Outage Performance Analysis of Cooperative D2D Communication

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Abstract

This study investigates the outage performance of cooperative device-to-device (D2D) communication reusing the uplink resource allocated to multiple cellular users which distribute uniformly in the cell. First, the explicit outage probability expressions for cooperative D2D with decode-and-forward (DF) and amplify-and -forward (AF) relaying schemes are both provided. Then based on this, the effects of network parameters including transmit power and user locations on outage probabilities are explored. Accordingly, the criteria for relay selection in cooperative D2D is further proposed. Simulations and numerical results validate the derivations and analyses, and reveal that at the cell-edge, the cooperative D2D mode can achieve significant outage performance gains over the traditional direct D2D case without relay cooperation, even with less transmit power.

Keywords: Device-to-Device, Cooperative relaying, Outage probability, Uniform distribution

1 Introduction

Recently, with the increasing density of mobile users and the rising demands of wireless communication services in cellular networks, the burdens on the base station (BS) worsen and the spectrum resources become scarce. The emergence of device-to-device (D2D) communication effectively alleviates these problems as D2D enables two mobile users to communicate directly without traversing the BS and reuse the cellular resources, which not only offloads the cellular traffic but also increases the spectral efficiency of the network [1]. Moreover, due to the potential of improving the energy efficiency, the cell coverage and throughput [2-3], D2D is recognized as a promising paradigm in next generation cellular networks.

To further enhance the cellular network performance, the cooperative D2D communication [4-5] introducing the cooperative relaying technique into traditional direct D2D is proposed, where the idle users in the network can serve as relays for the target D2D pair [6]. Currently, much efforts has been done on the investigation of relay assisted D2D using the common cooperative relaying protocols which include decode-and-forward (DF) and amplify-and -forward (AF) [7-15]. For DF relaying assisted D2D, a distributed relay selection scheme was developed in [7] which first eliminates improper relays considering the interference between D2D and cellular communication, and then chooses the best one from the candidate relays by using the distributed algorithm. A criterion of applying relay assisted D2D mode was provided in [8] by comparing the sum-capacity with cellular communication based on the interference constrained precondition and the optimal path selection. An energy saving zone between a D2D pair was mathematically described in [9] where the relay resides in this geometric region is energy efficient. In [10], the optimal access density and power allocation of D2D users were designed, and the achievable transmission capacity was analyzed. In [11], the transmit power of cellular and D2D systems were optimized, and the optimal relay selection range was given. For AF relaying assisted D2D, a heuristic algorithm about resource blocks allocation was presented in [12] utilizing the interference measurement technology [13]. In [14] and [15], the system energy-efficiency and spectral-efficiency were analyzed, and the optimal power allocation to maximize the energy-efficiency was discussed. It is worth noting that the aforementioned literatures on relay assisted D2D mainly focus on the scenario without a direct link between D2D users, considering that D2D users are not in near proximity or the quality of the channel between D2D users is poor. When the two limitations mentioned above, which are described as large distance and poor propagation condition [16] in briefly, are absent, the direct connectivity will be allowed, and therefore a true sense of cooperative D2D communication can be established which means that

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the signal broadcasted by the D2D transmitter will first be received by both the D2D receiver and the relay nearby, and then the relay will retransmit the processed source signal to the D2D receiver [17-18]. More specifically, the direct link will provide one more information path that is received at destination with the relaying link to achieve potential diversity benefits [19].

This paper investigates the outage performance of cooperative D2D communication involving a direct link in the interference scenario where multiple cellular users distribute uniformly in the cell, and the allocated uplink resources are shared by cooperative D2D users. First, the closed-form expression for the outage probability of cooperative D2D with DF relaying scheme is derived, and the effect of the transmit power and the locations of cooperative D2D users on the outage performance is analyzed by the outage probability upper bound, which indicates that this performance can be improved with increasing transmit power of the D2D transmitter and the relay when the locations of cooperative users are fixed, as well as with increasing radial coordinates of cooperative users when the transmit power control mechanism limiting a maximum acceptable threshold [20-21] is applied on the D2D transmitter and the relay. Then, the explicit outage probability expression for cooperative D2D with AF relaying scheme is derived, while the outage performance analysis is made using the outage probability upper bound that is obtained through the property of the modified Bessel function [22], and the same inference presented in DF relaying mode can be achieved. Next, the optimal relay selection criterion and the suboptimal one are proposed, where the former selects the optimal relay from candidate users by directly comparing outage probabilities of direct D2D and cooperative D2D, and the latter presents the more specific relay selection areas by the comparison of approximate expressions for various D2D modes using first order Taylor approximation. Finally, simulations and numerical results are provided to verify the accuracy of analytical results. The innovations of this paper are twofold: (1) the interference scenario is modeled as a cell where cellular users are uniformly distributed. As opposed to most existing works which assume the locations of cellular users are fixed, this model more conforms to reality. (2) Exact expressions for outage probabilities of cooperative D2D communication with a direct link between D2D users are provided. Two relaying schemes including DF and AF are both considered, and outage performances are analyzed accordingly.

The remainder of this paper is structured as follows. In Section 2, the system model is stated. In Section 3, the outage probability of cooperative D2D is derived along with the outage performance analysis, and the relay selection criterion is proposed. In Section 4, simulations and numerical results are presented. In Section 5, conclusions are drawn and the future research direction is suggested.

2 System Model

Let us consider a single cell scenario as shown in Figure 1. There exist one BS, one D2D pair including a transmitter (S) and a receiver (D), one relay (R), and M cellular users (C_i , $i \in \{1,2,\cdots,M\}$) which are uniformly distributed in this cell. We assume that cooperative D2D communication reuses the cellular uplink resources, and thus the mutual interference problem will be produced, which involves the interferences to the BS from S and R, and the cellular interferences to R and D.

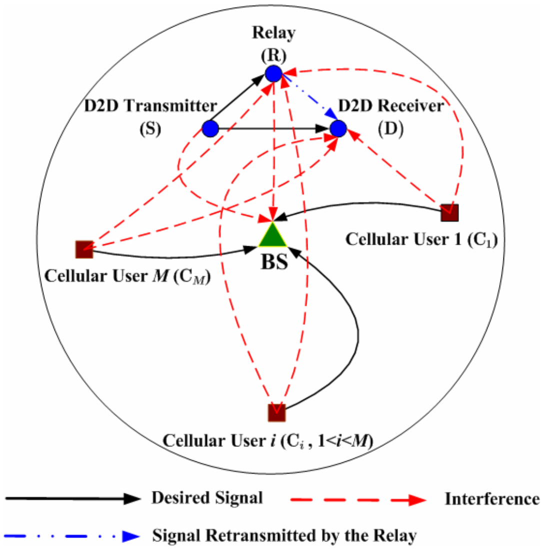

Figure 1. System model

Since the relay is introduced into the D2D system to participate in the communication, the transmission will be fulfilled within two time slots [14]. Details are described as follows.

In the first time slot, S broadcasts its signal, while R and D receive this singnal. The received signals at R and D are written as

$$y_R = \sqrt{P_S} g_{SR} h_{SR} s + I_R^{(1)} + n_R^{(1)} \quad \textbf{(1)}$$

$$y_D^{(1)} = \sqrt{P_S} g_{SD} h_{SD} s + I_D^{(1)} + n_D^{(1)} \quad \textbf{(2)}$$

where $g_{T_1T_2} = \left[1 + \left(d_{T_1T_2}\right)^{\alpha/2}\right]^{-1}$ denotes the large-scale path loss [23] of the T_1-*to*-T_2 link ($T_1 \in \{S,R\}$ and $T_2 \in \{R,D\}$), $d_{T_1T_2}$ is the distance of this link, and α is the path loss exponent. $h_{T_1T_2}$ denotes the small-scale fading of the T_1-*to*-T_2 link which follows the independent complex Gaussian distribution $\mathcal{CN}(0,1)$. P_{T_1} denotes the transmit power of user T_1. s denotes the original data symbol transmitted by S which has the constant unit power. $I_{T_2}^{(t)}$ and $n_{T_2}^{(t)}$ denote the received interfering signal, and the additive noise following $\mathcal{CN}\left(0, N_0\right)$ at user T_2 in time slot t ($t \in \{1,2\}$), respectively.

In the second time slot, S remains silent and R broadcasts its processed signal, while D receives this signal.

(1) If R adopts the DF strategy, the received signal at D is written as

$$y_D^{(2)} = \sqrt{P_R} g_{RD} h_{RD} \hat{s} + I_D^{(2)} + n_D^{(2)} \tag{3}$$

where $\hat{s}$ denotes the decoded data symbol transmitted by R with a unit power.

(2) If R adopts the AF strategy, it will only amplify the signal received in the first time slot, and then retransmit the amplified one to D. The received signal at D in this case is written as

$$\begin{aligned} y_D^{(2)} &= \beta g_{RD} h_{RD} y_R + I_D^{(2)} + n_D^{(2)} \\ &= \beta \sqrt{P_S} g_{SR} g_{RD} h_{SR} h_{RD} s + \beta g_{RD} h_{RD} I_R^{(1)} + I_D^{(2)} \\ &+ \beta g_{RD} h_{RD} n_R^{(1)} + n_D^{(2)} \end{aligned} \tag{4}$$

where β denotes the relay amplifier gain [24-25].

According to the above description, consider the free space scenario with $\alpha = 2$ [26], and the average received interference power of T_2 in time slot t can be obtained from our previous work [27] as

$$\begin{aligned} &\mathrm{E}\left[\left|I_{T_2}^{(t)}\right|^2\right] \\ &= \frac{Mk}{2\pi} \int_0^{2\pi} \int_0^1 \frac{\left(1 + r\sqrt{u}\right)^2}{\left\{1 + \left[r^2 u + r_{T_2}^2 - 2 r r_{T_2} \sqrt{u} \cos\left(\theta - \theta_{T_2}\right)\right]^{\frac{1}{2}}\right\}^2} du d\theta \end{aligned} \tag{5}$$

where r denotes the cell radius, k denotes the average received power at the BS in the uplink, $\left(r_{T_2}, \theta_{T_2}\right)$ denotes the polar coordinate of T_2, and u is a random variable which is drawn from the uniform distribution $U(0,1)$.

3 Outage Probability of Cooperative D2D Communication

3.1 The Outage Probability of Cooperative D2D with DF Relaying Scheme

In this subsection, the expression for the outage probability of cooperative D2D with DF relaying scheme is derived, and the effects of transmit power and user locations on the outage probability are analyzed.

First, making use of the fact that the aggregate interference look Gaussian when the number of interferers is large [28], the received SINR of R is written from (1) as

$$SINR_R = \frac{P_S \left(g_{SR}\right)^2 \left|h_{SR}\right|^2}{\mathrm{E}\left[\left|I_R^{(1)}\right|^2\right] + N_0} \tag{6}$$

The received SINR of D can be written from (2) and (3) using the maximal ratio combing (MRC) technique [29] as

$$SINR_D^{DF} = \frac{P_S \left(g_{SD}\right)^2 \left|h_{SD}\right|^2 + P_R \left(g_{RD}\right)^2 \left|h_{RD}\right|^2}{\mathrm{E}\left[\left|I_D\right|^2\right] + N_0} \tag{7}$$

where $\mathrm{E}\left[\left|I_D\right|^2\right]$ is equal to $\mathrm{E}\left[\left|I_D^{(1)}\right|^2\right] = \mathrm{E}\left[\left|I_D^{(2)}\right|^2\right]$ which can been verified by (5).

Then, by definition of the outage probability of the cooperative DF relaying system [17], the expression for the outage probability of cooperative D2D with DF relaying scheme can be given by

$$\begin{aligned} P_{out}^{DF} &= \Pr\left[SINR_R \le \gamma_{th}\right] + \Pr\left[SINR_D^{DF} \le \gamma_{th}\right] \\ &- \Pr\left[SINR_R \le \gamma_{th}\right] \Pr\left[SINR_D^{DF} \le \gamma_{th}\right] \end{aligned} \tag{8}$$

where $\gamma_{th} = 2^{2R_0} - 1$ denotes the predetermined SINR threshold, and R_0 is the communication rate [20].

Finally, the explicit expression for (8) can be obtained from Appendix A as

$$P_{out}^{DF} = \begin{cases} 1 - \exp\left(-\frac{\gamma_{th}}{L_1}\right) \dfrac{L_2 \exp\left(-\frac{\gamma_{th}}{L_2}\right) - L_3 \exp\left(-\frac{\gamma_{th}}{L_3}\right)}{L_2 - L_3}, & L_2 \ne L_3 \\ 1 - \left(1 + \frac{\gamma_{th}}{L_2}\right) \exp\left(-\frac{\gamma_{th}}{L_1} - \frac{\gamma_{th}}{L_2}\right), & L_2 = L_3 \end{cases} \tag{9}$$

where $L_1 = P_S \left(g_{SR}\right)^2 / \mu_1$ is the average received SINR of R, $L_2 = P_S \left(g_{SD}\right)^2 / \mu_2$ and $L_3 = P_R \left(g_{RD}\right)^2 / \mu_2$ are respectively the average received SINR of D in time slot 1 and 2, $\mu_1 = \mathrm{E}\left[\left|I_R^{(1)}\right|^2\right] + N_0$ and $\mu_2 = \mathrm{E}\left[\left|I_D\right|^2\right] + N_0$.

As seen from (9), the outage performance of cooperative D2D is affected by the values of L_j ($j = 1,2,3$) when γ_{th} is fixed, while L_j mainly depend on the transmit power and locations of users T ($T \in \{S, D, R\}$).

(1) If the locations of T are all determined, by the upper bound of (9) which is expressed as

$$P_{out}^{DF} \le \begin{cases} 1-\exp\left(-\frac{\gamma_{th}}{L_1}-\frac{\gamma_{th}}{\min\left(L_2,L_3\right)}\right), & L_2 \ne L_3 \\ 1-\left[1-\left(\frac{\gamma_{th}}{L_2}\right)^2\right]\exp\left(-\frac{\gamma_{th}}{L_1}\right), & L_2 = L_3 \end{cases} \quad \textbf{(10)}$$

(where the second inequality comes from the identity $\exp(-t) \ge 1-t$ for $t \ge 0$) it indicates that the outage probability decreases with increasing P_S and P_R. Note that since the power control mechanism [20] is applied on S and R to avoid influencing the quality of the cellular communication, the transmit power can not exceed the maximum acceptable thresholds which are given by [21]:

$$P_{T_1} \le k\delta\left(1+r_{T_1}\right)^2 \quad \textbf{(11)}$$

where $T_1 \in \{S,R\}$, δ denotes the maximum acceptable received interference-to-signal ratio (ISR) at the BS.

(2) If the maximum transmit power thresholds shown in (11) are utilized, the outage probability will only be related to the locations of users T which are the polar coordinates (r_T,θ_T). Without loss of generality, we consider the symmetry scenario where r_T are identical and $\theta_S+\theta_D=2\theta_R$ ($\theta_T \in (0,2\pi]$). Then, by the upper bound of (5) which can be obtained from the appendix in our previous work [27], i.e.,

$$\mathrm{E}\left[\left|I_{T_2}^{(t)}\right|^2\right] \le Mk + \frac{Mk\left(r_{T_2}^2+2r\right)}{r^2}\ln\left(1+r^2+r-r_{T_2}^2\right) \quad \textbf{(12)}$$

the lower bounds of L_j are calculated as

$$\begin{aligned} L_j &\ge k\delta(1+r_T)^2\omega_j\left[Mk+\frac{Mk\left(r_T^2+2r\right)}{r^2}\ln\left(1+r^2+r-r_T^2\right)+N_0\right]^{-1} \\ &\ge \left[\frac{Mk+N_0}{k\delta(1+r_T)^2\omega_j}+\frac{Mk\ln\left(1+r^2+r-r_T^2\right)}{k\delta r^2\omega_j}\left(1+\frac{2r}{r_T^2}\right)\right]^{-1} \end{aligned} \quad \textbf{(13)}$$

where ω_j is equal to $(g_{SR})^2$ if $j=1$, $(g_{SD})^2$ if $j=2$, and $(g_{RD})^2$ if $j=3$. Combine (13) with (10), it indicates that the outage probability decreases with increasing r_T (note that d_{SD} is in general determinated, while d_{SR} and d_{RD} decreases with increasing r_T in this case).

3.2 The Outage Probability of Cooperative D2D with AF Relaying Scheme

This subsection derives the expression for the outage probability of cooperative D2D with AF relaying scheme, and analyzes the effects of transmit power and user locations on the outage probability.

First, the received SINR of D is written from (2) and (4) using the MRC as

$$SINR_D^{AF} = \frac{P_S\left(g_{SD}\right)^2\left|h_{SD}\right|^2}{\mu_2} + \frac{\beta^2 P_S\left(g_{SR}g_{RD}\right)^2\left|h_{SR}h_{RD}\right|^2}{\beta^2\left(g_{RD}\right)^2\left|h_{RD}\right|^2\mu_1+\mu_2} \quad \textbf{(14)}$$

Substituting the AF relay amplifier gain [24] $\beta=\sqrt{P_R\Big/\left[P_S\left(g_{SR}\right)^2\left|h_{SR}\right|^2+\mu_1\right]}$ into (14), the received SINR can be rewritten as

$$SINR_D^{AF} = SINR_D^{(1)} + \frac{SINR_D^{(2)} \times SINR_R}{SINR_D^{(2)} + SINR_R + 1} \quad \textbf{(15)}$$

where $SINR_R = L_1\left|h_{SR}\right|^2$, $SINR_D^{(1)} = L_2\left|h_{SD}\right|^2$ and $SINR_D^{(2)} = L_3\left|h_{RD}\right|^2$.

Then, by definition of the outage probability of the cooperative AF relaying system [17], the expression for the outage probability of cooperative D2D with AF relaying scheme can be given by

$$P_{out}^{AF} = \Pr\left[SINR_D^{AF} \le \gamma_{th}\right] \quad \textbf{(16)}$$

Finally, the explicit expression for (16) can be obtained from Appendix B as

$$\begin{aligned} P_{out}^{AF} =& 1-\exp\left(-\frac{\gamma_{th}}{L_2}\right)-\frac{1}{L_2}\exp\left(-\frac{\gamma_{th}}{L_1}-\frac{\gamma_{th}}{L_3}\right) \\ &\times 2\int_0^{\gamma_{th}}\exp\left[\left(\frac{1}{L_1}+\frac{1}{L_3}-\frac{1}{L_2}\right)x\right]\sqrt{\frac{(\gamma_{th}-x)(\gamma_{th}-x+1)}{L_1L_3}} \\ &\times K_1\left(2\sqrt{\frac{(\gamma_{th}-x)(\gamma_{th}-x+1)}{L_1L_3}}\right)dx \end{aligned} \quad \textbf{(17)}$$

where $K_v(x)=\int_0^{+\infty}e^{-x\cosh(t)}\cosh(vt)dt$ denotes v^{th}-order modified Bessel function of the second kind [30].

Similar to the outage performance analysis in Section 3.1, by the upper bound of (17) which is expressed as

$$\begin{aligned} &P_{out}^{AF} \\ &\le 1-\exp\left(-\frac{\gamma_{th}}{L_2}\right)-\frac{\gamma_{th}}{L_2}\exp\left(-\frac{\gamma_{th}}{L_1}-\frac{\gamma_{th}}{L_3}\right) \\ &\times\int_0^1\exp\left[\left(\frac{\gamma_{th}}{L_1}+\frac{\gamma_{th}}{L_3}-\frac{\gamma_{th}}{L_2}\right)x'-2\sqrt{\frac{(\gamma_{th}-\gamma_{th}x')(\gamma_{th}-\gamma_{th}x'+1)}{L_1L_3}}\right]dx' \\ &\le 1-\exp\left(-\frac{\gamma_{th}}{L_2}\right)-\frac{\gamma_{th}}{L_2}\exp\left(-\frac{\gamma_{th}}{L_1}-\frac{\gamma_{th}}{L_3}\right) \\ &\times\exp\left[\int_0^1\left(\frac{\gamma_{th}}{L_1}+\frac{\gamma_{th}}{L_3}-\frac{\gamma_{th}}{L_2}\right)x'-2\sqrt{\frac{(\gamma_{th}-\gamma_{th}x')(\gamma_{th}-\gamma_{th}x'+1)}{L_1L_3}}dx'\right] \end{aligned}$$

$$\begin{aligned}&\overset{(a)}{=}1-\exp\left(-\frac{\gamma_{th}}{L_2}\right)-\frac{\gamma_{th}}{L_2}\exp\left(-\frac{\gamma_{th}}{2L_1}-\frac{\gamma_{th}}{2L_3}-\frac{\gamma_{th}}{2L_2}\right.\\&\left.-\frac{2(2\gamma_{th}+1)\sqrt{\gamma_{th}(\gamma_{th}+1)}+\ln\left[2\gamma_{th}+1-2\sqrt{\gamma_{th}(\gamma_{th}+1)}\right]}{4\gamma_{th}\sqrt{L_1L_3}}\right)\\&\le\frac{\gamma_{th}}{L_2}\left(\frac{\gamma_{th}}{2L_1}+\frac{\gamma_{th}}{2L_3}+\frac{\gamma_{th}}{2L_3}\right.\\&\left.+\frac{2(2\gamma_{th}+1)\sqrt{\gamma_{th}(\gamma_{th}+1)}+\ln\left[2\gamma_{th}+1-2\sqrt{\gamma_{th}(\gamma_{th}+1)}\right]}{4\gamma_{th}\sqrt{L_1L_3}}\right)\end{aligned}\tag{18}$$

(where the first inequality comes from the identity $K_1(t)\ge\exp(-t)/t$ for $t\ge0$ [22] and the change of variables $x=\gamma_{th}x'$, the second inequality results from the Jensen's inequality [31] as $\exp(t)$ is the convex function of all t, the equality (a) is reached using [32, eqs. (2.261) and (2.262.1)], and the third inequality follows from the identity $1-\exp(-t)\le t$ for $t\ge0$) it also indicates that the outage probability in this case decreases with increasing P_S and P_R if the locations of T are determined, and decreases with increasing r_T if the maximum transmit power thresholds shown in (11) are utilized.

3.3 Relay Selection Criterion

In the previous subsections, the expressions for outage probabilities of cooperative D2D with various relaying schemes have been derived. Based on this, when the total transmit power keep constant, and the equal power allocation is introduced (i.e., P_S=P_R), the relay cooperation mode can be chosen if its outage probability is lower than that of the direct D2D mode which is given by

$$P_{out}^{Direct}=1-\exp\left(-\frac{\gamma_0}{L_2}\right)\tag{19}$$

where $\gamma_0=2^{R_0}-1$. Accordingly, when N idle users in the cell are available to serve as optional relays for the target D2D pair, the optimal selection criterion including the index and relaying mode of the selected relay can be mathematically described as

$$\left(l^*,Mode^*\right)=\underset{\substack{l=1,\cdots,N\\Mode=DF,AF}}{\arg\max}\left\{\left[P_{out}^{Direct}-P_{out}^{Mode}\left(r_{R_l},\theta_{R_l}\right)\right]^+\right\}\tag{20}$$

where $[x]^+=\max(x,0)$.

Although (20) provides a way of choosing the optimal relay, it requires the BS to acquire the location informations of all optional relays, and decide the relay selection for D2D communication, which increases the computational overhead of the BS. For this, we will give more specific relay selection areas, by which the BS only needs to handle the relay selection procedure in these areas, and the processing burden at the BS shall be reduced. Details are given as following.

First, by using first order approximation of Taylor expansion on (19), (9) and (17), we can obtain the approximate expressions for outage probabilities of various D2D modes as $P_{out}^{Direct}\approx\gamma_0/L_2$, $P_{out}^{DF}\approx\gamma_{th}/L_1$ and $P_{out}^{AF}\approx(\gamma_{th}/2L_2)(\gamma_{th}/L_1+\gamma_{th}/L_3)$ (see Appendix C).

Then, by means of the contrast of these approximations, the relay selection areas in which $P_{out}^{DF}\le P_{out}^{Direct}$, $P_{out}^{AF}\le P_{out}^{Direct}$ and $P_{out}^{AF}\le P_{out}^{DF}$ can be respectively calculated as

$$\frac{(1+d_{SR})^2}{(1+d_{SD})^2}\le\frac{\varepsilon_1}{\mu_1}\tag{21}$$

$$(1+d_{SR})^2\mu_1+(1+d_{RD})^2\mu_2\le\varepsilon_2\tag{22}$$

$$\frac{(1+d_{RD})^2}{(1+d_{SR})^2}\le\mu_1\varepsilon_3\tag{23}$$

where the parameters ε_i ($i=1,2,3$) shown in the above equations are defined as $\varepsilon_1=\mu_2\gamma_0/\gamma_{th}$, $\varepsilon_2=2P_S\gamma_0/(\gamma_{th})^2$ and $\varepsilon_3=(2L_2-\gamma_{th})/(\mu_2\gamma_{th})$, respectively. Note that the defined parameters are irrelevant to the location of the intended relay, which can be computed utilizing the contents shown in the previous subsections, and hence it is reasonable to regard them as constants.

Since the the location of the relay is unkonwn, the value of $\mathrm{E}\left[\left|I_R^{(1)}\right|^2\right]$ can not be determined which makes (21)-(23) hard to solve. Therefore, we will find out the bounds of $\mathrm{E}\left[\left|I_R^{(1)}\right|^2\right]$, and give tighter relay selection areas.

Next, consider S adopts the maximum power shown in (11) which is equal to $P_S=k\delta(1+r_S)^2$. Due to $P_R=P_S$ and $P_R\le k\delta(1+r_R)^2$, it indicates that $r_R\in[r_S,r]$, and thus the upper bound of $\mathrm{E}\left[\left|I_R^{(1)}\right|^2\right]$ denoted as φ_{upper} can be derived from (12) as

$$
\begin{aligned}
&\mathrm{E}\left[\left|I_R^{(1)}\right|^2\right] \\
&\le Mk+\frac{Mk\left(r^2+2r\right)}{r^2}\ln\left[1+r+r^2-r_R^2\right] \\
&\le\begin{cases} Mk+\dfrac{Mk\left(r^2+2r\right)}{r^2}\ln\left[1+r+\left(r+r_R\right)\left(r-r_D\right)\right], & r_S\ge r_D \\ Mk+\dfrac{Mk\left(r^2+2r\right)}{r^2}\ln\left[1+r+r^2-r_S^2\right], & r_S\le r_D \end{cases} \\
&\le\begin{cases} Mk+\dfrac{Mk\left(r^2+2r\right)}{r^2}\ln\left[1+r+r^2+r\left(r-r_D\right)-r_S r_D\right], & r_S\ge r_D \\ Mk+\dfrac{Mk\left(r^2+2r\right)}{r^2}\ln\left[1+r+r^2-r_S^2\right], & r_S\le r_D \end{cases}
\end{aligned} \tag{24}
$$

By substituting (24) into (21), the tighter relay selection area in which $P_{out}^{DF}\le P_{out}^{Direct}$ can be restricted to

$$
d_{SR}\le\sqrt{\frac{\varepsilon_1}{\varphi_{upper}+N_0}}\left(1+d_{SD}\right)-1 \tag{25}
$$

Further, similar to the derivation in (24), it can also use (12) to obtain that $\mathrm{E}\left[\left|I_D\right|^2\right]\le\varphi_{upper}$. By substituting this inequality and (24) into (22), while considering $\left(1+d_{SR}\right)^2+\left(1+d_{RD}\right)^2\le\left(2+d_{SR}+d_{RD}\right)^2$, the tighter relay selection area in which $P_{out}^{AF}\le P_{out}^{Direct}$ can be restricted to

$$
d_{SR}+d_{RD}\le\sqrt{\frac{\varepsilon_2}{\varphi_{upper}+N_0}}-2 \tag{26}
$$

Finally, since the the lower bound of $\mathrm{E}\left[\left|I_R^{(1)}\right|^2\right]$ denoted as φ_{lower} is derived from (5) as

$$
\begin{aligned}
\mathrm{E}\left[\left|I_R^{(1)}\right|^2\right] &\ge Mk\int_0^1\frac{\left(1+r\sqrt{u}\right)^2}{\left(1+r\sqrt{u}+r_R\right)^2}du \\
&\ge Mk\left[1-2r_R\int_0^1\frac{x}{1+r_R+rx}dx\right]^2 \\
&\overset{(a)}{=} Mk\left\{1-2r_R\left[\frac{1}{r}+\frac{1+r_R}{r^2}\ln\left(1-\frac{r}{1+r_R+r}\right)\right]\right\}^2 \\
&\ge Mk\left\{1-2r\left[\frac{1}{r}+\frac{1+r}{r^2}\ln\left(1-\frac{r}{1+2r}\right)\right]\right\}^2
\end{aligned} \tag{27}
$$

(where the first inequality comes from the identity $\cos(t)\ge-1$ for all t, the second inequality results from the Jensen's inequality as t^2 is the convex function of all t, and the change of variables $x=\sqrt{u}$, the equality (a) is reached using [32, eq. (2.152)], and the third inequality follows from $r_R\le r$) by substituting (27) into (23), while considering the triangle inequality $d_{SR}+d_{RD}\ge d_{SD}$, the tighter relay selection area in which $P_{out}^{AF}\le P_{out}^{DF}$ can be restricted to

$$
\begin{aligned}
&\frac{\left(1+d_{RD}\right)^2}{\left(1+d_{SD}-d_{RD}\right)^2}\le\varepsilon_3\left(\varphi_{lower}+N_0\right) \\
&\Rightarrow d_{RD}\le\frac{\sqrt{\varepsilon_3\left(\varphi_{lower}+N_0\right)}\left(1+d_{SD}\right)-1}{\sqrt{\varepsilon_3\left(\varphi_{lower}+N_0\right)}+1}
\end{aligned} \tag{28}
$$

According to (25), (26) and (28), it can be seen that the relay selection areas from geometry view as a circle centered at S ($P_{out}^{DF}\le P_{out}^{Direct}$), an ellipse with the two focal pints S and D ($P_{out}^{AF}\le P_{out}^{Direct}$), and a circle centered at D ($P_{out}^{AF}\le P_{out}^{DF}$), respectively. More intuitively, these areas could be plotted as ones shown in Figure 2.

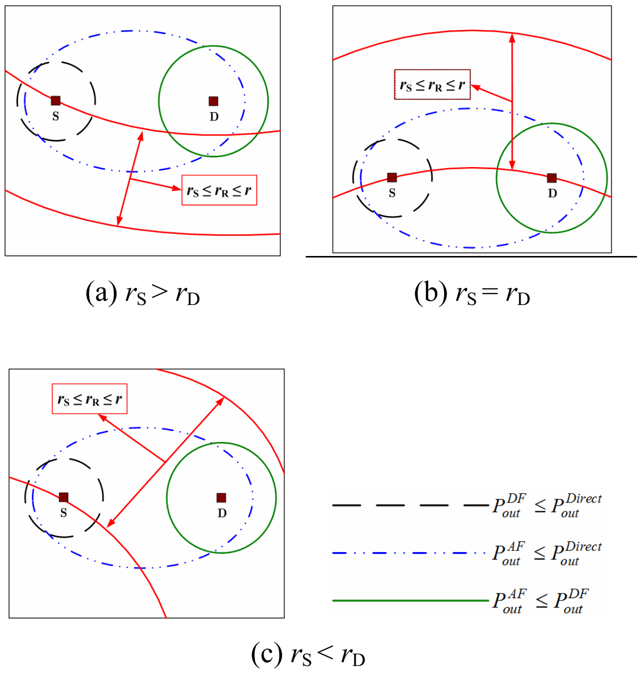

Figure 2. Relay selection areas for different locations of the D2D pair

It is worth noting that, (1) the relay selection areas shown in Figure 2 are tighter ones, and the pratical areas should be larger. (2) The sizes of the the derived areas mainly depend on the location of the D2D pair, and the target rate. Different parameter settings will lead to various results. (3) As the first order approximation of Taylor expansion is utilized throughout the derivation of relay selection areas, the obtained results will be accurate especially under the condition that the D2D pair and candidate relays get close to the edge of the cell, and the the target rate is low (i.e., $L_j >> \gamma_{th}$, $j = 1,2,3$).

4 Numerical Results

Here, simulations and numerical results are presented to validate the derivations and analyses shown in Section 3. Without loss of generality, we consider the symmetry scenario where the radial coordinates of D2D transmitter and receiver are identical (i.e., $r_S = r_D$), and the angular coordinates of that meet $\theta_S - \pi/2 = \pi/2 - \theta_D$ for $\theta_S \in (\pi/2, \pi)$ and $\theta_D \in (0, \pi/2)$. Besides, all small-scale channel fading coefficients are assumed to follow the independent complex Gaussian distribution with zero mean and unit variance, and other simulation parameters are summarized in Table 1.

Table 1. Simulation parameters

Parameter	Definition	Value
M	Number of cellular users	100
r	Cell radius	500 m
d_{SD}	D2D communication distance	10 m
α	Path loss exponent	2
γ_{th}	Predetermined SINR threshold	0 dB
k/N_0	Average received SNR at the BS	10 dB
δ	Maximum acceptable ISR at the BS	0 dB

Figure 3 shows the outage probability of cooperative D2D as compared with that of the traditional direct D2D without relay. The trnsmit power of S in this cooperative mode adopts $P_{S,coop} = \zeta \cdot P_{S,\text{direct}}$, where $P_{S,\text{direct}}$ denotes the the transmit power of S in the direct mode which takes the maximum acceptable threshold expressed in (11), and the power ratio ζ changes within [0, 1]. Besides, the equal power allocation is introduced which means $P_R = P_{S,coop}$, while the radial coordinates are set as $r_T = 350m$ ($T \in \{S,D,R\}$) and the relay angular coordinate is set as $\theta_R = \pi/2$. This figure shows that, outage probabilites of cooperative D2D with DF and AF relaying schemes both decrease as ζ increases, it verifies the analysis about the effect of transmit power on the outage performance which is presented in Sections 3.1 and 3.2. Meanwhile, this figure suggests a interesting result that for the DF relaying mode, the outage performance of cooperative D2D can outperform that of direct D2D when $0.9 < \zeta \le 1$, while for the AF relaying mode, the outage performance gain can be achieved when $0.6 < \zeta \le 1$. This signifies that cooperative D2D is superior to direct D2D in terms of outage performance, even with less transmit power.

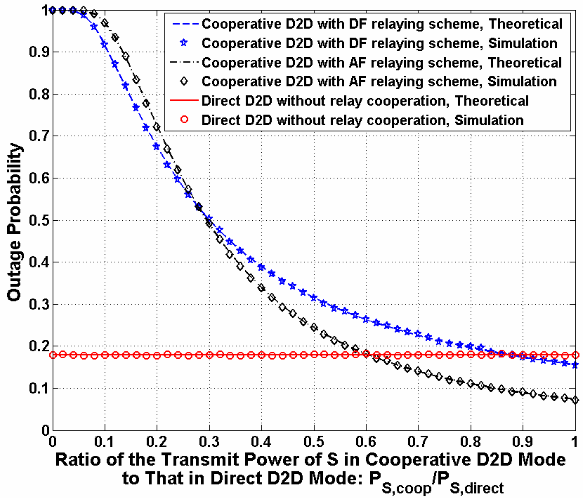

Figure 3. Outage probability of cooperative D2D with different tansmit power

Further, Figure 4 varies the value of the radial coordinate r_T and plot the outage probability of cooperative D2D. The relay angular coordinate is also set as $\theta_R = \pi/2$, and the maximum transmit power expressed in (11) is adopted on S and R for the cooperative mode, as well as for the direct mode. This figure suggests that outage probabilites of cooperative D2D with two different relaying schemes both decrease with increasing r_T, it validates the analysis about the locations of cooperative D2D users on the outage performance which is also shown in Sections 3.1 and 3.2. Additionally, we observe that when $r_T > 100$ m, cooperative D2D will provide significant outage performance gains compared to direct D2D, either with DF relaying scheme or in the AF relaying case. For instance, when $r_T = 400$ m, outage performance gains achieved by DF and AF relaying modes reach 14.46% and 62.69%, respectively. This further proves the superiority of cooperative D2D communication, especially at the edge of the cell.

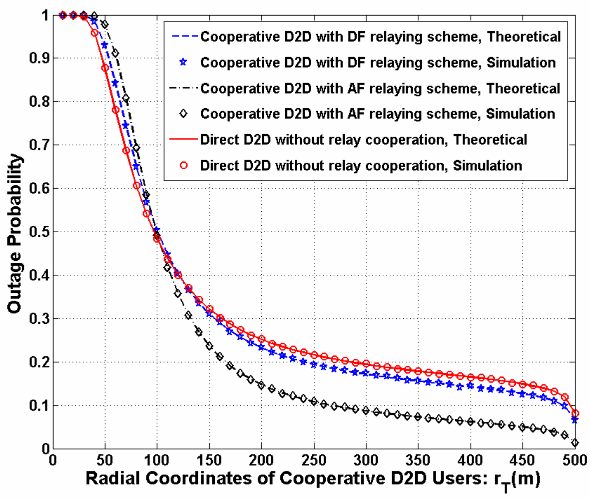

Figure 4. Outage probability of cooperative D2D versus varying radial coordinates r_T

Figure 5 shows the outage probability of cooperative D2D within the relay selection areas proposed in Section 3.3. For area 1 ($P_{out}^{DF} \le P_{out}^{Direct}$), area 2 ($P_{out}^{AF} \le P_{out}^{Direct}$) and area 3 ($P_{out}^{AF} \le P_{out}^{DF}$), the relay angular coordinate is respectively set as $\theta_R = \theta_S$, $\theta_R = \pi/2$ and $\theta_R = \theta_D$, while the chosen relay is assumed to be located at the circumference of the circle and ellipse. Besides, the equal power allocation is introduced, the maximum transmit power threshold is adopted on S whether in cooperative or direct mode (i.e., $P_R = P_{S,coop} = P_{S,\text{direct}}$), and r_S varies between 460m to 490m. As seen from this figure, the displayed results comply to the analysis shown in Section 3.3. For instance, when $r_S = 475$ m, the cooperative D2D with DF relaying scheme in relay selection area 1 achieves an outage performance gain of 41.46% over the direct D2D, the cooperative AF relaying mode in area 2 achieves a gain of 52.45% over the direct mode, and in area 3, the outage probability of AF relaying mode is far lower than that of DF relaying mode.

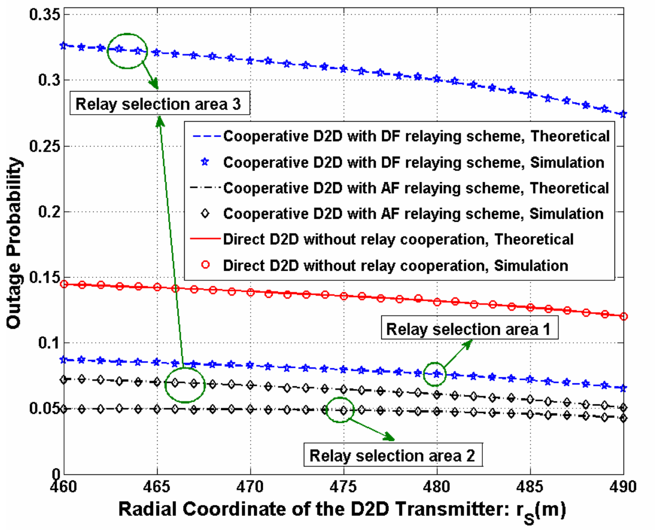

Figure 5. Outage probability of cooperative D2D within various relay selection areas

5 Conclusion

This paper establishes the model for the relay-assisted cooperative D2D communication involving a direct link between D2D users, and considers the interference scenario where cellular users distribute uniformly in the cell along with the uplink resources reusing. Based on this, the explicit outage probability expressions for cooperative D2D with DF and AF relaying schemes are both derived. By analyzing the outage probability upper bounds, this paper shows how the transmit power and user locations affect the outage performance of cooperative D2D. Specifically, it demonstrates that the outage performance can be improved as the transmit power of the D2D transmitter and the relay increase within an acceptable threshold when the locations of cooperative users are fixed, as well as the radial coordinates of cooperative users increase when the maximum transmit power control mechanism is applied on the D2D transmitter and the relay. Also, this paper shows that the outage probability of cooperative D2D is smaller than that of traditional direct D2D without relay cooperation at the cell-edge, even with less transmit power. Furthermore, with use of the proposed optimal relay selection criterion and suboptimal relay selection areas, the problem of how to choose the best relay from candidate users for cooperative D2D is addressed. This work provides an academic suggestion on determining proper D2D communication modes, power allocation and user locations, which will be useful in a practical network. In future research, the more complex interference case in which multiple D2D pairs share the same resources with multiple cellular users should be taken into consideration.

Acknowledgments

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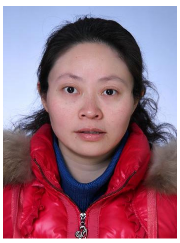

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Appendix A

Since $h_{T_1T_2} \sim \mathcal{CN}(0,1)$ for $T_1 \in \{S,R\}$ and $T_2 \in \{R,D\}$, $|h_{T_1T_2}|^2$ will follow an independent exponential distribution with the probability distribution function (PDF) $f(t) = \exp(-t)$ for $t \geq 0$ [14]. Therefore, we have

$$\begin{aligned}\Pr[SINR_R \leq \gamma_{th}] &= \Pr\left[|h_{SR}|^2 \leq \frac{\gamma_{th}}{L_1}\right] \\ &= \int_0^{\frac{\gamma_{th}}{L_1}} \exp(-x)\,dx \\ &= 1 - \exp\left(-\frac{\gamma_{th}}{L_1}\right)\end{aligned} \tag{29}$$

$$\begin{aligned}&\Pr\left[SINR_D^{DF} \leq \gamma_{th}\right] \\ &= \Pr\left[L_2|h_{SD}|^2 \leq \gamma_{th} - L_3|h_{RD}|^2\right] \\ &= \int_0^{\frac{\gamma_{th}}{L_3}} F_X\left(\frac{\gamma_{th} - L_3 y}{L_2}\right) f_Y(y)\,dy \\ &= \int_0^{\frac{\gamma_{th}}{L_3}} \left[1 - \exp\left(-\frac{\gamma_{th} - L_3 y}{L_2}\right)\right]\exp(-y)\,dy \\ &= \begin{cases} 1 - \exp\left(-\frac{\gamma_{th}}{L_3}\right) - \frac{L_2\left[\exp\left(-\frac{\gamma_{th}}{L_3}\right) - \exp\left(-\frac{\gamma_{th}}{L_2}\right)\right]}{L_3 - L_2}, & L_2 \neq L_3 \\ 1 - \left(1 + \frac{\gamma_{th}}{L_2}\right)\exp\left(-\frac{\gamma_{th}}{L_2}\right), & L_2 = L_3 \end{cases}\end{aligned} \tag{30}$$

where L_j ($j \in \{1,2,3\}$) is defined below (9), and the result when $L_2 = L_3$ shown in (30) is reached by using the L'Hôpital's rule. Consequently, substituting (29) and (30) into (8) yields the intended outage probability expression shown in (9).

Appendix B

According to (15), let $X = SINR_R$, $Y = SINR_D^{(2)}$, $Z = \frac{SINR_R \times SINR_D^{(2)}}{SINR_R + SINR_D^{(2)} + 1}$ and $T = SINR_D^{(1)}$. By Using [33, eq. (5-6)], the PDF of X, Y and T can be obtained as $f_X(x) = (1/L_1)\exp(-x/L_1)$, $f_Y(y) = 1/L_3\exp(-y/L_3)$ and $f_T(t) = 1/L_2\exp(-t/L_2)$, respectively. Based on this, the cumulative distribution function (CDF) of Z can be derived as

$$\begin{aligned}
&F_Z(z) \\
&=\Pr\left[\frac{XY}{X+Y+1}\le z\right] \\
&=\Pr\left[X(Y-z)\le z(Y+1)\right] \\
&=\int_0^z f_Y(y)dy+\int_z^\infty F_X\left(\frac{z(y+1)}{y-z}\right)f_Y(y)dy \\
&=\frac{1}{L_3}\int_0^z \exp\left(-\frac{y}{L_3}\right)dy \\
&\quad+\frac{1}{L_3}\int_z^\infty\left[1-\exp\left(-\frac{z(y+1)}{L_1(y-z)}\right)\right]\exp\left(-\frac{y}{L_3}\right)dy \\
&=1-\frac{1}{L_3}\exp\left(-\frac{z}{L_1}-\frac{z}{L_3}\right)\int_0^\infty\exp\left(-\frac{z(z+1)}{L_1 y}-\frac{y}{L_3}\right)dy \\
&=1-\exp\left(-\frac{z}{L_1}-\frac{z}{L_3}\right)\times 2\sqrt{\frac{z(z+1)}{L_1L_3}}K_1\left(2\sqrt{\frac{z(z+1)}{L_1L_3}}\right)
\end{aligned} \tag{31}$$

where the last equality is reached using [32, eq. (3.471-9)], and the definition of the function $K_1(\cdot)$ is shown below (17). Therefore, we have

$$\begin{aligned}
&\Pr\left[SINR_D^{AF}\le\gamma_{th}\right] \\
&=\Pr\left[Z\le\gamma_{th}-T\right] \\
&=\int_0^{\gamma_{th}}F_Z(\gamma_{th}-t)f_T(t)dt \\
&=\frac{1}{L_2}\int_0^{\gamma_{th}}\exp\left(-\frac{t}{L_2}\right)\left[1-\exp\left(-\frac{\gamma_{th}-t}{L_1}-\frac{\gamma_{th}-t}{L_3}\right)\right. \\
&\quad\left.\times 2\sqrt{\frac{(\gamma_{th}-t)(\gamma_{th}-t+1)}{L_1L_3}}K_1\left(2\sqrt{\frac{(\gamma_{th}-t)(\gamma_{th}-t+1)}{L_1L_3}}\right)\right]dt \\
&=1-\exp\left(-\frac{\gamma_{th}}{L_2}\right)-\frac{1}{L_2}\exp\left(-\frac{\gamma_{th}}{L_1}-\frac{\gamma_{th}}{L_3}\right) \\
&\quad\times\int_0^{\gamma_{th}}\exp\left[\left(\frac{1}{L_1}+\frac{1}{L_3}-\frac{1}{L_2}\right)t\right]\times 2\sqrt{\frac{(\gamma_{th}-t)(\gamma_{th}-t+1)}{L_1L_3}} \\
&\quad\times K_1\left(2\sqrt{\frac{(\gamma_{th}-t)(\gamma_{th}-t+1)}{L_1L_3}}\right)dt
\end{aligned} \tag{32}$$

Appendix C

According to (19), (9) and (17), the outage probabilities for direct D2D and cooperative D2D can be approximated using first order Taylor series expansion of $\exp(t)\approx 1+t$ as

$$P_{out}^{Direct}\approx\frac{\gamma_0}{L_2} \tag{33}$$

$$P_{out}^{DF}\approx\begin{cases}1-\left(1-\dfrac{\gamma_{th}}{L_1}\right)\dfrac{L_2\left(1-\dfrac{\gamma_{th}}{L_2}\right)-L_3\left(1-\dfrac{\gamma_{th}}{L_3}\right)}{L_2-L_3}, & L_2\ne L_3\\[2ex] 1-\left(1-\dfrac{\gamma_{th}}{L_1}\right)\exp\left(\dfrac{\gamma_{th}}{L_2}\right)\exp\left(-\dfrac{\gamma_{th}}{L_2}\right), & L_2=L_3\end{cases}=\frac{\gamma_{th}}{L_1} \tag{34}$$

$$\begin{aligned}
P_{out}^{AF}&=\frac{1}{L_2}\int_0^{\gamma_{th}}\left[\exp\left(-\frac{x}{L_2}\right)-\exp\left(-\frac{x}{L_2}-\frac{\gamma_{th}-x}{L_1}-\frac{\gamma_{th}-x}{L_3}\right)\right. \\
&\quad\left.\times 2\sqrt{\frac{(\gamma_{th}-x)(\gamma_{th}-x+1)}{L_1L_3}}K_1\left(2\sqrt{\frac{(\gamma_{th}-x)(\gamma_{th}-x+1)}{L_1L_3}}\right)\right]dx \\
&\approx\frac{1}{L_2}\int_0^{\gamma_{th}}\left[1-\frac{x}{L_2}-1+\frac{x}{L_2}+\frac{\gamma_{th}-x}{L_1}+\frac{\gamma_{th}-x}{L_3}\right]dx \\
&=\frac{1}{L_2}\int_0^{\gamma_{th}}\left(\frac{\gamma_{th}-x}{L_1}+\frac{\gamma_{th}-x}{L_3}\right)dx \\
&=\frac{1}{L_2}\left(\frac{\gamma_{th}^2}{2L_1}+\frac{\gamma_{th}^2}{2L_3}\right)
\end{aligned} \tag{35}$$

Note that in (35), the second step is reached using the first order Taylor approximation of $f(t)=tK_1(t)$ for $t>0$:

$$\begin{aligned}
f(t)&=tK_1(t) \\
&\approx\lim_{t_0\to 0^+}\left[f(t_0)+f'(t_0)(t-t_0)\right] \\
&\overset{(a)}{=}\lim_{t_0\to 0^+}\left[t_0K_1(t_0)\right]-\lim_{t_0\to 0^+}\left[t_0K_0(t_0)\times(t-t_0)\right] \\
&\overset{(b)}{\approx}1-\lim_{t_0\to 0^+}\left[-t_0\ln t_0\times t\right]+\lim_{t_0\to 0^+}\left[-(t_0)^2\ln t_0\right] \\
&\overset{(c)}{=}1-\lim_{\tau\to+\infty}\left[\frac{\ln\tau}{\tau}\times t\right]+\lim_{\tau\to+\infty}\left[\frac{\ln\tau}{\tau^2}\right] \\
&\overset{(d)}{=}1-\lim_{\tau\to+\infty}\left[\frac{1}{\tau}\times t\right]+\lim_{\tau\to+\infty}\left[\frac{1}{2\tau^2}\right] \\
&\approx 1
\end{aligned} \tag{36}$$

where the equality (a) comes from $\frac{d}{dz}\{zK_1(z)\}=K_1(z)+z\frac{d}{dz}K_1(z)=-zK_0(z)$ for $z>0$ [32, eq. (8.486-12)], the approximate formula (b) results from $\lim_{z\to 0^+}K_1(z)\sim 1/2\cdot\Gamma(1)(1/2\cdot z)^{-1}=z^{-1}$ [34, eq. (9.6.9)], [32, eq. (8.338-1)] and $\lim_{z\to 0^+}K_0(z)\sim-\ln z$ [34, eq. (9.6.8)], the equality (c) follows from the change of variables $\tau=1/t_0$, and the equality (d) is reached by using the L'Hôpital's rule.