significantly increases the average capacity of the cellular network as well as the D2D networks by dynamically controlling the parameters of ($\mathbf{V}_k$, $\mathbf{U}_k^H$, d_k) according to the number of data streams used in the cellular network and the channel environment between each DT and a CU. In particular, the proposed scheme can be applied to heterogeneous networks regardless of the number of data streams for a cellular network. Our future work will study the interference mitigation scheme for D2D networks when the channel state information at the transmitter is not perfect due to the delay or limited feedback.

References

[1] 3GPP, "3rd Generation Partnership Project; Technical Specification Group Services and System Aspects; Feasibility study for proximity services (ProSe) (Release 12)," *TR 22.803, V12.2.0,* Jun. 2013. Article (CrossRef Link).

[2] L. Wei, R. Q. Hu, Y. Qian, and G. Wu, "Enable device-to-device communications underlaying cellular networks: Challenges and research aspects," *IEEE Commun. Mag.*, vol. 52, no. 6, pp. 90-96, Jun. 2014. Article (CrossRef Link).

[3] A. Asadi, Q. Wang, and V. Mancuso, "A survey on device-to-device communication in cellular networks," *IEEE Commun. Surveys Tuts.*, vol. 16, no. 4, pp. 1801-1819, Apr. 2014. Article (CrossRef Link).

[4] W. Shin, W. Noh, K. Jang, and H.-H. Choi, "Hierarchical interference alignment for downlink heterogeneous networks," *IEEE Trans. Wireless Commun.*, vol. 11, no. 12, pp. 4549-4559, Dec. 2012. Article (CrossRef Link).

[5] H. Men, N. Zhao, M. Jin, and J. M. Kim, "Optimal transceiver design for interference alignment based cognitive radio networks," *IEEE Commun. Lett.*, vol. 19, no. 8, pp. 1442-1445, Aug. 2015. Article (CrossRef Link).

[6] L. Yang, W. Zhang, and S. Jin, "Interference alignment in device-to-device LAN underlaying cellular networks," *IEEE Trans. Wireless Commun.*, vol. 14, no. 7, pp. 3715-3723, Jul. 2015. Article (CrossRef Link).

[7] B. Guler and A. Yener, "Selective interference alignment for MIMO cognitive femtocell networks," *IEEE J. Sel. Areas Commun.*, vol. 32, no. 3, pp. 439-450, Mar. 2014. Article (CrossRef Link).
[8] W. Zhong, Y. Fang, S. Jin, K.-K. Wong, S. Zhong, and Z. Qian, "Joint resource allocation for device-to-device communications underlaying uplink MIMO cellular networks," *IEEE J. Sel. Areas Commun.*, vol. 33, no. 1, pp. 41-54, Jan. 2015. Article (CrossRef Link).
[9] Y. Yang, G. Scutari, P. Song, and D. P. Palomar, "Robust MIMO cognitive radio systems under interference temperature constraints," *IEEE J. Sel. Areas Commun.*, vol. 31, no. 11, pp. 2465-2482, Nov. 2013. Article (CrossRef Link).
[10] X. Gui, G. Kang, and P. Zhang, "Linear precoding design in multi-user cognitive MIMO systems with cooperative feedback," *IEEE Commun. Lett.*, vol. 16, no. 10, pp. 1580-1583, Oct. 2012. Article (CrossRef Link).
[11] Y. Noam and A. J. Goldsmith, "Blind null-space learning for MIMO underlay cognitive radio with primary user interference adaptation," *IEEE Trans. Wireless Commun.*, vol. 12, no. 4, pp. 1722-1734, Apr. 2013. Article (CrossRef Link).
[12] M. J. Rahman and L. Lampe, "Robust transceiver optimization for underlay device-to-device communications," in *Proc. of IEEE Int. Conf. Commun. (ICC)*, pp. 7695-7700, Jun. 2015. Article (CrossRef Link).
[13] X. Gui, G. X. Kang, and P. Zhang, "Sum-rate maximising in cognitive MIMO ad-hoc networks using weighted MMSE approach," *Electron. Lett.*, vol. 48, no. 19, pp. 1240-1242, Sep. 2012. Article (CrossRef Link).
[14] S. Ma, H. Du, T. Ratnarajah, and L. Dong, "Robust joint signal and interference alignment in cognitive radio networks with ellipsoidal channel state information uncertainties," *IET Commun.*, vol. 7, no. 13, pp. 1360-1366, Sep. 2013. Article (CrossRef Link).
[15] Y. Zhang, E. Dall'Anese, and G. B. Giannakis, "Distributed optimal beamformers for cognitive radios robust to channel uncertainties," *IEEE Trans. Signal Process.*, vol. 60, no. 12, pp. 6495-6508, Dec. 2012. Article (CrossRef Link).
[16] A. Alizadeh, H. R. Bahrami, M. Maleki, and S. Sastry, "Spatial sensing and cognitive radio communication in the presence of a *K*-user interference primary network," *IEEE J. Sel. Areas Commun.*, vol. 33, no. 5, pp. 741-754, May 2015. Article (CrossRef Link).
[17] R. Mei, "Rayleigh quotient based interference alignment spectrum sharing in MIMO cognitive radio networks," *China Commun.*, vol. 12, no. 6, pp. 96-105, Jun. 2015. Article (CrossRef Link).
[18] M. Amir, A. El-Keyi, and M. Nafie, "Constrained interference alignment and the spatial degrees of freedom of MIMO cognitive networks," *IEEE Trans. Inf. Theory*, vol. 57, no. 5, pp. 2994-3004, May 2011. Article (CrossRef Link).
[19] F. Rezaei and A. Tadaion, "Sum-rate improvement in cognitive radio through interference alignment," *IEEE Trans. Veh. Technol.*, vol. 65, no. 1, pp. 145-154, Jan. 2016. Article (CrossRef Link).
[20] S. Yasukawa, H. Harada, S. Nagata, and Q. Zhao, "D2D communications in LTE-Advanced Release 12," *NTT DOCOMO Technical Journal*, vol. 17, no. 2, pp. 56-64, Oct. 2015.
[21] O. E. Ayach, S. W. Peters, and R. W. Heath Jr., "The practical challenges of interference alignment," *IEEE Wireless Commun.*, vol. 20, no. 1, pp. 35-42, Feb. 2013. Article (CrossRef Link).
[22] T. Wang, Y. Liao, B. Zhang, and L. Song, "Joint spectrum access and power allocation in full-duplex cognitive cellular networks," in *Proc. of IEEE Int. Conf. Commun. (ICC)*, Jun. 2015, pp. 3329-3334. Article (CrossRef Link).
[23] H. Sung, S.-H. Park, K.-J. Lee, and I. Lee, "Linear precoder designs for *K*-user interference channels," *IEEE Trans. Wireless Commun.*, vol. 9, no. 1, pp. 291-301, Jan. 2010. Article (CrossRef Link).
[24] B. Nosrat-Makouei, J. G. Andrews, and R. W. Heath Jr., "MIMO interference alignment over correlated channels with imperfect CSI," *IEEE Trans. Signal Process.*, vol. 59, no. 6, pp. 2783-2794, Jun. 2011. Article (CrossRef Link).

[25] K. Gomadam, V. R. Cadambe, and S. A. Jafar, "A distributed numerical approach to interference alignment and applications to wireless interference networks," *IEEE Trans. Inf. Theory*, vol. 57, no. 6, pp. 3309-3322, Jun. 2011. Article (CrossRef Link).

[26] K. Gomadam, V. R. Cadambe, and S. A. Jafar, "Approaching the capacity of wireless networks through distributed interference alignment," in *Proc. of IEEE Global Telecommunications Conference (GLOBECOM)*, pp. 1-6, Nov. 2008. Article (CrossRef Link).

[27] E. K. P. Chong and S. H. Żak, *An introduction to optimization*, 2nd Edition, Wiley, New York, 2004. Article (CrossRef Link).

[28] H. Ji, Y. Kim, J. Lee, E. Onggosanusi, Y. Nam, J. Zhang, B. Lee, and B. Shim, "Overview of full-dimension MIMO in LTE-Advanced Pro," *IEEE Commun. Mag.*, vol. PP, no. 99, pp. 2-11, Oct. 2016. Article (CrossRef Link).

[29] 3GPP, "3rd Generation Partnership Project; Technical Specification Group Radio Access Network; Requirements for further advancements for evolved universal terrestrial radio access (E-UTRA) (LTE-Advanced) (Release 13)," *TR 36.913*, *V13.0.0*, Dec. 2015. Article (CrossRef Link).

[30] F. Rosas and C. Oberli, "Energy-efficient MIMO SVD communications," in *Proc. of IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC)*, pp. 1588-1593, Sep. 2012. Article (CrossRef Link).

[31] D. Tse and P. Viswanath, *Fundamentals of wireless communication*, 1st Edition, Cambridge University Press, 2005. Article (CrossRef Link).

[32] 3GPP, "3rd Generation Partnership Project; Technical Specification Group Radio Access Network; Evolved universal terrestrial radio access (E-UTRA); Radio frequency (RF) system scenarios (Release 13)," *TR 36.942*, *V13.0.0*, Jan. 2016. Article (CrossRef Link).

[33] M. Peng, Y. Li, T. Q. S. Quek, and C. Wang, "Device-to-device underlaid cellular networks under rician fading channels," *IEEE Trans. Wireless Commun.*, vol. 13, no. 8, pp. 4247-4259, Aug. 2014. Article (CrossRef Link).

[34] 3GPP, "3rd Generation Partnership Project; Technical Specification Group Radio Access Network; LTE device to device (D2D) proximity services (ProSe); User equipment (UE) radio transmission and reception (Release 12)," *TR 36.877*, *V12.0.0*, Mar. 2015. Article (CrossRef Link).

[35] 3GPP, "Universal Mobile Telecommunications System (UMTS); Selection procedures for the choice of radio transmission technologies of the UMTS (UMTS 30.03 version 3.2.0)," *TR 30.03U*, *V3.2.0*, Mar. 1998. Article (CrossRef Link).

Yujin Nam received the B.S. and the M.S. degrees in Electronic Engineering from Sogang University, Seoul, Korea, in 2009 and 2012, respectively. He is currently working towards his Ph.D. degree at Sogang University, Seoul, Korea. His research interests include space division multiple access, MIMO communications, and vehicle communications.

Jaewoo So received the B.S. degree in electronic engineering from Yonsei University, Seoul, Korea, in 1997, and received the M.S. and Ph.D. degrees in electrical engineering from the Korea Advanced Institute of Science and Technology (KAIST), Daejeon, Korea, in 1999 and 2002, respectively. From 2001 to 2005, he was with IP One, Seoul, Korea, where he led several research projects and developed IEEE 802.11a/b/g products and heterogeneous network solutions. From 2005 to 2007, he was a Senior Engineer at Samsung Electronics, Suwon, Korea, where he involved in the design, performance evaluation, and development of mobile WiMAX systems and B3G wireless systems. From 2007 to 2008, he was a Postdoctoral Fellow in the Department of Electrical Engineering, Stanford University, Stanford, CA, USA. From August 2014 to July 2015, he was a visiting professor in the Department of Electrical and Computer Engineering, University of Illinois at Urbana-Champaign, IL, USA. Since September 2008, he has been with the Department of Electronic Engineering, Sogang University, Seoul, Korea, where he is currently an Associate Professor. His current research interests include 4G/5G radio access networks, vehicle communications, cognitive radio networks, and IoT networks. He is a Member of KSII, a Senior Member of IEEE, a Life Member of KICS, a Member of IEEK, and a Member of IEICE.

Jinsung Kim received the B.S. and Ph.D. degrees in electrical engineering from Korea University, Seoul, Korea in 2006 and 2012, respectively. From 2012 to 2015, he was a Member of Technical Staff with Bell Laboratories Seoul, Alcatel-Lucent. He is currently a Manager of Encored Technologies, Seoul, Korea. His research interests are signal processing techniques for wireless and smart grid systems.