Cross-Layer Joint Scheduling Scheme for Relay-Involved D2D Communications in Cellular Systems

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Abstract. In order to further improve the system performance under device-to-device(D2D) communication, considering the reuse of D2D mode is a very promising way. However, involving the reuse mode will make the design of scheduling scheme at the base station (BS) side even more challenging. This work focuses on the design of a scheduling scheme involving multiplexing relay D2D mode for the base station which jointly considers the user's requirements of service quality and delay comprehensively, and proposes a cross-layer joint scheduling algorithm aiming at maximizing the transmission rate of the whole system. We formulate such a scheduling issue into a mathematical optimization problem, and then we decompose the problem into three sub-problems according to power allocation, channel allocation and mode selection, and solve them respectively. The simulation results verify the importance of considering the multiplexing relay D2D mode and the influence of some main parameter Settings on the delay and transmission rate of the system, which provides a reference value for improving the transmission rate of the system by changing the parameter of the system.

Keywords: Device-to-device (D2D) communication · Channel state information · Transmission delay

1 Introduction

With the improvement of living standards, more and more advanced wireless network applications, such as smart home, unmanned, augmented reality, began to appear in the field of vision of people, to meet the needs of people's life convenient [1], but at the same time, the emergence of these new wireless network applications also brings great

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challenge to the communication network, resulting in the boost of data traffic and the scarcity of frequency resources. At the same time, the time delay and data transmission rate requirements are also increasingly high.

D2D communication allows devices that are close to each other to directly transmit data [2], which can reduce transmission delay and improve data transmission rate. The introduction of D2D technology can not only relieve the pressure of the base station to transmit the internal data of the cellular network, reduce the end-to-end transmission delay, but also reduce the power loss of the equipment and extend the working time of the communication equipment [3]. Therefore, it is significant to study the introduction of D2D communication in the cellular network. But at the same time, it will also bring another problem, that is, the whole system resource scheduling problem.

Since this paper mainly considers the scheduling g algorithm of the base station, the following will analyze the state of art of D2D. According to the functions realized by the algorithm, it can be generally divided into two categories: one is the base station scheduling algorithm which only considers mode selection, resource allocation or power control; The other is the joint scheduling algorithm of base station.

However, the early base station scheduling algorithms are mostly focused on the first type of resource allocation and power control scheduling algorithms and are mostly used to reuse direct D2D mode. Among them, most scheduling algorithms on resource allocation are based on graph theory [4, 5]. For the power control algorithm, in order to reduce the interference caused by reuse, the commonly used schemes including: limiting the transmitted power of D2D users to reduce the interference [6]; Power regulator is set to increase the transmitting power of cellular users to reduce the interference from D2D users [7]. Under the condition of ensuring the communication quality between cellular users and D2D users, the joint power allocation of D2D users and cellular users based on optimization theory is proposed [8]. However, the above scheduling algorithms only consider a single aspect. [9] considers using the size between the actual distance and the threshold to select the working mode of D2D users, but the premise of its application is multiple base stations and D2D users have mobility. [10] proposed a selection scheme based on the traffic load mode, and verified that the method would improve the packet rate of the system and the performance of end-to-end transmission delay, and the optimization objective was the total packet loss rate of the system. However, no matter it only considers mode selection, resource allocation or power control, it is only expanded for one aspect of the scheduling problem, and it has constraints for the system scheduling that introduces D2D communication in the cellular network, so a more comprehensive consideration should be conducted for the joint scheduling algorithm.

In this paper, we propose a cross-layer joint scheduling algorithm for maximizing the transmission rate of the whole system under the condition that the channel state information is partially known and the user's service quality and delay requirements are considered comprehensively. In this paper, the transmission delay of D2D users is calculated under the two modes of multiplexing direct D2D and multiplexing relay, and mode selection is needed for D2D users. Finally, the proposed algorithm is evaluated by simulation.

The remainder of this paper is organized as follows. Section 2 introduce the system model. In Sect. 3, in order to maximize the transmission rate of the whole system under the condition of satisfying the user's requirements of service quality and delay, the mathematical modeling is carried out. The optimization objective is solved by power allocation, channel allocation and mode selection in Sect. 4. Simulation results are provided in Sect. 5. Finally, the paper is concluded in Sect. 6.

2 System Model

When the communication distance is too large, the quality of communication link is poor, D2D communication is prone to interrupt. Therefore, this paper considers the combination of reusing direct D2D mode and reusing relay D2D mode to ensure the effective and reliable transmission of information. Aiming at the above two working modes, a cross-layer joint scheduling algorithm is proposed to maximize the transmission rate of the whole system under the condition that the channel state information is partially known and the user's service quality and delay requirements are considered comprehensively.

2.1 System Hypothesis

The system model considered in this paper is shown in Fig. 1. There are M cellular users and K pairs of D2D users, respectively denoted as $\{C_1, C_2, ..., C_m, ..., C_M\}$, $\{S_1, S_2, ..., S_k, ..., S_K\}$, $\{D_1, D_2, ..., D_k, ..., D_K\}$, The latter two terms respectively correspond to the sender and receiver of the D2D user, and it is assumed that the base station has allocated a channel with the same bandwidth and orthogonal to each other for each cellular user, and a fully loaded cellular network is considered. In the system model, D2D users have two working modes, that is, reusing direct D2D mode and reusing relay D2D mode. When the user works in reuse direct D2D mode, it is provided that the D2D user can only reusing one channel of the cellular user, and it is assumed that only the uplink channel of the cellular user can be reused. When working in the reuse relay D2D mode, assume that each pair of D2D users is surrounded by N alternative relay users which support their work in the reusable relay D2D mode, and it is assumed that the D2D sender and the relay node, the relay node and the D2D receiver can reuse the same cellular user's channel, and only the uplink-channel can be reused. The communication between the two hop links should be completed in two time slots. In this system, the channel of a cellular user can only be reused by a pair of D2D users at most.

The communication mode in which D2D users work depends on the final scheduling results of the base station. It is assumed that the base station only grasps part of the channel state information between the cellular user and the D2D receiver (CUE-DUE) and the cellular user and the relay node (CUE-RUE), i.e. the path loss based on distance. However, for other related channels, the base station grasps their perfect channel state information.

2.2 Channel Model

According to the channel state information collected by the base station, channels in the system model can be divided into two categories. One is the channel where the base station has perfect channel state information. The new channel belonging to this type are the channel from the relay node to the base station (RUE-BS), the channel from the D2D sender to the relay node (DUE-DUE), and the channel from the relay node to the D2D receiver (RUE-DUE). The channel gains are respectively $g_{R_{k,n},B}$, $g_{S_k,R_{k,n}}$ and $g_{R_{k,n},D_k}$, respectively. The other is the channel where the base station only holds partial channel state information. The new channel belonging to this type is Cellular User to Relay Interference Channel (CUE-RUE). For the channel base station, only the path loss based on distance is mastered, $H_{C_m,R_{k,n}} = k_0 l_{C_m,R_{k,n}}^{-\alpha}$. Its channel gain is expressed as:

$$h_{C_m,R_{k,n}} = k_0 \beta_{C_m,R_{k,n}} l_{C_m,R_{k,n}}^{-\alpha} \tag{1}$$

where $\beta_{C_m,R_{k,n}}$ is the channel fading component, and $l_{C_m,R_{k,n}}$ represents the distance between the sending node and the receiving node.

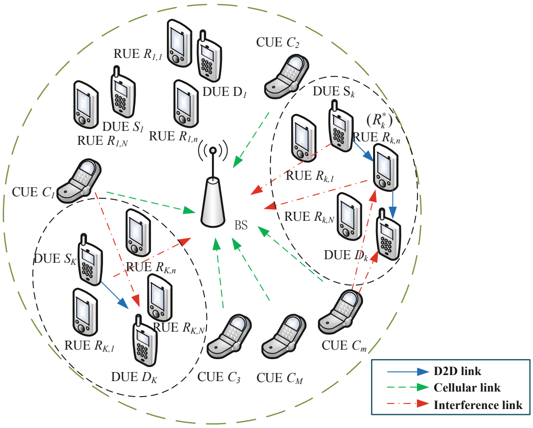

Fig. 1. A system model with relays

3 Problem Formulation

3.1 Transmission Model

When the D2D user works in the reusing relay D2D mode, it is stipulated that the communication process of the D2D user should be completed in two time slots. In the first slot, data is transmitted from the sending node to the relay node, and in the second slot, data is transmitted from the relay node to the receiving node. However, before data transmission, it is necessary to select the optimal relay R_k^* from N alternative relay nodes to assist D2D users in data transmission.

Then, after the selection of the relay nodes is completed, the QoS requirements of D2D users and cellular users should be guaranteed in the first place if the k-pair D2D users want to reuse the channel of cellular user C_m and work in the relay mode. Since the base station does not know the accurate channel gain from the cellular user to the relay node and the interference channel of the D2D user's receiver, the QoS requirement of the D2D user under the two-hop link at this time requires the channel probability statistics characteristics to ensure that the transmission interrupt probability of the D2D user will not exceed a certain value.

Based on the characteristics of channel probability and statistics, the probability that the actual SNR of the D2D user receiving terminal is set to be less than the requirement of the SNR of the link does not exceed a given threshold:

$$\Pr\left\{\frac{p_{k,m}^{(D)}g_{S_k,D_k}}{\sigma^2 + p_{k,m}^{(C1)}h_{C_m,D_k}} < \xi_{\min}\right\} \le \psi \tag{2}$$

where, $p_{k,m}^{(D)}$ is the kth pair of D2D users reuse the transmitting power of the cellular user channel when it is working, $p_{k,m}^{(C1)}$ denotes the transmitted power of cellular user C_m when it is reused by the kth pair of D2D users, σ^2 indicates noise power, $\xi_{\min}$ represents the requirements of minimum signal-to-noise ratio (SNR)/signal-to-noise ratio (SNR),and ψ is the system sets the maximum interrupt overflow probability acceptable to D2D users.

At the same time, when the base station does not know the accurate channel gain information from the cellular user to the D2D receiver, the transmission interruption phenomenon is inevitable in the communication process of the D2D user. Indicator function is used to represent the transmission interrupt event of the D2D receiver [11], i.e. when the actual SNR of the D2D receiver is less than the SNR required by the system, the D2D receiver cannot demodulate the signal sent by the starting terminal. In this case, the indicator function $\Phi = 1$; Otherwise, the indicator function is 0, indicating that the D2D receiver can demodulate the signal sent by the starting terminal. When $\Phi = 0$, the D2D receiver can demodulate the signal sent by the transmitting end, and the transmission rate of the D2D user in this case can be expressed as

$$r_{k,m}^{D} = B_0 \log_2\left(1 + \frac{p_{k,m}^{(D)}g_{S_k,D_k}}{\sigma^2 + p_{k,m}^{(C1)}h_{C_m,D_k}}\right) \tag{3}$$

where, B_0 is the channel bandwidth.

On the contrary, when $\Phi = 1$, the D2D receiver cannot demodulate the signal sent by the sending terminal, and the transmission rate of the D2D user is 0. In summary, considering the transmission rate of D2D users in the two cases, the transmission rate of D2D users can be expressed as

$$r_{k,m}^{D} = \mathbb{E}\left\{\left[\mathrm{B}_0 \log_2\left(1 + \frac{\mathrm{p}_{\mathrm{k,m}}^{(\mathrm{D})}\mathrm{g}_{\mathrm{S_k,D_k}}}{\sigma^2 + \mathrm{p}_{\mathrm{k,m}}^{(\mathrm{C1})}\mathrm{h}_{\mathrm{C_m,D_k}}}\right)\right] | \Phi = 0\right\} \tag{4}$$

where $\mathbb{E}\{\cdot\}$ is the conditional expectations.

According to reference [12], Eq. (4) can be expressed as

$$r_{k,m}^{D} = \int_0^l B_0 \log_2\left(1 + \frac{p_{k,m}^{(D)}g_{S_k,D_k}}{\sigma^2 + \beta_{C_m,D_k}p_{k,m}^{(C1)}H_{C_m,D_k}}\right)\frac{f(\beta_{C_m,D_k})}{F(l)}d\beta_{C_m,D_k} \tag{5}$$

where l denotes the critical value of β_{C_m,D_k}, $l = \frac{p_{k,m}^{(D)} g_{S_k,D_k} - \xi_{\min}\sigma^2}{p_{k,m}^{(C1)} \xi_{\min} H_{C_m,D_k}}$.

Above discussion guarantees for D2D users and QoS requirements are completed. Next, there are delay requirements for D2D users. Assuming that the end-to-end transmission delay of D2D user k reusing cellular user C_m channel is $u_{k,m}$, the delay shall meet the requirements:

$$u_{k,m} \le u_{\max} \tag{6}$$

where, $u_{\max}$ denotes the requirements of D2D end-to-end transmission delay.

The optimization objective in this paper is to maximize the overall system transmission rate. When no D2D user reuses the channel of the cellular user, the transmission rate of the cellular user is expressed as

$$r_m^{(C)} = B_0 \log_2\left(1 + \frac{p_m^{(C)} g_{C_m,B}}{\sigma^2}\right) \tag{7}$$

where $p_m^{(C)}$ is the transmitted power of cellular users.

When the cellular user's uplink channel is reused by the kth D2D pair in direct D2D mode, the transmission rate of the cellular user's uplink channel can be expressed as

$$r_{k,m}^{(C1)} = B_0 \log_2\left(1 + \frac{p_{k,m}^{(C1)} g_{C_m,B}}{p_{k,m}^{(D)} g_{S_k,B} + \sigma^2}\right) \tag{8}$$

When the cellular user's uplink channel is reused by the kth D2D pair in relay-assisted D2D mode, the transmission rate of the cellular user's uplink channel in the first and second transmission time slots corresponding to the two-hop relay-assisted D2D transmission can be expressed respectively as

$$\begin{cases} r_{(k,m)}^{(C21)} B_0 \log_2\left(1 + \frac{p_{k,m}^{(CR1)} g_{C_m,B}}{p_{k,m}^{(R1)} g_{S_k,B} + \sigma^2}\right) \\ r_{(k,m)}^{(C22)} B_0 \log_2\left(1 + \frac{p_{k,m}^{(CR2)} g_{C_m,B}}{p_{k,m}^{(R2)} g_{R_k^*,B} + \sigma^2}\right) \end{cases} \tag{9}$$

where $p_{k,m}^{(CR1)}$ is the transmit power of the cellular user in the first time slot; $p_{k,m}^{(R1)}$ is the transmit power of the transmitter of D2D users in reused relay mode; $p_{k,m}^{(CR2)}$ is the transmitting power of the cellular user in the second time slot; $p_{k,m}^{(R2)}$ is transmit power of the relay node.

Then the transmission rate of the cellular user in a scheduling time slot of the base station is expressed as

$$r_{k,m}^{(C2)} = \frac{1}{2}(r_{k,m}^{(C21)} + r_{k,m}^{(C22)}) \tag{10}$$

In the first time slot, the transmission rate from the D2D sender to the relay node is expressed as

$$r_{k,m}^{(R1)} = \mathbb{E}\left\{\left[\mathrm{B}_0 \log_2\left(1 + \frac{\mathrm{p}_{\mathrm{k,m}}^{(\mathrm{R1})} \mathrm{g}_{\mathrm{S_k},\mathrm{R_k^*}}}{\sigma^2 + \mathrm{p}_{\mathrm{k,m}}^{(\mathrm{CR1})} \mathrm{h}_{\mathrm{C_m},\mathrm{R_k^*}}}\right)\right] | \Phi = 0\right\} \tag{11}$$

In the second slot, the transmission rate from the relay node to the receiver is expressed as

$$r_{k,m}^{(R2)} = \mathbb{E}\left\{\left[\mathrm{B}_0 \log_2\left(1 + \frac{\mathrm{p}_{\mathrm{k,m}}^{(\mathrm{R2})} \mathrm{g}_{\mathrm{R}_\mathrm{k}^*,\mathrm{D}_\mathrm{k}}}{\sigma^2 + \mathrm{p}_{\mathrm{k,m}}^{(\mathrm{CR2})} \mathrm{h}_{\mathrm{C}_\mathrm{m},\mathrm{D}_\mathrm{k}}}\right)\right] | \Phi = 0\right\} \tag{12}$$

Then the transmission rate of a D2D user in a scheduled time slot of the base station is expressed as

$$r_{k,m}^{(R)} = \frac{1}{2} \min\left\{r_{k,m}^{(R1)}, r_{k,m}^{(R2)}\right\} \tag{13}$$

3.2 Transmission Delay Estimation

The packet queuing state transition can be described and solved by using a finite state Markov chain (FSMC) to obtain the stable probability of packet queuing state and then the average queue length. Suppose $\Omega_{k,m}^i$ is the source node, and there is a stability probability of packet caching, and $\Omega_{k,m}$ is a stability probability vector composed of $\Omega_{k,m}^i$, then the stability probability vector can be expressed as $\Omega_{k,m}$

$$\begin{cases} \Omega_{k,m} = \Omega_{k,m} P \\ \sum_{i=0}^{B} \Omega_{k,m}^i = 1 \end{cases} \tag{14}$$

Then, the average length of the packet queue of the source node can be expressed as

$$\overline{Q_{k,m}} = \sum_{i=0}^{B} \left(i \times \Omega_{k,m}^i\right) \tag{15}$$

If $u_{k,m}$ represents the end-to-end transmission delay, it can be obtained by the following formula according to Little's rule

$$u_{k,m} = \overline{Q_{k,m}} / \left(\left(1 - \phi_{k,m}\right) \times E[A_{k,t}]\right) \tag{16}$$

where $E[A_{k,t}]$ represents the average number of packets arriving at the sending node in a time slot, where $E[A_{k,t}] = \lambda_k \Delta T$; $\phi_{k,m}$ represents the packet drop rate.

The formula for calculating packet loss rate is as follows

$$\phi_{k,m} = D_{k,m} / (E[A_k]) \tag{17}$$

where $D_{k,m}$ represents the number of packets lost by the source node due to the limited cache capacity; A_k is a stable distribution of $A_{k,t}$ and $E[A_k] = E[A_{k,t}]$.

Where $D_{k,m}$ can be obtained by the following formula

$$D_{k,m} = \sum_{m=1}^{B} \Omega_{k,m}^{m} \sum_{n=0}^{m-1} \Pr\{U_k = n\} \sum_{j=B+n-m}^{\infty} (m + j - n - B) \Pr\{A_k = j\}$$
$$+ \sum_{m=1}^{B} \Omega_{k,m}^{m} \sum_{n=m}^{\infty} \Pr\{U_k = n\} \sum_{j=B}^{\infty} (j - B) \Pr\{A_k = j\} \tag{18}$$
$$+\Omega_{k,m}^{0} \sum_{j=B}^{\infty} (j - B) \Pr\{A_k = j\}$$

When a D2D user works in the reuse of relay D2D mode, it is equivalent to two hop links. The first hop link is the link from the D2D sender to the relay node, and the second hop link is the link from the relay node to the D2D receiver. Assuming that the transmission delay of the link from the D2D sender to the relay node is $u_{k,m}^{R1}$, and the transmission delay of the link from the relay node to the D2D receiver is $u_{k,m}^{R2}$, then the total end-to-end transmission delay is expressed as:

$$u_{k,m}^{R} = u_{k,m}^{R1} + u_{k,m}^{R2} \tag{19}$$

For the second hop link, that is, the link from the relay node to the D2D receiver, the packet arrival process of the relay node in the t slot is no longer subject to the Poisson arrival process, but is related to the number of packets $Q_{k,t-1}$ at the D2D sender at the end of the $t-1$ slot of the a hop link and the number of packets transmitted by the a hop link in the t slot $U_{k,t}$. When $Q_{k,t-1} \leq U_{k,t}$, the number of packets arriving at the relay node in time slot t is $Q_{k,t-1}$, otherwise $U_{k,t}$. Assuming that the number of relay nodes arriving in time slot t is j, then when $j = 0$, its arrival probability is

$$p\left(A_{r,t} = 0\right) = \Omega_{k,m}^{0} + (1 - \Omega_{k,m}^{0}) \Pr\left\{U_{k,t} = 0\right\} \tag{20}$$

when $1 \leq j \leq B$, its arrival probability is

$$\Pr\left\{U_{k,t} \geq j\right\} + (1 - \sum_{i=0}^{j} \Omega_{k,m}^{i}) \Pr\left\{U_{k,t} = j\right\}$$
$$= \left\{1 - \sum_{n=0}^{j-1} \Pr\left\{U_{k,t} = n\right\}\right\} \Omega_{k,m}^{j} + (1 - \sum_{i=0}^{j} \Omega_{k,m}^{i}) \Pr\left\{U_{k,t} = j\right\} \tag{21}$$

Another difference is that during the delay measurement of the second hop link, if the average length of the packet queue of the relay node is already $\overline{Q_{k,m}^{R}}$, then the delay calculation formula of the second hop link is

$$u_{k,m}^{R2} = \overline{Q_{k,m}^{R}} / \left(\left(1 - \phi_{k,m}^{R}\right) \times E[A_{r,t}]\right) \tag{22}$$

where, $\phi_{k,m}^{R}$ represents the packet loss rate of the relay node; $E[A_{r,t}]$ represents the average number of packets arriving at a relay node in a slot.

Where, $E[A_{r,t}]$ calculation formula should be obtained by the following formula

$$E[A_{r,t}] = \sum_{j=0}^{B} \left[j \times p\left(A_{r,t} = j\right)\right] \tag{23}$$

3.3 Joint Scheduling Problem Formulation

The goal of the scheduling algorithm in this paper is to maximize the transmission rate of the whole system while ensuring the QoS requirements of D2D users, cellular users and the delay requirements of D2D users. Then the mathematical expression can be expressed as follows:

$$\begin{aligned}(\boldsymbol{p}^*, \boldsymbol{x}^*) = \arg\max_{p,x} \Bigg\{ & \sum_{k=1}^{K}\sum_{m=1}^{M} x_{k,m}^{(1)}\left(r_{k,m}^{(C1)} + r_{k,m}^{(D)}\right) \\ & + \sum_{k=1}^{K}\sum_{m=1}^{M} x_{k,m}^{(2)}\left(r_{k,m}^{(C2)} + r_{k,m}^{(R)}\right) + \sum_{m=1}^{M}\left(1 - \sum_{k=1}^{K} x_{k,m}^{(1)} - \sum_{k=1}^{K} x_{k,m}^{(2)}\right) r_m^{(C)} \Bigg\}\end{aligned} \tag{24}$$

$$subject\ to : x_{k,m}^{(1)}, x_{k,m}^{(2)} \in \{0, 1\}, \forall k, m \tag{25}$$

$$\sum_{k=1}^{K} (x_{k,m}^{(1)} + x_{k,m}^{(2)}) \le 1, \forall m \tag{26}$$

$$\sum_{m=1}^{M} (x_{k,m}^{(1)} + x_{k,m}^{(2)}) \le 1, \forall k \tag{27}$$

$$\sum_{m=1}^{M} (x_{k,m}^{(1)} u_{k,m} + x_{k,m}^{(2)} u_{k,m}^{R}) \le u_{\max}, \forall k \tag{28}$$

$$\sum_{m=1}^{M} x_{k,m}^{(1)} p_{k,m}^{(D)} + \sum_{m=1}^{M} x_{k,m}^{(2)} \max(p_{k,m}^{(R1)}, p_{k,m}^{(R2)}) \le P_{max}^{D}, \forall k \tag{29}$$

$$\begin{aligned}& \sum_{k=1}^{K} x_{k,m}^{(1)} p_{k,m}^{(C1)} + \sum_{k=1}^{K} x_{k,m}^{(2)} \max(p_{k,m}^{(CR1)}, p_{k,m}^{(CR2)}) \\ & + \left(1 - \sum_{k=1}^{K} x_{k,m}^{(1)} - \sum_{k=1}^{K} x_{k,m}^{(2)}\right) p_m^{(C)} \le P_{\max}^{C}, \forall m\end{aligned} \tag{30}$$

$$\begin{aligned}& \sum_{m=1}^{M} x_{k,m}^{(2)} \max\left\{ \Pr\left\{ \frac{p_{k,m}^{(R1)} g_{S_k,R_k^*}}{\sigma^2 + p_{k,m}^{(CR1)} h_{C_m,R_k^*}} < \xi_{\min} \right\}, \Pr\left\{ \frac{p_{k,m}^{(R2)} g_{R_k^*,D_k}}{\sigma^2 + p_{k,m}^{(CR2)} h_{C_m,D_k}} < \xi_{\min} \right\} \right\} \\ & + \sum_{m=1}^{M} x_{k,m}^{(1)} \Pr\left\{ \frac{p_{k,m}^{(D)} g_{S_k,D_k}}{\sigma^2 + p_{k,m}^{(C1)} h_{C_m,D_k}} < \xi_{\min} \right\} \le \sum_{m=1}^{M} x_{k,m}^{(2)} \psi + \sum_{m=1}^{M} x_{k,m}^{(1)} \psi, \forall k\end{aligned} \tag{31}$$

$$\begin{aligned}& \sum_{k=1}^{K} x_{k,m}^{(1)} \frac{p_{k,m}^{(C1)} g_{C_m,B}}{p_{k,m}^{(D)} g_{S_k,B} + \sigma^2} + \sum_{k=1}^{K} x_{k,m}^{(2)} \min\left(\frac{p_{k,m}^{(CR1)} g_{C_m,B}}{p_{k,m}^{(R1)} g_{S_k,B} + \sigma^2}, \frac{p_{k,m}^{(CR2)} g_{C_m,B}}{p_{k,m}^{(R2)} g_{R_k^*,B} + \sigma^2}\right) \\ & + \left(1 - \sum_{k=1}^{K} x_{k,m}^{(1)} - \sum_{k=1}^{K} x_{k,m}^{(2)}\right) \times \frac{p_m^{(C)} g_{C_m,B}}{\sigma^2} \ge \xi_{\min}, \forall m\end{aligned} \tag{32}$$

where $x_{k,m}^{(1)}$,$x_{k,m}^{(2)}$ respectively denote mode selectors and channel selectors for reuse of direct D2D modes and reuse of relay D2D modes. When the kth pair of D2D users works in reusing direct D2D mode and reusing the mth cellular user channel, $x_{k,m}^{(1)} = 1$, otherwise $x_{k,m}^{(1)} = 0$. When the kth pair of D2D users works in reusing relay D2D mode and reusing the mth cellular user channel, $x_{k,m}^{(2)} = 1$, otherwise $x_{k,m}^{(2)} = 1$.

where, $u_{k,m}^{R}$ denotes the end-to-end transmission delay for the kth D2D user when working in the reusing relay D2D mode and the MTH cellular user is reused by it.

Formula (25) indicates that the value of mode selection and channel selection factor is 0 or 1; Formula (26) indicates that the D2D user can only choose one of the direct D2D mode or the relay mode and that the channel of a cellular user can only be reused by a pair of D2D users. Formula (27) indicates that D2D users can only choose one of the two working modes to work and a pair of D2D users can only reuse the channel of one cellular user at most. Formula (28) indicates that the end-to-end transmission delay of D2D users under two working modes cannot exceed the delay requirements; Formula (29) indicates that the transmitted power of D2D sender in the reusing direct D2D mode and the transmitted power of D2D sender and relay node in the reusing relay mode shall not exceed the power constraint of D2D user. Formula (30) indicates that the transmitting power of the cell user reused in the direct D2D mode, the transmitting power of the cell user reused in the relay D2D mode at two time slots and the transmitting power of the cell user without D2D user reusing shall not exceed the power constraint of the cell user. Formulas (31) to (32) represent the QoS guarantee for the relevant transmission link.

4 Joint Scheduling Scheme Design

4.1 D2D User Access Control

This section will determine whether a D2D user can access the network in a reused relay D2D mode. To determine whether a D2D user can access the network in a reused relay D2D mode, it is necessary to determine whether there is a cellular user in the network that can be reused. The judgment condition of reusing relay D2D mode is that there are power pairs $(p_{k,m}^{(CR1)}, p_{k,m}^{(R1)})$ and $(p_{k,m}^{(CR2)}, p_{k,m}^{(R2)})$ in the first and second time slots, so that they meet the formula (33) ~ (37), namely delay requirements, power constraint requirements and user's QoS requirements:

$$u_{k,m}^{R} \le u_{\max} \tag{33}$$

$$\max(p_{k,m}^{(R1)}, p_{k,m}^{(R2)}) \le P_{max}^{D} \tag{34}$$

$$\max(p_{k,m}^{(CR1)}, p_{k,m}^{(CR2)}) \le P_{\max}^{C} \tag{35}$$

$$\max\left\{\Pr\left\{\frac{p_{k,m}^{(R1)} g_{S_k,R_k^*}}{\sigma^2 + p_{k,m}^{(CR1)} h_{C_m,R_k^*}} < \xi_{\min}\right\}, \Pr\left\{\frac{p_{k,m}^{(R2)} g_{R_k^*,D_k}}{\sigma^2 + p_{k,m}^{(CR2)} h_{C_m,D_k}} < \xi_{\min}\right\}\right\} \le \psi \tag{36}$$

$$\min\left(\frac{p_{k,m}^{(CR1)} g_{C_m,B}}{p_{k,m}^{(R1)} g_{S_k,B} + \sigma^2}, \frac{p_{k,m}^{(CR2)} g_{C_m,B}}{p_{k,m}^{(R2)} g_{R_k^*,B} + \sigma^2}\right) \ge \xi_{\min} \tag{37}$$

The first is based on distance judgment, and the second is based on time delay judgment. If the two power pairs $(p_{k,m}^{(CR1)}, p_{k,m}^{(R1)})$ and $(p_{k,m}^{(CR2)}, p_{k,m}^{(R2)})$ meet the time delay requirements, then at least the power pairs $(p_{k,m}^{(CR1)}, p_{k,m}^{(R1)})$ and $(p_{k,m}^{(CR2)}, p_{k,m}^{(R2)})$ in the first and second time slots are guaranteed, so that the whole link can meet the time delay requirements when reusing the cellular user channel. Otherwise, it means that the link cannot reusing the cellular user channel at this time in the multiplexing relay D2D mode.

4.2 Resource Allocation and Mode Selection Design

(1) Power allocation

This section will mainly complete the power allocation of D2D users in the reused relay D2D mode and the cell users that are reused.

For users working in reused relay D2D mode, it is hoped that the optimal transmission power pairs $(p_{k,m}^{(CR1)}, p_{k,m}^{(R1)})$ and $(p_{k,m}^{(CR2)}, p_{k,m}^{(R2)})$ can be found in the two links for D2D users and their reused cellular users. Reuse the D2D communication relay mode needs to be done in two time slots, that is the first time slot for sending node to relay node communication, and the second time slot for the relay node to the receiving node communication. Therefore, for the power allocation in the multiplex relay mode, the power can be allocated to each hop link separately. The only factor that needs to be considered is whether the power allocation result meets the time delay requirement. The answer is yes, because the power allocation result of each link is the value brought in when judging whether the D2D user can access the network in the multiplexed relay D2D mode.

(2) Channel allocation and mode selection

After power allocation, mode selection and channel allocation are required. Based on the results of power allocation, the original optimization problems (24) ~ (32) can be simplified into the following expressions:

$$(\boldsymbol{x}^*) = \arg\max_{x}\left\{\sum_{k=1}^{K}\sum_{m=1}^{M} x_{k,m}^{(1)}\left(r_{k,m}^{(C1)} + r_{k,m}^{(D)} - r_m^{(C)}\right) + \sum_{k=1}^{K}\sum_{m=1}^{M} x_{k,m}^{(2)}\left(r_{k,m}^{(C2)} + r_{k,m}^{(R)} - r_m^{(C)}\right)\right\} \tag{38}$$

subject to: (25) ~ (27).

Where, $r_{k,m}^{(C1)} + r_{k,m}^{(D)} - r_m^{(C)}$ and $r_{k,m}^{(C2)} + r_{k,m}^{(R)} - r_m^{(C)}$ are a constant based on the obtained power allocation $\boldsymbol{p}^*$, so the above optimization problem can be converted into a 0–1 integer optimization problem for $x_{k,m}^{(1)}$ and $x_{k,m}^{(2)}$.

Then the base station can schedule the resources of the whole system according to the scheduling algorithm mentioned above.

5 Performance Evaluation

In this section, a cell with a radius of 500 m centered on the base station is considered. The positions of the transmitting terminal of cellular users and D2D users are randomly distributed centered on the base station, while the receiving terminal of D2D users is randomly distributed centered on the sending terminal of D2D users. There are alternative relay users around each pair of D2D users, and the position of the candidate relay user is in a circle enclosed by the D2D sender as the center and the distance of the D2D user pair as a radius. The main parameters are shown in Table 1.

We jointly consider the multiplexed direct D2D mode and multiplexed relay D2D mode, hoping to make up for the impact of the multiplexed direct D2D mode on the transmission performance of the system, which is easily affected by the communication distance and communication link. Therefore, the comparison of the change of the total transmission rate of the system with the number of D2D is simulated in the case that only the multiplexed direct D2D mode is considered and the two D2D modes. The results are shown in Fig. 2.

Table 1. The main parameters in the simulation are set.

Parameter Settings	The numerical
Radius of neighborhood	500 m
Path loss index α	4
Path loss constant k_0	10^{-2}
Noise power spectral density	174 dBm/Hz
Channel bandwidth	0.9 MHz
Maximum transmitting power for cellular users $P_{\max}^{C}$	24 dBm
The maximum transmitting power of the D2D user P_{max}^{D}	21 dBm
User minimum SNR requirement $\xi_{\min}$	10 dB
The number of bits contained in a packet L	1024
Time slot width ΔT	1 ms
Multipath fading	An exponential distribution with a mean of 1
Shadow fading	The standard deviation is 8 dB log normal distribution

The parameters involved in simulation are set as follows: the number of cellular users $M = 10$, the number of relay nodes $N = 10$, the maximum interrupt overflow probability $\psi = 0.2$, the packet arrival rate $\lambda = 7000$ packet/s, the maximum cache capacity of nodes $B = 30$, and the delay requirement $u_{\max} = 4$ ms. When the number of D2D users is certain, the total transmission rate corresponding to the two working modes of multiplexing direct D2D mode and multiplexing relay D2D mode is indeed higher than the system transmission rate corresponding to the multiplexing direct D2D mode. It indicates that it is meaningful to consider the multiplexing relay D2D mode in this section. At the same time, it can be seen that the system transmission rate corresponding to the two working modes involved in this section increases as the number of D2D user pairs increases. The simulation results also demonstrate the effectiveness of the proposed scheduling algorithm.

It can be seen that the delay varies with the main parameters, and the simulation results only retain a relatively small delay, as shown in Fig. 3, where the transmission power of the transmitter and relay node of the D2D user is $p_{k,m}^{(R1)} = p_{k,m}^{(R2)} = 21$ dBm, and the transmitting power of the cellular user in the first time slot and the second time slot is $p_{k,m}^{(CR1)} = p_{k,m}^{(CR2)} = 24$ dBm. The conclusion can be drawn from the figure, when nodes cache capacity must be biggest, the increase of packet arrival rate will affect the transmission delay, delay will increase with the increase of packet arrival rate (diagram node, at a maximum capacity of 10 data is also increasing, only increases not much), and design in this experiment three nodes under the maximum cache capacity, when the packet arrival rate must be. The latency increases as the maximum cache capacity of the node increases.

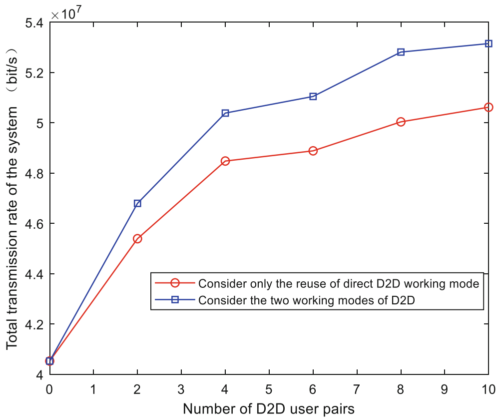

Fig. 2. The total transmission rate of the system varies with the number of D2D user pairs

Finally, this section will evaluate the influence of the maximum probability of outage overflow and different settings of delay requirements on the total transmission rate of the system. The simulation results are shown in Fig. 4. The parameters set in the simulation are the number of cellular users $M = 20$, the number of D2D user pairs $K = 10$, the number of relay nodes $N = 10$, packet arrival rate $\lambda = 7000$ Packets /s, and the maximum cache capacity of nodes $B = 50$.

The following conclusions can be drawn, overall increase maximum interrupt overflow probability can improve the transmission rate of the system, secondly, with the increase of delay for the system transmission rate also increases, the reason is that when the delay requirement increases, the increase in the number of D2D users will meet the requirements of delay, lead to more optional D2D users can select the power allocation model and channel allocation, so the total transfer rate will go up.

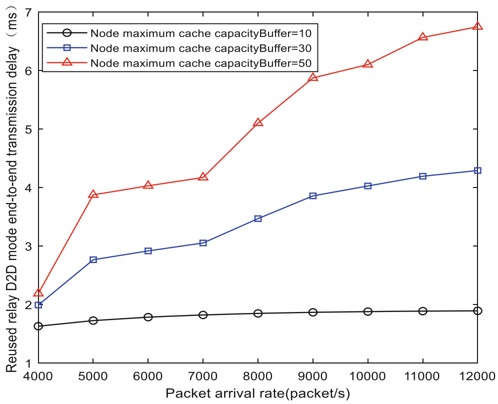

Fig. 3. Delay performance in multiplexed relay D2D mode varies with node maximum cache capacity and packet arrival rate Settings

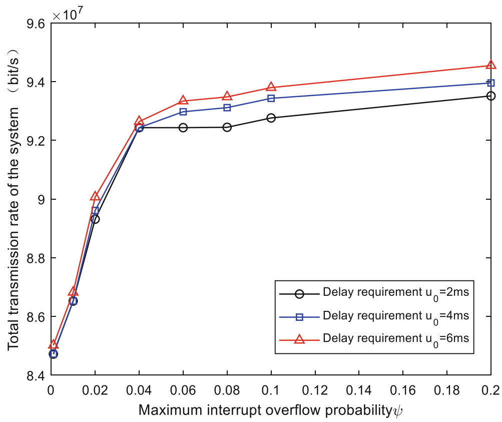

Fig. 4. The change curve of the system transmission rate with the maximum interrupt overflow probability under different delay requirements

6 Conclusion

This paper mainly focuses on the base station scheduling algorithm design problems faced after the introduction of D2D communication technology in the cellular network. Completed the time delay estimation problem of multiplexing direct D2D mode and multiplexing relay D2D mode in the case of the channel state information part, and the cross-layer joint scheduling problem of base stations for the transmission rate of the entire system. The specific research content and results are as follows:

First, a system model that comprehensively considers the two D2D working modes is constructed, and then the work in the multiplexing relay D2D is introduced in detail. The calculation of the transmission rate of the mode users and their multiplexed cellular users, and then the mathematical modeling is carried out for the purpose of maximizing the transmission rate of the entire system while meeting the service quality and delay requirements, and then the multiplexing relay is given. The calculation method of the end-to-end transmission delay in the D2D mode, and finally the optimization goal is solved through power allocation, channel allocation and mode selection. After that, it was verified through simulation that the importance of considering the D2D mode of multiplexing relays and the impact of some main parameter settings in the system on the delay and system transmission rate. It is hoped that these parameter settings will affect the transmission rate.

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