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# Interference-Limited Device-to-Device Multi-User Cooperation Scheme for Optimization of Edge Networking

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**Abstract** Device-to-device (D2D) communication is an emerging technology for improving cellular networks, which plays an important role in realizing Internet of Things (IoT). The spectrum efficiency, energy efficiency and throughput of network can be enhanced by the cooperation among multiple D2D users in a self-organized method. In order to limit the interference of D2D users and load off the energy consumption of D2D users without decreasing communication quality, an interference-limited multi-user cooperation scheme is proposed for multiple D2D users to solve the energy problem and the interference problem in this paper. Multiple D2D users use non-orthogonal spectrums to form clusters by self-organized method. Multiple D2D users are divided into different cooperative units. There is no interference among different cooperative units so as to limit the interference of each D2D user in cooperative units. When the link capacity cannot meet the requirements of the user rate, it will produce an interrupt event. In order to evaluate the communication quality, the outrage probability of D2D link is derived by considering link delay threshold, data rate and interference. Besides the energy availability and signal-to-noise ratio (SNR) of each D2D user, the distance between D2D users is considered when selecting the relaying D2D users so as to enhance the signal-to-interference-plus-noise ratio (SINR) of D2D receiving users. Combining the derived outrage probability, the relationships among the average link delay threshold, the efficiency of energy and the efficiency of capacity are studied. The simulation results show that the interference-limited multiple D2D users cooperation scheme can not only help to offload energy consumption and limit the interference of D2D users, but also enhance the efficiency of energy and the efficiency of capacity.

**Keywords** device-to-device (D2D) user cooperation, relay selection, efficiency of energy, efficiency of capacity, Internet of Things (IoT)

## 1 Introduction

Recent technology advances in wireless mobile communications, sensor networks, machine-to-machine communications, and fog computing enable a fog computing based Internet of Things (IoT) paradigm that may have a significant impact on the development and utilization of IoT applications[1-2].

Device-to-device (D2D) communication, one of the important parts of IoT, is widely applied in mobile cellular communication at present, aiming to solve problems of the coverage, spectrum and energy through short-range communication among devices directly by reusing the spectrum of cellular users[3-6]. However, reusing spectrum leads to co-channel interference in heterogeneous networks where the cellular users get interference from D2D users and D2D users get interference from base station in downlink. Hence, there are plenty of studies about solving the co-channel interference among cellular users and D2D users[7-9]. But

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the interference among D2D users is always ignored because of the short-range communication with the low transmission power of D2D users[10].

In fact, as multimedia communication is developing, the traditional cellular communication cannot deal with the big data and complex communication environment anymore, while D2D has great potential to adapt itself to the upcoming complex heterogeneous networks since D2D communication is flexible enough and D2D users are active in heterogeneous networks[11-12]. Communicating directly among D2D users is helpful to prompt the cooperation among multiple D2D users so as to enhance the spectrum efficiency, the efficiency of capacity and the efficiency of energy with providing a better experience for the users in heterogeneous networks[13-15].

The related work about incentive mechanisms for D2D communications is introduced below. The work in [16] proposes a collaborative D2D communication method. It adaptively selects the D2D users to forward data by multiplexing, opportunistic and dedicated manners according to parameters such as the channel quality, which effectively guarantees the data transmission efficiency. The work in [17-19] pointed out that the cellular data distribution can be achieved through D2D opportunistic deliveries, which could reduce the BS load and enhance the data transmission efficiency. The studies in [20-22] proposed some multiuser cooperation methods in wireless networks. However, above work does not consider the relationship between the number of cooperative D2D users and the interference and energy consumption among multiple cooperative D2D users. On the one hand, as the number of cooperative D2D users is increasing, the user density within certain realms is increasing so that the distance between users is decreasing. The interference among D2D users cannot be ignored anymore. On the other hand, when the number of cooperative D2D users is increasing, the energy consumption for sharing data packet of each D2D user is increasing. Hence, the energy availability should be considered when there are multiple cooperative D2D users.

To solve the problems of D2D users' energy and interference caused by non-orthogonal reusing the spectrum resource in D2D multi-user cooperation communication, outrage probability is proposed in this paper. Then the relationship between interference and link outrange probability is analyzed to design the interference-limited D2D multi-user cooperation scheme which can not only help to offload energy consumption and limit the interference of D2D users, but also enhance the efficiency of energy and efficiency of capacity.

The main contributions of this paper are summarized as follows.

1) The link outrage probability is derived by combining the link delay threshold and the data rate based on Shannon formula. When the link capacity cannot meet the requirements of the user rate, it will produce an interrupt event. Therefore, the link outrage probability can be exploited to evaluate the communication quality.

2) An interference-limited multi-user cooperation scheme is proposed by analyzing the relationship between interference and link outrange probability. In particular, each D2D receiving user is interfered by no more than two D2D users in our paper. The proposed cooperation scheme takes the energy availability, signal-to-noise ratio (SNR) and location of D2D users into account when selecting relaying D2D users to offload energy consumption and limit the interference of D2D users.

3) The relationships among the average link delay threshold, the efficiency of energy and the efficiency of capacity are analyzed to preserve the quality of the user experience and improve the network performance.

The rest of this paper is organized as follows. Section 2 briefly introduces the cooperation system model with inter-interference among D2D users. In Section 3, the link outrage probability is derived and the proposed cooperation scheme is introduced. Next, Section 4 formulizes the efficiency of energy and capacity according to the derived outrage probability. In Section 5, the relationships among the link delay threshold and link outrage probability, the efficiency of capacity and the efficiency of energy are analyzed. Finally, some concluding remarks are provided in Section 6. The definitions of main notations are shown in Table 1.

## 2 System Model

In the heterogeneous network which consists of cellular and D2D communication, when the number of D2D users is larger than that of cellular users, the situation that multiple D2D users reuse the same spectrum of one cellular user is inevitable. Hence the D2D users who reuse the same spectrum will interfere with each other, increasing the link outrage probability. In mesh type D2D service, multiple D2D users who want to receive the same data from the base station form a cluster and one of them is chosen as the head. At present, D2D

**Table 1.** Definitions of Main Notations

| Notation | Definition |
|---|---|
| $R^S_{m\text{-}max}$ | Maximum data rate of link $S$-*to*-$U_m$ |
| $R^m_{j\text{-}max}$ | Maximum data rate of link $S$-*to*-$U_m$ and link $U_m$-*to*-$U_j$ |
| $B^x_y$ | Bandwidth of the link between $U_x$ and $U_y$ |
| $Pow^x_y$ | Transmitting power of $U_x$ sending data packet to $U_y$ |
| $X_{U_x,U_y}$ | Distance between $U_x$ and $U_y$ |
| $\lvert h^x_y\rvert^2$ | Channel gain of link $U_x$-*to*-$U_y$ |
| $P^T_{R\text{-}out}$ | Outrage probability of link $U_T$-*to*-$U_R$ |
| $\tau_{R\text{-}th}$ | Link delay threshold |
| $\tau^T_{R\text{-}min}$ | Minimum link delay |
| $SINR^T_R$ | Signal-to-interference-plus-noise ratio (SINR) of link $U_T$-*to*-$U_R$ |
| $f_x(x)$ | Probability density function of $x$ |
| $F_z(z)$ | Probability distribution function of $z$ |
| $f_{xy}(x,y)$ | Joint probability density function of $x$ |
| $E^S_{i\text{-}t}$ | Energy consumption of $S$ for transmitting $U_d$-*to*-$U_i$ |
| $D_d$ | Length of each piece of data |
| $EE$ | Energy efficiency |
| $EC$ | Efficienly of capacity |

can discover neighbor devices and information by two modes: network-assisted mode and ad hoc mode[23]. In the network-assisted mode, the cellular base station assists the neighbor discovery process among D2D users. But in the ad hoc mode, users proactively send the discovery signal to detect the potential neighbors and information. Due to the precision, rapidness and flexibility, the ad hoc mode is the major research trend. The head of the cluster has responsibility to receive data and share data with cluster members. For instance, 20% of the popular videos in top video streaming sites have 80% of the click-through rate (CTR). Obviously, local users are very likely to request same video services and the resulting repeated multimedia data transmission consumes massive network resources in the traditional cellular network, which notably affects the delay performance and efficiency of the transmission process. Therefore, it is critical to improve the efficiency of the same video-on-demand transmission by such a system model. If all the D2D users within the cluster reuse the same spectrum, the communication model is showed in Fig.1. $S$ is the head of the cluster, $T_i$ is the D2D transmitting user and $R_i$ is the D2D receiving user, $i = \{1, 2, 3\}$.

It can be seen from Fig.1 that all the D2D receiving users will be interfered by all the D2D transmitting users. If there are $K$ D2D users and one head within the cluster and $S$ firstly sends data packets to $x$ D2D users who will relay data packets to the rest of $K-x$ D2D users, each relaying user will be interfered by at least $x-1$ D2D transmitting users and each non-relaying user will be interfered by $S$ and $x-1$ D2D relaying users. The link between $S$ and D2D users can be expressed as $S$-*to*-$U_m$ and the link between D2D users can be expressed as $U_m$-*to*-$U_j$, $m = \{1, \dots, x\}$, $j = \{x+1, \dots, K\}$. Hence, $S$-*to*-$U_m$ is interfered by at least $x-1$ D2D transmitting users and $U_m$-*to*-$U_j$ is interfered by at least $x$ D2D transmitting users.

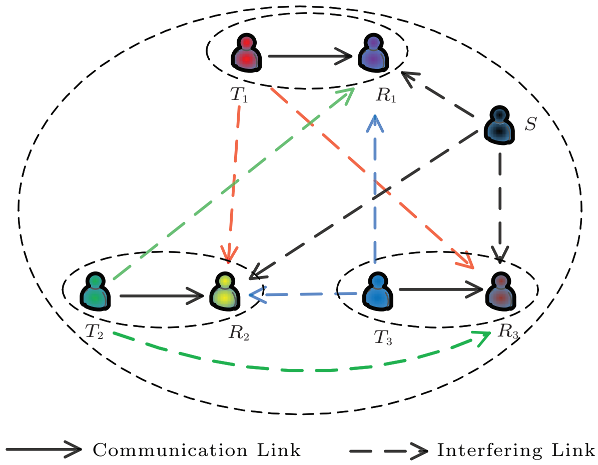


Fig.1. Interference model of a cluster where all D2D users use the same spectrum.

According to the Shannon formula and some work[24], channel fading obeys Rayleigh distribution and the maximum data rate of link $S$-*to*-$U_m$ and link $U_m$-*to*-$U_j$ can be described in (1) and (2) respectively:

$$R^S_{m\text{-}max} = B^S_m \log_2\left(1 + \frac{Pow^S_m \times |X_{S,U_m}|^{-\varepsilon}\,|h^S_m|^2}{\sum\limits_{i=1}^{x} Pow^i_m \times |X_{U_i,U_m}|^{-\varepsilon}\,|h^i_m|^2 + N_0 B^S_m}\right), \quad i \neq m, \tag{1}$$

$$\begin{aligned} R^m_{j\text{-}max} = {} & B^m_j \log_2(1 + (Pow^m_j \times |X_{U_m,U_j}|^{-\varepsilon} \times |h^m_j|^2)/(\sum_{i=1}^{x} Pow^i_j \times |X_{U_i,U_j}|^{-\varepsilon}\,|h^i_j|^2 + \\ & Pow^s_j \times |X_{U_S,U_j}|^{-\varepsilon} \times |h^s_j|^2 + N_0 B^m_j)), \quad m \neq j, \end{aligned} \tag{2}$$

where $N_0$ refers to noise power spectral density, $B_y^x$ is the bandwidth of link between $U_x$ and $U_y$, $Pow_y^x$ is the transmitting power of $U_x$ sending data packets to $U_y$, $X_{U_x,U_y}$ is the distance between $U_x$ and $U_y$, $|h_y^x|^2$ is the channel gain of link $U_x$-*to*-$U_y$ and follows the independent exponential distribution[25], and $\varepsilon$ is the path loss exponent.

Since the transmitting power of each D2D user has the same order of magnitude, the power of interference signal is $x$ times bigger than that of desired signal. If $x$ keeps increasing, the signal-to-interference-plus-noise ratio (SINR) will be very small, which will decrease the capacity seriously. Hence, it is necessary to design the cooperation scheme to limit the interference of each D2D user so as to reduce link outrage probability.

## 3 Outrage Probability and Cooperation Architecture

### 3.1 Link Outrage Probability

Both links $S$-*to*-$U_m$ and $U_m$-*to*-$U_j$ can be regarded as the link between the transmitter and the receiver $U_T$-*to*-$U_R$. $h_R^T$ is the channel gain, $B_R^T$ is the bandwidth, $Pow_R^T$(J/s) is the transmitting power and $X_{U_T,U_R}$ is the distance between the transmitter and the receiver[26]. The maximum data rate of link $U_T$-*to*-$U_R$ can be shown in (3).

Link $U_T$-*to*-$U_R$ will not interrupt only when the data rate $R_R^T$ is less than the maximum data rate $R_{R\text{-}max}^T$ and the minimum link delay $\tau_{R\text{-}min}^T$ is less than the link delay threshold $\tau_{R\text{-}th}$. Hence, the probability of uninterrupted link can be expressed, namely in (4).

The minimum link delay $\tau_{R\text{-}min}^T$ can be described in (5), where $\tau_{Rt\text{-}min}^T$ is the minimum transmitting delay, $\tau_{Rr\text{-}min}^T$ is the minimum receiving delay and $\tau_p$ is the propagation delay. We suppose $\tau_{Rt\text{-}min}^T = \tau_{Rr\text{-}min}^T$ and ignore the propagation delay $\tau_p$ because of the short distance between the transmitter and the receiver. Hence, the minimum link delay $\tau_{R\text{-}min}^T$ can be expressed as (6).

The outrage probability of link $U_T$-*to*-$U_R$ can be shown in (7).

The SINR of link $U_T$-*to*-$U_R$ can be described in (8).

Obviously, the key of deriving the outrage probability is to derive the probability distribution function of SINR, namely, $F_{\text{SINR}}(x) = P(SINR < x)$. It can be shown in (9) and (10).

$$R_{R\text{-}max}^T = B_R^T \log_2 \times \left(1 + \frac{Pow_R^T \times |X_{U_T,U_R}|^{-\varepsilon} \left|h_R^T\right|^2}{\sum_{i=1}^{x} Pow_R^i \times |X_{U_i,U_R}|^{-\varepsilon} \left|h_R^i\right|^2 + N_0 B_R^T}\right), \tag{3}$$

$$P_{R\text{-}pass}^T = \left\{R_R^T \leqslant R_{R\text{-}max}^T, \tau_{R\text{-}min}^T \leqslant \tau_{R\text{-}th}\right\}, \tag{4}$$

$$\tau_{R\text{-}min}^T = \tau_{Rt\text{-}min}^T + \tau_{Rr\text{-}min}^T + \tau_p, \tag{5}$$

$$\tau_{R\text{-}min}^T = 2\tau_{Rt\text{-}min}^T = \frac{2D_d}{R_{R\text{-}max}^T}, \tag{6}$$

$$\begin{aligned} &P_{R\text{-}out}^T \\ &= 1 - P\left\{R_R^T \leqslant R_{R\text{-}max}^T, \tau_{R\text{-}min}^T \leqslant \tau_{R\text{-}th}\right\} \\ &= P\left\{2^{\frac{R_R^T}{B_R^T}} - 1 \leqslant \frac{Pow_R^T |X_{U_T,U_R}|^{-\varepsilon} \left|h_R^T\right|^2}{\sum_{i=1}^{x} Pow_R^i |X_{U_i,U_R}|^{-\varepsilon} \left|h_R^i\right|^2 + N_0 B_R^T}, 2^{\frac{2D_d}{B_R^T \tau_{R\text{-}th}}} - 1 \leqslant \frac{Pow_R^T |X_{U_T,U_R}|^{-\varepsilon} \left|h_R^T\right|^2}{\sum_{i=1}^{x} Pow_R^i |X_{U_i,U_R}|^{-\varepsilon} \left|h_R^i\right|^2 + N_0 B_R^T}\right\}, \\ &U_i \neq U_R, \end{aligned} \tag{7}$$

$$SINR_R^T = \frac{Pow_R^T \times |X_{U_T,U_R}|^{-\varepsilon} \left|h_R^T\right|^2}{\sum_{i=1}^{x} Pow_R^i \times |X_{U_i,U_R}|^{-\varepsilon} \left|h_R^i\right|^2 + N_0 B_R^T}, \tag{8}$$

$$P(SINR \geqslant x) = 1 - P(SINR < x) = 1 - F_{\text{SINR}}(x). \tag{9}$$

Hence,

$$P_{R\text{-}pass}^T = \begin{cases} P\left\{SINR_R^T \geqslant 2^{\frac{R_R^T}{B_R^T}} - 1\right\}, & \text{if } R_R^T \geqslant \frac{2D_d}{\tau_{R\text{-}th}}, \\ P\left\{SINR_R^T \geqslant 2^{\frac{2D_d}{B_R^T \tau_{R\text{-}th}}} - 1\right\}, & \text{if } R_R^T \leqslant \frac{2D_d}{\tau_{R\text{-}th}}. \end{cases} \tag{10}$$

When $x = 1$, the SINR of link $U_T$-*to*-$U_R$ can be described in (11):

$$SINR_R^T = \frac{Pow_R^T \times |X_{U_T,U_R}|^{-\varepsilon} \times \left|h_R^T\right|^2}{Pow_R^1 \times |X_{U_1,U_R}|^{-\varepsilon} \times |h_R^1|^2 + N_0 B_R^T}, \quad (11)$$

which means that link $U_T$-*to*-$U_R$ is just interfered by only one D2D user and additive white Gaussian noise (AWGN). We suppose that

$$Pow_R^T \times |X_{U_T,U_R}|^{-\varepsilon} = \alpha, Pow_R^1 \times |X_{U_1,U_R}|^{-\varepsilon} = \beta,$$
$$N_0 B_R^T = \delta_R^T, x = \alpha \times \left|h_R^T\right|^2, y = \beta \times \left|h_R^1\right|^2 + \delta_R^T.$$

Hence, $z = SINR_R^T = x/y$. The probability density functions of $x$ and $y$ can be shown in (12) and (13) respectively:

$$f_x(x) = \frac{1}{\alpha} f_{|h_R^T|^2}\left(\frac{x}{\alpha}\right) = \frac{1}{\alpha}\exp\left(-\frac{x}{\alpha}\right) U(x), \quad (12)$$

$$\begin{aligned} f_y(y) &= \frac{1}{\beta} f_{|h_R^1|^2}\left(\frac{y-\delta_R^T}{\beta}\right) \\ &= \frac{1}{\beta}\exp\left(-\frac{y}{\beta} + \frac{\delta_R^T}{\beta}\right) U\left(y - \delta_R^T\right), \end{aligned} \quad (13)$$

where $U(\cdot)$ is the Heaviside step function. (12) and (13) can be got with the help of (5)~(18) of [16].

The probability distribution function of $z$ can be described in (14):

$$F_z(z) = 1 - \frac{\alpha}{\alpha + \beta z}\exp\left(-\frac{z\delta_R^T}{\alpha}\right), z = SINR_R^T. \quad (14)$$

*Proof.* The proof is presented in Appendix A.1. □

The probability of uninterrupted link can be shown in (15):

$$P_{R\text{-}pass}^T = \begin{cases} 1 - F_z\left(2^{\frac{R_R^T}{B_R^T}} - 1\right), & \text{if } R_R^T \geqslant \frac{2D_d}{\tau_{R\text{-}th}}, \\ 1 - F_z\left(2^{\frac{2D_d}{B_R^T \tau_{R\text{-}th}}} - 1\right), & \text{if } R_R^T \leqslant \frac{2D_d}{\tau_{R\text{-}th}}. \end{cases} \quad (15)$$

When $i = 2$, the SINR can be described in (16):

$$\begin{aligned} SINR_R^T = {} & (Pow_R^T \times |X_{U_T,U_R}|^{-\varepsilon} \times |h_R^T|^2)/ \\ & (Pow_R^1 \times |X_{U_1,U_R}|^{-\varepsilon} \times |h_R^1|^2 + \\ & Pow_R^2 \times |X_{U_2,U_R}|^{-\varepsilon} \times \left|h_R^2\right|^2 + \\ & N_0 B_R^T). \end{aligned} \quad (16)$$

We suppose that

$$Pow_R^T \times |X_{U_T,U_R}|^{-\varepsilon} = \alpha, Pow_R^1 \times |X_{U_1,U_R}|^{-\varepsilon} = \beta,$$
$$Pow_R^2 \times |X_{U_2,U_R}|^{-\varepsilon} = \omega, N_0 B_R^T = \delta_R^T, x = \alpha\left|h_R^T\right|^2,$$
$$y = \beta\left|h_R^1\right|^2 + \omega\left|h_R^2\right|^2 + \delta_R^T.$$

According to the above analysis, the probability density function of $x$ can be shown in (17):

$$f_x(x) = \frac{1}{\alpha} f_{|h_R^T|^2}\left(\frac{x}{\alpha}\right) = \frac{1}{\alpha}\exp\left(-\frac{x}{\alpha}\right) U(x). \quad (17)$$

As for $y = \beta|h_R^1|^2 + \omega|h_R^2|^2 + \delta_R^T$, the probability density function will be analyzed in two situations:

1) $\beta = \omega$:

$$\begin{aligned} f_y(y) &= \frac{1}{\beta\omega}\int_{\delta_R^T}^{y} \exp\left(\frac{\delta_R^T}{\omega} - \frac{y}{\beta}\right) \mathrm{d}n \\ &= \frac{y - \delta_R^T}{\beta\omega}\exp\left(\frac{\delta_R^T}{\omega} - \frac{y}{\beta}\right). \end{aligned} \quad (18)$$

*Proof.* The proof is presented in Appendix A.2. □

The joint probability density function of $x$, $y$ can be described in (19):

$$\begin{aligned} f_{xy}(x,y) &= f_x(x) \times f_y(y) \\ &= \frac{1}{\alpha}\exp\left(-\frac{x}{\alpha}\right) \times \frac{y-\delta_R^T}{\beta\omega}\exp\left(\frac{\delta_R^T}{\omega} - \frac{y}{\beta}\right) \\ &= \frac{y-\delta_R^T}{\alpha\beta\omega}\exp\left(-\frac{x}{\alpha} + \frac{\delta_R^T}{\omega} - \frac{y}{\beta}\right). \end{aligned} \quad (19)$$

Hence, when $\beta = \omega$, the probability density function of $z$ can be shown in (20):

$$\begin{aligned} f_z(z) &= \int_{y=\delta_R^T}^{\infty} y f_{xy}(yz, y)\,\mathrm{d}y \\ &= \int_{y=\delta_R^T}^{\infty} y \times \frac{y-\delta_R^T}{\alpha\beta\omega}\exp\left(-\frac{yz}{\alpha} + \frac{\delta_R^T}{\omega} - \frac{y}{\beta}\right)\mathrm{d}y \\ &= \frac{1}{\alpha\beta\omega}\left(\frac{2}{\left(\frac{z}{\alpha}+\frac{1}{\beta}\right)^3} + \frac{\delta_R^T}{\left(\frac{z}{\alpha}+\frac{1}{\beta}\right)^2}\right) \times \\ &\quad \exp\left(-\delta_R^T\left(\frac{z}{\alpha}+\frac{1}{\beta}\right) + \frac{\delta_R^T}{\omega}\right), \quad \beta = \omega. \end{aligned} \quad (20)$$

The probability distribution function of $z$ can be described in (21) and (22):

$$\begin{aligned} F_z(z) &= \int_0^z f_z(x)\mathrm{d}x \\ &= \frac{1}{\alpha\beta\omega}\int_0^z \left(\frac{2}{\left(\frac{x}{\alpha}+\frac{1}{\beta}\right)^3} + \frac{\delta_R^T}{\left(\frac{x}{\alpha}+\frac{1}{\beta}\right)^2}\right) \times \\ &\quad \exp\left(-\delta_R^T\left(\frac{x}{\alpha}+\frac{1}{\beta}\right) + \frac{\delta_R^T}{\omega}\right)\mathrm{d}x, \quad \beta = \omega. \end{aligned} \quad (21)$$

2) $\beta \neq \omega$:

$$\begin{aligned} f_y(y) &= \frac{1}{\beta\omega}\int_{\delta_R^T}^{y}\exp\left(n\left(\frac{1}{\beta}-\frac{1}{\omega}\right)+\frac{\delta_R^T}{\omega}-\frac{y}{\beta}\right)\mathrm{d}n \\ &= \frac{1}{\omega-\beta}\left(\exp\left(\frac{\delta_R^T}{\omega}-\frac{y}{\omega}\right)-\exp\left(\frac{\delta_R^T}{\beta}-\frac{y}{\beta}\right)\right), \\ &\quad y \geqslant \delta_R^T. \end{aligned} \tag{22}$$

*Proof*. The proof is presented in Appendix A.2. □

Hence, the joint probability density function of $x$, $y$ can be shown in (23):

$$\begin{aligned} f_{xy}(x,y) &= f_x(x)\times f_y(y) \\ &= \frac{1}{\alpha(\omega-\beta)}\times\left(\exp\left(-\frac{x}{\alpha}+\frac{\delta_R^T}{\omega}-\frac{y}{\omega}\right)-\right. \\ &\quad \left.\exp\left(-\frac{x}{\alpha}+\frac{\delta_R^T}{\beta}-\frac{y}{\beta}\right)\right),\quad y\geqslant\delta_R^T. \end{aligned} \tag{23}$$

The probability density function of $z$ is described in (24):

$$\begin{aligned} f_z(z) &= \int_{y=\delta_R^T}^{\infty} y f_{xy}(yz,y)\,\mathrm{d}y \\ &= \frac{1}{\alpha(\omega-\beta)}\left(\begin{array}{c}\frac{\delta_R^T}{\left(\frac{z}{\alpha}+\frac{1}{\omega}\right)}-\frac{\delta_R^T}{\left(\frac{z}{\alpha}+\frac{1}{\beta}\right)}+\\ \frac{1}{\left(\frac{z}{\alpha}+\frac{1}{\omega}\right)^2}-\frac{1}{\left(\frac{z}{\alpha}+\frac{1}{\beta}\right)^2}\end{array}\right)\times \\ &\quad \exp\left(-\frac{z\delta_R^T}{\alpha}\right),\quad \beta\neq\omega. \end{aligned} \tag{24}$$

Hence, when $\beta \neq \omega$, the probability distribution function of $z$ can be shown in (25):

$$\begin{aligned} F_z(z) &= \int_0^z f_z(x)\,\mathrm{d}x \\ &= \int_0^z \frac{1}{\alpha(\omega-\beta)}\left(\begin{array}{c}\frac{\delta_R^T}{\left(\frac{x}{\alpha}+\frac{1}{\omega}\right)}-\frac{\delta_R^T}{\left(\frac{x}{\alpha}+\frac{1}{\beta}\right)}+\\ \frac{1}{\left(\frac{x}{\alpha}+\frac{1}{\omega}\right)^2}-\frac{1}{\left(\frac{x}{\alpha}+\frac{1}{\beta}\right)^2}\end{array}\right)\times \\ &\quad \exp\left(-\frac{x\delta_R^T}{\alpha}\right)\mathrm{d}x,\beta\neq\omega. \end{aligned} \tag{25}$$

If $i \geqslant 3$, the SINR can be described in (26):

$$\begin{aligned} & SINR_R^T \\ &= (Pow_R^T\times|X_{U_T,U_R}|^{-\varepsilon}\times\left|h_R^T\right|^2)/ \\ &\quad (Pow_R^1\times|X_{U_1,U_R}|^{-\varepsilon}\times\left|h_R^1\right|^2+\cdots+ \\ &\quad Pow_R^n\times|X_{U_n,U_R}|^{-\varepsilon}\left|h_R^n\right|^2+N_0B_R^T), n\geqslant 3. \end{aligned} \tag{26}$$

We suppose that:

$$\begin{aligned} x &= Pow_R^T\times|X_{U_T,U_R}|^{-\varepsilon}\times\left|h_R^T\right|^2, \\ y &= Pow_R^1\times|X_{U_1,U_R}|^{-\varepsilon}\times\left|h_R^1\right|^2+\cdots+ \\ &\quad Pow_R^n\times|X_{U_n,U_R}|^{-\varepsilon}\left|h_R^n\right|^2+N_0B_R^T. \end{aligned}$$

Although the probability density function of $x$ can be derived according to above analysis, the probability density function of $y$ is hard to derive when $i \geqslant 3$. Besides, when $i \geqslant 3$ the power of interference signal is three times bigger than that of desired signal, which deduces the SINR seriously. Hence, in order to simplify the computational complexity and ensure high SINR, it is necessary to limit the interference of each D2D user. In other words, each D2D receiving user is interfered by no more than two D2D users.

### 3.2 Interference-Limited Multi-User Cooperation Scheme

In order to enhance the spectrum efficiency, there should be D2D users as many as possible to reuse the same spectrum. However, the inter-interference will become serious and reduce the quality of communication badly because of too many D2D users who reuse the same spectrum. Hence, the proposed cooperation scheme divides multiple D2D users into different cooperative units. The D2D users in different cooperative units reuse orthogonal spectrums, and thus D2D users in different cooperative units will not interfere with each other so as to limit the interference of each D2D user. Moreover, the D2D users within the same cooperative unit reuse the same spectrum. In order to ensure that each D2D user is interfered by no more than two D2D users, the number of D2D transmitting users who reuse the same spectrum should not be bigger than 3. The proposed cooperative architecture is shown in Fig.2.

As shown in Fig.2, the specific cooperative processes are as follows.

1) The head of cluster $S$ uses a separate spectrum $f_0$ to share data packet to $x$ D2D relaying users.

2) D2D user $U_1$ uses spectrum $f_1$ to share data packet to two D2D users (if so) $U_{11}$ and $U_{12}$. After receiving data packet, D2D users $U_{11}$ and $U_{12}$ use spectrum $f_1$ to share data packet to two D2D users (if so) respectively, namely, $U_{111}$, $U_{112}$, $U_{121}$, $U_{122}$.

3) If there are other D2D users who have not received data packet yet, these D2D users will get data packet from the cooperative units which $U_2$, …, $U_x$ belong to and the spectrums used by $U_2$, …, $U_x$ are $f_2$, …, $f_x$ respectively.

4) If there are other D2D users who have not received data packet yet, these D2D users will get data packet from the cooperative units which $U_{111}$, $U_{112}$, $U_{121}$, $U_{122}$, …, $U_{x11}$, $U_{x12}$, $U_{x21}$, $U_{x22}$ belong to.

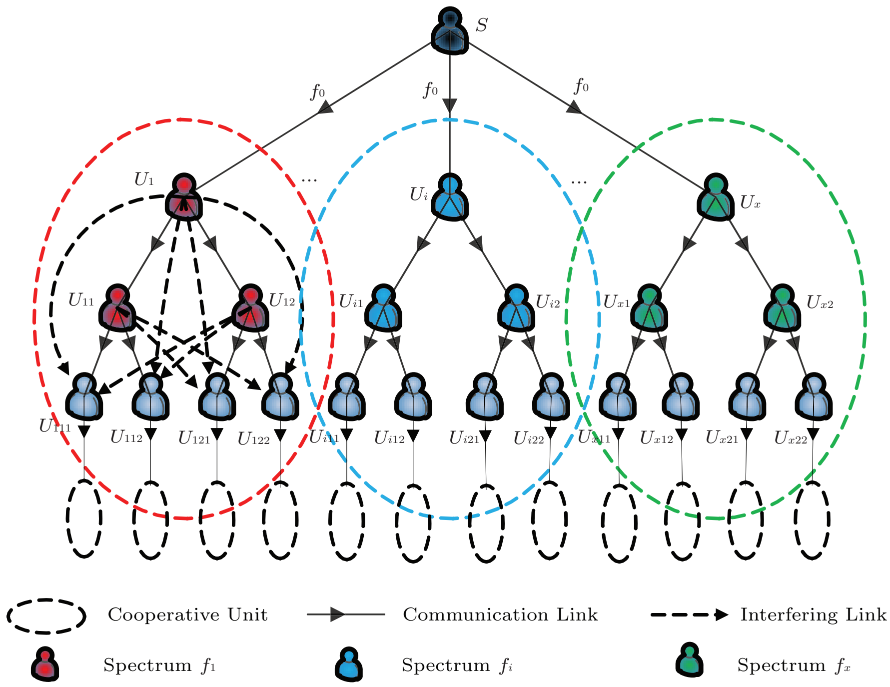


Fig.2. Cooperative architecture of multiple interference-limited D2D users.

5) If there are other D2D users who have not received data packet yet, these D2D users get data packet from the cooperative units who do not have full members so as to save spectrum resources. Besides, the D2D users who have more energy, better channel quality and closer distance are more likely to be chosen as the relay to share data packet.

It can be seen from Fig.2 that D2D users share data packets with each other in the manner of multi-lop communication. Besides receiving their own data packet, the D2D users who are chosen as relays need to relay data packets to others as well. Thus, the relay selection is the key of cooperation, including selecting D2D users as relays by $S$ and selecting D2D users as next hops by D2D relaying users.

1) As for selecting D2D users as relays by $S$, since the power of $S$ is bigger than that of other cluster members, $S$ has enough power to broadcast data packets to multiple D2D users as many as possible with a separate spectrum $f_0$ so as to enhance the efficiency of spectrum. In order to ensure that the chosen D2D relaying users have enough power to share data packets to at least one D2D user, $S$ firstly chooses $v$ D2D users whose powers are bigger than the power threshold $I$ from $K$ D2D users and these $v$ D2D users form set $V$, namely in (27):

$$V = \{U_j | B_j \geqslant I, 1 \leqslant j \leqslant v, x \leqslant v \leqslant K\}, \qquad (27)$$

where $B_j$ is the power of D2D user $U_j$.

Then, $S$ will choose $x$ appropriate D2D users as relays according to the energy availability itself and channel qualities which are represented by SNRs between $S$ and candidate D2D relaying users. Since $S$ uses separate spectrum to broadcast data packets to D2D relaying users, these broadcasting links are uninterrupted by other D2D users. Hence, there is no need to consider the distances between $S$ and candidate D2D relaying users when selecting relays. Suppose that the SNRs (signal-to-noise ratios) of D2D users in $V$ are $SNR_1, \cdots, SNR_v$, bit error rates (BERs) are $P_b^1, \cdots, P_b^v$ and the powers consumed to transmit data packet $D$ (bits) are $E_d^1, \cdots, E_d^v$. After sorting these powers from small to large, we get the power sequence $E_1, E_2, \cdots, E_v$. The sum of the first $x$ powers can be described in (28):

$$E_{x\text{-}sum} = E_1 + \cdots + E_x, 1 \leqslant x \leqslant v. \qquad (28)$$

If $E_{x\text{-}sum} \leqslant B_s$, where $B_s$ is remaining energy of $S$, $x$ D2D relaying users who are corresponding to $E_1, \cdots, E_x$ are chosen as D2D relaying users.

2) As for selecting D2D users as next hops by D2D relaying users, considering limiting the inter-interference among D2D users, saving energy of D2D users and ensuring good communication quality, the rules that have to be observed when selecting the next hops are summarized as follows.

a) Each D2D user shares the same data packet with up to two other D2D users so as to save energy and limit interference.

b) The D2D user who belongs to the cooperative unit where there are not full members has priority to choose the next hop so as to save spectrum resource.

c) If there are the cooperative units where there are not full members and there are some D2D users who have not received data packet yet, as shown in Fig.2, the D2D users who belong to the upper layer cooperative units have higher priority to select the next hop. As for the D2D users who belong to the cooperative units who are on the same layer, the D2D users belonging to the left cooperative unit have higher priority to select the next hop.

d) If multiple D2D users belonging to the same cooperative unit select the same D2D user as the next hop, the upper layered D2D user has higher priority to select the next hop. If multiple D2D users belong to the same cooperative unit and are on the same layer, the candidate D2D user will choose the closest one as the relay.

Since the D2D users who are chosen as the next hops by D2D relaying users will have chance to relay data packets to other D2D users, the remaining energy and channel quality have to be considered when D2D relaying users select the next hops. For example, when D2D relaying user $U_i$ selects two D2D users as the next hop from $K-x$ D2D users, $v$ D2D users whose remaining energies are bigger than energy threshold $B_{th}$ are chosen firstly. Secondly, $v'$ D2D users whose SNRs are bigger than SNR threshold $\gamma_{th}$ are chosen from $v$ D2D users, $v' \leqslant v$. SNR threshold $\gamma_{th}$ is designed to ensure that the received data packet can be decoded correctly with two interferences. Lastly, $U_i$ will choose two closest D2D users from $v'$ D2D users as the next hop.

## 4 Efficiency of Energy and Capacity

According to the analysis in Section 3, there are two kinds of links including link $S$-*to*-$U_i$ and link $U_i$-*to*-$U_j$. The link $S$-*to*-$U_i$ which will not be interfered by others is named zero-layer link. The links $U_i$-*to*-$U_j$ which will be interfered by one D2D user or two D2D users are named one-layer link or two-layer link. Combing the derived link outrage probability and considering two kinds of links, the efficiencies of energy and capacity are studied in this section. Before studying the energy, the total energy needs to be studied firstly.

1) As for the energy consumption of $S$ for broadcasting data packets to D2D relaying users, suppose that $S$ will share data $L$ with $K$ D2D users. Data $L$ is divided into $n$ pieces and the length of each piece of data is $D_d$, namely, $L = \sum_{d=1}^{n} D_d$. When sharing each data packet $D_d$, $S$ will use separate spectrum $f_0$ to broadcast packets to $x_d$ D2D relaying users. Bandwidth is $B_i^s$ and the delay threshold of each link is $\tau_{i\text{-}th}$. According the analysis in Section 3, the maximum capacity of link $S$-*to*-$U_i$ can be shown in (29):

$$R_{i\text{-}max}^S = B_i^S \log_2\left(1 + \frac{Pow_i^S \left|X_{S,U_i}\right|^{-\varepsilon} \left|h_i^S\right|^2}{N_0 B_i^S}\right). \quad (29)$$

The uninterrupted probability of link $S$-*to*-$U_i$ can be described in (30):

$$P_{i\text{-}pass}^S = \begin{cases} \exp\left(-\frac{2^{R_i^S/B_i^S}-1}{\bar{r}_i^S}\lambda_i^S\right), & \text{if } R_i^S \geqslant \frac{2D_d}{\tau_{i\text{-}th}}, \\ \exp\left(-\frac{2^{2D_d/\tau_{i\text{-}th}B_i^S}-1}{\bar{r}_i^S}\lambda_i^S\right), & \text{if } R_i \leqslant \frac{2D_d}{\tau_{i\text{-}th}}, \end{cases} \quad (30)$$

where $d \in (1, \cdots, n)$, $i \in (1, \cdots, x_d)$ and

$$\bar{r}_i^S = \frac{Pow_i^S \left|X_{U_S,U_i}\right|^{-\varepsilon}}{N_0 B_i^S}.$$

Hence, the energy consumption of $S$ for transmitting $D_d$ to $U_i$ can be shown in (31):

$$E_{i\text{-}t}^S = \frac{D_d \times E_{i\text{-}bit}^S}{P_{i\text{-}pass}^S}, \quad (31)$$

where $E_{i\text{-}bit}^S$ is the energy consumption of $S$ for transmitting one bit to $U_i$. Since the total energy consumption for sharing $D_d$ involves transmitting, receiving and processing energy, namely, $E_{i\text{-}t}^S$, $E_{i\text{-}r}^S$ and $E_{ip}$, and we suppose $E_{i\text{-}t}^S = E_{i\text{-}r}^S$, the total energy consumption for sharing of $S$ for sharing $D_d$ to $x_d$ D2D relaying users can be described in (32):

$$_dE_{S\to U} = \sum_{i=1}^{x_d} E_i^S = \sum_{i=1}^{x_d}\left(\frac{2D_d \times E_{i\text{-}bit}^S}{P_{i\text{-}pass}^S} + E_{ip}\right). \quad (32)$$

2) As for the total energy consumption of D2D relaying users for sharing data packets with the rest of D2D users, since there two types of links, one-layer link and two-layer link are studied separately to analyze the efficiency of energy and capacity.

As for the one-layer link, such as link $U_1$-*to*-$U_{11}$, according to the analysis in Section 3, the SINR can be shown in (33):

$$SINR_{11}^1 = \frac{Pow_{11}^1 \left|X_{U_1,U_{11}}\right|^{-\varepsilon} \left|h_{11}^1\right|^2}{Pow_{11}^{12} \left|X_{U_{12},U_{11}}\right|^{-\varepsilon} \left|h_{11}^{12}\right|^2 + N_0 B_{11}^1}, \quad (33)$$

where $Pow_{11}^{1}$ and $Pow_{11}^{12}$ are the transmission power of users $U_1$ and $U_{12}$ respectively. $h_{11}^{1}$ and $h_{11}^{12}$ are the channel gain of links $U_1$-*to*-$U_{11}$ and $U_{12}$-*to*-$U_{11}$ respectively. $B_{11}^{1}$ is the channel bandwidth.

When the link capacity cannot meet the requirements of the user rate, it will produce an interrupt event. Such an event is following the probability distribution, and depends on the link of the average SINR and its channel fading distribution model. In particular, the probability distribution function of $SINR_{11}^{1}$ can be described in (34):

$$F_z(z) = 1 - \frac{\alpha}{\alpha + \beta z} \exp\left(-\frac{z\delta_{11}^{1}}{\alpha}\right), \quad z = SINR_{11}^{1}, \tag{34}$$

where $Pow_{11}^{1}|X_{U_1,U_{11}}|^{-\varepsilon} = \alpha$, $Pow_{11}^{12}|X_{U_{12},U_{11}}|^{-\varepsilon} = \beta$, $N_0 B_{11}^{1} = \delta_{11}^{1}$. Hence the uninterrupted probability of link $U_1$-*to*-$U_{11}$ can be shown in (35):

$$P_{11\text{-}pass}^{1} = \begin{cases} 1 - F_z\left(2^{\frac{R_{11}^{1}}{B_{11}^{1}}} - 1\right), & \text{if } R_{11}^{1} \geqslant \frac{2D_d}{\tau_{11\text{-}th}}, \\ 1 - F_z\left(2^{\frac{2D_d}{B_{11}^{1}\tau_{11\text{-}th}}} - 1\right), & \text{if } R_{11}^{1} \leqslant \frac{2D_d}{\tau_{11\text{-}th}}, \end{cases} \quad z = SINR_{11}^{1}, \tag{35}$$

where $\tau_{11\text{-}th}$ is the delay threshold of $U_{11}$.

As for the two-layer link, such as link $U_{11}$-*to*-$U_{111}$, the SINR can be described in (36):

$$\begin{aligned} SINR_{111}^{11} &= (Pow_{111}^{11}|X_{U_{11},U_{111}}|^{-\varepsilon}|h_{111}^{11}|^2)/ \\ &\quad (Pow_{111}^{1}|X_{U_1,U_{111}}|^{-\varepsilon}|h_{111}^{1}|^2 + \\ &\quad Pow_{111}^{12}|X_{U_{12},U_{111}}|^{-\varepsilon}|h_{111}^{12}|^2 + N_0 B_{111}^{11}), \end{aligned} \tag{36}$$

where $Pow_{111}^{11}|X_{U_{11},U_{111}}|^{-\varepsilon} = \alpha$, $Pow_{111}^{1}|X_{U_1,U_{111}}|^{-\varepsilon} = \beta$, $Pow_{111}^{12}|X_{U_{12},U_{111}}|^{-\varepsilon} = \omega$, $N_0 B_{111}^{11} = \delta_{111}^{11}$. Hence the probability distribution function of $z = SINR_{111}^{11}$ can be shown in (37) and (38):

$$\begin{aligned} F_z(z) &= \int_0^z f_z(x)\mathrm{d}x \\ &= \frac{1}{\alpha\beta\omega}\int_0^z \left(\frac{2}{\left(\frac{x}{\alpha}+\frac{1}{\beta}\right)^3} + \frac{\delta_{111}^{11}}{\left(\frac{x}{\alpha}+\frac{1}{\beta}\right)^2}\right) \times \\ &\quad \exp\left(-\delta_{111}^{11}\left(\frac{x}{\alpha}+\frac{1}{\beta}\right) + \frac{\delta_{111}^{11}}{\omega}\right)\mathrm{d}x, \\ &\quad \beta = \omega, \end{aligned} \tag{37}$$

$$\begin{aligned} F_z(z) &= \int_0^z f_z(x)\mathrm{d}x \\ &= \int_0^z \frac{1}{\alpha(\omega-\beta)} \left(\begin{array}{c} \frac{\delta_{111}^{11}}{\left(\frac{x}{\alpha}+\frac{1}{\omega}\right)} - \frac{\delta_{111}^{11}}{\left(\frac{x}{\alpha}+\frac{1}{\beta}\right)} + \\ \frac{1}{\left(\frac{x}{\alpha}+\frac{1}{\omega}\right)^2} - \frac{1}{\left(\frac{x}{\alpha}+\frac{1}{\beta}\right)^2} \end{array}\right) \times \\ &\quad \exp\left(-\frac{x\delta_{111}^{11}}{\alpha}\right)\mathrm{d}x, \quad \beta \neq \omega. \end{aligned} \tag{38}$$

Hence, the uninterrupted probability of link $U_{11}$-*to*-$U_{111}$ can be described in (39):

$$P_{111\text{-}pass}^{11} = \begin{cases} 1 - F_z\left(2^{\frac{R_{111}^{11}}{B_{111}^{11}}} - 1\right), \\ \quad \text{if } R_{111}^{11} \geqslant \frac{2D_d}{\tau_{111\text{-}th}}, \\ 1 - F_z\left(2^{\frac{2D_d}{B_{111}^{11}\tau_{111\text{-}th}}} - 1\right), \\ \quad \text{if } R_{111}^{11} \leqslant \frac{2D_d}{\tau_{111\text{-}th}}, \end{cases} \quad z = SINR_{111}^{11}. \tag{39}$$

Suppose that $K - x_d = 6a + b$, $0 \leqslant a < \infty$ and $0 \leqslant b < 6$. According to Fig.2, there are $x_d$ zero-layer links in the cluster and there are up to two one-layer links and four two-layer links in each cooperative unit. Hence, the energy consumption of each cooperative unit can be analyzed by combing with the derived outrage probabilities. For example, in a cooperative unit which $U_1$ belongs to, the energy consumption for sharing data packet $D_d$ of a one-layer link such as link $U_1$-*to*-$U_{11}$ can be shown in (40):

$$E_{11\text{-}d}^{1} = \frac{2D_d \times E_{11\text{-}bit}^{1}}{P_{11\text{-}pass}^{1}} + E_{11p}. \tag{40}$$

The energy consumption of links $U_{11}$-*to*-$U_{112}$, $U_{12}$-*to*-$U_{121}$, $U_{12}$-*to*-$U_{122}$ can be got in the same way, namely, $E_{112\text{-}d}^{11}$, $E_{121\text{-}d}^{12}$ and $E_{122\text{-}d}^{12}$ respectively. Hence, if the cooperative unit has full members, the total energy consumption for sharing data packet $D_d$ can be described in (41):

$$\begin{aligned} E_d^{1} &= E_{11\text{-}d}^{1} + E_{12\text{-}d}^{1} + E_{111\text{-}d}^{11} + E_{112\text{-}d}^{11} + \\ &\quad E_{121\text{-}d}^{12} + E_{122\text{-}d}^{12}. \end{aligned} \tag{41}$$

If there are just $b$ members in a cooperative unit, $0 \leqslant b < 6$ and suppose that this cooperative unit is the $(a+1)$-th one, the total energy consumption $E_d^{a+1}$ of sharing data packet $D_d$ needs to be studied in three situations:

1) $b = 0$, $E_d^{a+1} = 0$;

2) $1 \leqslant b \leqslant 2$, namely, there are $b$ one-layer links:

when $b = 1$, $E_d^{a+1} = E_{a+1,1\text{-}d}^{a+1}$;

when $b=2$, $E_d^{a+1} = E_{(a+1)1\text{-}d}^{a+1} + E_{(a+1)2\text{-}d}^{a+1}$;

3) $3 \leqslant b < 6$, namely, there are two one-layer links and $b-2$ two-layer links:

when $b = 3$, $E_d^{a+1} = E_{(a+1)1\text{-}d}^{a+1} + E_{(a+1)2\text{-}d}^{a+1} + E_{(a+1)11\text{-}d}^{(a+1)1}$;

when $b = 4$, $E_d^{a+1} = E_{(a+1)1\text{-}d}^{a+1} + E_{(a+1)2\text{-}d}^{a+1} + E_{(a+1)11\text{-}d}^{(a+1)1} + E_{(a+1)12\text{-}d}^{(a+1)1}$;

when $b = 5$, $E_d^{a+1} = E_{(a+1)1\text{-}d}^{a+1} + E_{(a+1)2\text{-}d}^{a+1} + E_{(a+1)11\text{-}d}^{(a+1)1} + E_{(a+1)12\text{-}d}^{(a+1)1} + E_{(a+1)21\text{-}d}^{(a+1)2}$.

Hence, the total energy consumption of sharing data packet $D_d$ with $K$ D2D users can be shown in (42):

$$E_d = {}_dE_{S\to U} + \sum_{i=1}^{a+1} E_d^i. \tag{42}$$

The total energy consumption of sharing data $L$ with $K$ D2D users can be described in (43):

$$E_L = \sum_{d=1}^{n} E_d. \tag{43}$$

The energy efficiency can be shown in (44):

$$EE = E'_L/E_L, \tag{44}$$

where $E'_L$ represents the energy consumption of sharing data packet $L$ among $K$ D2D users with zero outrage probability.

As for the capacity, since the maximum capacity of links $S$-to-$U_i$ and $U_i$-to-$U_j$ is $R_{i\text{-}max}^S$ and $R_{j\text{-}max}^i$ respectively, the efficiency of capacity can be described in (45):

$$EC = \sum_{i=1}^{x_d} R_{i\text{-}max}^S \times P_{i\text{-}pass}^S + \sum_{j=1}^{K-x_d} R_{j\text{-}max}^i \times P_{j\text{-}pass}^i. \tag{45}$$

## 5 Simulation Results

The relationships among link delay threshold and link outrage probability, the efficiency of capacity and the efficiency of energy are analyzed in this section. In simulation, the channel has additive white Gaussian noise (AWAN) and the quadrature amplitude modulation (QAM) is adopted. The bandwidth is 10 MHz, and the single sideband power spectral density is −174 dBm/Hz. The distance between the interfering user and the receiving user is 15 m∼25 m and the distance between the transmitter and the receiver is 10 m∼20 m. Other simulation parameters are shown in Table 2.

Fig.3 shows the relationships between the communication distance $X$ and the ratio of desired signal power to interfering signal power in different communication environment with different fading factors. The interfering user and transmitter have the same transmitting power. The distance between the interfering user and the interfering transmitter is 15 m and the distance between the transmitter and the receiver is 5 m∼20 m. It can be seen that as $X$ is increasing, the ratio is deducing obviously and the higher fading factor leads to a faster decline. Hence, if the remaining energy and SNR are qualified, the closest D2D user should be chosen when D2D relaying users choose the next hop, especially in bad communication environment.

**Table 2.** Simulation Parameters

| Parameter | Value |
|---|---|
| Communication distance (m) | 10∼25 |
| Transmission power (dBm) | 15∼30 |
| White Gaussian noise density (dBm/Hz) | −174 |
| Total length of data $L$ (bit) | 256, 512, 1 024 |
| Constant overhead of data packet (bit) | 10 |
| Link delay threshold (µs) | 1, 3, 6 |
| Number of D2D users | 10∼200 |
| Number of data packets | 6 |
| Variance of channel gain | 1 |
| Path loss factor $\varepsilon$ | 4 |

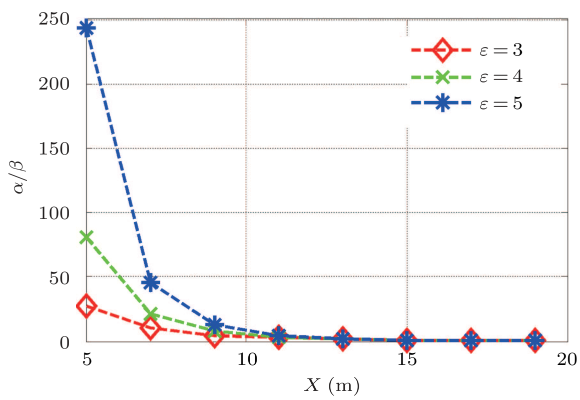


Fig.3. Relationships between the communication distance $X$ and $\alpha/\beta$.

Fig.4 shows the relationships between outrage probability and delay threshold for three types of links. The length of data packet is constant $D_d = 128$ bits and $\beta = \omega$. It can be seen that the outrage probability of zero-layer link is lower than that of one-layer and two-layer links. This is because that $S$ uses separate spectrum to broadcast data packets, which brings no interference to zero-layer link. Besides, the outrage probability is reducing with the increase of delay threshold and interference has more obvious effect on outrage probability with a more demanding delay threshold.

Fig.5 shows the relationships among the number of D2D relaying users chosen by $S$, the average link delay threshold and the energy efficiency, namely, $x$, $\tau_{th}$ and $EE$ respectively. $K = 100$, $n = 6$, $L = 512$ bits. It can be seen that as $x$ is increasing, $EE$ will increase gradually and stay stable finally. This is because when $x$ is smaller than a constant number and the number of D2D users is constant, that $x$ becomes bigger means that less D2D users will be interfered, which enhances $EE$. Besides, it is obvious that a more demanding delay threshold leads to lower $EE$ and more D2D relaying users are needed to be chosen by $S$ so as to reach the highest $EE$. This is because the shorter delay threshold leads to higher outrage probability and has a serious effect on outrage probability. Hence, in order to reach higher $EE$, less D2D users should be interfered, which has higher requirements on the remaining energy of $S$ and the communication environment.

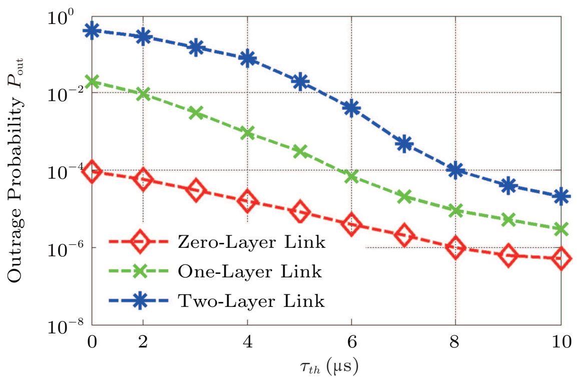


Fig.4. Relationships between outrage probability and delay threshold for three types of links.

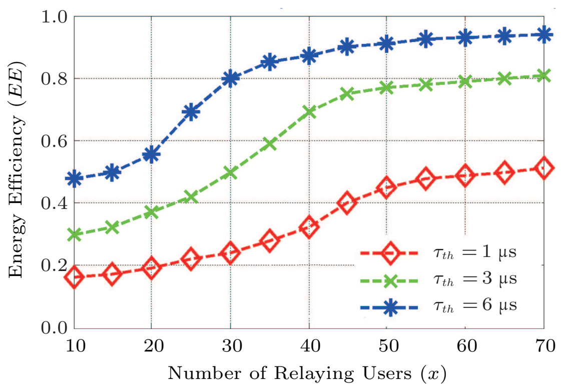


Fig.5. Relationships among the number of D2D relaying users chosen by $S$, average link delay threshold and energy efficiency.

Fig.6 shows the relationships among the number of D2D users, the average delay threshold and the energy efficiency, namely, $K$, $\tau_{th}$ and $EE$. $n = 6$, $L = 512$ bits, $x = 50$, $SINR = 8$ dB. It can be seen that when $K$ is smaller than about 50, $EE$ is increasing with $K$ increasing. But when $K$ is bigger than about 50, $EE$ will reduce with $K$ increasing and will reduce faster with a more demanding delay threshold. This is because when $K$ is smaller than 50, $S$ has enough energy to broadcast data packets to all D2D users and these D2D users will not be interfered. But when $K$ keeps increasing, the number of cooperative units is increasing, which leads to more interfered D2D users so as to reduce $EE$. Besides, if delay threshold is more demanding, the interference has more obvious effect on outrage probability, which leads $EE$ to reduce faster.

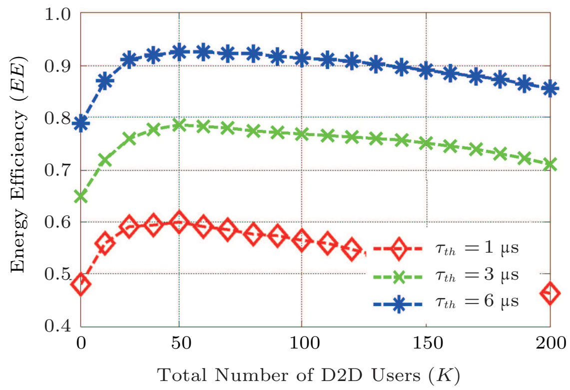


Fig.6. Relationships among the number of D2D users, the average delay threshold and the energy efficiency.

Fig.7 shows the relationships among the number of D2D users, the average delay threshold and the efficiency of capacity, namely, $K$, $\tau_{th}$ and $EC$. $n = 6$, $L = 512$ bits, $x = 50$, $SINR = 8$ dB. It can be seen that as $K$ is increasing, $EC$ will increase and keep stable finally. This is because when $K$ is smaller, $S$ has enough energy to broadcast data packets to most of D2D users, which means that less D2D users are interfered so that $EC$ increases obviously with $K$ increasing. However, when $K$ keeps increasing, most of D2D users will be interfered by at least one D2D user, which leads the capacity to reduce. But $EC$ keeps stable finally with $K$ increasing because of the increasing cooperative links. Besides, the more demanding delay threshold leads to lower maximum capacity and this is because of the higher outrage probability.

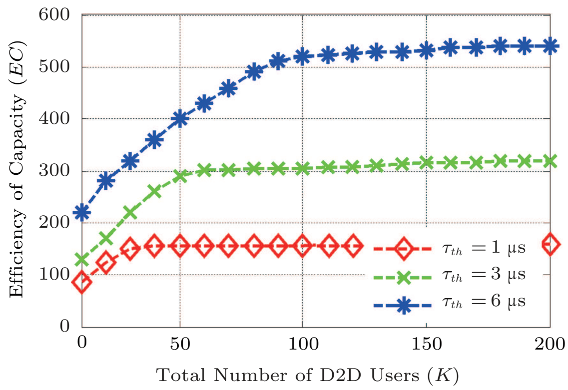


Fig.7. Relationships among the number of D2D users, the average delay threshold and the efficiency of capacity.

Combing Fig.6 and Fig.7, it is can be seen that the average delay threshold has obvious bad effect on both $EE$ and $EC$, especially when the number of D2D users is big. This is mainly because of the high outrage probability which is led by interference, especially when the delay threshold is severe.

## 6 Conclusions

In this paper, an interference-limited multi-user cooperation scheme was proposed for multiple D2D users to solve the energy problem and the interference problem. These multiple D2D users use non-orthogonal spectrums to form a cluster by a self-organized method. Considering link delay threshold, data rate and interference, the outrage probability of D2D link is derived based on Shannon equation. Multiple D2D users are divided into different cooperative units. There is no interference among different cooperative units so as to limit the interference of each D2D user. Besides the energy availability and SNR of each D2D user, the distance between D2D users is considered when selecting the relaying D2D users so as to enhance the signal-to-interference-plus-noise ratio (SINR) of D2D receiving users. Combining the derived outrage probability, the relationships among a average link delay threshold, the system efficiency of energy and the system efficiency of capacity were studied. The simulation results showed that the interference-limited multiple D2D users cooperation scheme can not only help to offload energy consumption to the D2D users and limit the interference of D2D users but enhance the system efficiency of energy and the system efficiency of capacity.

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## Appendix

### A.1 Proof of (14)

Sicne $x$ and $y$ are independent, the joint probability density function of $x$ and $y$ can shown in (A1) and (A2):

$$\begin{aligned} f_{xy}(x,y) &= f_x(x) \times f_y(y) \\ &= \frac{1}{\alpha}\exp\left(-\frac{x}{\alpha}\right) \times \frac{1}{\beta}\exp\left(-\frac{y}{\beta}+\frac{\delta_R^T}{\beta}\right) \\ &= \frac{1}{\alpha\beta}\exp\left(-\frac{x}{\alpha}-\frac{y}{\beta}+\frac{\delta_R^T}{\beta}\right). \qquad \text{(A1)} \end{aligned}$$

Hence,

$$\begin{aligned} f_{xy}(yz,y) &= \frac{1}{\alpha\beta}\exp\left(-\frac{yz}{\alpha}-\frac{y}{\beta}+\frac{\delta_R^T}{\beta}\right), \\ & y \geqslant \delta_R^T. \qquad \text{(A2)} \end{aligned}$$

Since $x$ and $y$ are bigger than 0, the probability density function of $z$ can be described in (A3):

$$\begin{aligned} f_z(z) &= \int_{y=0}^{\infty} y f_{xy}(yz, y)\,\mathrm{d}y \\ &= \left(\frac{\delta_R^T}{(z\beta+\alpha)} + \frac{\alpha\beta}{(z\beta+\alpha)^2}\right)\exp\left(-\frac{z\delta_R^T}{\alpha}\right). \end{aligned} \quad \text{(A3)}$$

From the probability distribution, function of $z$ can be shown in (A4):

$$F_z(z) = \int_0^z \left(\frac{\delta_R^T e^{-\frac{x\delta_R^T}{\alpha}}}{(x\beta+\alpha)} + \frac{\alpha\beta e^{-\frac{x\delta_R^T}{\alpha}}}{(x\beta+\alpha)^2}\right)\mathrm{d}x. \quad \text{(A4)}$$

Using the integration by parts, the right term in (A4) can be described in (A5):

$$\begin{aligned} &\int_0^z \frac{\alpha\beta e^{-\frac{x\delta_R^T}{\alpha}}}{(x\beta+\alpha)^2}\mathrm{d}x \\ &= \left.\frac{-\alpha e^{-\frac{x\delta_R^T}{\alpha}}}{\alpha+\beta x}\right|_{x=0}^{z} - \int_0^z \frac{e^{-\frac{x\delta_R^T}{\alpha}} \times \delta_R^T}{\alpha+\beta x}\mathrm{d}x \\ &= 1 - \frac{\alpha e^{-\frac{z\delta_R^T}{\alpha}}}{\alpha+\beta z} - \int_0^z \frac{e^{-\frac{x\delta_R^T}{\alpha}} \times \delta_R^T}{\alpha+\beta x}\mathrm{d}x. \end{aligned} \quad \text{(A5)}$$

By substituting (A5) into (A4), the desired result (14) can be obtained. □

### A.2 Proof of (18) and (22)

As for $y = \beta|h_R^1|^2 + \omega|h_R^2|^2 + \delta_R^T$, we suppose that $m = \beta|h_R^1|^2$ and $n = \omega|h_R^2|^2 + \delta_R^T$. Since the probability density functions of $m$ and $n$ are shown in (A6) and (A7):

$$\begin{aligned} f_m(m) &= \frac{1}{\beta} f_{|h_R^1|^2}\left(\frac{m}{\beta}\right) \\ &= \frac{1}{\beta}\exp\left(-\frac{m}{\beta}\right) U(m), \end{aligned} \quad \text{(A6)}$$

$$\begin{aligned} f_n(n) &= \frac{1}{\omega} f_{|h_R^2|^2}\left(\frac{n-\delta_R^T}{\omega}\right) \\ &= \frac{1}{\omega}\exp\left(-\frac{n}{\omega} + \frac{\delta_R^T}{\omega}\right) U\left(n-\delta_R^T\right). \end{aligned} \quad \text{(A7)}$$

Since $m$, $n$ are independent, the joint probability density functions of $m$ and $n$ can be described in (A8) and (A9):

$$\begin{aligned} f_{mn}(m,n) &= \frac{1}{\beta}\exp\left(-\frac{m}{\beta}\right) \times \frac{1}{\omega}\exp\left(-\frac{n}{\omega} + \frac{\delta_R^T}{\omega}\right) \\ &= \frac{1}{\beta\omega}\exp\left(-\frac{m}{\beta} - \frac{n}{\omega} + \frac{\delta_R^T}{\omega}\right). \end{aligned} \quad \text{(A8)}$$

Hence,

$$f_{mn}(y-n, n) = \frac{1}{\beta\omega}\exp\left(-\frac{y-n}{\beta} - \frac{n}{\omega} + \frac{\delta_R^T}{\omega}\right). \quad \text{(A9)}$$

Since $y = m + n$ and both $m$ and $n$ are bigger than 0, the probability density function of $y$ can be shown in (A10):

$$\begin{aligned} f_y(y) &= \int_{\delta_R^T}^{y} f_{mn}(y-n, n)\,\mathrm{d}n \\ &= \int_{\delta_R^T}^{y} \frac{1}{\beta\omega}\exp\left(-\frac{y-n}{\beta} - \frac{n}{\omega} + \frac{\delta_R^T}{\omega}\right)\mathrm{d}n \\ &= \frac{1}{\beta\omega}\int_{\delta_R^T}^{y} \exp\left(n\left(\frac{1}{\beta} - \frac{1}{\omega}\right) + \frac{\delta_R^T}{\omega} - \frac{y}{\beta}\right)\mathrm{d}n \\ &= \frac{1}{\omega-\beta}\left(\exp\left(\frac{\delta_R^T}{\omega} - \frac{y}{\omega}\right) - \exp\left(\frac{\delta_R^T}{\beta} - \frac{y}{\beta}\right)\right), \\ &\quad y \geqslant \delta_R^T. \end{aligned} \quad \text{(A10)}$$

(18) can be got when $\beta = \omega$ and (22) can be got when $\beta \neq \omega$. □