Distance-based resource allocation scheme for device-to-device communications underlaying cellular networks

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Recently, there has been growing interest in device-to-device (D2D) communications in a cellular network such as LTE-advanced. However, enabling D2D links in a cellular network presents a challenge in radio resource management due to the interference between cellular and D2D links. Some studies have considered cellular users as the primary and proposed methods to protect them from the additional interference from D2D links. However, considering that the D2D function is suitable for short-range and high-rate links, and local multimedia services, it is also important to guarantee these D2D links reliable. Thus, in this paper, we propose a method to properly choose a cellular user that shares radio resource with D2D users in the uplink to mitigate the interference from the cellular user to the D2D receivers. Numerical results show that by applying our method the reliability of D2D communication improves significantly without degrading the performance of the cellular connection. In addition, we derive a closed-form expression for the conditional outage probabilities of D2D links in the case when more than one D2D pair share the same resource with one cellular user, and discuss how the base station can choose a cellular user to optimize the performance of the D2D links.

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1. Introduction

In the last few years, we have witnessed the emergence of new types of mobile devices, such as smart phones and tablets, and various new applications running on these devices. Those have led to a tremendous increase in mobile data traffic, which imposes the need for increasing network capacity. Device-to-device (D2D) communications are emerging as a promising technique to improve the user experience and resource utilization in cellular networks. Mobile devices in close proximity, with high signal-to-interference-plus-noise ratio (SINR) between them, may communicate directly instead of through the base station (BS). D2D communications underlaying a cellular network may be realized either in the network-controlled manner such that the cellular operator manages the D2D link configuration and resource allocation or in the autonomous manner without operator control [1]. The use of D2D communications is expected to bring a lot of advantages: improved energy efficiency, improved spectrum reuse and system throughput, improved user experience, cellular traffic offloading, extended coverage, enabling of new local services, such as video streaming, online gaming, media downloading, peer-to-peer (P2P) file sharing, etc. [2–4].

Although D2D communication accommodates large volume of traffic and provides better services to users, it also brings up two kinds of intra-cell interferences that were not present in the conventional cellular systems: the D2D-to-cellular (D2C) interference and the cellular-to-D2D (C2D) interference. The BS can mitigate these interferences using power control and resource allocation. In [2], a method to control the maximum transmit power of D2D transmitter has been proposed in order to suppress the D2C interference. A power optimization has been performed in [3] and [5] to maximize the sum rate of the cellular and D2D links considering the interference in both directions. In [6], a resource allocation method that can minimize the interference has been proposed. In [7], the authors discuss an algorithm to optimize the resource allocation, in which D2D links can reuse the resources of more than one cellular user. All of these works have focused on the D2C interference, and they are based on a channel-based resource allocation. In the channel-based resource allocation, the BS needs to know the channel state information (CSI) of all involved links, which increases the complexity and signaling overhead of the system. Recently, there have been some works that paid attention to the C2D interference and resource allocation based on the distance between nodes [8,9]. In [8], in particular, a distance-constrained resource-sharing criterion (DRC) was proposed for the BS to select a cellular resource to be
shared with a D2D link, such that the C2D interference is controlled by keeping a minimum distance between them.

The distance-based resource allocation schemes are more simple and practical for D2D communications than the channel-based ones. Moreover, it is necessary to guarantee reliability of D2D communications by dealing with the C2D interference so that the D2D communication system underlaying a cellular network is advantageous. Therefore, we consider distance-based resource allocation to mitigate the C2D interference and focus on only the uplink interference from the cellular users to the D2D receivers. In a prior work [10], the authors have presented the outage probability analysis and proposed an improved distance-based resource allocation scheme, in the case when each D2D pair shares radio resource with one cellular user. In this paper, we elaborate the idea in [10] and extend the result to the case where three users share the same resource. In particular, we consider the case in which the BS supports two D2D pairs that could share resource with one cellular user simultaneously. In that case, one D2D receiver would experience interference from the cellular user and the other D2D transmitter. We derive closed-form expressions for the outage probability of these D2D links, and propose various criteria for the BS to choose the most appropriate cellular resource for them. We present the performance improvement of the proposed scheme over the previously proposed scheme in terms of the average outage probability of the D2D link.

The rest of this paper is organized as follows. Section 2 describes the system model of D2D communications underlaying a cellular network. In Section 3, a resource allocation algorithm is proposed first for the case of one D2D pair, and then it is extended to the case of two D2D pairs. Moreover, we will discuss how to further extend the algorithm for two D2D pairs to the general case of the arbitrary number of D2D pairs. The resource allocation algorithm is developed based on the derivation of the outage probability of each D2D link, conditioned on the location of a cellular user. Section 4 presents and discusses numerical results. Finally, conclusion is drawn in Section 5.

2. System and channel models

We first consider the scenario as illustrated in Fig. 1, where the BS is located in the cell center and cellular user equipments (CUEs) are uniformly distributed over the cell area. We assume that there is one D2D pair and $N$ cellular users, though the scenario where there are more than one D2D pair will be discussed in Section 3.2. For any cellular user, the probability density function (PDF) of its distance $r_C$ from the BS is $f(r_C) = \frac{2}{\pi R^2} r_C \in [0, R]$, while the angle $\theta$ between the $x$-axis and the line from the BS to the cellular user is uniformly distributed over $[0, 2\pi]$. D2D communications underlaying a cellular network will be limited to local traffic, and application utilizing D2D communications should be designed accordingly [2]. Thus, we assume that D2D transmitter (D2D-Tx) and D2D receiver (D2D-Rx) are close to each other. In addition, we assume that the D2D link uses the uplink resource of the cellular system, since it is accepted to be more practical than the downlink resource [11]. Then, the D2D pair should be near the cell edge [12]. The BS will choose radio resource of a particular CUE among the $N$ cellular users randomly distributed over the cell for sharing with the D2D pair. For example, in Fig. 1, D2D-Rx is receiving data from D2D-Tx under the interference from CUE$_i$’s uplink transmission. $L_{C_i}$ denotes the distance corresponding to the C2D interference link between CUE$_i$ and D2D-Rx. In general, the distance $L_{C_i}$ between the CUE$_i$ and D2D-Rx is given as

$$L_{C_i} = \sqrt{r_{C_i}^2 + r_D^2 - 2r_{C_i}r_D \cos \theta_i}. \tag{1}$$

It should be noted that the distance $\rho$ between the D2D-Tx and D2D-Rx should be kept small so as to lower the power consumption of user equipments, which is one of primary reasons of enabling D2D links in cellular systems. For instance, the authors in [2] suggest 50 m of D2D transmission range in a macro-cell with the radius of 500 m, according to which the D2D transmitter and receiver are assumed to be in proximity if the distance between them is less than 10% of the cell radius. We focus to deal with the C2D interference rather than the D2C interference. The reason is that the victim of D2C interference is the base station when the uplink resources are shared. Since the range of D2D links is usually small, the power level required for a D2D link will be much lower than that for the cellular uplink which uses the same resources. Moreover, the BS will have more capability of managing the D2C interference. Therefore, the D2C interference can be negligible, whereas the C2D interference is crucial.

When CUE$_i$ share the same resource with the D2D pair, the received signal at the D2D-Rx can be expressed as

$$y_i = h_0 \sqrt{P_D \rho^{-\alpha} x_0} + h_{C_i} \sqrt{P_C_{C_i} L_{C_i}^{-\alpha}} x_{C_i} + n_0, \tag{2}$$

where $x_0$ denotes signal transmitted from D2D-Tx, $x_{C_i}$ is the uplink signal that CUE$_i$ transmits to the BS, $h_0$ and $h_{C_i}$ stand for fading coefficients in the D2D link and the CUE$_i$ to D2D-Rx link, respectively, both following the independent complex Gaussian distribution, $P_D$ and $P_{C_{C_i}}$ are the transmit power of the D2D-Tx and CUE$_i$, respectively, $\alpha$ is the path-loss exponent, and $n_0$ represents the additive white Gaussian noise (AWGN). Therefore, depending on which CUE$_i$ is selected, the SINR at the D2D-Rx is given as

$$\gamma_i = \frac{\left|h_0\right|^2 P_D \rho^{-\alpha}}{h_{C_i} \left|P_{C_{C_i}} L_{C_i}^{-\alpha}\right| + N_0}, \tag{3}$$

where $N_0$ denotes the variance of the AWGN. A fixed signal-to-noise ratio (SNR) target $\eta/N_0$ is assumed to be adopted for the D2D link, where $\eta = P_D \rho^{-\alpha}$ denotes the received signal power at the D2D-Rx. We also assume that a target SNR power control scheme is employed for the uplink transmission of a cellular user [6]: the uplink transmit power of CUE$_i$ is adjusted to provide a fixed SNR target $\xi$ at the BS as [8]

$$\xi = \frac{P_{C_{C_i}}}{N_0 f_{C_i}}. \tag{4}$$
With these power control strategies of the D2D-Tx and cellular users, (3) can be rewritten as
\[
\gamma_0 = \frac{|h_{B2}|^2 \eta}{|h_c|^2 \mathbb{E} N_0 \gamma^* L_c} + N_0. \tag{5}
\]

As mentioned earlier, some resource allocation algorithm requires the CSIs of all involved link. However, this is too complex and may be impractical for D2D communications. As a low complexity and practical solution, our proposed method is based on the location of cellular users. Therefore, it is important to devise a method for the BS to obtain this information in an accurate and efficient manner. One simple method is to have each user measure its location from the global positioning system (GPS) and report it to the BS. However, when the users are in indoor or in urban area, the GPS signal may not be strong enough to assure reliable estimation. In addition, the feedback of the location information from each user to the BS could cause delay in resource allocation. Some methods have been proposed to track the location of users without relying on the GPS. In a scheme proposed in [13], in particular, the location is estimated using time-of-arrival method and it is updated using a Kalman filter. The velocity as well as the location of the user is estimated for the Kalman filter. In order to improve the accuracy of velocity estimation, [14] introduced a velocity renewal process. More accurate velocity estimation will enhance the performance of the location estimation and shorten the transient time of the estimation. This location estimation method would be appropriate to be used in many location-based schemes including our approach of distance-based resource allocation.

As a prior work for distance-based resource allocation, the DRC algorithm proposed in [8] selects a CUE for sharing its power with that of a specific D2D link. Here, _L_ is a pre-selected constant to control the C2D interference from the selected cellular user to the D2D-Rx. As an enhancement of the algorithm, we will propose in the following section a distance-based algorithm that selects a CUE to minimize the outage probability of the D2D link, which should be a function of the location of CUE

3. Resource allocation algorithm

We propose a distance-based resource allocation scheme by deriving the conditional outage probability of D2D links. In Section 3.1, we first develop a resource allocation scheme in the case when only one D2D pair shares radio resource with a cellular user. Then, in Section 3.2, the scheme is extended to the case when two D2D pairs share resource with a cellular user. Furthermore, in Section 3.3, we discuss how to extend the scheme to the general case of the arbitrary number of D2D pairs.

### 3.1. Case of one D2D pair

We first derive the outage probability of D2D link, based on which we propose a method to select a cellular user that shares radio resource with a D2D link. According to the system model described in Section 2, we define the outage probability of the D2D link to be the probability that the instantaneous SINR \( \gamma_0 \) in (5) falls below a predetermined SINR threshold \( \gamma_0 \). Thus, the outage probability of the D2D link conditioned on the location \( \{r_c, \theta_c\} \) of a selected CUE can be expressed as [8]
\[
P_{\text{out}}(\gamma_0) = \text{Pr} \left[ \gamma_0 < \gamma_0 | r_c, \theta_c \right] = \int_0^{\gamma_0} f_{\gamma_0}(\gamma_0) d\gamma_0 = F_{\gamma_0}(\gamma_0), \tag{6}
\]
where \( f_{\gamma_0}(\cdot) \) and \( F_{\gamma_0}(\cdot) \) refer to the PDF and the cumulative distribution function (CDF) of \( \gamma_0 \), respectively. Since \( |h_{B2}|^2 \) and \( |h_c|^2 \)

Fig. 2. Extended scenario where two D2D pairs share the same resource with a cellular user – an example with \( N = 4 \) active cellular users and two D2D pairs. 

follow the independent exponential distribution, the CDF of \( \gamma_0 \) can be obtained as
\[
F_{\gamma_0}(\gamma_0) = 1 - \frac{\eta}{\eta + \gamma_0} \exp\left(-\frac{\gamma_0}{\eta}\right) \tag{7}
\]

If \( \eta \gg N_0 \gamma_0 \), (7) can be simplified using the first-order Taylor series approximation \( \exp(x) \approx 1 + x \) as
\[
F_{\gamma_0}(\gamma_0) = 1 - \frac{\eta - N_0 \gamma_0}{\eta + \gamma_0} L_c \tag{8}
\]

Once two users in the proximity of each other want to communicate directly, they will send the request to the BS. The BS already knows the location information of all available cellular users in the cell and will select the CUE for sharing with the D2D link as
\[
i^* = \text{arg min}_{i \in \{1, 2, \ldots, N\}} F_{\gamma_0}(\gamma_0)
\]

which implies that the proposed scheme selects the cellular user that minimizes the outage probability of the D2D link. In the case when a D2D link requires more than one resource, it is more likely that the D2D link has high channel gain due to short-range communication. We could consider the D2D link use multiple resources to increase data rate. In terms of OFDM transmission, BS should choose different resource blocks (RB) for the certain D2D link. The D2D-Tx will transmit multiple data streams on multiple RBs. Thus, the SINR of different streams are different, and it depends on the cellular resource which use the same RBs. One can define the average outage probability of a D2D link as the probability that the average instantaneous SINR of all streams falls below a predetermined SINR threshold. Therefore, the resource allocation algorithm has slightly changed that the BS selects a set of cellular users that minimizes the average outage probability of a D2D link.

### 3.2. Case of two D2D pairs

In this subsection, we extend the scenario in the previous subsection to support two D2D pairs that could share radio resource with a cellular user, as illustrated in Fig. 2. There are \( N \) active cellular users in a single cell. In order to increase the bandwidth efficiency and total cell throughput, two D2D pairs could be allowed to simultaneously use the same resource as a cellular user. In this case, the.
BS needs to consider the mutual interference between the two D2D pairs as well as the interference between cellular and D2D links. Moreover, BS should choose the best cellular user to optimize the resource sharing with the two D2D pairs at the same time.

When D2D pair 1 and D2D pair 2 use the same resource with CUEi, the SINR at the D2D-Rx1 and D2D-Rx2 is, respectively, given as

\[ \gamma_{\text{D}1} = \frac{|h_{d1}|^2 \eta}{|h_{c1}|^2 P_{\text{c1}} L_{\text{c1}}^{-\alpha} + |h_{d2}|^2 P_{\text{d2}} L_{\text{d2}}^{-\alpha} + N_0}, \]

\[ \gamma_{\text{D}2} = \frac{|h_{d2}|^2 \eta}{|h_{c2}|^2 P_{\text{c2}} L_{\text{c2}}^{-\alpha} + |h_{d1}|^2 P_{\text{d1}} L_{\text{d1}}^{-\alpha} + N_0}, \]

where \( h_{d1} \) and \( h_{d2} \) are channel gain of the two D2D links, respectively, and \( h_{c1} \) and \( h_{c2} \) are channel gains of the links from CUEi to D2D-Rx1 and to D2D-Rx2, respectively. \( L_{c1} \) and \( L_{c2} \) denote the distance between CUEi and D2D-Rx1 and that between CUEi and D2D-Rx2, respectively. By taking the power control strategy of the cellular user and D2D-Tx into account, the SINRs in (10a) and (10b) can be rewritten as

\[
\rho_{\text{old}}^{\text{D}1} = \begin{cases}
1 - \frac{1}{\left(\frac{L_0}{\rho}\right)^{-\alpha} - \frac{P_{\text{c1}} L_{\text{c1}}^{-\alpha}}{\eta^2}} \left(\frac{1}{\gamma_0 + \left(\frac{\rho}{L_0}\right)^{-\alpha}} - \frac{1}{\gamma_0 + \frac{\eta}{P_{\text{c1}} L_{\text{c1}}}}\right) \exp\left(-\frac{\gamma_0 N_0}{\eta}\right), & L_D \neq L_{\text{c1}}, \frac{P_{\text{c1}}}{\eta} \alpha \\
1 - \frac{1}{\left(\frac{L_0}{\rho}\right)^{-\alpha} - \frac{P_{\text{c1}} L_{\text{c1}}^{-\alpha}}{\eta^2}} \left(\frac{1}{\gamma_0 + \left(\frac{\rho}{L_0}\right)^{-\alpha}} - \frac{1}{\gamma_0 + \frac{\eta}{P_{\text{c1}} L_{\text{c1}}}}\right) \exp\left(-\frac{\gamma_0 N_0}{\eta}\right), & L_D = L_{\text{c1}}, \frac{P_{\text{c1}}}{\eta} \alpha
\end{cases}
\]

Similarly, the outage probability of the D2D pair 2 conditioned on the location of cellular user and D2D pair 1 can be obtained as

\[
\rho_{\text{old}}^{\text{D}2} = \begin{cases}
1 - \frac{1}{\left(\frac{L_0}{\rho}\right)^{-\alpha} - \frac{P_{\text{c2}} L_{\text{c2}}^{-\alpha}}{\eta^2}} \left(\frac{1}{\gamma_0 + \left(\frac{\rho}{L_0}\right)^{-\alpha}} - \frac{1}{\gamma_0 + \frac{\eta}{P_{\text{c2}} L_{\text{c2}}}}\right) \exp\left(-\frac{\gamma_0 N_0}{\eta}\right), & L_D \neq L_{\text{c2}}, \frac{P_{\text{c2}}}{\eta} \alpha \\
1 - \frac{1}{\left(\frac{L_0}{\rho}\right)^{-\alpha} - \frac{P_{\text{c2}} L_{\text{c2}}^{-\alpha}}{\eta^2}} \left(\frac{1}{\gamma_0 + \left(\frac{\rho}{L_0}\right)^{-\alpha}} - \frac{1}{\gamma_0 + \frac{\eta}{P_{\text{c2}} L_{\text{c2}}}}\right) \exp\left(-\frac{\gamma_0 N_0}{\eta}\right), & L_D = L_{\text{c2}}, \frac{P_{\text{c2}}}{\eta} \alpha
\end{cases}
\]

Based on these closed-form outage probabilities, the BS could easily make a decision whether or not to allow the two D2D pairs to use the same resource with a cellular user. In particular, the BS computes the conditional outage probabilities of the two D2D links, when they are allowed to share resource with a certain cellular user. We propose three options for the BS to choose a cellular user as follows.

- **Option 1-1**: Choose the CUEi that minimizes the outage probability of D2D pair 1 as
  \[
  i^* = \arg \min_{i \in \{1,2,\ldots,N\}} \rho_{\text{old}}^{\text{D}1},
  \]

- **Option 1-2**: Choose the CUEi that minimizes the outage probability of D2D pair 2 as
  \[
  i^* = \arg \min_{i \in \{1,2,\ldots,N\}} \rho_{\text{old}}^{\text{D}2}.
  \]
• **Option 2**: Choose the CUE, that minimizes the sum of outage probabilities of the two D2D pairs as
\[
\mathbf{1}^* = \arg\min_{i \in \{1, 2, ..., N\}} (P_{D1i}^{O} + P_{D2i}^{O}).
\] (17)

• **Option 3**: Choose the CUE, that minimizes the maximum of outage probabilities of the two D2D pairs as
\[
\mathbf{1}^* = \arg\min_{i \in \{1, 2, ..., N\}} \max (P_{D1i}^{O}, P_{D2i}^{O}).
\] (18)

Depending on the requirements of services on each D2D pair, the BS would use a suitable option to choose the best cellular user. For example, when the D2D pair 1 has higher requirement quality of services than D2D pair 2, the BS might use **Option 1-1** to guarantee the performance of D2D pair 1. **Option 2** considers the summation of the outage probability of the D2D pairs. It cannot guarantee the minimum outage probability of each individual D2D pair. However, it reflects the average outage probability of D2D pairs and acts as a reference for comparison with other methods. **Option 3** restricts the maximum of the outage probabilities of the two D2D pairs, thus keeping the performance of the D2D pairs at the acceptable level. Note that in (13) and (14), \(\eta\) is fixed, and thus the outage probabilities depend only on \(P_{C1}, L_D, L_{C1j}\), and \(I_{Cj}\), where \(P_{C1}\) depends on the distance between the CUE and the BS. Therefore, the BS only requires the location information of cellular users and D2D pairs. This information could be estimated at the cellular and D2D users and reported to the BS.

3.3. General case

The selection methods in (15)–(18) can be extended to the general case of an arbitrary number of D2D pairs without restriction to only two D2D pairs, once the conditional outage probabilities are available. When \(K\) D2D pairs share the same resource, straightforward extensions of (15)–(18) can be made as follows.

• **Option 1-k**: Choose the CUE, that minimizes the outage probability of a specific D2D pair, say D2D pair \(k\), \(k = 1, 2, ..., K\), as
\[
\mathbf{1}^* = \arg\min_{i \in \{1, 2, ..., N\}} P_{Dki}^{O}.
\] (19)

• **Option 2**: Choose the CUE, that minimizes the sum of outage probabilities of the \(K\) D2D pairs as
\[
\mathbf{1}^* = \arg\min_{i \in \{1, 2, ..., N\}} \sum_{k=1}^{K} P_{Dki}^{O}.
\] (20)

• **Option 3**: Choose the CUE, that minimizes the maximum of outage probabilities of the \(K\) D2D pairs as
\[
\mathbf{1}^* = \arg\min_{i \in \{1, 2, ..., N\}} \left( \max_{i \in \{1, 2, ..., K\}} P_{Dki}^{O} \right).
\] (21)

However, the conditional outage probabilities become more difficult to compute, as the number of D2D links sharing the same resource increases. One solution for relieving the difficulty is to consider only the most dominant interference from another D2D pair in computing the conditional outage probability of each D2D link. Then, the conditional outage probability of each D2D link will take the same form as (13).

The proposed resource allocation algorithm can be further generalized to the case of an arbitrary number of D2D pairs and arbitrary number of cellular users. In this case, the D2D pairs can be grouped such that each group contains at least one D2D pair. The D2D pairs in each group will share the same resource with a cellular user, which can be chosen according to one of the criteria in (19)–(21). The order of selecting a cellular user will be determined by that of priority of the groups. The proposed algorithm can also be extended to the case of heterogeneous resource requirements for different D2D links in the following way. Basically, the resources that each user requires can be represented in the unit of resource blocks. In the case that a certain user requires \(n\) resource blocks, we can deal with it as the case where each of \(n\) users in the same position requires a single resource block.

Finally, it should be remarked that the proposed resource allocation algorithm is designed to handle only the intracell interference but the intercell interference is not taken into account, as in most of the previous works on D2D resource allocation. To tackle the intercell interference, however, adjacent BS’s need to coordinate the resource allocation by exchanging relevant information, which will incur backhaul overhead and increase computational complexity [15]. The proposed algorithm can also be extended to take the intercell interference into account by allowing coordination among the BS’s.

4. Numerical results

In this section, we evaluate the performance of the proposed resource allocation scheme through computer simulations. We first evaluate and compare the performance of the proposed scheme and the DRC scheme in [8], when one D2D pair shares resource with a cellular user. Then, we also present the performance of the proposed scheme for an extended scenario where two D2D pairs share resource with a cellular user. We assume that the BS has perfect knowledge on the location of users. As a performance measure, we consider the average outage probability of D2D links. For each realization of one or two D2D links, a cellular user is selected with the proposed criterion and the corresponding outage probability is computed using (6). Then, the outage probabilities are averaged over 10,000 different realizations of D2D links. The system parameters used in simulations are tabulated in Table 1.

In Fig. 3, we consider a circular cell of the radius normalized to one. The green dot at the right corner indicates the location of the D2D-Rx, while the white dot at the center indicates that of the BS. A fixed SNR target of D2D link is set to \(\eta/N_0 = 30\) dB. According to (8), we have computed the conditional outage probability of the D2D link for each location of a cellular user in the cell. The colors in Fig. 3a illustrate the outage probability. We can see that if the BS selects a cellular user in proximity of the D2D-Rx, the outage is extremely high and these locations do not guarantee high performance of the D2D link. In Fig. 3b, we depict the same results just in the left half of the cell area. We observe that the nearer the location of cellular user to the BS in this area, the lower the outage probability of the D2D link is attained. This result comes from the fact that as the cellular user becomes close to the BS, it reduces the transmit power, causing less interference to the D2D link.

In order to compare the proposed scheme with the DRC scheme, we realize a single cell in which there are one D2D pair and \(N\) uniformly distributed cellular users. The location of the D2D pair is assumed to be independent of those of the cellular users. The D2D pair is generated with a restriction that the distance of the D2D link is within 0.05. Then, we apply the proposed and DRC schemes to

| Table 1: Simulation parameters. |
| Parameters | Value |
| Cell radius (\(R\)) | 1 (normalized) |
| Maximum distance of the D2D link (\(\rho\)) | 0.05 |
| Path loss exponent (\(\alpha\)) | 4 |
| Distribution of cellular users | Uniform |
| Number of active cellular users per cell (\(N\)) | 10, 20, 30 |
| Fixed SNR target of the cellular uplink (\(\xi\)) | 20 dB |
select a cellular user that shares resource with the D2D link. For each realization, a cellular user is selected and the corresponding outage probability of the D2D link is evaluated. Fig. 4 illustrates the average outage probability of the D2D link. It reveals that by applying the proposed scheme, the outage probability of the D2D link is significantly reduced. For example, when $N=10$ and $\eta/N_0=30$ dB, the outage probability is approximately $7.4 \times 10^{-3}$ for the DRC scheme, while $1.4 \times 10^{-3}$ for the proposed scheme. As $N$ increases, the performance of the DRC scheme nearly changes, whereas that of the proposed scheme improves significantly. This is because the proposed scheme provides a form of multiuser diversity in the selection of a cellular user among $N$ candidates.

For an extended scenario where two D2D pairs use the same resource with a cellular user, Fig. 5 shows the performance of the two D2D links for various selection criteria proposed in Section 3. The number of cellular users $N$ is fixed to 10. For the Option 1-1 where the BS chooses the best cellular user for the D2D pair 1, the gap between the performance of the two D2D pairs is about 6 dB. That is the same for the Option 1-2, except that the outage probability of the D2D pair 2 is lower than that of the D2D pair 1 in this case. With the Option 2 and Option 3, there is no performance disparity between the two D2D links, and they generally perform better than Options 1-1 and Option 1-2 in the average sense. This suggests that we can exploit a trade-off between the performance of a specific D2D link and the average performance of all D2D links according to different requirements of services for different D2D links.

5. Conclusion

D2D communication is an advanced technology that can increase the spectral efficiency of the system and reduce energy consumption of mobile terminals by reusing the radio resource of cellular links. In this paper, we have investigated resource allocation for D2D communications underlaying a cellular network. For the case when a D2D link shares resource with a cellular user, we have proposed a new distance-based resource allocation scheme, in which the BS can select a best cellular user to mitigate the interference from the cellular link to the D2D link. While developing the proposed scheme, we have derived the conditional outage
probability of the D2D link in a simple form, so that the BS only requires the location information of cellular and D2D users. Moreover, we have developed resource allocation scheme for the case of two D2D pairs, and extended it to the general case of multiple D2D pairs. Numerical results have demonstrated that the proposed scheme outperforms a previously proposed distance-based resource allocation scheme in terms of the outage probability of the D2D link. Furthermore, the performance of the proposed scheme has been found to improve as the number of cellular users increases, since the proposed scheme achieves a form of multiuser diversity in the selection of a cellular user. It is left for future work to consider the intercell interference in the design of the resource allocation algorithm.

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**Appendix: Proof of Lemma 1**

The PDFs of X, Y and Z are expressed as $f_x(x) = \frac{1}{\beta} \exp \left( -\frac{x}{\beta} \right) u(x)$, $f_y(y) = \frac{1}{\beta} \exp \left( -\frac{y}{\beta} \right) u(y)$, and $f_z(z) = \frac{1}{\chi} \exp \left( -\frac{z}{\chi} + \frac{1}{\chi \alpha} \right) u(z - \frac{1}{\chi})$, respectively, where $u(\cdot)$ denotes the unit step function. First, the PDF of $W = X + Y$ can be found as

\[
f_w(w) = f_x(w) \times f_x(w) = \int_{1/\alpha}^{w} f_x(w - z) f_x(z) dz \quad (w > 1/\alpha)
\]

\[
= \int_{1/\alpha}^{w} \frac{1}{\beta} \exp \left( -\frac{w - z}{\beta} \right) \frac{1}{\chi} \exp \left( -\frac{z}{\chi} + \frac{1}{\chi \alpha} \right) dz
\]

\[
= \int_{1/\alpha}^{w} \frac{1}{\beta \chi} \exp \left( -\frac{w}{\beta} + \frac{1}{\chi \alpha} \right) \exp \left[ -z \left( \frac{1}{\chi} - \frac{1}{\beta} \right) \right] dz.
\]

(A. Case of $\chi \neq \beta$

\[
f_w(w) = \int_{1/\alpha}^{w} A e^{-\frac{w}{\beta}} dz = \frac{A}{\beta} \left( e^{-\frac{w}{\beta}} - e^{-\frac{1}{\beta}} \right),
\]

where $A = \frac{1}{\beta \chi} \exp \left( -\frac{w}{\beta} + \frac{1}{\chi \alpha} \right)$ and $B = \frac{1}{\chi} - \frac{1}{\beta}$. Hence, the PDF of W is

\[
f_w(w) = \frac{1}{\beta} \left[ \exp \left( \frac{1}{\chi \alpha} \right) \exp \left( -\frac{w}{\chi} \right) - \exp \left( \frac{1}{\beta \alpha} \right) \exp \left( -\frac{w}{\beta} \right) \right]
\times u \left( w - \frac{1}{\alpha} \right).
\]

Next, the PDF of $G = X/W$ can be evaluated as

\[
f_c(g) = \int_{1/\alpha}^{\infty} w f_w(gw, w) dw = \int_{1/\alpha}^{\infty} w f_x(gw) f_x(w) dw
\]

\[
= \int_{1/\alpha}^{w} \frac{1}{\beta} \exp \left( -\frac{gw}{\beta} \right) \frac{1}{\chi} \left[ e^{\frac{1}{\chi \alpha}} e^{-\frac{w}{\chi}} - e^{\frac{1}{\beta \alpha}} e^{-\frac{w}{\beta}} \right] \left[ e^{\frac{1}{\chi \alpha}} e^{-\frac{w}{\chi}} - e^{\frac{1}{\beta \alpha}} e^{-\frac{w}{\beta}} \right]
\]

\[
= \frac{1}{\beta \chi} \left[ e^{\frac{1}{\chi \alpha}} I_1 - e^{\frac{1}{\beta \alpha}} I_2 \right]
\]

where $I_1 = \int_{1/\alpha}^{\infty} we^{-\frac{w}{\chi}} dw$ and $I_2 = \int_{1/\alpha}^{\infty} we^{-\frac{w}{\beta}} dw$.

Using the integration by parts, $I_1$ and $I_2$ can be expressed as

\[
l_1 = -\frac{w}{g} e^{\frac{w}{\chi} + \frac{1}{\chi \alpha}} I_1^{\infty}_{1/\alpha} \quad \text{and} \quad l_2 = \frac{w}{g} e^{\frac{w}{\beta} + \frac{1}{\beta \alpha}} I_2^{\infty}_{1/\alpha},
\]

\[
l_1 = -\frac{w}{g} e^{\frac{w}{\chi} + \frac{1}{\chi \alpha}} \left[ \frac{1}{\chi} e^{\frac{w}{\chi}} - \frac{1}{\beta} e^{\frac{1}{\beta \alpha}} e^{\frac{w}{\beta}} \right]
\]

\[
= \left[ \frac{1}{\sigma \left( \frac{1}{g} + \frac{1}{\chi} \right)} + \frac{1}{\sigma \left( \frac{1}{g} + \frac{1}{\beta} \right)} \right] \exp \left( \frac{w}{\sigma} \right),
\]

(26)

\[
l_2 = \left[ \frac{1}{\sigma \left( \frac{1}{g} + \frac{1}{\beta} \right)} + \frac{1}{\sigma \left( \frac{1}{g} + \frac{1}{\chi} \right)} \right] \exp \left( \frac{w}{\sigma} \right).
\]

(27)

By substituting (26) and (27) into (25), the PDF of G is found as

\[
f_c(g) = \frac{1}{\chi} \left[ \frac{1}{\sigma \left( \frac{1}{g} + \frac{1}{\chi} \right)} + \frac{1}{\sigma \left( \frac{1}{g} + \frac{1}{\beta} \right)} \right]
\]

\[
\times \exp \left( \frac{w}{\sigma} \right) dx.
\]

(28)

The CDF of G can be expressed as

\[
f_c(g) = \int_{g}^{\infty} \frac{w}{\beta \chi} \left[ \frac{1}{\sigma \left( \frac{1}{g} + \frac{1}{\chi} \right)} + \frac{1}{\sigma \left( \frac{1}{g} + \frac{1}{\beta} \right)} \right] \exp \left( \frac{w}{\sigma} \right) dx
\]

\[
= \frac{1}{\chi} \left[ \frac{1}{\sigma \left( \frac{1}{g} + \frac{1}{\chi} \right)} + \frac{1}{\sigma \left( \frac{1}{g} + \frac{1}{\beta} \right)} \right] e^{\frac{w}{\sigma}}.
\]

(29)

Using the integrations

\[
\int_{0}^{\infty} e^{-\frac{w}{x + \frac{1}{\beta}}} dx = -\frac{k^2 e^{-\frac{w}{x + \frac{1}{\beta}}} }{\left( x + \frac{1}{\beta} \right)^2} \left( x + \frac{1}{\beta} \right) e^{\frac{w}{x + \frac{1}{\beta}}}
\]

and

\[
\int_{0}^{\infty} e^{-\frac{w}{x + \frac{1}{\beta}}} dx = -\frac{k^2 e^{-\frac{w}{x + \frac{1}{\beta}}} }{\left( x + \frac{1}{\beta} \right)^2} \left( x + \frac{1}{\beta} \right) e^{\frac{w}{x + \frac{1}{\beta}}}
\]

the CDF of G in (29) is simplified to

\[
f_c(g) = 1 - \frac{k}{\chi} \left( \frac{1}{g + \frac{1}{\chi} + \frac{1}{\beta}} \right) e^{\frac{w}{\sigma}}.
\]

(32)

B. Case of $\chi = \beta$

From (22), the PDF of W is

\[
f_w(w) = \int_{1/\alpha}^{w} \frac{1}{\beta} \exp \left( -\frac{w}{\beta} + \frac{1}{\beta \alpha} \right) \left( w - \frac{1}{\alpha} \right) \exp \left( -\frac{w}{\beta} \right) u \left( w - \frac{1}{\alpha} \right) dx
\]

\[
= \frac{1}{\beta \alpha} \exp \left( -\frac{w}{\beta} \right) \left( w - \frac{1}{\alpha} \right) \exp \left( -\frac{w}{\beta} \right) u \left( w - \frac{1}{\alpha} \right).
\]

\[
= \frac{1}{\beta \alpha} \exp \left( -\frac{w}{\beta} \right) \left( w - \frac{1}{\alpha} \right) \exp \left( -\frac{w}{\beta} \right) u \left( w - \frac{1}{\alpha} \right).
\]

Then, the PDF of G can be evaluated as

\[
f_c(g) = \int_{1/\alpha}^{w} \frac{1}{\beta} e^{-\frac{w}{\beta}} \exp \left( -\frac{w}{\beta} \right) \left( w - \frac{1}{\alpha} \right) \exp \left( -\frac{w}{\beta} \right) dw
\]

\[
= \frac{1}{\beta \alpha} \left( l_1 - l_2 \right)
\]
where \( I_3 = \int_{1/\kappa}^{\infty} w^2 e^{-\left(\frac{w}{\kappa} + \frac{1}{\beta}\right)} \, dw \) and \( I_4 = \int_{1/\kappa}^{\infty} w e^{-\left(\frac{w}{\kappa} + \frac{1}{\beta}\right)} \, dw \).

Using the integration by parts, we can rewrite \( I_3 \) as

\[
I_3 = -\frac{w^2}{\kappa + 1/\beta} e^{-\left(\frac{w}{\kappa} + \frac{1}{\beta}\right)} \bigg|_{1/\kappa}^{\infty} + \frac{2}{\kappa} I_4.
\]

Substituting (35) into (34), we get the PDF of \( G \) as

\[
f_G(g) = \frac{1}{\kappa \beta^2} \left[ \frac{1}{\sigma \left(\frac{g}{\kappa} + \frac{1}{\beta}\right)^2} + \frac{2}{\sigma \left(\frac{g}{\kappa} + \frac{1}{\beta}\right)^3} \right] e^{-\frac{g}{\kappa \beta}}.
\]

From which the CDF of \( G \) is found as

\[
F_G(g) = \int_0^g \frac{1}{\kappa \beta^2} \left[ \frac{1}{\sigma \left(\frac{x}{\kappa} + \frac{1}{\beta}\right)^2} + \frac{2}{\sigma \left(\frac{x}{\kappa} + \frac{1}{\beta}\right)^3} \right] e^{-\frac{x}{\kappa \beta}} \, dx.
\]

Using the integration

\[
\int_0^g \frac{2e^{-\frac{x}{\kappa \beta}}}{\left(\frac{x}{\kappa} + \frac{1}{\beta}\right)^2} \, dx = -\kappa^3 e^{-\frac{g}{\kappa \beta}} \left(\frac{g}{\kappa} + \frac{1}{\beta}\right)^2 - \int_0^g \frac{e^{-\frac{x}{\kappa \beta}}}{\sigma \left(\frac{x}{\kappa} + \frac{1}{\beta}\right)^2} \, dx,
\]

the CDF of \( G \) is obtained as

\[
F_G(g) = 1 - \frac{\left(\frac{g}{\kappa \beta} + \frac{1}{\beta}\right)^2}{\left(\frac{g}{\kappa} + \frac{1}{\beta}\right)^2} \exp \left(-\frac{g}{\kappa \beta}\right).
\]

References


