Robust Null-Space Based Interference Avoiding Scheme for D2D Communication Underlaying Cellular Networks

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***Abstract*—In this paper, we design a null-space based robust interference avoiding strategy for the Device-to-Device (D2D) communication underlaying network. Thanks to the coordination between D2D user and the regular user, the interfering channel state information (CSI) among the base station (BS), cellular user equipment (CUE) and the D2D user equipments (DUEs) can be estimated from the training approach. Then, the null-space based transmit and receive beamformings are designed at appropriate terminals to mitigate the interference caused in the future data transmission. To make the design practical, we also characterize the null-space uncertainty that is resulted from the imperfect channel estimation. Moreover, we derive the optimal transmission strategy that can achieve the best training-throughput tradeoff. Simulation results are provided to corroborate the proposed studies.**

I. Introduction

In recent years, frequency reuse models, e.g., multi-cell, pico-cell, and femto-cell, have attracted lots of attentions due to their capabilities of increasing the system throughput and enhancing the spectrum efficiency. For the short range transmission, a new technology named device-to-device (D2D) communication has been introduced into LTE-Advanced standards, which reuses the same cellular resources and works as an underlay to the cellular networks [1], [2]. In D2D scenario, one D2D user Equipment (DUE) communicates with the other over the direct link without aid of base station (BS) by reusing the uplink (UL) or downlink (DL) frequency of a cellular user equipment (CUE) when the quality of the D2D connectivity is good enough to meet the transmission criterion.

A number of D2D works [2]–[7] focused on the interference cancellation strategy. To protect CUEs from being interfered by DUEs, [2] proposed to control the maximum transmission power of DUE transmitters by BS. In [3], the throughput of DUEs was optimized under spectral efficiency constraints and energy limitations both in orthogonal and non-orthogonal resource sharing situations. In [4], the authors designed a practical interference-aware resource allocation scheme according to the local awareness of the interference between CUEs and DUEs, which exploits multi-user diversity in the cellular system. To mitigate CUE-to-DUE interference, the authors in [5] proposed a retransmission of the interference from BS to DUE, helping DUE to cancel the interference. In [6], the interference from BS to DUE was avoided from a sophisticatedly designed precoding scheme in the cellular downlink transmission. In [7], the authors proposed a δ_d-interference limited area, and the coexistence of CUEs and DUEs is not permitted in such area if the interference to signal ratio is greater than the predefined threshold.

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Most of the above mentioned works [2]–[7] assumed that the accurate channel state information (CSI) is available at the receivers, which is not realistic from the practical viewpoint. In this paper, we design a robust D2D interference avoiding strategy based on the estimated CSI. Considering in the D2D underlaying cellular network that different terminals can work cooperatively, the CUE and BS can facilitate the DUE to obtain the interfering CSI. We first resort to the linear minimum mean-square error (LMMSE) channel estimation method to obtain the CSI from CUE and BS to DUEs. Then the transmit beamforming is designed at the DUE transmitter (DUE-T) to direct the signals only towards the nullspace of the estimated DUE-T→BS channel. Meanwhile, the receive beamforming is applied at DUE receiver (DUE-R) to receive the signals only through the nullspace of the estimated CUE→DUE-R channel. All the errors that are caused by the imperfect CSI are analytically characterized to facilitate the later design. Finally, an optimal training-throughput tradeoff of the DUE link is studied.

II. System Model

Let us consider a single cellular network, where one D2D pair shares UL resources with one CUE. The number of the antennas at DUE-T, DUE-R, CUE, and BS are M_T, M_R, M_C, M_B, respectively, as illustrated in Fig.1. Nevertheless, our scheme is also feasible when D2D pair shares DL resources.

Denote the channels from DUE-T to BS and from CUE to DUE-R as the $M_B \times M_T$ matrix $\mathbf{H}_{TB}$ and the $M_R \times M_C$ matrix $\mathbf{H}_{CR}$, respectively. We assume that channels are independent circularly symmetric complex Gaussian (CSCG)

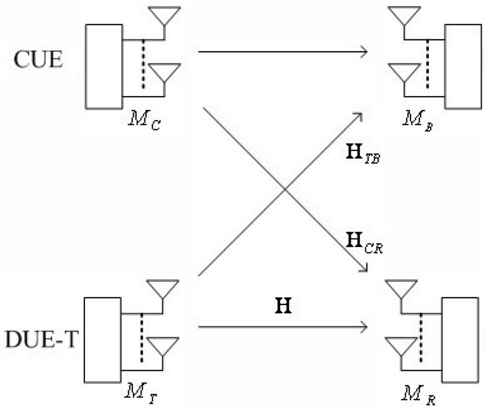

Fig. 1. System model for D2D underlaying cellular network sharing the uplink resource.

random variable with zero mean and unit variance.[1] Moreover, the channels are quasi-static that keep constant during one block transmission but can vary from block to block.

III. D2D Interference Avoiding Strategy

We propose to remove the interference by coordinately transmitting and receiving from the nullspace between CUE and DUE.[2] For example, if $M_T > M_B$, then the transmit beamforming will be applied at DUE-T such that the signal of DUE will be direct to the nullspace of $\mathbf{H}_{TB}$. However, if $M_T < M_B$, then, BS can receive the signal of CUE from the null space of $\mathbf{H}_{TB}$. In this paper, for the ease of the illustration, we assume $M_T > M_B$ and $M_R > M_C$, namely, both the transmit and receive beamforming will be performed at DUE side.

A. Channel Estimation

Thanks to the coordination between BS and DUEs, we can estimate the channel $\mathbf{H}_{TB}$ at BS while estimate $\mathbf{H}_{CR}$ at DUE-R from a training process. Then the nullspace can be derived from the estimated channels. We can ask BS to feed back either $\mathbf{H}_{TB}$ or the nullspace to DUE-T.[3]

Suppose N time slots are used for training, then the received signal block at BS can be expressed as [8]

$$\mathbf{Y}_B = \mathbf{H}_{TB}\mathbf{T} + \mathbf{Z}, \tag{1}$$

where $\mathbf{T}$ is the $M_T \times N$ training matrix and $\mathbf{Z}$ is the $M_B \times N$ noise matrix at DUE-T whose element has variance σ_z^2. In order to obtain a valid estimation of $\mathbf{H}_{TB}$, the length of the training sequence should satisfy $N \geq M_T$.

[1]This assumption is only necessary when we use LMMSE channel estimation. One can also refer to zero forcing (ZF) channel estimation and remove this assumption.

[2]Though the optimal beamforming design should be derived using the CSI itself, pointing the beam directly to the nullspace will be much less complex and more practical to implement.

[3]In time-division-multiplexing (TDD) system, we can directly perform the channel estimation at DUE-T and obtain $\mathbf{H}_{TB}$ from the reciprocity.

The LMMSE based channel estimator for $\mathbf{H}_{TB}$ can be obtained as [9]

$$\tilde{\mathbf{H}}_{TB} = \mathbf{Y}_B(\mathbf{T}^H\mathbf{T} + \sigma_z^2 M_B \mathbf{I})^{-1}\mathbf{T}^H\mathbf{R}_{H_{TB}}, \tag{2}$$

where $\mathbf{R}_{H_{TB}} = \mathrm{E}\{\mathbf{H}_{TB}^H\mathbf{H}_{TB}\} = \mathbf{I}$ is utilized in the above derivation. The error matrix, defined as

$$\Delta\mathbf{H}_{TB} = \mathbf{H}_{TB} - \tilde{\mathbf{H}}_{TB}, \tag{3}$$

has the covariance as [10]

$$\mathbf{R}_{TB} = \mathrm{E}[\Delta\mathbf{H}_{TB}\Delta\mathbf{H}_{TB}^H] = \left(\mathbf{I} + \frac{1}{\sigma_z^2 M_B}\mathbf{T}\mathbf{T}^H\right)^{-1}. \tag{4}$$

Suppose the average transmit power on each antenna at DUE-T is σ_d^2, then the optimal training that could minimize the mean square error is the orthogonal training, i.e., $\mathbf{T}\mathbf{T}^H = N\sigma_d^2\mathbf{I}$, and the corresponding covariance is $\mathbf{R}_{TB} = (1 + \frac{N\sigma_d^2}{M_B\sigma_z^2})^{-1}\mathbf{I}$.

The estimation of $\mathbf{H}_{CR}$ can be obtained in the same way, which is omitted here. For the ease of illustration, we assume the same number of time slots N and the same average power σ_d^2 that will be used from CUE. The corresponding CSI error, defined as $\Delta\mathbf{H}_{CR}$, has covariance $\mathbf{R}_{CR} = (1 + \frac{N\sigma_d^2}{M_R\sigma_z^2})^{-1}\mathbf{I}$.

B. Nullspace Derivation

Since $\mathbf{H}_{TB}$ is a fat matrix, its singular-value decomposition (SVD) can be expressed as

$$\mathbf{H}_{TB} = \mathbf{U}_{TB}\begin{bmatrix}\mathbf{\Sigma}_{TB} & \mathbf{0}\end{bmatrix}\begin{bmatrix}\mathbf{V}_{TBs}^H \\ \mathbf{V}_{TBn}^H\end{bmatrix}, \tag{5}$$

where $\mathbf{\Sigma}_{TB}$ is an $M_B \times M_B$ diagonal matrix, while $\mathbf{U}_{TB}$, $\mathbf{V}_{TBs}$ and $\mathbf{V}_{TBn}$ are the corresponding eigenmatrices. Note that $\mathbf{V}_{TBn}$ of size $M_T \times (M_T - M_B)$ span the nullspace of $\mathbf{H}_{TB}$ with $\mathbf{H}_{TB}\mathbf{V}_{TBn} = \mathbf{0}$. That is, if DUE-T transmit only through the space spanned by $\mathbf{V}_{TBn}$, i.e., precoding the transmitted signal by $\mathbf{V}_{TBn}$, then no interference would be generated to BS.

However, since only N time slots are used for training, the estimation of $\mathbf{V}_{TBn}$, denoted as $\tilde{\mathbf{V}}_{TBn}$, cannot be perfectly orthogonal to $\mathbf{H}_{TB}$. In order to provide a robust design, we need to characterize the imperfection in $\tilde{\mathbf{V}}_{TBn}$. Since $\tilde{\mathbf{V}}_{TBn}$ is obtained from $\tilde{\mathbf{H}}_{TB}$, there is

$$\tilde{\mathbf{H}}_{TB}\tilde{\mathbf{V}}_{TBn} = \mathbf{0}, \tag{6}$$

which can be further expanded as

$$(\mathbf{H}_{TB} + \Delta\mathbf{H}_{TB})(\mathbf{V}_{TBn} + \Delta\mathbf{V}_{TBn}) = \mathbf{0} \tag{7}$$

$$\Longrightarrow \quad \mathbf{H}_{TB}\Delta\mathbf{V}_{TBn} \approx -\Delta\mathbf{H}_{TB}\mathbf{V}_{TBn}, \tag{8}$$

where the fact that $\mathbf{H}_{TB}\mathbf{V}_{TBn} = \mathbf{0}$ is used and the higher order statistics $\Delta\mathbf{H}_{TB}\Delta\mathbf{V}_{TBn}$ is omitted.

Remark 1: Unfortunately, since $\mathbf{H}_{TB}$ is a fat matrix, we cannot left multiply both side by $(\mathbf{H}_{TB})^\dagger$ to obtain the expression of $\Delta\mathbf{V}_{TBn}$. Nevertheless, it will be seen later that knowing $\mathbf{H}_{TB}\Delta\mathbf{V}_{TBn}$ is already enough for the future design.

Similarly, DUE-R will be interfered by CUE during the transmission. Let the SVD of the tall matrix $\mathbf{H}_{CR}$ be

$$\mathbf{H}_{CR} = [\mathbf{U}_{CRs}, \mathbf{U}_{CRn}]\begin{bmatrix}\mathbf{\Sigma}_{CR} \\ \mathbf{0}\end{bmatrix}\mathbf{V}_{CR}^H \tag{9}$$

where $\mathbf{\Sigma}_{TB}$ is an $M_C \times M_C$ diagonal matrix, while $\mathbf{U}_{CRs}$, $\mathbf{U}_{CRn}$, and $\mathbf{V}_{CR}$ represent the corresponding eigenmatrices. Note that $\mathbf{U}_{CRn}$ of size $M_R \times (M_R - M_C)$ spans the nullspace of $\mathbf{H}_{CR}$ with $\mathbf{U}_{CRn}^H \mathbf{H}_{CR} = \mathbf{0}$. That is, if DUE-R receive only through the space spanned by $\mathbf{U}_{CRn}$, i.e., filter the received signal by $\mathbf{U}_{CRn}^H$, then no interference would be generated to DUE-R. The imperfection in $\mathbf{U}_{CRn}$, denoted by $\Delta\mathbf{U}_{CRn}$, can be characterized as

$$\mathbf{H}_{CR}^H \Delta\mathbf{U}_{CRn} = -\Delta\mathbf{H}_{CR}^H \mathbf{U}_{CRn}. \tag{10}$$

C. Data Transmission with Imperfect Beamforming

Denote the signals from DUE-T and CUE as $\mathbf{d}_T$ and $\mathbf{d}_C$, respectively. The transmitted signals from DUE-T are precoded by $\tilde{\mathbf{V}}_{TBn}$, and the received signals at DUE-R are denoted as

$$\mathbf{y}_R = \mathbf{H}\tilde{\mathbf{V}}_{TBn}\mathbf{d}_T + \mathbf{H}_{CR}\mathbf{d}_C + \mathbf{z}_R, \tag{11}$$

where $\mathbf{H}$ is the channel between DUE-T and DUE-R and $\mathbf{z}_R$ is the CSCG noise at DUE-R. After applying the receive beamforming at DUE-R, the received signals are rewritten as

$$\begin{aligned} \bar{\mathbf{y}}_R &= \tilde{\mathbf{U}}_{CRn}^H \mathbf{H}\tilde{\mathbf{V}}_{TBn}\mathbf{d}_T + \Delta\mathbf{U}_{CRn}^H \mathbf{H}_{CR}\mathbf{d}_C + \tilde{\mathbf{U}}_{CRn}^H \mathbf{z}_R \\ &= \mathbf{A}\mathbf{d}_T + \Delta\mathbf{U}_{CRn}^H \mathbf{H}_{CR}\mathbf{d}_C + \bar{\mathbf{z}}_R, \end{aligned} \tag{12}$$

where $\mathbf{A}$ and $\bar{\mathbf{z}}_R$ denote the equivalent channel and noise, and $\Delta\mathbf{U}_{CRn}^H \mathbf{H}_{CR}\mathbf{d}_C$ is the residue interference from CUE. Since $\mathbf{H}$ (or $\mathbf{A}$) is the channel between the transceiver of D2D, we can assume that the estimation of $\mathbf{H}$ (or $\mathbf{A}$) is perfect, for the time being.

The covariance matrix of the residue interference from CUE can be computed as

$$\begin{aligned} &\mathbf{E}_{CR} = \mathbf{E}[\Delta\mathbf{U}_{CRn}^H \mathbf{H}_{CR}\mathbf{d}_C\mathbf{d}_C^H\mathbf{H}_{CR}^H\Delta\mathbf{U}_{CRn}] \\ &= \mathbf{E}[\mathbf{U}_{CRn}^H \Delta\mathbf{H}_{CR}\mathbf{R}_{dC}\Delta\mathbf{H}_{CR}^H\mathbf{U}_{CRn}] \\ &= \mathbf{U}_{CRn}^H \times \frac{tr(\mathbf{R}_{dC})}{1+\frac{N\sigma_d^2}{M_R\sigma_z^2}}\mathbf{I} \times \mathbf{U}_{CRn} = \frac{M_C\sigma_d^2}{1+\frac{N\sigma_d^2}{M_R\sigma_z^2}}\mathbf{I}, \end{aligned} \tag{13}$$

where the result in (10) is used and $\mathbf{R}_{dC} = E[\mathbf{d}_C\mathbf{d}_C^H] = \sigma_d^2\mathbf{I}$ is the signal covariance matrix from CUE.

Another impact of the imperfect CSI is that DUE-T will bring residual interference to BS, i.e., $\mathbf{H}_{TB}\Delta\mathbf{V}_{TBn}\mathbf{d}_T$ whose covariance is

$$\begin{aligned} &\mathbf{E}_{TB} = \mathbf{E}[\mathbf{H}_{TB}\Delta\mathbf{V}_{TBn}\mathbf{d}_T\mathbf{d}_T^H\Delta\mathbf{V}_{TBn}^H\mathbf{H}_{TB}] \\ &= \mathbf{E}[\Delta\mathbf{H}_{TB}\mathbf{V}_{TBn}\mathbf{R}_{dT}\mathbf{V}_{TBn}^H\Delta\mathbf{H}_{TB}^H] \\ &= \frac{tr(\mathbf{R}_{dT})}{1+\frac{N\sigma_d^2}{M_B\sigma_z^2}}\mathbf{I} = \frac{M_T\sigma_d^2}{1+\frac{N\sigma_d^2}{M_B\sigma_z^2}}\mathbf{I}, \end{aligned} \tag{14}$$

where $\mathbf{R}_{dT} = \mathbf{E}[\mathbf{d}_T\mathbf{d}_T^H] = \frac{M_T\sigma_d^2}{M_T - M_B}\mathbf{I}$ is the covariance matrix of $\mathbf{d}_T$. Note that the scaling factor $\frac{M_T}{M_T - M_B}$ is used to keep the overall data transmit power at DUE-T unchanged.

Remark 2: With the proposed nullspace beamforming, the interference between DUE and CUE can be viewed as white on both sides, which may assist the joint optimization of both DUE and CUE transmission. In this paper, nevertheless, we adopt a different designing process for the ease of illustration, that is BS set a restriction ζ on the overall interfering power received from DUE-T.[4] The advantage of this process is that the design of D2D link and CUE link can be separately performed because the interference powers at DUE and CUE are only related with $tr(\mathbf{R}_{dC})$ and $tr(\mathbf{R}_{dT})$, i.e., the transmit power. Therefore, the design of the structure of $\mathbf{R}_{dC}$ at CUE will not affect the design at DUE-T and vice versa.

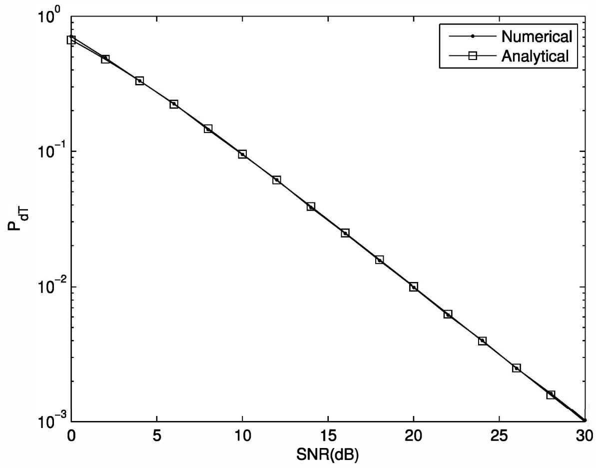

Fig. 2. Numerical and analytical results of interference power at BS.

The interference power at BS can be computed as

$$\mathbf{P}_{dT} = \; tr(\mathbf{E}_{TB}) = \frac{M_B M_T \sigma_d^2}{1+\frac{N\sigma_d^2}{M_B\sigma_z^2}}. \tag{15}$$

We numerically examine our analytical result (15) in Fig. 2, where the parameters are set as $M_T = M_R = 4$, $M_B = 2$, $M_C = 1$. Clearly, the numerical result matches the analytical one quite well.

Remark 3: Analytically characterizing the error covariance matrices (13) and (14) is helpful for any kind of the future analysis, for example, maximizing the system throughput, minimizing the detection BER, etc.

D. The Optimization

In this paper, we will select maximizing the system throughput as our objective. Suppose the overall transmission time is T. Since $2N$ time slots are spent on the channel estimation of $\mathbf{H}_{TB}$ and $\mathbf{H}_{CR}$, the time left for D2D data transmission is $T - 2N$. Since $\Delta\mathbf{U}_{CRn}^H\mathbf{H}_{CR}\mathbf{d}_C$ may not be white Gaussian, we cannot use the well known Shannon formulation [11] to derive the system capacity. Nevertheless, we know from [12] that a lower bound on the average throughput of D2D link can be expressed as

$$\mathcal{C}_{D2D} = \frac{T-2N}{T}\log\left|\mathbf{I} + \frac{\mathbf{A}\mathbf{R}_{dT}\mathbf{A}^H}{\sigma_z^2 + w}\right|, \tag{16}$$

[4]Since the interference is white, we can also set the interference restriction on each antenna and this does not change the following discussion.

where $w=\sigma_d^2 M_C/(1+\frac{N\sigma_d^2}{M_R\sigma_z^2})$.

Considering the interference limitation at BS, the transmit covariance design at DUE-T should satisfy:

$$tr(\mathbf{R}_{dT}) \leq \frac{M_B\sigma_z^2+N\sigma_d^2}{M_B^2\sigma_z^2}\zeta. \tag{17}$$

The self-power constraint is expressed as

$$tr(\mathbf{R}_{dT}) \leq M_T\sigma_d^2. \tag{18}$$

Then the optimization for D2D throughput is then formulated as

$$\begin{aligned} \max_{N,\mathbf{R}_{dT}} \quad & \mathcal{C}_{D2D} \\ \text{s.t.} \quad & tr(\mathbf{R}_{dT}) \leq J, \quad \mathbf{R}_{dT} \succcurlyeq \mathbf{0}, \quad 0<N<T/2, \end{aligned} \tag{19}$$

where $J=\min\{M_T\sigma_d^2, \frac{M_B\sigma_z^2+N\sigma_d^2}{M_B^2\sigma_z^2}\zeta\}$.

Let the eigenvalue decomposition (EVD) of $\mathbf{A}^H\mathbf{A}$ be $\mathbf{Q}\mathbf{\Lambda}\mathbf{Q}^H$, where $\mathbf{Q}$ is an $(M_T-M_B)\times(M_T-M_B)$ unitary matrix and $\mathbf{\Lambda}=\text{Diag}(\lambda_1^2,\ldots,\lambda_{M_T-M_B}^2)$, with λ_i's being arranged in a descending order. Define $\mathbf{X}=\mathbf{Q}^H\mathbf{R}_{dT}\mathbf{Q}$. Then, the optimization of the throughput lower bound is expressed as

$$\begin{aligned} \max_{N,\mathbf{R}_{dT}} \quad & \frac{T-2N}{T}\log\left|\mathbf{I}+\frac{\mathbf{X}\mathbf{\Lambda}}{\sigma_z^2+w}\right| \\ \text{s.t.} \quad & tr(\mathbf{R}_{dT}) \leq J, \quad \mathbf{R}_{dT} \succcurlyeq \mathbf{0}, \quad 0<N<T/2, \end{aligned} \tag{20}$$

By the standard approach, the optimal structure of $\mathbf{X}$ is diagonal, i.e., $\mathbf{X}=\text{Diag}(x_1,\ldots,x_{M_T-M_B})$, and x_i's can be obtained from the following water-filling algorithm [11], [13]:

$$\begin{aligned} \max_{N,\{x_i\}} \quad & \frac{T-2N}{T}\sum_{i=1}^{M_T-M_B}\log\left(1+\frac{x_i\lambda_i^2}{\sigma_z^2+w}\right) \\ \text{s.t.} \quad & \sum_{i=1}^{M_T-M_B} x_i \leq J, \quad x_i \geq 0, \quad 0<N<T/2. \end{aligned} \tag{21}$$

The solution is expressed as

$$x_i=\left(\nu-\frac{\sigma_z^2+w}{\lambda_i^2}\right)^+, \tag{22}$$

where $(\cdot)^+=\max\{0,\cdot\}$, and ν represents the water level that should satisfy

$$\sum_{i=1}^{M_T-M_B}\left(\nu-\frac{\sigma_z^2+w}{\lambda_i^2}\right)^+=J. \tag{23}$$

With the optimal signal covariance, the throughput lower bound can be rewritten as a function of N, i.e.,

$$\begin{aligned} \mathcal{C}_{D2D} =& \frac{T-2N}{T}\sum_{i=1}^{M_T-M_B}\log\left(1+\left(\frac{\nu\lambda_i^2}{\sigma_z^2+w}-1\right)^+\right) \\ =& \frac{T-2N}{T}\sum_{i=1}^{M_T-M_B}\left(\log\frac{\nu\lambda_i^2}{\sigma_z^2+w}\right)^+. \end{aligned} \tag{24}$$

Since the waterfilling algorithm is, in fact, an iterative algorithm, (24) cannot be counted as a closed-form expression, whose convexity cannot be checked simply through taking the second order derivative. Here we only make a general remark while a rigorous proof will be provided in our future work.

Remark 4: When N increases, channel estimation becomes better, resulting in two effects: (i) the residue interference from the CUE becomes less, i.e., w reduces; (ii) the constraint (15) is relaxed, i.e., more power from DUE-T is allowed at this constraint. However, there is a negative effect from increasing N, that is the time left for data transmission becomes less, i.e, $T-2N$ reduces. From the above discussion, we see that there must be an optimal point when we adjust the value of N.

Although we could not obtain the convexity (24) for the time being, we note that N can only take discrete values from M_T-M_B to $2T-1$. Therefore, we can simply perform the finite number searching to find the optimal training time.

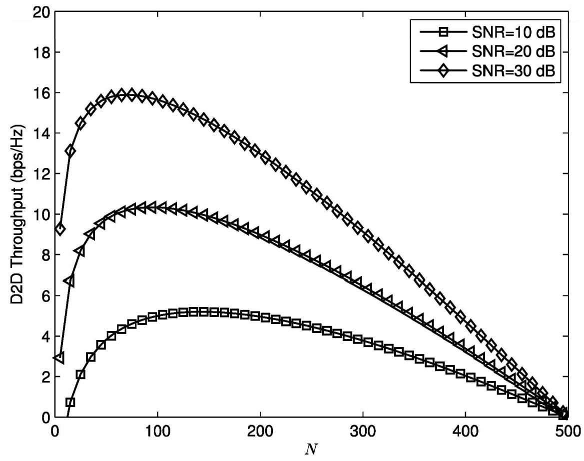

Fig. 3. D2D link throughput versus N under different SNR.

IV. Simulations

In this section, we numerically evaluate our proposed subspace based transmission scheme for D2D underlaying cellular networks. We consider a system with the parameters $M_T=M_R=4$, $M_B=2$, $M_C=1$. The parameter T is taken as 1000 and the lowest value of N is 2. The noise variance is set as 1 and the SNR is defined as σ_d^2.

A. D2D Throughput versus N

In the first example, we fix ζ as 0.04 as the tolerable interference threshold at BS and show the throughput variations as a function of N with SNR= 10 dB, SNR= 20 dB and SNR= 30 dB, respectively. From Fig. 3, we see that there is a clear optimal training time N that maximizes the throughput of D2D link. The curves seem to be concave but unfortunately we cannot analytically prove it. Nevertheless, this can be left as an interesting future topic. It is also observed that when SNR increases, the optimal N becomes smaller, which says that less training is needed. This is because that the channel estimation is sufficiently good at high SNR and it is not worthy to further improve the channel estimation.

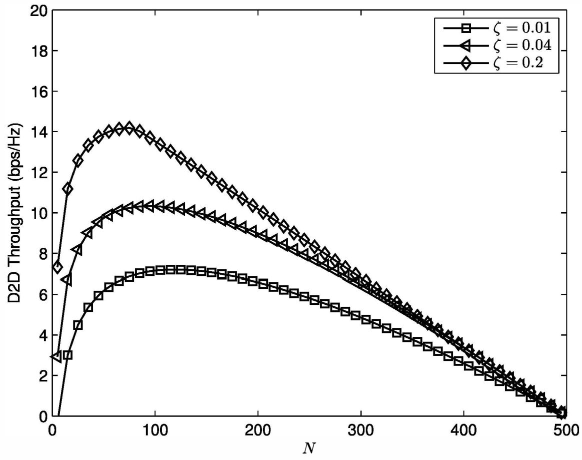

Fig. 4. D2D link throughput versus N under different ζ.

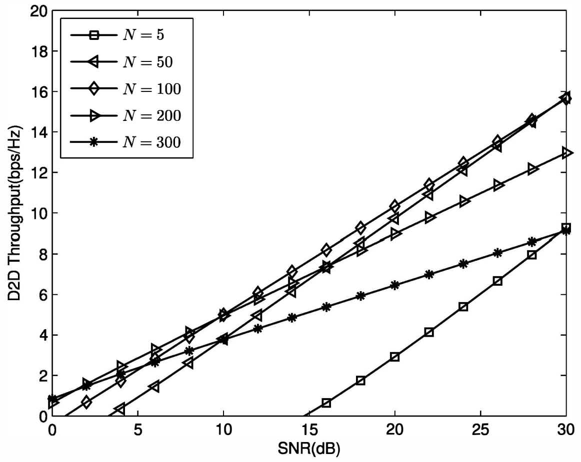

Fig. 5. D2D link throughput versus SNR.

We then fix SNR as 20 dB and display the D2D throughput versus N with different ζ in Fig. 4. We see that the maximum throughput of D2D increases with ζ because more interference leakage power can be tolerated by BS and then more power from DUE-T is allowed. Moreover, the optimal N becomes smaller with the increase of ζ. This is because that when more interference is tolerable at BS, then, the requirement for accurate channel estimation reduces and the number of the training becomes less. Another observation is that the D2D throughputs under different ζ merge when the training time N is sufficiently large. The reason lies in that the constraint (17) is not active and ζ has no effect on the throughput.

B. D2D Throughput versus SNR

In this example, we set ζ as 0.04 and demonstrate the D2D throughput versus SNR under different values of N. Obviously, the D2D throughput increases when SNR increases for a given N. The reason lies in two facts: (i) data transmission enjoys a higher power; (ii) the channel estimation becomes accurate when SNR increase. However, the increasing rate of throughput, i.e., the slope of the curve, becomes slower when N is large. The main reason is that the predominant factor that determines the value of D2D throughput is the coefficient $(T - 2N)/T$ when N goes sufficiently large, which leaves fewer time for data communication. Moreover, the intersection of curves says that the optimal N changes with different SNR, which is the same observation in Fig. 3.

V. Conclusions

In this paper, we have proposed a robust interference mitigation scheme for the multiple-antenna D2D underlaying cellular network. Spending a short time for channel estimation, the nullspace between the CUE and DUE can be obtained, and the practical transmit and receive beamforming are designed pointing to the direction of the nullspace to minimize the resultant interference to BS and from CUE. More importantly, we have characterized different kinds of errors, e.g., CSI, nullspace, residue interference at both sides etc., and, therefore, ease the future design with any kind of the objective functions and constraints. In this paper, we have selected maximizing the lower bound of the D2D throughput as an example due to the convenience of the illustration.

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