On Selecting Communication Mode for a D2D Pair in Underlay Cellular Network With Multi-Antenna Base Station

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***Abstract*—In D2D communication underlaying cellular network, a D2D transmitter can communicate to a receiver either directly in D2D mode or via a base station in cellular mode. In this study, the base station is assumed to have multiple receive antennas. We formulate a mode-selection problem that minimizes transmission power for the D2D transmitter and is subject to constraints on the minimum rate and maximum interference to primary users in the network. Solutions to the problem are found by numerical method. Numerical example shows that by increasing the number of antennas of the base station from 1 to 2 in some setting, the minimum transmission power decreases substantially.**

I. Introduction

Device-to-device (D2D) communication is defined as a direct connection between mobile devices without involvement of base stations in a cellular network, and has gained great interest due to increasing demand of wireless transmission [1]. D2D communication between two devices within a short distance from one another can minimize transmission power, increase transmission rate, or decrease interference to other users in the network.

In this work, we consider underlay inband transmission in which a single D2D transmitter-receiver pair shares an uplink channel with another cellular user who is a primary user of the network. In general, D2D devices are assumed to be able to choose to communicate in either D2D or cellular mode, depending on their objective. In [2], [3], sum rate or throughput is maximized over different communication modes of D2D pairs while in [4], [5], power consumption or power efficiency is optimized. Reference [6] considers mode selection in time-division duplex to maximize energy efficiency. In [7], devices and base stations are placed according to a Poisson point process, and mode of communication is shown to depend on the distance between devices, and the distance between transmitting device and base station.

In our previous work [8], we also considered an inband underlay system in which a mobile device can select to communicate to another device in either D2D or cellular mode. For that work and this current work, the transmitting device selects the mode that minimizes its transmission power. The optimal mode was analyzed for both general and Rayleigh fading channels. In this work, we assume that the base station has multiple receive antennas instead of a single receive antenna. The solution to the problem is stated. Numerical examples show that the minimum transmission power can be substantially reduced by increasing the number of antennas at the base station.

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II. System model

We assume a pair of transmitter and receiver, which is able select to communicate in either D2D or cellular mode, in a single-cell network. In D2D mode, the transmitter to which we refer as Tx transmits data directly to the receiver to which we refer as Rx. Tx shares an uplink channel with some cellular user and thus, Rx will be interfered by that user to which we refer as UEc. Each Tx, Rx, and UEc have single antenna. For all communication links, we assume that the transmitted signal propagates through a rich-scattering channel whose delay spread is much shorter than a symbol period. Thus, the channel for each link is independent Rayleigh fading with single channel-filter tap. Assuming additive white Gaussian noise with zero mean and variance σ_n^2, an achievable rate for Tx-Rx link is given by

$$R_{\mathsf{D2D}} = E\left[\log\left(1 + \frac{|h_{\mathsf{Tx-Rx}}|^2 g_{\mathsf{Tx-Rx}}^2 P_{\mathsf{D2D}}}{\sigma_n^2 + \frac{|h_{\mathsf{Tx-Rx}}^* h_{\mathsf{UEc-Rx}}|^2}{|h_{\mathsf{Tx-Rx}}|^2} g_{\mathsf{UEc-Rx}}^2 P_{\mathsf{UEC}}}\right)\right] \quad (1)$$

where P_{D2D} denotes the transmission power of Tx in D2D mode, P_{UEC} denotes the transmission power of UEc, $h_{\mathsf{i-j}}$ denotes a random fading gain between nodes i and j with complex Gaussian density function with zero mean and unit variance, and $g_{\mathsf{i-j}}$ denotes a deterministic channel gain between nodes i and j, which decreases with the distance between the two nodes. The expectation in (1) denoted by $E[\cdot]$ is over random gains $h_{\mathsf{Tx-Rx}}$ and $h_{\mathsf{UEc-Rx}}$.

In this study, we assume that the base station to which we refer as BS, has N_r receive antennas. When Tx is in D2D mode, the UEc-BS link will be interfered by the Tx-Rx link, which shares the same frequency band. Assuming that maximum ratio combining is applied at BS, we can compute an achievable rate for UEc as follows

$$R_{\mathsf{UEC}} = E\left[\log\left(1 + \frac{\|\boldsymbol{h}_{\mathsf{UEc-BS}}\|^2 g^2_{\mathsf{UEc-BS}} P_{\mathsf{UEC}}}{\sigma_n^2 + \frac{|\boldsymbol{h}_{\mathsf{UEc-BS}}\boldsymbol{h}^{\dagger}_{\mathsf{Tx-BS}}|^2}{\|\boldsymbol{h}_{\mathsf{UEc-BS}}\|^2} g^2_{\mathsf{Tx-BS}} P_{\mathsf{D2D}}}\right)\right] \quad (2)$$

where $\boldsymbol{h}_{\mathsf{i-BS}}$ is a $1 \times N_r$ vector of fading gains between node i and each receive antenna of BS.

In cellular mode, Tx will communicate with Rx through BS and hence, will not interfere with any other cellular user. An achievable rate for Tx in cellular mode is given by

$$R_c = E\left[\log\left(1 + \frac{1}{\sigma_n^2}\|\boldsymbol{h}_{\mathsf{Tx-BS}}\|^2 g^2_{\mathsf{Tx-BS}} P_c\right)\right] \quad (3)$$

where P_c denotes the transmission power of Tx in cellular mode. In this mode, UEc with no interference from Tx can transmit at the following rate

$$R_{\mathsf{UEc\backslash D2D}} = E\left[\log\left(1 + \frac{1}{\sigma_n^2}\|\boldsymbol{h}_{\mathsf{UEc-BS}}\|^2 g^2_{\mathsf{UEc-BS}} P_{\mathsf{UEC}}\right)\right]. \quad (4)$$

We would like to minimize transmission power of Tx in either D2D or cellular mode for given constraints on the minimum rate R and on the maximum rate degradation factor for UEc denoted by ϵ, where $R \geq 0$ and $0 < \epsilon < 1$. The optimization problem can be stated as follows

$$\begin{aligned} \text{Minimize} \quad & \min\{P_{\mathsf{D2D}}, P_c\} \\ \text{subject to} \quad & R_{\mathsf{D2D}} \geq R, \\ & R_{\mathsf{UEc}} \geq (1-\epsilon) R_{\mathsf{UEc\backslash D2D}}, \\ & R_c \geq R, \\ & P_{\mathsf{D2D}} \geq 0,\ P_c \geq 0. \end{aligned} \quad (5)$$

III. Mode Selection

In (1), both $|h_{\mathsf{Tx-Rx}}|^2$ and $|h^*_{\mathsf{Tx-Rx}} h_{\mathsf{UEc-Rx}}|^2 / |h_{\mathsf{Tx-Rx}}|^2$ are exponentially distributed and can be shown to be independent of each other since $h_{\mathsf{Tx-Rx}}$ and $h_{\mathsf{UEc-Rx}}$ are independent. By applying [9, eq. (20)], we previously have obtained the expression for R_{D2D} in [8, eq. (24)] as follows

$$R_{\mathsf{D2D}}(P_{\mathsf{D2D}}) = \left(1 - \frac{g^2_{\mathsf{UEc-Rx}} P_{\mathsf{UEc}}}{g^2_{\mathsf{Tx-Rx}} P_{\mathsf{D2D}}}\right)^{-1} \left[\mathcal{R}\left(\frac{g^2_{\mathsf{Tx-Rx}}}{\sigma_n^2} P_{\mathsf{D2D}}\right) - \mathcal{R}\left(\frac{g^2_{\mathsf{UEc-Rx}}}{\sigma_n^2} P_{\mathsf{UEc}}\right)\right] \quad (6)$$

where $\mathcal{R}(x) \triangleq e^{\frac{1}{x}} E_1\left(\frac{1}{x}\right)$ and the exponential integral $E_1(x) \triangleq \int_1^{\infty} \frac{1}{t} e^{-xt}\,dt$. We note that R_{D2D} is an increasing function of P_{D2D}.

Since $\boldsymbol{h}_{\mathsf{UEc-BS}}$ in (2) is a $1 \times N_r$ vector of independent complex Gaussian random gains with zero mean and unit variance, it follows that $\|\boldsymbol{h}_{\mathsf{UEc-BS}}\|^2$ is a scaled Chi-square random variable with $2N_r$ degrees of freedom. It can be shown that $|\boldsymbol{h}_{\mathsf{UEc-BS}}\boldsymbol{h}^{\dagger}_{\mathsf{Tx-BS}}|^2 / \|\boldsymbol{h}_{\mathsf{UEc-BS}}\|^2$ is exponentially distributed and is independent of $\|\boldsymbol{h}_{\mathsf{UEc-BS}}\|^2$. We apply [10, Lemma 1] to obtain, for $N_r \geq 2$,

$$R_{\mathsf{UEC}}(P_{\mathsf{D2D}}) = F_e\left(\frac{g^2_{\mathsf{Tx-BS}} P_{\mathsf{D2D}}}{g^2_{\mathsf{UEc-BS}} P_{\mathsf{UEC}}}, \frac{\sigma_n^2}{g^2_{\mathsf{UEc-BS}} P_{\mathsf{UEC}}}, N_r\right) \quad (7)$$

where $F_e(\cdot,\cdot,\cdot)$ is defined in [10, eq. (6)-(9)]. Unlike R_{D2D}, R_{UEC} is a decreasing function of P_{D2D}.

Next we determine the rates in (3) and (4). Since $\boldsymbol{h}_{\mathsf{Tx-BS}}$ and $\boldsymbol{h}_{\mathsf{UEc-BS}}$ are $1 \times N_r$ vectors of independent complex Gaussian random gains with zero mean and unit variance, it follows that $\|\boldsymbol{h}_{\mathsf{Tx-BS}}\|^2$ and $\|\boldsymbol{h}_{\mathsf{UEc-BS}}\|^2$ are scaled Chi-square random variables with $2N_r$ degrees of freedom. Applying [11, eq. (7)], we have

$$R_c(P_c) = \mathcal{C}_{N_r}\left(\frac{1}{\sigma_n^2} g^2_{\mathsf{Tx-BS}} P_c\right), \quad (8)$$

$$R_{\mathsf{UEc\backslash D2D}} = \mathcal{C}_{N_r}\left(\frac{1}{\sigma_n^2} g^2_{\mathsf{UEc-BS}} P_{\mathsf{UEC}}\right) \quad (9)$$

where

$$C_{N_r}(x) \triangleq E_1(1/x)\,\mathcal{P}_{N_r}(-1/x) + \sum_{k=1}^{N_r-1} \frac{1}{k} \mathcal{P}_k(1/x)\,\mathcal{P}_{N_r-k}(-1/x), \quad (10)$$

and the Poisson distribution function is given by $\mathcal{P}_k(x) \triangleq \sum_{l=0}^{k-1}(x^l/l!)e^{-x}$. Apparently, R_c increases with P_c.

To obtain the feasible range of P_{D2D}, we solve the following equations for $\underline{P}_{\mathsf{D2D}}$ and $\bar{P}_{\mathsf{D2D}}$:

$$R_{\mathsf{D2D}}(\underline{P}_{\mathsf{D2D}}) = R, \quad (11)$$

$$R_{\mathsf{UEC}}(\bar{P}_{\mathsf{D2D}}) = (1-\epsilon) R_{\mathsf{UEc\backslash D2D}}. \quad (12)$$

Closed-form solutions are not available and some numerical method is required to find the solutions. If $\underline{P}_{\mathsf{D2D}} \leq \bar{P}_{\mathsf{D2D}}$, the feasible range for P_{D2D} is given by

$$\underline{P}_{\mathsf{D2D}} \leq P_{\mathsf{D2D}} \leq \bar{P}_{\mathsf{D2D}}. \quad (13)$$

However, if $\underline{P}_{\mathsf{D2D}} > \bar{P}_{\mathsf{D2D}}$, D2D mode is not feasible. The feasible range of P_c is given by

$$P_c \geq \underline{P}_c \quad (14)$$

where $\underline{P}_c$ is obtained by numerically solving $R_c(\underline{P}_c) = R$.

Finally, the solution to problem (5) is given by

$$\text{Optimal Tx's power} = \begin{cases} \min\{\underline{P}_{\mathsf{D2D}}, \underline{P}_c\} & : \underline{P}_{\mathsf{D2D}} \leq \bar{P}_{\mathsf{D2D}} \\ \underline{P}_c & : \underline{P}_{\mathsf{D2D}} > \bar{P}_{\mathsf{D2D}} \end{cases}. \quad (15)$$

IV. Numerical Results

In a 2-dimensional cell, we place BS at coordinate (0, 0), UEc at (2, 2), Tx at (20, 20), and Rx at (22, 22). The deterministic gain between nodes i and j is given by

$$g_{\mathsf{i-j}} = \left(\frac{d_0}{d_{\mathsf{i-j}}}\right)^{0.6} \quad (16)$$

where the reference distance $d_0 = 1$ and $d_{\mathsf{i-j}} \geq d_0$. Fig. 1 shows 2 sets of graphs. The first set shows $\bar{P}_{\mathsf{D2D}}$, which is the largest feasible P_{D2D}, with the minimum degraded rate for UEc in D2D mode, and the number of receive antennas at BS, N_r. For this and the next figures, we set $\epsilon = 0.05$ and $\sigma_n^2 = 1$. As expected, $\bar{P}_{\mathsf{D2D}}$ decreases with the rate $(1 - \epsilon)R_{\mathsf{UEc\backslash D2D}}$. We also see that $\bar{P}_{\mathsf{D2D}}$ increases with N_r since UEc can tolerate larger interference from Tx with increasing number of receive antennas at BS. This also implies that the likelihood that D2D mode is available is increasing with N_r. The other graph shown by solid line without markers, displays $\underline{P}_{\mathsf{D2D}}$ with the minimum required rate for D2D pair, R. We note that $\underline{P}_{\mathsf{D2D}}$ increases with R as expected.

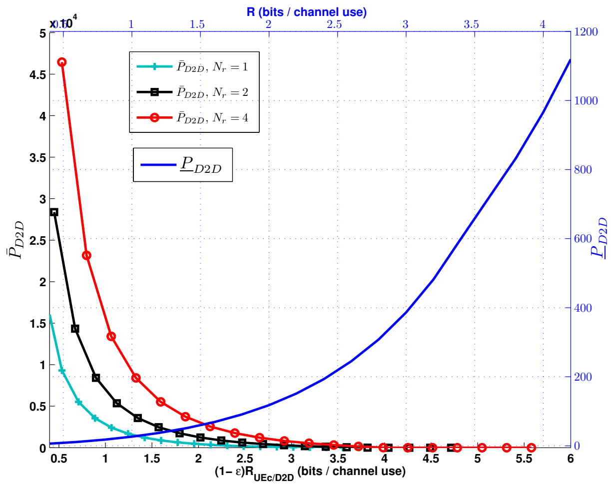

Fig. 1: $\bar{P}_{\mathsf{D2D}}$ and $\underline{P}_{\mathsf{D2D}}$ are plotted with rates.

For Fig. 2, we set BS at (0, 0), UEc at (100, 0), Rx at (0, 100), and Tx at $(0, 100 + d_{\mathsf{Tx-Rx}})$ where $d_{\mathsf{Tx-Rx}}$ will be varied from 0 to 10. For each location of Tx, we find the minimum transmission power for Tx and plot it with $d_{\mathsf{Tx-Rx}}$. For $N_r = 1$, the results are from [8]. For $N_r > 1$, the graphs for the minimum transmission power are piece-wise linear. The first piece of the graph is $\underline{P}_{\mathsf{D2D}}$ since D2D mode is optimal when $d_{\mathsf{Tx-Rx}}$ is sufficiently small. When $d_{\mathsf{Tx-Rx}}$ is larger, cellular mode is optimal and its transmission power is $\underline{P}_c$. We also note that as N_r increases, the transmission power decreases due to combining gain of multiple receive antennas at BS.

V. Conclusions

We formulate a mode-selection problem for D2D transmitter in underlay cellular network in which the base station is equipped with multiple receive antennas. The solutions to the problem are not in closed form and requires some numerical method. Numerical results show that as the number of receive antennas at the base station increases, the minimum transmission power for D2D transmitter decreases and the range of feasible transmission power in D2D mode expands. This also implies that the area where D2D mode is available to the D2D pair will be larger. In this study, all nodes except the base station are equipped with single antenna. Future work may consider the system in which nodes can have multiple antennas.

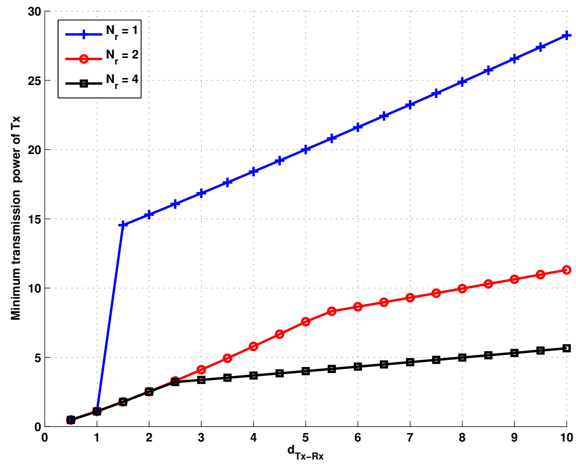

Fig. 2: Minimum transmission power for Tx with varying distance between the D2D pair ($d_{\mathsf{Tx-Rx}}$) and N_r.

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