Performance Analysis of Relay-Aided D2D Communications with Traffic Model

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Abstract. In this paper, we consider a communication scenario where relay users assist nearby a pair of D2D users underlaying cellular network. In our communication scenario, we analyze not only fading channel model but also different traffic models. In order to jointly consider the impact of interference level and network traffic condition, the packet loss probability (PLP) of D2D link is carefully orchestrated from two perspectives, i.e., link outage probability and packet delivery failure probability. The closed-form expressions of them are respectively obtained based on a Rician–Rayleigh fading model and different traffic models, and then the performance of our relay-aided D2D communication scenario is evaluated by the PLP of D2D link. Finally, the PLP of D2D link with three representative traffic models including Pareto, FBM, and Poisson traffic models are compared, respectively. We believe that the proposed analytical approach can provide a useful insight into the application of traffic model in relay-aided D2D communications.

Keywords: Relay-aided D2D communication · Traffic model
Packet loss probability

1 Introduction

Due to the demand for Internet access is increasing dramatically with the increment of mobile users, device-to-device (D2D) communication is proposed to address this issue. The close-range D2D communication underlaying cellular network has been considered as an effective way to improve transmission rate, reduce transmission latency and power consumption, and enhance spectrum efficiency. However, the direct D2D communication can only work with a very limited distance, but not apply to all communication scenarios. Therefore, a relay-aided D2D communication is considered to be indispensable in expanding D2D coverage [1].

The relay-aided D2D communication utilizes relay users to forward data packets. On the one hand, it can expand the signal communication range, which makes D2D communication adaptable to complex and diversified environments. On the other hand, it can also shorten the distance of per-hop D2D link, which

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eventually reduces the transmit power and energy consumption. Many efforts have been made to analyze the performance of relay-aided D2D communication. Wei et al. investigated a multi-hop D2D communication scenario where relay nodes assist to exchange information with PNC, and then analyzed the average energy efficiency and spectral efficiency under Rayleigh fading channel [2]. Hasan et al. proposed a robust distributed solution for resource allocation with a view to maximizing network rate when the interference from other relay nodes and the link gains are uncertain [3]. The authors of [4] proposed a game-theoretic model for the compensation power acquisition of D2D link transmitters underlaying cellular system. However, when the process of loss packet occurs at the per-hop D2D link, the receiver can not be able to correctly receive the desired data packets. Therefore, the packet loss probability (PLP) of D2D link is a key performance metric for relay-aided D2D communications [5].

In the most of related works, the Rayleigh fading model which ignores line-of-sight (LoS) signal components is adopted. But in fact, a close-range communication often leads to the existence of dominant LoS signal components in the received desired signals [6,7]. When multiple D2D users reuse a cellular uplink channel, they can be subject to interfering signals from cellular users. The larger interference can result in the higher outage probability of D2D link, which has an impact on the successful reception of the desired signals. In addition, the relay users in multi-hop D2D communication often consider limited queue capacity and service capability [8,9]. Therefore, how to select fading channel model and traffic model for multi-hop D2D communication scenario is of great significance. Our contribution is summarized in the following aspects. First, a general multi-hop D2D communication underlaying cellular network is introduced, followed by the formulation of corresponding fading channel model and traffic model. Second, in order to jointly consider the impact of interference level and network traffic condition, the PLP of D2D link is carefully orchestrated from two perspectives, i.e., the outage probability and packet delivery failure probability. Meanwhile, the closed-form expressions of them are respectively obtained based on fading channel model and traffic model.

The rest of this paper is organized as follows. In Sect. 2, a general relay-aided D2D communication underlaying cellular network is introduced, followed by the formulation of corresponding channel model and traffic model. In Sect. 3, the packet loss probability of D2D link is analyzed. In next section, simulation results verifying the link outage probability with fading channel model and the PLP of D2D link under different traffic models are provided, respectively. Finally, we conclude the paper in Sect. 5.

2 System Model

2.1 Network Model

In this paper, we consider a general relay-aided D2D communication underlaying cellular network, as shown in Fig. 1. There are some randomly distributed cellular user equipment (CUE) and a pair of D2D user equipment (DUE_1 and DUE_2) in this cell. This pair of D2D UE has the desire to establish D2D links to exchange some multimedia content like pictures, live video, or interactive games. It is assumed that the distance between DUE_1 and DUE_2 is too long to directly communicate with each other using the traditional one-hop D2D link. Therefore, the relay user equipment (RUE) is required to establish multi-hop D2D links. In this paper, we consider that the number of RUE is denoted by M and all of them are seen essentially as D2D UE. The scheduling and resource allocation for all D2D UE (DUE_1, DUE_2 and RUE) can be done by the eNodeB. In addition, it is considered that all D2D UE reuse the same cellular uplink channel that is assigned to the l-th cellular UE (CUE_l). Meanwhile, the eNodeB has the control over transmission power of the CUE_l and all D2D UE to reduce interference level. Figure 1 shows that there are $M+2$ user equipment including one cellular user equipment and $M+1$ D2D user equipment. For simplicity, we name DUE_1 as node 0, RUE_k as node k ($k \in \{1, 2, \cdots, M\}$), DUE_2 as node $M+1$, and CUE_l as node $M+2$. The notation (i, j) is used to represent the transmission link from node i to node j.

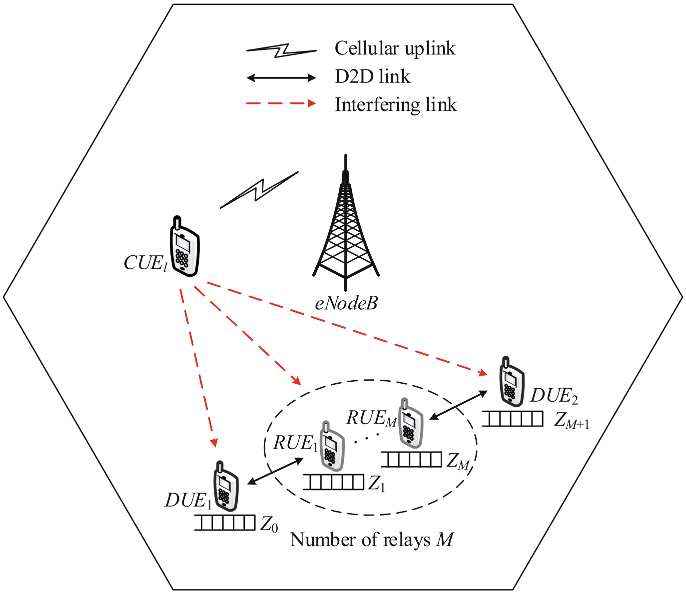


Fig. 1. A general relay-aided D2D communication underlaying cellular network

2.2 Channel Model

The path loss channel model and additive white Gaussian noise are considered in our channel model. The large-scale fading is determined by the Euclidean distance $d_{i,j}$ between node i and node j and the path loss exponent α which is relevant to the communication environment. Then, the small-scale fading of the link (i, j) is captured by a Rayleigh or Rician random variable $f_{i,j}$. Therefore, the instantaneous SINR at node j is given by

$$\gamma_j = \frac{P_{T_i} \cdot d_{i,j}^{-a} \cdot F_{i,j}}{P_{T_l} \cdot d_{l,j}^{-a} \cdot F_{l,j} + \sigma^2} = \frac{F_{i,j}}{b \cdot c \cdot F_{l,j} + b \cdot \sigma^2}, \tag{1}$$

where P_{T_i} is the transmit power of node i, $d_{i,j}^{-a}$ is the path loss of the link (i, j) and $F_{i,j} = |f_{i,j}|^2$ is the channel gain of the link (i, j). Similarly, $F_{l,j}$ is the interfering power used by node l. The symbols $d_{l,j}^{-a}$ and $F_{l,j} = |f_{l,j}|^2$ are the path loss and channel gain of the link (l, j), respectively. It is assumed that all nodes suffer the same additive white Gaussian power σ^2. For simplicity, we define $b = \frac{1}{P_{T_i} \cdot d_{i,j}^{-a}}$ and $c = P_{T_l} \cdot d_{l,j}^{-a}$.

2.3 Traffic Model

As illustrated in Fig. 1, each node has certain queue capacity and service capacity. In this paper, we assume that the node j has a limited queue capacity Z_j (packets) to store dynamically arrival data packets, and each packet has an equal length of b (bits). Moreover, the transmission in the time is slot-by-slot based and each slot has a fixed duration ΔT (ms). In each time slot, the spectrum resource can be allocated to one or more D2D links, depending on the resource sharing and scheduling strategies. Finally, during each time slot, the average service rate at node j, μ_j (packets/ms), is upper bounded by the channel capacity of the corresponding D2D link. In the following part, we will discuss several typical network traffic models.

The Pareto traffic model is a self-similar model that mainly describes the traffic inter-arrival time with a heavy-tailed probability density function (pdf). The inter-arrival time of such traffic is independent and identical distributed. Then, the pdf of the inter-arrival time X is the Pareto distribution as follows:

$$f(x) = \frac{S\beta^S}{x^{S+1}}, x \geq \beta, \tag{2}$$

where S is the shape parameter and β is the minimum value of inter-arrival time. The mean and variance are respectively $\frac{S\beta}{S-1}$ and $\frac{S\beta^2}{(S-1)^2(S-2)}$, $1 < S < 2$.

The fractional Brownian motion (FBM) traffic model is an important self-similar model that mainly describes the cumulative arrival amount of traffic and models the variation of connectionless traffic with a self-similar Gaussian process. A standard FBM random process $Y(t)$ with Hurst parameter $H \in [0.5, 1)$ is an essential Gaussian process with the zero mean and the variance of $|t|^{2H}$. Therefore, during each time slot, the cumulative arrival amount at the node j, $A_j(\Delta T)$, that satisfies the self-similar FBM input traffic model is expressed as [10]

$$A_j(\Delta T) = \lambda_j \Delta T + \sqrt{\eta \cdot \lambda_j} Y(\Delta T), \tag{3}$$

where η is a variance coefficient, and λ_j is the average packet arrival rate at node j.

The Poisson traffic model, unlike the above presentation, is a very attractive memoryless model (future behavior has no link to past behavior), which means that it is easy to analyze but cannot effectively reflect the burstiness nature of the traffic. During each time slot, the cumulative arrival amount $A_j\left(\varDelta T\right)$ is a Poisson process with a parameter $\lambda_j \varDelta T$, which is given by

$$\Pr\left\{A_j\left(\varDelta T\right)=n\right\}=e^{-\lambda_j \varDelta T}\frac{\left(\lambda_j \varDelta T\right)^n}{n!}, \tag{4}$$

where the expectation of $A_j\left(\varDelta T\right)$ is equal to $\lambda_j \varDelta T$, means $E\left(A_j\left(\varDelta T\right)\right)=\lambda_j \varDelta T$. Meanwhile, the packet inter-arrival time has an exponential distribution with mean $1/\lambda_j$.

3 The Packet Loss Probability of D2D Link

In Fig. 1, when the node 0, node $M+1$ and node k forming D2D links reuse the same cellular uplink channel, these nodes will be subject to interference from node $M+2$. However, the larger interference can result in the higher outage probability of D2D links, which has an impact on the successful reception of the desired signals. In addition, network traffic is an important factor in D2D links. It is found that each node has own limitation on queue capacity and service capability. When network traffic exceeds a certain level, the queue capacity and service capability cannot be sufficient, which eventually causes network congestion and compromise the packet delivery process in D2D links. Therefore, in order to jointly consider the impact of interference level and network traffic condition, the packet loss probability of D2D link proposed in [5] is adopted in this paper as follows

$$\Pr_{i,j}^{l}=\hat{\Pr}_{i,j}\cdot\Pr_{i,j}^{o}=\left(1-\bar{\Pr}_{i,j}\right)\cdot\Pr_{i,j}^{o}, \tag{5}$$

where $\Pr_{i,j}^{l}$ is the packet loss probability of link (i,j). $\hat{\Pr}_{i,j}$ is the packet delivery probability defined to reflect traffic conditions over the link (i,j). $\bar{\Pr}_{i,j}$ is the packet delivery failure probability. $\Pr_{i,j}^{o}$ is the outage probability of link (i,j).

3.1 The Link Outage Probability

The outage probability of transmission link needs to be analyzed based on its fading channel model. In previous research, most of the papers consider the desired signals and interfering signals of the receiving terminal from the perspective of Rayleigh fading. However, in the close-range D2D communication, the desired signals at the receiving terminal also contain the dominant LoS signal components in addition to the scattered signal components. Therefore, in this paper, the Rician fading is considered to model the channel gain of the per-hop D2D link, while for the interfering links with long distance, the Rayleigh fading is adopted. Such simulation is called a Rician–Rayleigh fading channel model.

In the Rician–Rayleigh fading channel model, the link outage probability is defined as the probability that the instantaneous SINR at node j expressed by Eq. (1) is less than the SINR threshold γ_0, that is

$$\Pr_{i,j}^{o} = \frac{(K+1)\,\gamma_0\left(1-\frac{\sigma^2}{c\cdot\omega+\sigma^2}\right)}{\gamma_a+(K+1)\,\gamma_0\left(1-\frac{\sigma^2}{c\cdot\omega+\sigma^2}\right)} e^{-\frac{K\cdot\gamma_a}{\gamma_a+(K+1)\gamma_0\left(1-\frac{\sigma^2}{c\cdot\omega+\sigma^2}\right)}+\frac{\sigma^2}{c\cdot\omega}}, \tag{6}$$

where $\gamma_a = \frac{\Omega}{b\cdot c\cdot\omega+b\cdot\sigma^2}$ is the average SINR at node j, K is the Rican factor and Ω is the expected receiving power. Note that the Eq. (6) can also express the link outage probability under the Rayleigh–Rayleigh fading channel model when $K=0$. When the mean interfering power $c\cdot\omega$ is much larger than white Gaussian power σ^2, the Eq. (6) can be shown that

$$\Pr_{i,j}^{o} \approx \frac{(K+1)\,\gamma_0}{\gamma_a+(K+1)\,\gamma_0} e^{-\frac{K\cdot\gamma_a}{\gamma_a+(K+1)\gamma_0}}. \tag{7}$$

It is found that this closed-form approximation is quite similar to the result of Yao and Sheikh [[11], Eq. (7)].

3.2 The Packet Delivery Failure Probability

The packet delivery failure probability is a network layer parameter that indicates the network congestion caused by the link traffic. When the queue length of relay nodes reaches queue capacity, the subsequent arriving data packets are dropped, which can lead to packet delivery failure. Let $Q_j\,(t)$ be the queue length (packets) of node j at the beginning of t-th time slot, which is also classified as either a continuous-time or a discrete-time queue length. In this paper, it is only considered to be a continuous-time queue length because equivalent results can also be obtained for the discrete-time case. During the t-th time slot, the queue length of $Q_j\,(t+1)$, the cumulative arrival amount of data packets placed in the queue capacity, expressed by

$$Q_j\,(t+1) = \min\left\{Z_j, \max\left\{0, Q_j\,(t) - \mu_j \Delta T + A_j\,(\Delta T)\right\}\right\}. \tag{8}$$

It is assumed that each node needs to send control signaling for requesting data forwarding to the base station before each time slot. Then, the arriving data packets during each time slot can only be transmitted at the next time slot. Finally, the base station achieves the sequence of the data forwarding. This assumption is based on the following aspects. First, the existing literature has little research on the sequence of multi-hop D2D data forwarding, which leads to having no uniform standard; Second, it is convenient that the base station can control the sequence of data forwarding, which can effectively reduce the complexity. According to the above assumption, it can be seen that the data packets placed in queue capacity at the beginning of $(t+1)$-th time slot have been transmitted, means $Q_j(t) = 0$.

In this paper, when the queue length of the node j, $Q_j(t+1)$, reaches its queue capacity Z_j, the packet delivery failure probability over the link (i,j) is defined as follows

$$\bar{\mathrm{P}}\mathrm{r}_{i,j} = \Pr\left\{Q_j(t+1) = Z_j\right\} = \Pr\left\{A_j(\varDelta T) \geq Z_j + \mu_j \varDelta T\right\}. \tag{9}$$

In the following part, the closed-form expressions $\bar{\mathrm{P}}r_{i,j}$ based on different traffic models are obtained, respectively.

The FBM traffic model can model the variation of connectionless traffic with a self-similar Gaussian process. According to substitute Eq. (3) to (9), the packet failure delivery probability over the link (i,j) is presented as

$$\bar{\mathrm{P}}\mathrm{r}_{i,j} = 1 - \varPhi\left(\frac{(\mu_j - \lambda_j)\varDelta T + Z_j}{\sqrt{\eta \cdot \lambda_j}\varDelta T^H}\right), \tag{10}$$

where $\varPhi(\cdot)$ is the cumulative distribution function of the standard Gaussian distribution. Similarly, the packet failure delivery probability based on the Poisson traffic model, substituting Eq. (4) to (9), can be calculated by

$$\bar{\mathrm{P}}\mathrm{r}_{i,j} = 1 - e^{-\lambda_j \varDelta T} \sum_{n=0}^{Z_j + \mu_j \varDelta T} \frac{(\lambda_j \varDelta T)^n}{n!}. \tag{11}$$

On the other hand, due to the Pareto traffic model mainly analyzes the packet inter-arrival time, we consider a Pareto/M/1 queue model. The packet failure delivery probability is given by [12]

$$\bar{\mathrm{P}}\mathrm{r}_{i,j} = \left[1 - \frac{S(S-1)}{\rho} M^{\frac{S}{2}-1} e^{M/2}\left(\sqrt{M} W_{-\frac{S+1}{2},-\frac{S}{2}}(M) - W_{-\frac{S}{2},-\frac{1-S}{2}}(M)\right)\right]\sigma^{Z_j} \tag{12}$$

where $\rho = \frac{\lambda_j}{\mu_j}$ is the service utilization, $W_{\eta,\xi}(\phi)$ is Whittakers function, M is equal to $\frac{(S-1)(1-\sigma)}{\rho}$ and $\sigma = \alpha M^{\frac{\alpha-1}{2}} e^{M/2} W_{-\frac{(a+1)}{2},-\frac{\alpha}{2}}(M)$ is a geometric parameter.

4 Numerical Result

In this section, we evaluate the performance of our relay-aided D2D communication scenario using the packet loss probability (PLP) of D2D link. Table 1 summarizes the list of main simulation parameters and their default values.

As shown in Fig. 2, we compare the link outage probability under different fading models when the range of SINR is appropriately chosen. For simplicity, we randomly select two SINR thresholds γ_0, -5 dB and 0 dB, respectively. According to numerically calculate Eq. (7), it is found that the link outage probability decreases with the increasing SINR under a fixed γ_0. In addition, the $\gamma_0 = 0$

Table 1. Parameters settings

Parameter description	Value
Reuse uplink bandwidth B	2 MHz
Path loss exponent α	4
Rician factor K	7 dB
The time slot duration ΔT	1 ms
The coefficient of variance η	1
Hurst parameter H	0.7
Pareto shape parameter S	1.5

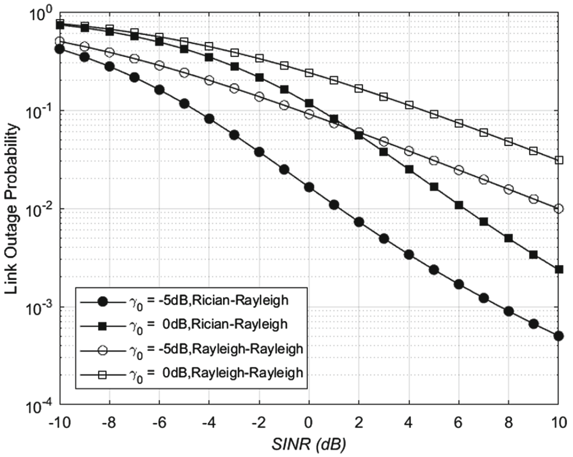
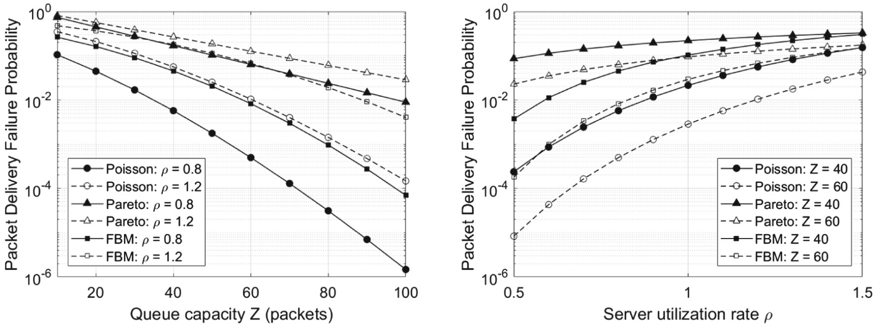


Fig. 2. The link outage probability with different SINR thresholds and fading channel models



(a) (b)

Fig. 3. The packet delivery failure probability with different traffic models

leads to much larger link outage probability than the $\gamma_0 = -5$. Meanwhile, the Rician–Rayleigh fading model which takes the LoS signal components into account leads to a lower link outage probability than the Rayleigh–Rayleigh fading model. In order to ensure a small link outage probability, we choose the value of γ_0 to be -5 dB rather than 0 dB in the subsequent analysis.

In order to characterize traffic conditions, three representative traffic models, i.e., Pareto, FBM, and Poisson traffic models, are adopted to represent $\bar{\mathrm{P}}r_{i,j}$ in the Eqs. (10), (11) and (12). Figure 3(a) and (b) illustrate the packet delivery failure probability with different parameter configurations. It is seen that the smaller queue capacity is, the more likely the packet delivery fails. Moreover, the $\rho > 1$ is more likely to cause packet delivery failure than the $\rho < 1$. Finally, it is found that the packet delivery failure probabilities of the Pareto and FBM traffic models which consider the burstiness and self-similarity of network traffic are higher than that of the Poisson traffic model.

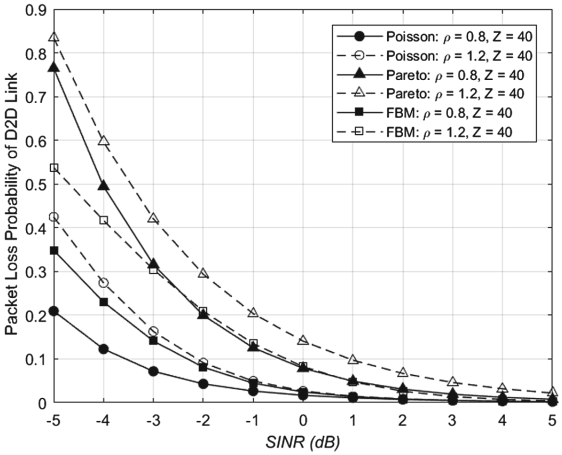


Fig. 4. The packet loss probability of D2D link with different traffic models

Figure 4 presents the PLP of D2D link expressed by Eq. (5) with the above traffic models. It is concluded that the PLP of Poisson traffic model is smaller than that of the other traffic models. When the node 0 and node $M + 1$ send a small number of data packets to each other at the communication scenario of Fig. 1, the D2D links usually have less traffic burstiness. The PLP of Poisson traffic model is more suitable than other traffic models.

5 Conclusion

In this paper, we consider a general relay-aided D2D communication underlaying cellular network. In our communication scenario, we consider not only fading channel model but also different traffic models. It is verified that the Rician–Rayleigh fading model which takes the LoS signal components into account leads to a lower link outage probability than Rayleigh-Rayleigh fading model. Then, the packet delivery failure probabilities of the Pareto and FBM traffic models which consider the burstiness and self-similarity of network traffic are higher than that of the Poisson traffic model. Finally, it is concluded that the PLP of Poisson traffic model is smaller than that of the other traffic models. In short, the insight is expected to shed light on the application of traffic model in relay-aided D2D communications.

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