Power-Minimizing Transmission Mode for Cell-Edge D2D Pair Underlaying Cellular Network

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***Abstract*—We consider device-to-device (D2D) communication underlaying cellular network in which D2D devices share uplink bands with cellular users and thus, will interfere with those users. D2D pair can also communicate via a base station in cellular mode, which does not cause interference with other cellular users, but will compete with them for available uplink channels. We formulate a mode-selection problem that minimizes transmission power for the D2D transmitter subject to constraints on signal-to-interference plus noise ratio (SINR). The D2D receiver is assumed to be at the cell edge while the location of the interfering cellular user is random with uniform distribution over the cell. We derive the inequality, which tests if D2D mode is feasible and find that the optimal mode of transmission depends largely on the cell radius and the distance between the D2D transmitter and receiver.**

I. Introduction

Device-to-device (D2D) communication can be integrated into cellular network to enhance network efficiency and thus, has attracted great interest recently [1]. In this study, we consider an underlay inband transmission in which a D2D pair shares an uplink channel with one primary user of the cellular network when the pair transmits in D2D mode. The D2D pair can also communicate via a base station in cellular mode. However, it has to compete for available uplink channels with other cellular users in the cell. In [2], [3], sum throughput is maximized over different communication modes of D2D pairs while in [4]–[6], power consumption or energy efficiency is optimized. 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. Some of the works mentioned attempt to optimize the whole network, which is exceedingly complex. Thus, suboptimal or heuristic approaches are usually proposed instead of the optimal one.

Our approach is optimal and distributed since each D2D pair determines its own mode of transmission to minimize its transmission power. We assume that the receiver of the D2D pair is at the cell edge and that the location of the cellular user with which the D2D pair in D2D mode interferes, is uniformly distributed over the whole cell. This assumption differentiates this work from our previous work [8] in which coordinates of all nodes are deterministic. We derive the feasibility test for D2D mode and find that D2D transmission mode may not be possible for a large cell due to a strong interference from cellular users. We find that the minimum transmission power and the corresponding mode of transmission largely depend on the cell radius and the distance between the two devices.

This work was supported by Kasetsart University Research and Development Institute (KURDI) under the FY2016 Kasetsart University research grant, and the Royal Golden Jubilee Ph.D. program.

II. System model

We consider a cell with radius R_c in cellular network and a base station denoted by BS placed at the cell center. Within that cell, there is at least one pair of D2D transmitter and receiver denoted by Tx and Rx, respectively. If there are multiple D2D pairs, we assume that they communicate in different uplink channels and hence, will not interfere with each other. Depending on transmission power, Tx and Rx can choose to communicate directly with each other in D2D mode or via BS in cellular mode. In D2D mode, the D2D pair shares an uplink channel with some cellular user denoted by UEc and will interfere with that user, which is a primary user of the network. Fig. 1 illustrates the model we just described. In this work, Rx is assumed to be at the cell edge and thus, is farthest away from BS. Consequently, Tx is likely to select to communicate in D2D mode if it is not too far from Rx.

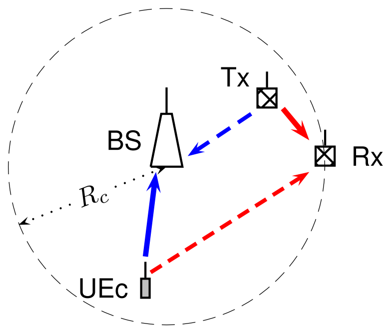

Fig. 1: The R_c-radius cell consists of D2D transmitter (Tx), D2D receiver (Rx), which is at the cell edge, the cellular user (UEc) whose uplink is shared with Tx, and the base station (BS). Assuming D2D mode is active, solid lines represent the desired signals while dashed lines represent the interfering signals.

Assuming a discrete-time flat-fading model, the received symbol at Rx is given by

$$r_{\mathsf{Rx}} = g_{\mathsf{Tx-Rx}} h_{\mathsf{Tx-Rx}} \sqrt{P_{\mathsf{D2D}}}\, s_{\mathsf{Tx}} + g_{\mathsf{UEc-Rx}} h_{\mathsf{UEc-Rx}} \sqrt{P_{\mathsf{UEc}}}\, s_{\mathsf{UEc}} + n \quad (1)$$

where s_{Tx} and s_{UEc} are transmitted symbols with zero mean and unit variance from Tx and UEc, respectively, 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, $g_{\mathsf{i-j}}$ denotes a large-scale fading gain between nodes i and j, and n is additive white Gaussian noise with zero mean and variance σ_n^2. Assuming that signals propagate through independent paths with similar statistical properties, $h_{\mathsf{i-j}}$ is independent with $E[|h_{\mathsf{i-j}}|^2] = 1$ for all i − j links. We also assume there is no random shadowing effect and that signal loss between nodes i and j reflects in the squared large-scale gain as follows

$$g_{\mathsf{i-j}}^2 = \left(\frac{d_0}{d_{\mathsf{i-j}}}\right)^2 \quad (2)$$

where $d_{\mathsf{i-j}}$ denotes the distance between nodes i and j, and the reference distance $d_0 \leq d_{\mathsf{i-j}}$. From (2), the path-loss exponent is set to 2. However, the results in this work can be straightforwardly extended to other exponents.

In this model, the coordinates of BS, Tx, and Rx are fixed while that of UEc is random since it is impractical to assume that an exact coordinate of a cellular user is known. We assume that the coordinate of UEc is uniformly distributed over the circular cell. (In our previous work [8], the coordinates of all nodes are deterministic.) As a result, the associated large-scale gains $g_{\mathsf{UEc-BS}}$ and $g_{\mathsf{UEc-Rx}}$ are random while other large-scale gains are deterministic.

To maintain grade of service for cellular users, power allocation of UEc is assumed to be channel inversion and hence,

$$P_{\mathsf{UEC}} = K g_{\mathsf{UEc-BS}}^{-2} \quad (3)$$

where K is the received power of UEc at BS averaging over $h_{\mathsf{UEc-BS}}$. Since $g_{\mathsf{UEc-BS}}$ is random, P_{UEC} is also random. From (1), we can compute signal-to-interference plus noise ratio (SINR) at Rx as follows

$$\begin{aligned} \mathsf{SINR}_{\mathsf{D2D}} &= \frac{E[|g_{\mathsf{Tx-Rx}} h_{\mathsf{Tx-Rx}} \sqrt{P_{\mathsf{D2D}}} s_{\mathsf{Tx}}|^2]}{E[|g_{\mathsf{UEc-Rx}} h_{\mathsf{UEc-Rx}} \sqrt{P_{\mathsf{UEc}}} s_{\mathsf{UEc}} + n|^2]} && (4)\\ &= \frac{P_{\mathsf{D2D}} g_{\mathsf{Tx-Rx}}^2}{E[P_{\mathsf{UEC}}]E[g_{\mathsf{UEc-Rx}}^2] + \sigma_n^2} && (5)\\ &\geq \beta && (6)\end{aligned}$$

where in (5), we apply $E[|h_{\mathsf{i-j}}|^2] = 1$ for all i − j links and in (6), we require that $\mathsf{SINR}_{\mathsf{D2D}}$ must exceed or equal some threshold β.

When Tx and Rx communicates in D2D mode, UEc will be interfered by Tx since they share the same uplink band. With power allocation for UEc in (3), we can compute SINR for UEc at BS as follows

$$\mathsf{SINR}_{\mathsf{UEc}} = \frac{K}{P_{\mathsf{D2D}} g_{\mathsf{Tx-Rx}}^2 + \sigma_n^2} \geq (1-\epsilon)\gamma \quad (7)$$

where $\gamma = K/\sigma_n^2$ is the SINR of UEc when there is no interference from Tx and $0 \leq \epsilon \leq 1$ is a degradation factor. If UEc can tolerate substantial interference, ϵ will be moderate (e.g., $\epsilon = 0.3$ or 30%). Hence, we require that $\mathsf{SINR}_{\mathsf{UEc}}$ must not decrease below the threshold $(1-\epsilon)\gamma$ when D2D mode is active.

In cellular mode, Tx will communicate with Rx through BS and hence, will not interfere with any other cellular user. SINR of Rx in cellular mode is given by

$$\mathsf{SINR}_c = \frac{P_c g_{\mathsf{Tx-BS}}^2}{\sigma_n^2} \quad (8)$$

where P_c denotes the transmission power of Tx in cellular mode. When D2D pair is in cellular mode, it must request a dedicated uplink channel that is available at the time from BS. If there are many cellular users in the cell, there is a chance that no channel can be assigned to the D2D pair and hence, cellular mode for the pair is not possible. We let $0 \leq \lambda \leq 1$ be the probability that there is an uplink channel available for the D2D pair to switch to cellular mode. When the cell is crowded, λ will be small and closer to 0. Similar to D2D mode, we require that in cellular mode, the average SINR must exceed or equal some threshold as follows

$$\lambda \mathsf{SINR}_c \geq \beta. \quad (9)$$

Ultimately, we would like to minimize the transmission power of Tx in either D2D or cellular modes for given SINR constraints. The proposed optimization problem can be stated as follows

$$\begin{aligned} \text{Minimize} \quad & \min\{P_{\mathsf{D2D}}, P_c\} \\ \text{subject to} \quad & \mathsf{SINR}_{\mathsf{D2D}} \geq \beta, \\ & \mathsf{SINR}_{\mathsf{UEc}} \geq (1-\epsilon)\gamma, \\ & \lambda \mathsf{SINR}_c \geq \beta, \\ & P_{\mathsf{D2D}} \geq 0,\ P_c \geq 0. \end{aligned} \quad (10)$$

III. Optimal Transmission Power And Mode

To find the minimum transmission power of Tx and the corresponding mode, we first evaluate $\mathsf{SINR}_{\mathsf{D2D}}$. With (2) and (3), we obtain

$$E[P_{\mathsf{UEC}}] = \frac{K}{d_0^2} E[d_{\mathsf{UEc-BS}}^2]. \quad (11)$$

Since UEc is uniformly placed in the circular area with radius R_c, the distance from UEc to BS at the center is random with a well-known probability density function (pdf) given by

$$f_{d_{\mathsf{UEc-BS}}}(x) = \frac{2x}{R_c^2}, \quad 0 \leq x \leq R_c. \quad (12)$$

Thus,

$$E[d_{\mathsf{UEc-BS}}^2] = \int_{d_0}^{R_c} x^2 f_{d_{\mathsf{UEc-BS}}}(x)\,\mathrm{d}x = \frac{1}{2}\left(R_c^2 - \frac{d_0^4}{R_c^2}\right) \quad (13)$$

and substituting (13) in (11) gives

$$E[P_{\mathsf{UEC}}] = \frac{K}{2d_0^2}\left(R_c^2 - \frac{d_0^4}{R_c^2}\right) \quad (14)$$

where the reference distance $d_0 \ll R_c$. We remark from (14) that the average transmit power of UEc increases with the cell radius. As the cell becomes larger, the transmit power of UEc needs to increase to maintain the received power at BS.

Next we evaluate

$$E[g_{\mathsf{UEc-Rx}}^2] = d_0^2 E[d_{\mathsf{UEc-Rx}}^{-2}] \quad (15)$$

where we again apply (2). Since Rx is located at the cell edge or on the circumference of the cell as shown in Fig. 1, we set the Cartesian coordinates of Rx and BS to $(R_c, 0)$ and $(0, 0)$, respectively, without loss of generality. Applying the law of cosines, we obtain that

$$d_{\mathsf{UEc-Rx}} = \sqrt{R_c^2 + d_{\mathsf{UEc-BS}}^2 - 2d_{\mathsf{UEc-BS}} R_c \cos(\theta)} \quad (16)$$

where θ is the angle where UEc is located. Since UEc is randomly placed in the cell with uniform distribution, the angle θ has uniform pdf. Thus,

$$E[g_{\mathsf{UEc-Rx}}^2] = d_0^2 \iint_{\substack{\text{whole}\\ \text{cell}}} \left(R_c^2 + x^2 - 2xR_c \cos(\zeta)\right)^{-1} \times f_{d_{\mathsf{UEc-BS}}}(x)\, \mathrm{d}x \frac{1}{2\pi}\, \mathrm{d}\zeta. \quad (17)$$

It is easier to evaluate this double integral in polar coordinates centered at $(R_c, 0)$ instead of the origin as stated in (17). We apply a change-of-coordinate technique used in [9] to obtain

$$E[g_{\mathsf{UEc-Rx}}^2] = \frac{2d_0^2}{\pi R_c^2} \int_0^{\cos^{-1}(\frac{d_0}{2R_c})} \int_{d_0}^{2R_c \cos(\phi)} \frac{1}{r}\, \mathrm{d}r\, \mathrm{d}\phi \quad (18)$$

$$= \frac{2d_0^2}{\pi R_c^2} \int_0^{\cos^{-1}(\frac{d_0}{2R_c})} \ln(\cos\phi)\, \mathrm{d}\phi + \frac{2d_0^2}{\pi R_c^2} \ln\left(\frac{2R_c}{d_0}\right) \cos^{-1}\left(\frac{d_0}{2R_c}\right). \quad (19)$$

Since $d_0 \ll R_c$, $\cos^{-1}(d_0/2R_c) \approx \pi/2$ and hence,

$$\int_0^{\cos^{-1}(\frac{d_0}{2R_c})} \ln(\cos\phi)\, \mathrm{d}\phi \approx \int_0^{\frac{\pi}{2}} \ln(\cos\phi)\, \mathrm{d}\phi \quad (20)$$

$$= -\frac{\pi}{2} \ln(2) \quad (21)$$

where (21) is obtained from [10, eq. 18.102]. Substituting the above two approximations in (19) gives

$$E[g_{\mathsf{UEc-Rx}}^2] \approx \frac{d_0^2}{R_c^2} \ln\left(\frac{R_c}{d_0}\right). \quad (22)$$

As the cell expands (R_c increases), we expect the large-scale gain $g_{\mathsf{UEc-Rx}}$ to become smaller on average.

Next we derive a feasible range of P_{D2D} by solving (6) and (7) to obtain

$$\frac{\sigma_n^2 \beta}{g_{\mathsf{Tx-Rx}}^2} \left(1 + \frac{1}{\sigma_n^2} E[P_{\mathsf{UEC}}] E[g_{\mathsf{UEc-Rx}}^2]\right) \le P_{\mathsf{D2D}} \le \frac{\sigma_n^2}{g_{\mathsf{Tx-Rx}}^2} \left(\frac{\epsilon}{1-\epsilon}\right). \quad (23)$$

D2D mode is available if the upper bound of P_{D2D} is larger than or equal to the lower bound in (23). In other words, D2D mode is feasible if the following inequality is satisfied

$$1 + \frac{1}{\sigma_n^2} E[P_{\mathsf{UEC}}] E[g_{\mathsf{UEc-Rx}}^2] \le \frac{\epsilon}{\beta(1-\epsilon)}. \quad (24)$$

Thus, D2D mode is likely available if the SINR threshold $\beta < 1$ or less than 0 dB and the degradation factor is moderate. This implication can also be explained from (6) and (7). If β is large, then the required P_{D2D} is also large. As a result, Tx will significantly interfere with UEc and the level of interference may not be acceptable if ϵ is small. Hence, in this scenario, D2D mode is not possible. Another factor that affects the inequality (24) is $E[P_{\mathsf{UEC}}] E[g_{\mathsf{UEc-Rx}}^2]$. We can show from (14) and (19) that as the cell radius tends to infinity,

$$\lim_{R_c \to \infty} \frac{E[P_{\mathsf{UEC}}] E[g_{\mathsf{UEc-Rx}}^2]}{\ln(R_c)} = \frac{K}{2}. \quad (25)$$

We can also obtain the approximation of the product from (14) and (22) as follows

$$\frac{1}{\sigma_n^2} E[P_{\mathsf{UEC}}] E[g_{\mathsf{UEc-Rx}}^2] \approx \frac{\gamma}{2}\left(1 - \frac{d_0^4}{R_c^4}\right) \ln\left(\frac{R_c}{d_0}\right). \quad (26)$$

Thus, as R_c increases, the product $E[P_{\mathsf{UEC}}] E[g_{\mathsf{UEc-Rx}}^2]$ increases at the order of $\mathcal{O}(\ln(R_c))$ and thus, (24) is most likely not satisfied. Therefore, we expect that for larger cell, D2D mode is mostly not available.

If D2D mode is available, the minimum transmit power in that mode is given by

$$\min P_{\mathsf{D2D}} = \frac{\sigma_n^2 \beta}{g_{\mathsf{Tx-Rx}}^2} \left(1 + \frac{1}{\sigma_n^2} E[P_{\mathsf{UEC}}] E[g_{\mathsf{UEc-Rx}}^2]\right). \quad (27)$$

The minimum transmit power for cellular mode can be computed from (8) and (9) to obtain

$$\min P_c = \frac{\sigma_n^2 \beta}{\lambda g_{\mathsf{Tx-BS}}^2}. \quad (28)$$

Tx compares (27) and (28) and selects the mode in which the transmit power is smaller. D2D mode is likely to be selected if the cell is crowded with users (small λ) or if Tx is very close to Rx and is farther away from BS ($g_{\mathsf{Tx-Rx}}$ much smaller than $g_{\mathsf{Tx-BS}}$). On the other hand, cellular mode is preferred for large cell since the product $E[P_{\mathsf{UEC}}] E[g_{\mathsf{UEc-Rx}}^2]$ will be large and will increase $\min P_{\mathsf{D2D}}$.

IV. Numerical Results

In Fig. 2, we examine the D2D feasibility test (24) with cell radius $R_c = 400$ meters, the reference distance $d_0 = 0.1$ meters, and the cellular degradation factor $\epsilon = 0.20$ (or 20%). Assuming that BS can operate in a low signal-to-noise ratio (SNR) regime and hence, we set SINR of UEc without interference $\gamma = -10$ dB. With varying R_c, we plot the left-hand side (LHS) of (24) (blue solid curve) and its approximation from (26) (magenta circles) in Fig. 2. Since the approximation is almost identical to the exact value of LHS of (24) and is much simpler, we can safely use the approximation to test a feasibility of D2D mode. We also plot the right-hand side (RHS) of (24) with various β. (With similar assumption applied to UEc, Rx can operate in a low-SNR regime.) When $\beta = -6.5$ dB, D2D mode is not available for any cell size. As β decreases, the maximum cell radius in which D2D mode is available increases. When cell size increases, the average transmit power of UEc has to increase to keep SINR up at BS. This causes larger interference to the D2D pair and as a result, SINR threshold β must be reduced to satisfy the constraint in (6).

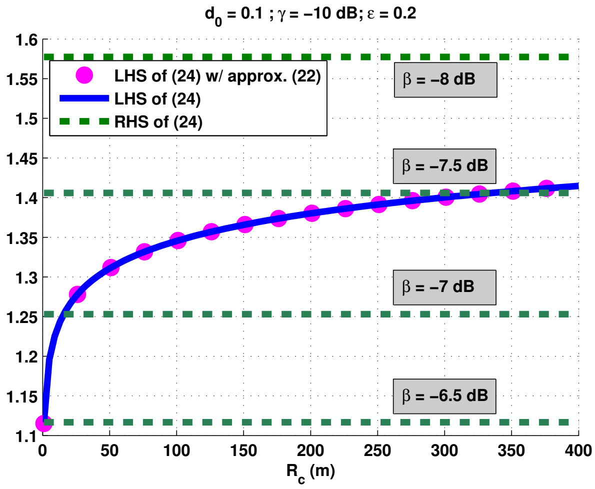

Fig. 2: LHS and RHS of (24) are plotted with various β. The approximation to LHS of (24) is also shown.

For Fig. 3, BS is placed at the point $(50, 50)$ in a Cartesian coordinate plane while Rx is placed at $(75, 50)$, which is on the cell edge (the magenta curve). The cell radius $R_c = 25$ meters. We find the region in which D2D mode is optimal by comparing the transmit power in D2D and cellular modes in (27) and (28). The D2D-optimal region is the set of all coordinates of Tx whose optimal mode of transmission is D2D. We set $\epsilon = 0.4$ and vary λ from 2% to 50%. We note that D2D mode is optimal when Tx is sufficiently close to Rx and thus, requires lesser transmit power. As the cell becomes busier (smaller λ), D2D-optimal region expands. Hence, Tx and Rx might not have to be as close to one other to communicate in D2D mode.

V. Conclusions

Availability of D2D mode for the device pair depends mostly on the cell size. If the cell radius exceeds certain threshold, D2D mode is not available. In addition to the cell size, the mode of transmission that minimizes the transmit power also depends on the distance between the D2D devices, the distance to the base station, and the probability that an uplink channel is available. From the analysis in this work, we conclude that when the cell is crowded or small, D2D mode is likely to be optimal. Although our analysis is based on the path-loss exponent equal to 2, it can be extended to other path-loss exponents, e.g., 2-4 and we expect similar conclusions. For future work, we can consider other user distribution besides uniform, or rate constraints instead of SINR constraints.

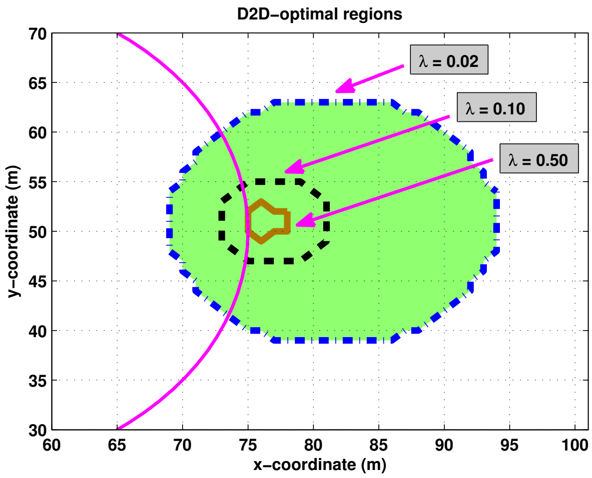

Fig. 3: D2D-optimal regions are shown with BS placed at the coordinate point $(50, 50)$ and Rx placed at $(75, 50)$. The magenta curve is the cell edge. The boundaries of the regions with $\lambda = 0.02$, 0.1, and 0.5 are shown with dashed-dotted, dashed, and solid lines, respectively.

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