Optimal Operating Condition for Co-located Device-to-Device Paris

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ABSTRACT

In device-to-device (D2D) communication, users in close proximity to each other can communicate directly without going through a base station; such direct communication can improve spectral efficiency. However, D2D links may generate high interference to cellular user equipment (UE) located in their communication areas if they use the same channel with the UE for data transmission. D2D communication could also generate interference for each D2D pair when the common wireless medium in a co-located limited area is accessed. Although, to solve this problem, research on reducing or avoiding interference between D2D and cellular UE in network supporting D2D communication was conducted, the interference managements are still not fully studied for between D2D pairs. In this paper, we investigate the problem of D2D pair coexistence in which interference is considered between D2D pairs. By analytically deriving an operating condition for D2D pairs deployed within the same region, we provide a lower bound on the throughput of D2D pair networks and the optimal number of D2D pairs that can coexist.

Keywords:
Co-located, Device-to-device communication, Interference, Operating condition.

1. INTRODUCTION

Device-to-device (D2D) communication commonly refers to the technologies that enable devices to communicate directly and without an infrastructure of access points or base stations, or the involvement of wireless operators. D2D increases the overall network spectral efficiency and thus allows the network to admit more users [1].

D2D use cases can be classified into peer-to-peer and relay [2]. For the peer-to-peer case, D2D communications can be used to provide local data service when two geographically proximate users or devices want to exchange data, e.g., in the case of content sharing or context-aware applications.

Although D2D communication brings improvement in spectral efficiency and system capacity, the interference caused by D2D links on the cellular communication must be contained. Additionally, D2D links also interfere with each other. Thus, interference management is one of the most critical issues for D2Ds underlying cellular networks.

There exist several works to reduce the interference between D2D pairs and cellular networks. In [3,4], restricting the transmit power schemes has been suggested to coordinate interference between D2D users and cellular users. Furthermore, in [5], author proposed that resource allocation scheme, in which a D2D link can reuse the resources more than one cellular user equipment (UE) by detecting the proximity cellular UE. In addition, a joint subcarrier and power allocation method using the spectrum sensing technique has been proposed in [6] to improve the spectrum efficiency.

Even though the interference management for between D2D pair and cellular networks was proposed, the interference reducing methods are still not fully studied for between D2D pairs. Because of an absence of coordination between independent D2D pairs when accessing a wireless medium, devices will encounter high interference if several D2D pairs are simultaneously operating in crowded places, such as airports, international conferences, and shopping malls, where potential D2D users are located close to each other. Therefore, the study of interference gains importance because interference affects the throughput of a D2D pair network.

In this paper, we investigate the issue of D2D pair coexistence, where there are several D2D pairs that need to communicate privately within the same region, as depicted in Figure 1. In this scenario, because many D2D pairs exist densely, the pairs cause severe interference problems for D2D pair communication. Accordingly, an operating condition to obtain maximum throughput is necessary for densely co-located D2D pair systems.
The main contribution of this work is to find the optimal operating condition of D2D pairs deployed within the same region. To obtain the optimal condition, we derive an analytical model. Moreover, this work considers a lower bound on the throughput of D2D pair networks and the optimal number of D2D pairs that can coexist within the same region.

The rest of this paper is organized as follows. Section 2 introduces the D2D system model and the analytical model that satisfy the sufficient condition of D2D pairs. In Section 3, analytical methods are discussed. In Section 4, numerical studies are discussed. Finally, some concluding remarks are presented in Section 5.

2. SYSTEM MODEL AND PROBLEM FORMULATION

2.1 System Topology and Signal Model

Let us consider a limited circular region interference scenario that involves co-located D2D pairs. We assume that the interference between the cellular network and the D2D pair is managed efficiently using location-based, D2D mode selecting mechanisms [7]. Hence, we focus only on the interference caused by the coexistence of D2D pairs. In this scenario, D2D pairs are assumed to be uniformly distributed in a circular region of radius \( R \) from the reference D2D receiver and organized in \( N \) D2D pairs with maximum radius \( D_R \), as shown in Figure 1.

Under the considered scenario, the signal received at the reference D2D receiver is

\[
y = \sqrt{(u_R)^{-a}P_D h_R s_R + (u_I)^{-a}P_D h_I s_I},
\]

where \( s_R \) and \( s_I \) are the signals transmitted from the reference D2D transmitter and from the interfering D2D transmitter, respectively. In addition, \( h_R \) and \( h_I \) are the channel coefficient of the reference D2D pair link and that of the reference D2D receiver-interfering D2D transmitter link; we assume that all channel coefficients follow an independent complex Gaussian distribution. Furthermore, \( u_R \) and \( u_I \) are the distance of the reference D2D pair link and that of the reference D2D receiver-interfering D2D transmitter link, respectively, in a circular region. In (1), a path-loss model defined as \( P_r = P_D (u_0)^{-\alpha} \) is used, where \( P_D \) and \( P_r \) denote the initial transmit power and signal power measured at \( u_0 \) away from the transmitter, respectively. Furthermore, \( \alpha \) is a path-loss exponent.

2.2 Problem Formulation

To find the optimal operating conditions for maximum throughput in the region, we define a throughput of D2D pair networks, denoted by \( T \), as

\[
T = \sum_{i=1}^{N} T_i,
\]

where \( T_i \) is the throughput of the D2D pair \( i \) conveyed to the D2D receiver in each of the \( N \) D2D pairs deployed in the region.

Let us assume that the most interfered D2D pair of our scenario is the central one, given the assumption we made on the distribution of D2D pairs, where the most interfered D2D pair has an index 1. Therefore, we can define a lower bound on the throughput of D2D pair networks, \( T_{\text{bound}} \), as

\[
T \geq NT_1 = T_{\text{bound}}.
\]

The main contribution of our work is to derive a lower bound, \( T_{\text{bound}} \), and the number, \( n_0 \), of D2D pairs that maximizes \( T_{\text{bound}} \).
3. ANALYSIS

3.1 Sufficient Condition in Co-located Device-to-Device Pairs

In order to evaluate the throughput of the reference D2D pair, $T_1$, let us focus our attention on a generic transmission performed by other D2D transmitters placed at a distance $u_R$ from the reference D2D receiver. In the following formulas, we assume that an ongoing interfering transmission, performed by a D2D pair placed at a distance $u_I$ from the reference D2D receiver, determines an outage event in the reference D2D receiver if $u_I \leq \beta^* u_R$, where $\beta^*$ will be derived in Section 3.2.

Therefore, for a given distance $u_R$, the conditional probability of an outage caused by an interfering D2D placed at a distance $u_I$ is given by

$$P_{\text{int}|u_R} = \text{Prob}[u_I \leq \beta^* u_R] = \int_0^{\beta^* u_R} f_{C_I}(u_I) du_I,$$  \hspace{1cm} (4)

where $f_{C_I}(\cdot)$ is the probability density function (PDF) of the random variable $u_I$ obtained by a circular region of radius $R$, and it is defined as

$$f_{C_I}(u_I) = \begin{cases} 2u_I/R^2, & 0 < u_I \leq R \\ 0, & \text{otherwise}. \end{cases}$$  \hspace{1cm} (5)

Substituting (5) into (4),

$$P_{\text{int}|u_R} = \frac{\beta^* u_R^2}{R^2}, \quad 0 < \beta^* u_R \leq R,$$

$$= 0, \quad \text{otherwise},$$  \hspace{1cm} (6)

where $u_R$ is the random variable for a distance between the reference D2D transmitter and receiver of radius $D_R$ and it has the same PDF as $u_I$.

After applying the total probability theorem over the random variable $u_R$ to (6), we can obtain $P_{\text{int}}$ as

$$P_{\text{int}} = \int_0^{D_R} P_{\text{int}|u_R} f_{C_R}(u_R) du_R = \frac{\beta^* D_R^2}{2R^2}.$$  \hspace{1cm} (7)

where $f_{C_R}(\cdot)$ denotes the PDF of $u_R$. $P_{\text{int}}$ represents the average probability that a generic interfering D2D pair is sufficiently close to the reference D2D receiver to prevent from communicating within the reference D2D pair in case of simultaneous and co-channel transmission.

From (7), for the presence of a potentially interfering transmission, the reference D2D receiver experiences a signal outage with an average probability given by

$$P_{\text{out}} = P_{\text{int}} \rho = \frac{\beta^* D_R^2}{2R^2} \rho,$$  \hspace{1cm} (8)

where $\rho$ is the probability that a co-channel is assigned to the reference D2D pair and the interfering D2D pair.

Because the reference D2D pair coincides with $N - 1$ potentially interfering D2D pairs in the region, the outage of the reference D2D pair communication can occur when it experiences disruption from at least one interfering D2D pair. Therefore, the outage probability of the reference D2D receiver is given by

$$P_{\text{out}}^N = 1 - (1 - P_{\text{out}})^{N-1} = 1 - \left(1 - \frac{\beta^* D_R^2}{2R^2} \rho\right)^{N-1}.$$  \hspace{1cm} (9)

Subsequently, we obtain the reference D2D pair throughput $T_1$ by $T_1 = M(1 - P_{\text{out}}^N)$, where $M$ represents the bits per symbol according to the modulation and coding scheme (MCS) level, as the signal-to-interference ratio (SIR) demanded by the D2D pair. Substituting (9) into (3),

$$T_{\text{bound}} = NM \left(1 - \frac{\beta^* u_R^2}{2R^2} \rho\right)^{N-1}.$$  \hspace{1cm} (10)

Then, the value of $n_o$ that maximizes $T_{\text{bound}}$ can be obtained by the deviation of $T_{\text{bound}}$ for $N$ as follows:

$$\frac{dT_{\text{bound}}}{dN} \bigg|_{N = n_o} = \left[ NM \left(1 - \frac{\beta^* u_R^2}{2R^2} \rho\right)^{N-1} \right]' = 0.$$  \hspace{1cm} (11)

Let $\theta = \frac{\beta^* u_R^2}{2R^2} \rho$; we can expand (10) as follows:

$$\frac{dT_{\text{bound}}}{dN} = M(1 - \theta)^{N-1} + NM \cdot \ln(1 - \theta) \cdot (1 - \theta)^{N-1}$$
$$= M(1 - \theta)^{N-1} \cdot \left[1 + N \cdot \ln(1 - \theta)\right].$$  \hspace{1cm} (12)

Consequently, $n_0$ is yielded as

$$\frac{1}{n_0} = \ln \left( \frac{1}{1 - \frac{\beta^* u_R^2}{2R^2} \rho} \right).$$  \hspace{1cm} (13)

3.2 Determination of the Parameter $\beta^*$

To determine the parameter $\beta^*$, we involve the SIR $\gamma$ of the reference D2D receiver, and assume that, if $\gamma$ is greater than a demanded SIR value $\gamma_{th}$ (dB), the signal
is correctly received; otherwise, an incorrect reception is assumed. In other words, the successive transmission of the reference D2D pair is available when

\[ 10 \log_{10} \gamma \geq \gamma_{th}. \]  

(14)

Let all D2D pairs in the channel model with Rayleigh fading be characterized by the same transmitting power; from (14), the SIR at the reference D2D receiver is expressed as

\[ \gamma = \frac{|h_R|^2 u_R^{-a} p_D}{|h_I|^2 u_I^{-a} p_D} = \frac{|h_R|^2 u_R^{-a} p_D}{|h_I|^2 u_I^{-a} p_D} = \frac{|h_R|^2}{|h_I|^2 \beta_s^{-a}}. \]  

(15)

To obtain the PDF of \( \gamma \), we first let \( x = |h_R|^2 \) and \( y = |h_I|^2 \). Because each channel coefficient follows an independent complex Gaussian distribution, the PDFs of \( x \) and \( y \) are \( f_z(z) = \exp(-z)U(z) \), where \( z = x \) or \( y \) and \( U(\cdot) \) is the unit step function. With the help of [8], the PDF of \( z = x/y \) is obtained as

\[ f_z(z) = \int_0^\infty y f_{xy}(yz, y) dy = \int_0^\infty y \exp(-(yz+y)) dy = \frac{1}{(z+1)^2}. \]  

(16)

Therefore, from (14) and (15), we can obtain \( \beta^* \) as follows:

\[ \beta^* = \int_0^\infty 10^{\gamma_{th}/(10 \alpha)} \left( \frac{1}{z} \right)^{1/2} f_z(z) dz. \]  

(17)

4. NUMERICAL STUDIES

We investigate the operating condition of D2D pairs such as a lower bound on the throughput of D2D pair networks and the optimal number of D2D pairs.

In Figure 2, the parameter \( \beta^* \) expressed by (17) is reported as a function of \( \gamma_{th} \) (dB). Based on the results depicted in Figure 2, if a demanded SIR value \( \gamma_{th} \) decreases, or \( \alpha \) increases, \( P_{out}^N \) is degraded by smaller values of \( \beta^* \).

In Figures 3–5, we set \( M = 3.32 \) bits/symbol and \( \gamma_{th} = 13 \) dB, according to MCS level 6 [9], respectively. We then set \( \alpha = 3 \).

In Figures 3 and 4, we consider \( \rho = 1/50 \), which means that each D2D pair randomly selects only one channel among 50 channels in a long-term evolution (LTE)-advanced cellular system with a 10 MHz channel bandwidth.

Figure 3 shows \( P_{out}^N \) as a function of the number of D2D pairs in the region \( N \) for three different values of the ratio \( R/D_R \). \( P_{out}^N \) increases as \( N \) increases and \( R/D_R \) decreases. As can be seen from the results in the graphs, variation in the density of D2D pairs has a significant impact on coexistence.

Figure 4 shows \( T_{bound} \) as a function of the number of D2D pairs in the region \( N \) for three different values of the ratio \( R/D_R \). As expected from Figure 3, \( T_{bound} \) increases as the ratio \( R/D_R \) increases. Through these results, we can obtain the optimum values of \( N = 252, 452, \) and \( 752 \) when \( R/D_R = 5, 7, \) and \( 9 \), respectively, to maximize \( T_{bound} \).

The curves related to the optimum value of \( n_0 \) that maximizes the throughput in the scenario, expressed...
by (13), are reported in Figure 5 as a function of the ratio $R/DR$ and $r$. Through the results, $n_0$ is approximately 200 and 500 when $r = 1/50$ and $1/100$, respectively, for $R/DR = 5$. As expected, owing to the mitigation effect on the mutual interference because of the propagation by density of D2D pairs and the probability that interference occurs, $n_0$ increases as the ratio $R/DR$ increases and $r$ decreases.

5. CONCLUSION

In this paper, the issue of the coexistence of D2D pairs deployed in the same region has been addressed. The analytical derivation of a lower bound on the maximum throughput offered by co-located D2D pair networks has been performed, considering propagation aspects with a fading effect. Moreover, the optimal number of D2D pairs that maximize the throughput of D2D pair networks has been assessed.

The results show that $P_{out}$ is decreased as a demanded SIR value decreases or path-loss exponent increases. The results also show that the maximum throughput of D2D pair networks and the optimal number of D2D pairs increase as the ratio $R/DR$ increases and $r$ decreases.

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REFERENCES

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