Performance Analysis and Resource Allocation for Cooperative D2D Communication in Cellular Networks With Multiple D2D Pairs

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***Abstract*— In this letter, we investigate cooperative device-to-device (D2D) communication in an uplink cellular network, where D2D users act as relays for cellular users. We derive the outage probability of a cellular user and the average achievable rate from a D2D transmitter to a D2D receiver in analytic form. We obtain optimal spectrum and power allocation to maximize the total average achievable rate under the outage probability constraint. The validity of the analysis is verified by computer simulations.**

***Index Terms*— Device-to-device communications, relaying, multiple D2D users, resource allocation, outage probability, average achievable rate.**

I. Introduction

DEVICE-TO-DEVICE (D2D) communication has received great attention to meet the rapidly increasing demand for data traffic [1]. In D2D communication in cellular networks, cellular and D2D users transmit signals simultaneously using the spectrum of cellular users.

To improve the performance of cellular and D2D users, various relaying techniques have been researched in D2D communication in cellular networks [2]–[6]. There are two D2D communications with relaying: relay-assisted D2D communication and cooperative D2D communication. In relay-assisted D2D communication, relays help the signal transmission to improve the performance of D2D users [2]. In cooperative D2D communication, D2D users act as relays for cellular users to improve the performance of cellular users [3]. The performance degradation of cellular users occurs due to the interference from D2D users in D2D communication in cellular networks. To reduce the performance degradation, many works have been conducted for cooperative D2D communication recently.

Previous works on cooperative D2D communication have focused on spectrum and power allocation when instantaneous channel state information (CSI) is available [3]–[5]. However, only statistical CSI may be available in practical situation. To allocate spectrum and power with statistical CSI, the system performances (e.g. outage probability, average achievable rate) of cellular and D2D users need to be analyzed. In some works, the system performances for relay-assisted D2D communication were analyzed [2], [6]. However, the performance analysis for cooperative D2D communication has not been done yet.

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In this letter, we investigate D2D communication in cellular networks where D2D transmitters relay data signals of cellular users. We derive the outage probability of a cellular user and the average achievable rate from a D2D transmitter to a D2D receiver for a single D2D pair case at first. By using the outage probability and the average achievable rate, we find optimal spectrum and power allocation for multiple D2D pairs case to maximize the total average achievable rate.

II. System Model for a Single D2D Pair Case

Consider an uplink cellular network consisting of a base station BS, a cellular user CU, a D2D transmitter DT, and a D2D receiver DR. Suppose that DT not only transmits its own signal to DR but also relays the data signal of CU on the spectrum of CU.

Assume that the coefficient of the channel from node i to node j $h_{i,j}$, $i \in \{CU, DT\}$, $j \in \{BS, DT, DR\}$, $i \neq j$, is an independent zero-mean complex Gaussian random variable with variance $\lambda_{i,j} = d_{i,j}^{-\alpha}$ where $d_{i,j}$ is the distance between node i and node j, and α is the path loss exponent.

The signal transmission is performed in two phases. In the first phase, CU transmits its data signal x_{CU} with power P_{CU}. The received signal at node i in the first phase is given by

$$y_{i,1} = h_{CU,i}x_{CU} + n_{i,1}, \quad i \in \{BS, DT, DR\}, \tag{1}$$

where $n_{i,1}$ is an AWGN with variance N_0. The D2D transmitter DT and D2D receiver DR decode the data signal of CU from their received signals $y_{DT,1}$ and $y_{DR,1}$, respectively.

In the second phase, it transmits no signal when DT fails to decode the data signal of CU in the first phase. When DT succeeds in decoding the data signal of CU in the first phase, DT transmits its own data signal x_{DT} with power $\beta_{DT}P_{DT}$ and the re-encoded signal of x_{CU}, denoted by $\tilde{x}_{CU}$, with power $(1-\beta_{DT})P_{DT}$ where P_{DT} is the transmit power of DT and β_{DT} is the power allocation coefficient for x_{DT}. The received signal at node i in the second phase is given by

$$y_{i,2} = h_{DT,i}x_{DT} + h_{DT,i}\tilde{x}_{CU} + n_{i,2}, \quad i \in \{BS, DR\}, \tag{2}$$

where $n_{i,2}$ is an AWGN with variance N_0. The base station decodes the data signal of CU from its received signals $y_{BS,1}$ and $y_{BS,2}$ by using maximal-ratio combining, and DR decodes the data signal of DT by using successive interference cancellation if it succeeds in decoding the data signal of CU.

III. Outage Probability of a Cellular User

The received signal-to-noise ratio (SNR) at node i in the first phase is given by

$$\gamma_{i,1} = \frac{P_{CU}|h_{CU,i}|^2}{N_0}, \quad i \in \{BS, DT, DR\}. \tag{3}$$

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Since the channel coefficient $h_{CU,i}$ is a complex Gaussian random variable, the CDF of $\gamma_{i,1}$ is given by

$$\begin{aligned} F_{\gamma_{i,1}}(x) &= \Pr[\gamma_{i,1} < x] \\ &= 1-\exp\left(-\frac{N_0 x}{\lambda_{CU,i} P_{CU}}\right), \ i \in \{BS, DT, DR\}. \end{aligned} \quad (4)$$

The achievable rate from CU to node i is given by

$$R_{CU,i} = \frac{1}{2}\log_2(1+\gamma_{i,1}), \quad i \in \{DT, DR\}. \quad (5)$$

If the achievable rate from CU to node i, $i \in \{DT, DR\}$, is equal to or higher than the target rate η, node i succeeds in decoding the data signal of CU. Since DT relays the data signal of CU when DT succeeds in decoding the data signal of CU, the received signal-to-interference-plus-noise ratio (SINR) at BS in the second phase is given by

$$\gamma_{BS,2} = \begin{cases} \tilde{\gamma}_{BS,2}, & R_{CU,DT} \geq \eta, \\ 0, & R_{CU,DT} < \eta, \end{cases} \quad (6)$$

where $\tilde{\gamma}_{BS,2} = \frac{(1-\beta_{DT})P_{DT}|h_{DT,BS}|^2}{\beta_{DT}P_{DT}|h_{DT,BS}|^2+N_0}$. Since BS decodes the data signal of CU from received signals $y_{BS,1}$ and $y_{BS,2}$ by using maximal-ratio combining, the achievable rate from CU to BS is given by

$$R_{CU,BS}^{\text{MRC}} = \frac{1}{2}\log_2(1+\gamma_{BS,1}+\gamma_{BS,2}). \quad (7)$$

Since DR can cancel the data signal of CU by using successive interference cancellation when it succeeds in decoding the data signal of CU, the received SINR at DR in the second phase is given by (8), shown at the top of the next page. The achievable rate from DT to DR in the second phase is given by

$$R_{DT,DR} = \frac{1}{2}\log_2(1+\gamma_{DR,2}). \quad (9)$$

An outage occurs at the base station if the achievable rate from a cellular user to the base station is lower than the target rate η. From (3), (6), and (7), the outage probability of CU is given by

$$\begin{aligned} \mathcal{P}_{CU}^{\text{out}} &= \Pr[R_{CU,BS}^{\text{MRC}} < \eta] \\ &= \Pr[\gamma_{DT,1} \geq \gamma_{\text{th}}] \Pr[\gamma_{BS,1} + \tilde{\gamma}_{BS,2} < \gamma_{\text{th}}] \\ &\quad + \Pr[\gamma_{DT,1} < \gamma_{\text{th}}] \Pr[\gamma_{BS,1} < \gamma_{\text{th}}] \\ &= \Pr[\gamma_{BS,1} + \tilde{\gamma}_{BS,2} < \gamma_{\text{th}}] - F_{\gamma_{DT,1}}(\gamma_{\text{th}}) \\ &\quad \times \{\Pr[\gamma_{BS,1} + \tilde{\gamma}_{BS,2} < \gamma_{\text{th}}] - F_{\gamma_{BS,1}}(\gamma_{\text{th}})\}, \end{aligned} \quad (10)$$

where $\gamma_{\text{th}} = 2^{2\eta} - 1$ and $F_X(\cdot)$ is the the cumulative distribution function (CDF) of a random variable X. The first term on the right hand side of (10) is given by

$$\begin{aligned} &\Pr[\gamma_{BS,1} + \tilde{\gamma}_{BS,2} < \gamma_{\text{th}}] \\ &= \int_0^\infty F_{\gamma_{BS,1}}\left(\gamma_{\text{th}} - \frac{(1-\beta_{DT})P_{DT}y}{\beta_{DT}P_{DT}y + N_0}\right) \frac{e^{-\frac{y}{\lambda_{DT,BS}}}}{\lambda_{DT,BS}} dy \\ &= 1 - \frac{1}{\lambda_{DT,BS}} \exp\left(-\frac{\gamma_{\text{th}} N_0}{\lambda_{CU,BS} P_{CU}} + \frac{\kappa_1 N_0}{\beta_{DT} P_{CU}} + \frac{N_0}{\beta_{DT}\lambda_{DT,BS} P_{DT}}\right) \\ &\quad \times \underbrace{\int_{\frac{N_0}{\beta_{DT}P_{DT}}}^\infty \exp\left(-\frac{\kappa_1 N_0^2}{P_{CU}P_{DT}y} - \frac{y}{\lambda_{DT,BS}}\right) dy}_{\mathcal{A}}, \end{aligned} \quad (11)$$

where $\kappa_1 = (1-\beta_{DT})/(\beta_{DT}^2 \lambda_{CU,BS})$. The integral in the right hand side of (11) cannot be obtained in analytic form. However, when $\beta_{DT}P_{DT}/N_0 \to \infty$, it can be approximated as

$$\begin{aligned} \mathcal{A} &\approx \int_0^\infty \exp\left(-\frac{\kappa_1 N_0^2}{P_{CU}P_{DT}y} - \frac{y}{\lambda_{DT,BS}}\right) dy \\ &= \sqrt{\frac{4\kappa_1 \lambda_{DT,BS} N_0^2}{P_{CU}P_{DT}}} K_1\left(\sqrt{\frac{4\kappa_1 N_0^2}{\lambda_{DT,BS} P_{CU} P_{DT}}}\right), \end{aligned} \quad (12)$$

where $K_1(\cdot)$ is the first order modified Bessel function of the second kind and the second equality follows from the fact that [7]

$$\int_0^\infty \exp\left(-\frac{a}{4y} - by\right) dy = \sqrt{\frac{a}{b}} K_1(\sqrt{ab}). \quad (13)$$

From (4), (10), (11), and (12), the outage probability of CU is approximated as (14), shown at the top of the next page, where $\kappa_2 = (\lambda_{CU,BS} + \lambda_{CU,DT})/\lambda_{CU,BS}\lambda_{CU,DT}$.

IV. Average Achievable Rate From a D2D Transmitter to a D2D Receiver

Let $\tilde{\gamma}_{DR,2} = \beta_{DT}P_{DT}|h_{DT,DR}|^2/N_0$ and $\hat{\gamma}_{DR,2} = \beta_{DT}P_{DT}|h_{DT,DR}|^2/\{(1-\beta_{DT})P_{DT}|h_{DT,DR}|^2 + N_0\}$. From (8) and (9), the average achievable rate from DT to DR is given by

$$\begin{aligned} &\bar{R}_{DT,DR} \\ &= \mathbb{E}[R_{DT,DR}] \\ &= \Pr[\gamma_{DT,1} \geq \gamma_{\text{th}}, \gamma_{DR,1} \geq \gamma_{\text{th}}] \mathbb{E}\left[\frac{1}{2}\log_2(1+\tilde{\gamma}_{DR,2})\right] \\ &\quad + \Pr[\gamma_{DT,1} \geq \gamma_{\text{th}}, \gamma_{DR,1} < \gamma_{\text{th}}] \mathbb{E}\left[\frac{1}{2}\log_2(1+\hat{\gamma}_{DR,2})\right] \\ &= \frac{\{1-F_{\gamma_{DT,1}}(\gamma_{\text{th}})\}\{1-F_{\gamma_{DR,1}}(\gamma_{\text{th}})\}}{2\ln 2} \int_0^\infty \frac{1-F_{\tilde{\gamma}_{DR,2}}(x)}{1+x} dx \\ &\quad + \frac{\{1-F_{\gamma_{DT,1}}(\gamma_{\text{th}})\}F_{\gamma_{DR,1}}(\gamma_{\text{th}})}{2\ln 2} \int_0^\infty \frac{1-F_{\hat{\gamma}_{DR,2}}(y)}{1+y} dy. \end{aligned} \quad (15)$$

Since the channel coefficient $h_{DT,DR}$ is a complex Gaussian random variable, the CDFs of $\tilde{\gamma}_{DR,2}$ and $\hat{\gamma}_{DR,2}$ are given by

$$F_{\tilde{\gamma}_{DR,2}}(x) = 1 - \exp\left(-\frac{N_0 x}{\beta_{DT}\lambda_{DT,DR}P_{DT}}\right) \quad (16)$$

and (17), shown at the top of the next page. From (4), (15), (16), and (17), we have

$$\begin{aligned} \bar{R}_{DT,DR} = &\frac{\{1-F_{\gamma_{DT,1}}(\gamma_{\text{th}})\}\{1-F_{\gamma_{DR,1}}(\gamma_{\text{th}})\}}{2\ln 2} \\ &\times \underbrace{\int_0^\infty \frac{1}{1+x} \exp\left(-\frac{N_0 x}{\beta_{DT}\lambda_{DT,DR}P_{DT}}\right) dx}_{\mathcal{B}} \\ &+ \frac{\{1-F_{\gamma_{DT,1}}(\gamma_{\text{th}})\}F_{\gamma_{DR,1}}(\gamma_{\text{th}})}{2\ln 2} \exp\left(\frac{N_0}{\kappa_3 P_{DT}}\right) \\ &\times \underbrace{\int_{\frac{1}{\kappa_4}}^\infty \left(-\frac{1}{y} + \frac{1}{y+\beta_{DT}-1}\right) \exp\left(-\frac{\kappa_4 N_0}{\kappa_3 P_{DT}} y\right) dy}_{\mathcal{C}}. \end{aligned} \quad (18)$$

$$\gamma_{DR,2} = \begin{cases} \frac{\beta_{DT} P_{DT} |h_{DT,DR}|^2}{N_0}, & \text{if } R_{CU,DT} \geq \eta \text{ and } R_{CU,DR} \geq \eta, \\ \frac{\beta_{DT} P_{DT} |h_{DT,DR}|^2}{(1-\beta_{DT}) P_{DT} |h_{DT,DR}|^2 + N_0}, & \text{if } R_{CU,DT} \geq \eta \text{ and } R_{CU,DR} < \eta, \\ 0, & \text{if } R_{CU,DT} < \eta. \end{cases} \quad (8)$$

$$\mathcal{P}_{CU}^{\text{out}} \approx 1 - \exp\left(-\frac{\gamma_{\text{th}} N_0}{\lambda_{CU,BS} P_{CU}}\right) + \exp\left(-\frac{\gamma_{\text{th}} \kappa_2 N_0}{P_{CU}}\right) - \sqrt{\frac{4\kappa_1 N_0^2}{\lambda_{DT,BS} P_{CU} P_{DT}}}$$
$$\times \exp\left(-\frac{\gamma_{\text{th}} \kappa_2 N_0}{P_{CU}} + \frac{(1-\beta_{DT}) N_0}{\beta_{DT} \lambda_{CU,BS} P_{CU}} + \frac{N_0}{\beta_{DT} \lambda_{DT,BS} P_{DT}}\right) K_1\left(\sqrt{\frac{4\kappa_1 N_0^2}{\lambda_{DT,BS} P_{CU} P_{DT}}}\right). \quad (14)$$

$$F_{\hat{\gamma}_{DR,2}}(x) = \begin{cases} 1 - \exp\left(-\frac{N_0 x}{(\beta_{DT} + \beta_{DT} x - x) \lambda_{DT,DR} P_{DT}}\right), & x < \frac{\beta_{DT}}{1-\beta_{DT}}, \\ 1, & x \geq \frac{\beta_{DT}}{1-\beta_{DT}}. \end{cases} \quad (17)$$

where $\kappa_3 = (1-\beta_{DT})\lambda_{DT,DR}$ and $\kappa_4 = \beta_{DT}/(1-\beta_{DT})$. By using the equality [7]

$$\int_0^\infty \frac{e^{-ax}}{b+x} dx = -\, e^{ab} \text{Ei}(-ab), \quad (19)$$

where $\text{Ei}(\cdot)$ is the exponential integral function, the integral in the first term on the right hand side of (18) is given by

$$\mathcal{B} = -\exp\left(\frac{N_0}{\beta_{DT} \lambda_{DT,DR} P_{DT}}\right) \times \text{Ei}\left(-\frac{N_0}{\beta_{DT} \lambda_{DT,DR} P_{DT}}\right). \quad (20)$$

By using the equality [7]

$$\int_a^\infty \frac{e^{-bx}}{c+x} dx = -\, e^{bc} \text{Ei}(-ab - bc), \quad (21)$$

the integral in the second term on the right hand side of (18) is given by

$$\mathcal{C} = \text{Ei}\left(-\frac{N_0}{\kappa_3 P_{DT}}\right) - \exp\left(\frac{\kappa_4 N_0}{\lambda_{DT,DR} P_{DT}}\right) \times \text{Ei}\left(-\frac{N_0}{\kappa_3 P_{DT}} - \frac{\kappa_4 N_0}{\lambda_{DT,DR} P_{DT}}\right). \quad (22)$$

From (4), (18), (20), and (22), the average achievable rate from DT to DR can be obtained in analytic form.

V. Spectrum and Power Allocation for Multiple D2D Pairs Case

In this section, we find optimal spectrum and power allocation for multiple D2D pairs by using outage probability of a cellular user and average achievable rate from a D2D transmitter to a D2D receiver obtained in previous sections. Consider an uplink cellular network consisting of a base station BS, M cellular users $CU_1, \cdots, CU_M$, and K D2D pairs DT_1-$DR_1, \cdots, DT_K$-DR_K, $K \geq M$. Assume that each D2D transmitter acts as a relay for at most one cellular user and each cellular user is helped by a distinct D2D transmitter. Let $\mathcal{P}_{CU_m}^{k,\text{out}}$, $\bar{R}_{DT_k,DR_k}^m$, and $\beta_{DT_k}^m$ denote the outage probability of CU_m, the average achievable rate from DT_k to DR_k, and the power allocation coefficient for x_{DT_k}, respectively, when DT_k acts as a relay for CU_m. Let $\rho_{DT_k}^m$ denote a spectrum allocation indicator. $\rho_{DT_k}^m = 1$ if the spectrum of CU_m is allocated to DT_k, i.e., DT_k acts as a relay for CU_m; $\rho_{DT_k}^m = 0$ otherwise. When only statistical CSI is available, it needs to find optimal spectrum allocation indicators and power allocation coefficients to maximize the total average achievable rate from D2D transmitters to D2D receivers when the outage probability of a cellular user is lower than the predetermined value ε. Then, the algorithm to find optimal spectrum allocation indicators and power allocation coefficients is as follows:

i) Find all power allocation coefficients $\beta_{DT_k}^m$ by using (14) such that

$$\mathcal{P}_{CU_m}^{k,\text{out}}(\beta_{DT_k}^m) = \varepsilon, \quad \forall k, m. \quad (23)$$

ii) Find optimal spectrum allocation indicators $\rho_{DT_k}^{m*}$ by using exhaustive search such that

$$\rho_{DT_k}^{m*} = \arg\max_{\rho_{DT_k}^m} \sum_{m=1}^{M} \sum_{k=1}^{K} \rho_{DT_k}^m \bar{R}_{DT_k,DR_k}^m (\beta_{DT_k}^m) \quad (24)$$

$$\text{subject to } \rho_{DT_k}^m \in \{0,1\}, \quad \forall k, m, \quad (25)$$

$$\sum_{m=1}^{M} \rho_{DT_k}^m \leq 1, \quad \forall k, \quad (26)$$

$$\sum_{k=1}^{K} \rho_{DT_k}^m = 1, \quad \forall m. \quad (27)$$

iii) Find optimal power allocation coefficients $\beta_{DT_k}^*$ such that

$$\beta_{DT_k}^* = \begin{cases} \beta_{DT_k}^{m'}, & \text{if } \rho_{DT_k}^{m'*} = 1, \\ 0, & \text{if } \rho_{DT_k}^{m'*} = 0, \quad \forall m'. \end{cases} \quad (28)$$

VI. Simulation Results and Discussion

Assume that the path loss exponent $\alpha = 3$. Suppose that the target rate $\eta = 1$ bps/Hz and the outage probability constraint $\varepsilon = 0.01$. In Figs. 1 and 2, we consider an uplink cellular

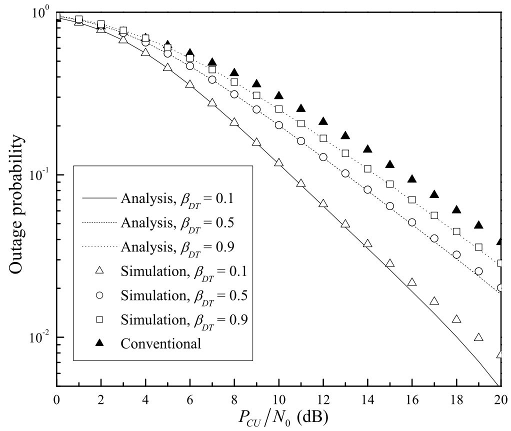

Fig. 1. Outage probability of a cellular user.

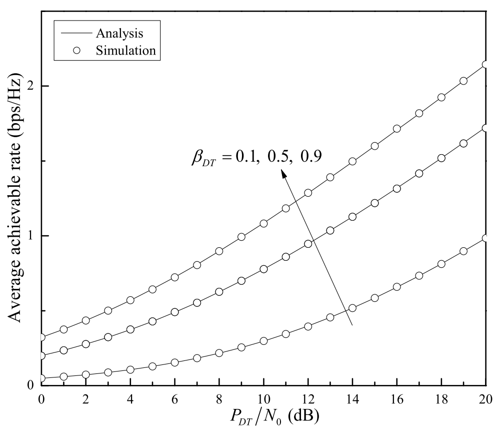

Fig. 2. Average achievable rate from a D2D transmitter to a D2D receiver.

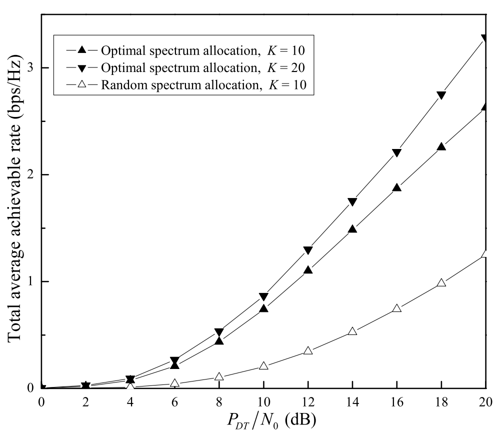

Fig. 3. Total average achievable rate from D2D transmitters to D2D receivers.

network with a cellular user and a D2D pair where the distance $d_{i,j} = 1$, $i \in \{CU, DT\}$, $j \in \{BS, DT, DR\}$, $i \neq j$. In Fig. 3, we consider an uplink cellular network with M cellular users and K D2D pairs where cellular users and D2D pairs are randomly located in the cell with radius 500 m.

Fig. 1 shows the outage probability of a cellular user versus P_{CU}/N_0 for $P_{DT}/N_0 = 10$ dB. For comparison, the performance for the conventional D2D communication is presented where a D2D transmitter does not relay the signal of a cellular user. The simulation result shows that the outage probability decreases as P_{CU}/N_0 increases or β_{DT} decreases. It is shown that the gap between the analytical and simulation results increases as P_{CU}/N_0 increases or β_{DT} decreases. It is because the analytical results are obtained when $\beta_{DT} P_{DT}/N_0 \to \infty$. Note that the gap between the analytical and simulation results is not large even though P_{DT}/N_0 is not high. It is shown that the cooperative D2D communication gives better outage performance than the conventional D2D communication.

Fig. 2 shows the average achievable rate from a D2D transmitter to its corresponding receiver versus P_{DT}/N_0 for $P_{CU}/N_0 = 10$ dB. It is shown that the average achievable rate increases as either P_{DT}/N_0 or β_{DT} increases. It is also shown that the analytical results perfectly match the simulation results.

Fig. 3 shows the total average achievable rate from D2D transmitters to D2D receivers for $P_{CU} = P_{DT}$ and $M = 10$. The performance for random spectrum allocation is presented for comparison. It is shown that the total average achievable rate for the optimal spectrum allocation increases as either P_{DT}/N_0 or the number of D2D pairs increases. It is also shown that the optimal spectrum allocation achieves higher total average achievable rate than the random spectrum allocation.

In conclusions, we consider cooperative D2D communication in a cellular network with multiple D2D pairs. We derive the outage probability of a cellular user and the average achievable rate from a D2D transmitter to a D2D receiver. We find optimal spectrum allocation indicator and power allocation coefficient to maximize the total average achievable rate. For future works, we aim to propose a new spectrum allocation scheme to reduce the computational complexity for optimal spectrum allocation.

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