Doctoral Thesis

Low-latency Data Uploading in D2D-enabled Cellular Networks

by

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Abstract

With the remarkable proliferation of mobile devices (e.g., smartphones and portable tablets) embedded with various sensors, such as camera, GPS, digital compass, gyroscope, and thermometers, more and more devices are used for collecting message from surrounding environment, and then deliver the collected message (e.g., photos or videos of the points of interest) to the control center for further processing, which drive the development of a new research paradigm on data uploading. Data uploading, which can provide mission-critical messages collected by mobile devices, and then make quick responses during flooding, hurricanes, earthquakes, or other natural disasters, is regarded as a critical issue in cellular networks. Various applications have been proposed based on data uploading, including public safety, healthcare, disaster response, environment monitoring, and traffic management. In such applications, as the data collected by the devices is delay-sensitive, data uploading may be required to be performed within a specified time frame. In practice, however, little attention has been paid to latency-aware data uploading. As a consequence, for an efficient support of mobile applications, it is of great importance to design low-latency data uploading scheme in cellular networks.

Extensive research efforts have been devoted to data uploading in cellular networks. Most of them focused on traditional cellular networks with no cooperation, where the devices directly deliver their data to the cellular infrastructure. In these works, to deliver data to the cellular infrastructure, the devices need to have uplink channels with good quality. That is to say, it is difficult for a device suffering from a poor quality uplink channel to directly deliver data to the cellular infrastructure. In light of this, device-to-device (D2D) communication among the devices is considered to be one promising solution to this limitation, where the devices in proximity can build D2D cooperation so that the device with poor quality uplink channel can select a device with good quality uplink channel to serve as a relay for data uploading. Our work focuses on the data uploading in D2D-enabled cellular networks.

The available studies on the data uploading in D2D-enabled cellular networks suffer from three major limitations. First, in these studies, D2D cooperation is only limited to devices with uploading data, while the devices without uploading data do not participate in D2D cooperation, which usually leads to a large data uploading latency. Second, these studies mainly consider cooperation scenario with full trust where cooperative devices have full trustworthy relationships with each other, which largely neglects the effect of human social relationships on the cooperation behaviors and may result in a low data uploading reliability. Third, these works lack of an incentive mechanism to stimulate devices to actively participate in the D2D cooperation, which may degrade the data uploading performances in terms of reliability and latency. To overcome the above limitations, this thesis investigates the low-latency data uploading in D2D-enabled cellular networks with the help of device cooperation, human social relationship and incentive mechanism.

Firstly, we propose a generalized cooperative data uploading scheme which considers D2D cooperation among both the devices with and without uploading data, so that the data uploading latency can be reduced. This scheme covers the conventional

schemes where D2D cooperation is only limited to devices with uploading data as special cases. In this scheme, to motivate D2D cooperation among all available devices, we organize the devices within communication range by offering them rewards to construct multi-hop D2D chains for data uploading. Specifically, we formulate the problem of chain formation among the devices for data uploading as a coalitional game. Based on merge-and-split rules, we develop a coalition formation algorithm to obtain the solution for the formulated coalitional game with convergence on a stable coalitional structure. Extensive numerical results show the effectiveness of our proposed scheme in reducing the average data uploading latency.

Considering the data uploading reliability, we further investigate the impact of human social relationships on cooperative behaviors, where the nearby devices with mutual trust can build D2D cooperative relationships. To model D2D cooperation, a coalition game is first developed, and then we devise a coalition formation algorithm to construct D2D chains by the bottom to top mode. Simulation results show that our proposed approach can effectively reduce the average data uploading latency compared with the state-of-the-art approaches under the real network scenario.

Under the social network scenario, an incentive mechanism is then proposed to motivate more devices to participate in D2D cooperation, such that data uploading latency can be reduced and data uploading reliability can be enhanced. With this incentive mechanism, the nearby devices can obtain rewards such that they are willing to construct a multi-hop D2D chain to assist the other devices in data uploading. To this end, we adopt coalitional game to formulate D2D chains with careful consideration of social-aware data uploading, where each device acts as a player and the individual reward is modeled as the utility function. We further design a coalition formation algorithm with merge-and-split rules to determine the solution for the proposed coalitional game. Extensive simulations are conducted to illustrate that the performance gain of our incentive mechanism outperforms that of non-incentive mechanism.

Finally, we summarize our contributions, which can provide the following insights. Firstly, the data uploading schemes developed in this thesis indicate that by carefully exploring the device cooperation, human social relationship and incentive mechanism, a low data uploading latency can be usually achieved while a high data uploading reliability is ensured. Then, the results obtained in this thesis provide an important guideline for designing low latency data uploading schemes in D2D-enabled cellular networks. Finally, we introduce our future works. In this thesis, we consider D2D cooperation among static devices, one interesting future direction is to further explore the impact of device mobility on cooperative behaviors. We study how to deliver data with high-reliability and low-latency, it will be an interesting direction to recruit devices to collect data while satisfying the coverage probability over the field of interest. We focus on cooperative D2D data uploading in 4G LTE cellular networks, it will be an interesting topic to exploit the cooperative D2D data uploading in 5G cellular networks.

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Chapter 1

Introduction

In this chapter, we first introduce the background of D2D-enabled cellular networks, and then describe the motivations and contributions of this thesis. Finally, we give the outline of this thesis.

1.1 Background

With the rapid development of wireless communication technology and the wide proliferation of mobile devices such as smartphones and tablets, the past few years have witnessed a tremendous growth of mobile applications in wireless systems, e.g., mobile social media [1], vehicular system [2] and real-time surveillance [3], which pushes the limits of current 4G cellular technologies. It is predicted by Cisco visual networking index that, the global mobile data traffic will increase by nearly 15 times from 2014 to 2019, and will take up nearly 75 percent of the world's mobile data traffic by 2019 [4]. Such explosive growth in these emerging mobile applications and services poses a significant challenge on the limited frequency resources. Therefore, it is critical for researchers to better utilize the limited network radio resources by seeking for new cellular architectures and paradigms.

Compared to current 4G cellular networks, Third Generation Partnership Project (3GPP) has been developing an enhanced Long Term Evolution (LTE) radio interface called LTE-Advanced (LTE-A). LTE-A radio interface is designed to provide a lot of advanced communication techniques for high data rate transmission systems and mobile data demands, by employing the carrier aggregation massive multiple-input multiple-output (MIMO), millimeter waves, low-power nodes, as well as Device-to-Device (D2D)communication [5]. Among these LTE-A techniques, D2D communication is considered as one of the most promising and indispensable component in next generation cellular technologies, by utilizing the short-range wireless links, to establish direct connections between mobile devices for data delivery [6–9].

D2D communications underlying cellular networks, which utilizes the same spectrum as cellular user (CU), is defined as a direct communication between two mobile devices without traversing cellular infrastructures, whereby under the control of evolved Node B's (eNBs), i.e., base station (BS) or core network. Compared to available communication techniques (e.g., Wi-Fi and Bluetooth), D2D communication is a very flexible communication technique with unique advantages. Firstly, D2D devices can enjoy high data rates and low end-to-end delay due to the short range direct communication. Secondly, it is more spectral efficient for proximate devices to communicate directly with each other rather than routing through a cellular infrastructure. Thirdly, compared to normal downlink/uplink cellular communication, direct D2D communication saves energy and improves radio resource utilization. Due to these advancements, it is considered promising in various applications, including public safety, emergency rescue, cover extension for future 5G networks, disaster response, etc.

1.2 Motivations

Motivated by these promising applications of D2D communication, data delivery in D2D-enabled cellular networks including video multicast [10, 11], data offloading [12–15], file sharing [16, 17] and data uploading [18] has experienced a massive improvement in the past few years. As illustrated in Figure 1-1, from the Great East Japan Earthquake and Tsunami [3], we can observe that when the communication infrastructures are physically damaged or lack the energy necessary to operate in this real disaster situation, we can apply D2D communication to deliver emergent information toward the outside and share information among disaster victims in evacuation centers.

Data uploading, which refers to a certain number of users cooperatively delivering the photos and videos from the surrounding environment to the control center by exploiting their carried mobile devices, is a critical issue in D2D-enabled cellular networks. Various applications have been proposed based on data uploading, traffic monitoring [19], healthcare [20], public safety [21], and disaster recovery [3]. In such applications, as the data collected by devices is delay-sensitive, data uploading may be required to be performed within a specified time frame. In practice, however, little attention has been paid to latency-aware data uploading. As a consequence, for an efficient support of mobile applications, it is of great importance to design low-latency data uploading scheme in D2D-enabled cellular networks.

Extensive research efforts have been devoted to the data uploading study in D2D enabled cellular networks, which are divided into two cooperative cases: noncooperation and full cooperation. The former focuses on traditional cellular networks with no cooperative behavior among the devices, where the devices directly deliver their data to the cellular infrastructure. The data uploading scheme with noncooperation was investigated in [18, 22–24]. Zhu et al.[22] studied the problem of optimizing the time for uploading based on the preference measure as well as the cost of the wireless network available at the time of uploading. Zhang et al.[23] presented MapReduce framework to minimize the bandwidth cost for uploading deferral big data to a cloud computing platform. Wang et al.[24] proposed a novel proxy-oriented data uploading and remote data integrity checking model to solve the security problems in public cloud environment. Siekkinen et al.[18] studied optimal uploading strategies for live scalable video transmission from mobile devices. In these works, to deliver data to the cellular infrastructure, the devices need to have uplink channels with good quality. That is to say, it is challenging for a device suffering from a poor quality uplink channel to directly deliver data to the cellular infrastructure with high-reliability and low-latency.

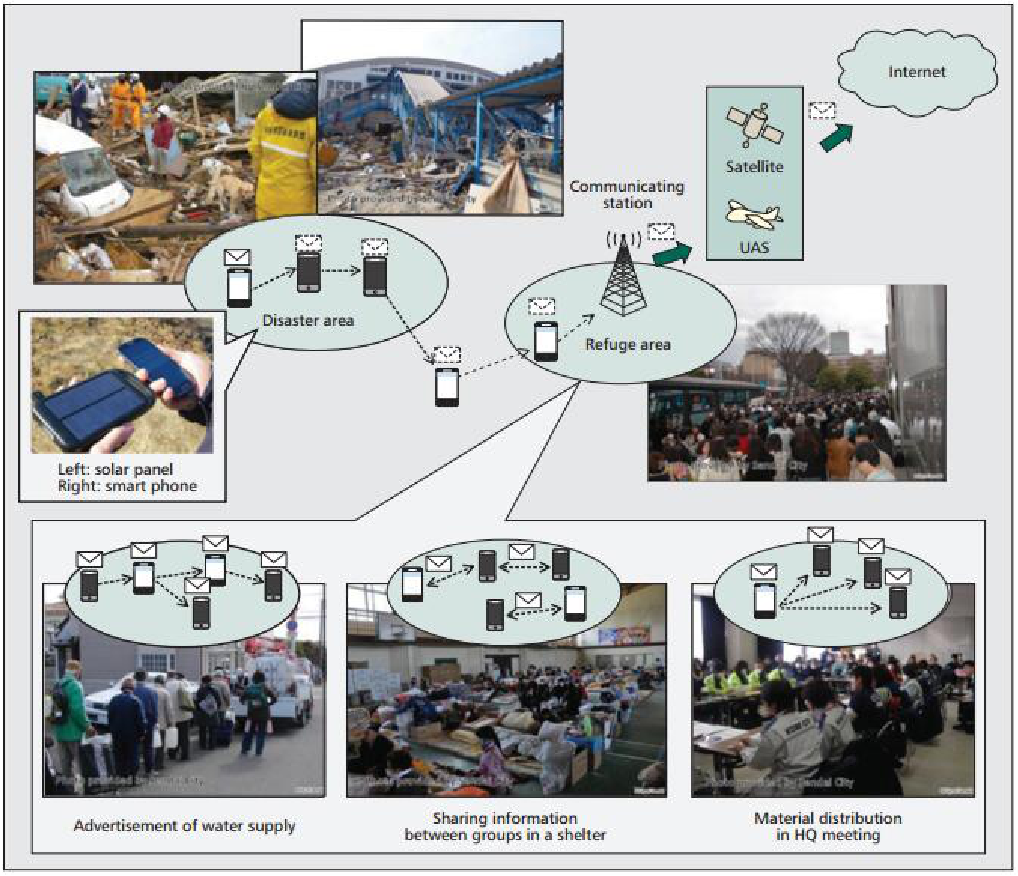

Figure 1-1: Applications of D2D communications in the disaster situations.

In light of this, the data uploading scheme with full cooperation is regarded as one promising solution to this limitation, where the devices in proximity can build D2D cooperation so that the device with poor quality uplink channel can select a device with good quality uplink channel to serve as a relay for data uploading. To carry out data uploading with full cooperation, a constrained coalition formation game [25] was introduced to characterize cooperative behavior of self-interested users so that the data uploading time is reduced. Furthermore, Militano et al.[26] considered social trust relationships among cooperative users, and then proposed a trust-based D2D forwarding scheme to construct multi-hop D2D chains from a game-theoretic point of view.

However, the available studies on data uploading in D2D-enabled cellular networks suffer from three major limitations. First, D2D cooperation there is only limited to devices with uploading data, while the devices without uploading data do not join in the D2D cooperation, which usually leads to a large data uploading latency. Second, these studies mainly consider cooperation scenario with full trust where cooperative devices have full trustworthy relationships with each other, which largely neglects the effect of human social relationships on the cooperation behaviors and may result in a low data uploading reliability. Third, these works lack of an incentive mechanism to stimulate devices to actively participate in the D2D cooperation, which may degrade the data uploading performances in terms of reliability and latency.

To address the above limitations, this thesis studies the low-latency data uploading in D2D-enabled cellular networks with the help of device cooperation, human social relationship and incentive mechanism. In this thesis, we made the following contributions:

- We first propose a generalized cooperative data uploading scheme, which considers D2D cooperation among both the devices with uploading data and the devices without uploading data, so that the data uploading latency can be reduced.
- Considering the data uploading reliability, we further investigate the impact of human social relationships on cooperative behaviors, where the nearby devices with mutual trust can build D2D cooperative relationships.
- Under this social network scenario, an incentive mechanism is then proposed to motivate more devices to participate in the D2D cooperation, such that the data uploading latency can be reduced and data uploading reliability can be enhanced.

1.3 Thesis Outline

The remainder of this thesis is outlined as follows:

Chapter 2 Related works. In this chapter, we introduce previous works related to cooperative D2D data delivery without social-awareness, cooperative D2D data delivery with social-awareness and cooperative D2D data delivery with incentive mechanism.

Chapter 3 Preliminaries. This chapter first gives a system description of cooperative D2D data uploading underlaying cellular networks, network model, cooperation model, communication model, and transmission model. Then, we formulate the system utility in terms of the data uploading latency. Finally, the main notations are introduced.

Chapter 4 Generalized cooperative D2D data uploading. In this chapter, we first introduce a coalitional game to formulate the problem of cooperative D2D data uploading. Based on merge-and-split rules, we then develop a coalition formation algorithm to obtain the solution for the formulated coalitional game with convergence on a stable coalitional structure. Extensive simulations demonstrate that our proposed scheme can reduce the average data uploading latency compared with other state-of-the-art schemes.

Chapter 5 Social-aware cooperative D2D data uploading. In this chapter, we first introduce the impact of human social relationships on cooperative behaviors. Then, a coalition game is adopted to formulate the problem of cooperative D2D data uploading. Based on the formulated coalition game, we develop a coalition formation algorithm to construct the D2D cooperation chains by adopting the bottom to top mode, where the devices with the poor uplink channel quality are first considered to join D2D cooperation. Simulation results show that our proposed approach can effectively reduce the average data uploading latency compared with the state-of-the-art approaches under the real network scenario.

Chapter 6 Social-aware cooperative D2D data uploading with incentive mechanism. In this chapter, we propose an incentive mechanism to motivate more devices to participate in D2D cooperation. With this incentive mechanism, we formulate cooperative D2D data uploading with the consideration of human social relationships as coalitional game, and then we apply merge-and-split rules to devise a coalition formation algorithm for obtaining formulated coalitional game. Extensive simulations are conducted to illustrate that the performance of our incentive mechanism outperforms that of non-incentive mechanism.

Chapter 7 Conclusion. This chapter concludes the whole thesis by summarizing our contributions of this thesis, and also discussing potential directions for future research.

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Chapter 2

Related Works

This chapter introduces the existing works related to our study of the thesis, including the works on cooperative D2D data delivery without social-awareness, the works on cooperative D2D data delivery with social-awareness and the works on cooperative D2D data delivery with incentive mechanism.

2.1 Cooperative D2D Data Delivery without Social-awareness

A lot of works have been dedicated to the study of cooperative D2D data delivery without consideration of social-awareness. Available studies mainly focus on either the case when all devices can help to forward data (full cooperation), or the case when none of the devices is willing to help in forwarding data (noncooperation). The data uploading with noncooperation was investigated in [18, 27–29]. In [18], Siekkinen *et al*. studied how to optimize content quality using scalable video coding (SVC) when mobile devices uploaded live multimedia content in cellular networks. In [27], Wang *et al*. proposed an energy-efficient and cost-effective data uploading framework named effSense, which adopted a distributed decision making scheme to minimize both energy consumption and data cost caused by data uploading in cellular networks. In [28, 29], different privacy preserving mechanisms for data uploading phase were designed to capture the privacy inference threat encountered by mobile devices while considering data quality requirements and energy conservation, respectively. In these works, to upload data to the cellular infrastructure, the devices need to have uplink channels with good quality. That is to say, it is challenging for a device suffering from a poor quality uplink channel to directly upload data to the cellular infrastructure with high-reliability and low-latency.

Later, the data uploading with full cooperation was investigated in [25, 30–34], where the devices in proximity can build D2D cooperation so that the device with poor quality uplink channel can select a device with good quality uplink channel to serve as a relay for data uploading. In [30], the users studied the joint channel and power allocation problem for D2D communications underlaying uplink cellular networks using a Stackelberg game, which aims to maximize the sum-rate of D2D communications while fulfilling the QoS requirements for both cellular users (CUs) and D2D pairs (DUs). In [31], the authors proposed an interference coordination/management strategy based D2D-management and designed an appropriately power control algorithm for mitigating the above-mentioned interference. The works [32–34] addressed the resource allocation problem for multiple D2D and cellular users using different theory methods (i.e., game theory and stochastic geometry). In addition, the authors [25] studied how to construct multi-hop D2D chain for data uploading from a game theoretical point of view, and designed the coalition formation algorithm to reduce the data uploading time.

In these schemes, D2D cooperation is only limited to devices with uploading data, while the devices without uploading data do not participate in D2D cooperation. To have an efficient data uploading, we propose a more generalized data uploading scheme where D2D cooperation applies to both devices with uploading data and devices without uploading data, such that the data uploading latency can be reduced.

2.2 Cooperative D2D Data Delivery with Social-awareness

Currently, data delivery has recently drawn great attention from the wireless research community. Most existing literatures mainly focus on cooperative D2D data delivery without the consideration of social-awareness, where these studies assume that cooperative devices have completely trustworthy relationships with each other and the collected data can be reliably delivered to the control center by D2D collaboration, which is not realistic in reality. Practical devices may expose themselves to potential privacy threats due to collaboration with unfamiliar devices. In addition, these devices may deliberately fabricate erroneous and malicious message to interrupt data delivery. As a result, it is desirable to provide safety-efficient data delivery while taking the trustworthiness among the devices into account.

With the explosive growth of online social networks such as Facebook and Twitter, more and more people are actively involved in online social interactions. Since mobile devices are carried by human beings, and social relationship (e.g., kinship, friendship and colleague relationship) among human beings can be utilized to achieve effective and trustworthy assistance for data delivery among the mobile devices. Here, social relationships among human beings contain two key social phenomena: social trust and social reciprocity. In social trust, it can be built up among humans such as kinship, friendship, colleague relationship, and altruistic behaviors are observed in many human activities [35]. Another key social phenomenon [36], social reciprocity is a powerful social paradigm to promote cooperation so that a group of individuals without social trust can exchange mutually beneficial actions, making all of them better off. By leveraging social relationship among human beings, this has opened up a new avenue for cooperative D2D data delivery system design.

Recently, there has been some studies on cooperative D2D data delivery with consideration of social relationship, e.g., social-aware video multicast [37], social data offloading(downloading) [12, 38], social-aware information exchange [39, 40], and social-aware data dissemination [17]. To meet the explosive demand on delivering high-definition video steams over cellular networks, Cao *et al* [37] designed a Social-aware video multiCast (SoCast) system leveraging D2D communications, which can stimulate effective cooperation among mobile users (clients), by making use of two types of important social ties, i.e., social trust and social reciprocity. In [12, 38], the authors improved packet transmission and reduced the load on the network's infrastructure by exploiting the social network characteristics. The literature [39, 40] exploited social ties in human social networks to enhance the information exchange with nearby devices in D2D communications. The work in [17] proposed a three-phase approach for D2D data dissemination, which exploited social-awareness and opportunistic contacts with user mobility.

We note that the available works mainly focus on social-aware multicast, offloading, information exchange and dissemination, while limited works consider the problem of social-aware data uploading. Considering the data uploading reliability, this thesis investigates the impact of human social relationships on cooperative behaviors, where the nearby devices with mutual trust can build D2D cooperative relationships.

2.3 Cooperative D2D Data Delivery with Incentive Mechanism

Although many applications and systems on cooperative D2D data delivery have been developed. Unfortunately, most of them assume that mobile devices would participate in cooperative D2D data delivery voluntarily, which is not true in reality. Mobile devices are generally reluctant to assist other devices or coalitions without getting payment. The major reasons account for mobile devices being reluctant. When assisting other devices or coalitions for data delivery, the devices will consume their own resources, such as power, memory, time, and wireless channel resources. Thus, it is of paramount importance for cooperative D2D data delivery to provide effective incentive mechanisms.

A couple of incentive mechanisms have been proposed for data delivery in D2D enhanced cellular networks [41–45]. In [41], Wang *et al.* studied the problem of resource allocation for D2D communications underlaying cellular networks by exploiting social ties in human-formed social networks, which aims to enhance the data transmission size of each coalition. Further, a social-community-aware D2D resource allocation framework was proposed, where the devices established D2D cooperative relationships with each other to maximize the community's payoff. Then, Yi *et al.* [42] studied a social-aware D2D offloading framework, and proposed an efficient resource management and incentive mechanism for social-aware D2D content sharing with proactive caching, which objective is to effectively offload cellular traffic and significantly improve system's energy and spectral efficiency. Later, Ning *et al.* [43] focused on the incorporation of incentive stimulations into data dissemination in autonomous mobile social networks with selfish nodes and multiple interest data types, which goal is to disseminate data messages to corresponding sinks with both delay and traffic overhead as low as possible. Finally, the works of [44, 45] considered a cooperative sensing system, where the users choose a set of tasks to participate in and then cooperatively deliver data to the BS. To motivate more users to participate in the sensing task, these works designed an incentive mechanism to maximize the users' profits.

Though incentive mechanisms on cooperative D2D data delivery in these works were developed, few works has paid enough attention to the incentive mechanisms on cooperative D2D data uploading. Motivated by this important observation, this thesis proposes an incentive mechanism to motivate more devices to participate in the D2D cooperation, such that the data uploading latency can be reduced and data uploading reliability can be enhanced. With this incentive mechanism, the nearby devices can obtain rewards such that they are willing to construct a multi-hop D2D chain to assist the other devices in data uploading.

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Chapter 3

Preliminaries

In this chapter, we first introduce the system models of data uploading in D2D-enabled cellular networks, regarding network model, cooperation model, communication model, and transmission model. Then we formulate the system utility of cooperative D2D data uploading in terms of the data uploading latency. Finally, the main notations involved in this thesis.

3.1 System Models

3.1.1 Network Model

As depicted in Figure 3-1, we focus on a single cell in the Long Term Evolution Advanced (LTE-A) involving N mobile devices, denoted by the set $\mathcal{N} = \{1, 2, ..., N\}$, under its coverage. In LTE-A cell, multiple devices, labelled as $\mathcal{M} = \{1, 2, ..., M\}$ with $\mathcal{M} \subset \mathcal{N}$ and $M \leq N$, need to upload data to the BS. Besides, these devices from set $\mathcal{M}$ are allocated orthogonal radio resources by the BS according to Maximum Throughput (MT) scheduling policy proposed in [25] and such an operation can be done before data uploading. Here, the BS collects the information of Channel Quality Indicators (CQIs) on each device-to-BS uplink, and then calculates and distributes the orthogonal resources to the devices in set $\mathcal{M}$ in an ascending order according to their uplink CQI.

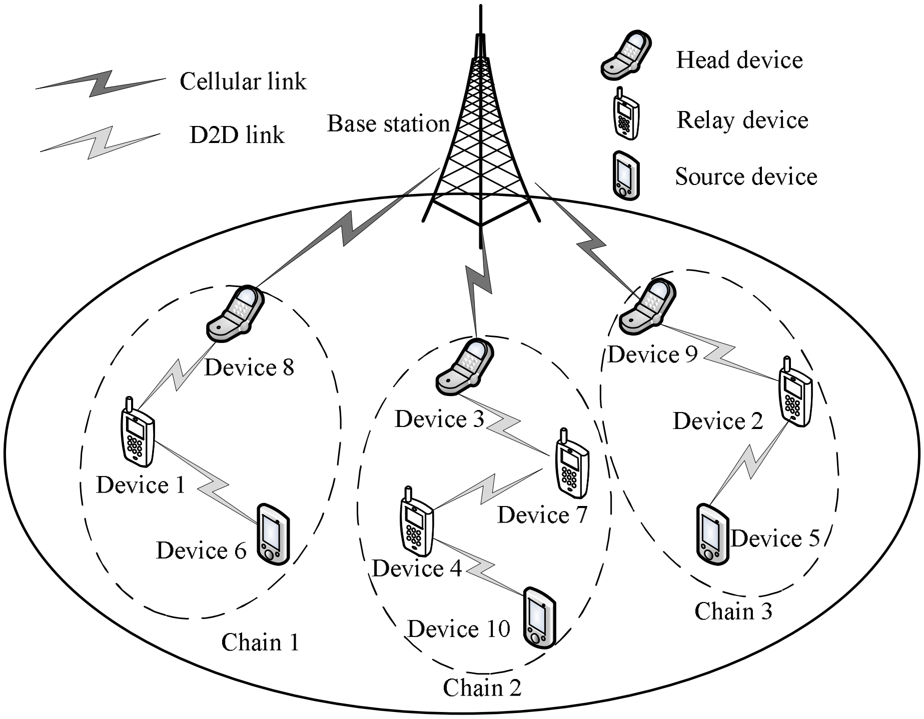

Figure 3-1: System of cooperative D2D data uploading.

3.1.2 Cooperation Model

In such a network scenario, when any two devices are within mutual communication range, the feasible cooperative relationships can be established. Taking such physical constraint into account, we introduce the physical cooperative graph $G^p = \{V^p, \varepsilon^p\}$ [39] to describe cooperative relationships among the devices. Here V^p is the set of vertices to denote the set of devices, and $\varepsilon^p = \{(uv) : e^p_{uv} = 1, \forall u, v \in \mathcal{N}\}$ is the set of edge, where $e^p_{uv} = 1$ if and only if device u and device v are within communication range. Based on G^P, each vertex (i.e., device) u can build its physical cooperative database $\mathcal{N}^p_u = \{v : e^p_{uv} = 1, \forall v \in \mathcal{N}\}$, which contains all cooperative candidates for device u.

To obtain the physical cooperative database $\mathcal{N}^p_u$ for a device $u \in \mathcal{N}$, we perform the ad hoc peer discovery [38] before establishing D2D communication, where device u periodically broadcasts a randomized probing beacon containing its ID and other information to the devices within D2D communication range. Once the other device receives the probing beacon, it will send feedback message that attaches its ID and other information to device u. Through a feedback process, the device u can obtain a list of cooperative candidates.

3.1.3 Communication Model

Taking the physical cooperative database into consideration, the devices can cooperate to construct multi-hop D2D chains for data uploading. As an illustration of the formed chains shown in Figure 3-1, all devices can form 3 multi-hop chains based on D2D cooperation. To form each chain, e.g., chain 1, device 6 chooses a feasible device 1 to serve as the relay for data uploading, and then the chosen device 1 continues to seek the next optimal relay 8 until no feasible device can help the current device 8. As such, a stable multi-hop chain 1 is formed. For each formed chain, the devices can be classified into three types: source device, relay device and head device. The source device (e.g.,device 6) at the bottom of the chain only transmits its own generated data to the next device (e.g.,device 1) in the chain. The head device (e.g.,device 8) is in charge of uploading all data of the chain to the BS. All remaining devices (e.g.,device 1) in the chain are regarded as relay devices, which are used for receiving data from the former devices, and then relaying data (its own and received one) to the next devices in the chain.

In the formulated D2D chains, we assume that the devices from the different chains are assigned with orthogonal resources to avoid mutual interference. In order to maximize the system performance [32], the devices from the same chain adopt time division duplex (TDD) mode [46] to share all radio resources of the chain, where the resource block (RB) is the smallest allocated unit. As depicted in Figure 3-2, it is divided into 12 consecutive sub-carriers occupying $180kHz$ in the frequency domain, whereas it spans for 10 ms and consists of 10 subframes lasting 1 ms or 20 time slots duration of 0.5 ms in the time domain.

However, the above allocated mode may lead to mutual interference for the devices in the same chain, and thus we consider two extreme cases to avoid mutual interference, i.e., best case and worst case. The former corresponds to that there is no interference among devices from the same coalition, so the same radio resource

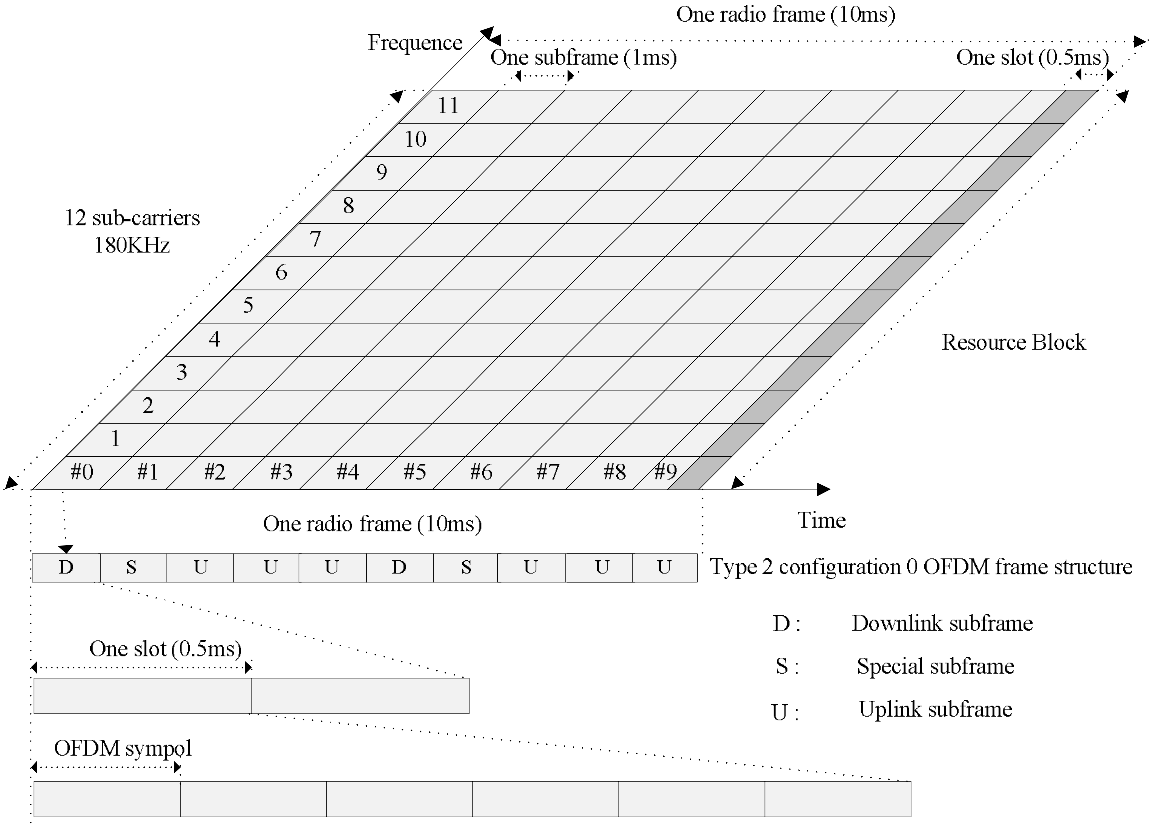

Figure 3-2: TDD (Time Division Duplex) frame structure.

can be shared by those devices. The latter represents that interference exists among devices from the same coalition, and thus those devices can only utilize the resources allocated to them in advance. In TDD mode, we adopt the type 2 configuration 0 LTE frame structure [47], which consists of ten sub-frames lasting for 1 ms in which six sub-frames are used for data uploading.

3.1.4 Transmission Model

In each TDD uplink sub-frame, we adopt the half-duplex mode [48] to describe cooperative behavior among the devices, in which the device may either deliver data to the subsequent device from the same chain or receive data from the former device in the same chain. Moreover, we apply the decode-and-forward (DF) protocol [49] to describe the transmission behavior of the devices. When the device transmits data to the subsequent device from the same chain, it first transmits its own generated data, and then transmits the received data from the previous device of the same chain.

In addition, in a given uplink sub-frame, we sort all devices from the same chain with a numerical order, and consider a reasonable assumption for these devices, where if the devices from even positions of the same chain transmit data to next devices of the chain simultaneously, the devices from odd positions of the same chain will receive data from the previous devices of the chain at the same time. Similarly, when the even devices transmit data, the odd devices will receive data in a given sub-frame.

3.2 Problem Formulation

In formed D2D chains, the data is uploaded to the BS by leveraging two modes, i.e., cellular transmission mode and D2D transmission mode. In the former transmission mode, the data is directly transmitted by the device to the BS, whereas the data is transmitted between two different devices in the latter transmission mode. In the following, we first calculate data rate of each device under the above two transmission modes. With the calculated data rate, we then formulate the system utility of cooperative D2D data uploading in terms of the data uploading latency.

3.2.1 Data Rate Calculation

For cellular transmission mode, to calculate data rate of a device $u \in \mathcal{M}$, we first compute the power received by the BS on the link between device u and the BS, denoted by s, say $u \rightarrow s$, and then calculate the signal to interference plus noise ratio (SINR) on link $u \rightarrow s$, which is considered as the CQI of device u. Finally, the expression of data rate of device u is given. According to the free space propagation loss model [50], the received power $P_{u,s}$ by the BS on the link $u \rightarrow s$ is written as

$$P_{u,s} = P_u^c \cdot d_{u,s}^{-a} \cdot |h_{u,s}|^2, \tag{3.1}$$

where a is the path loss compensation factor, $d_{u,s}$ is the distance between device u and the BS, P_u^c is the transmitted power of device u in cellular transmission mode, and $h_{u,s}$ is the channel coefficient of link $u \rightarrow s$. In our work, we model the uplink channel of the device as the Rayleigh fading channel [32]. Therefore, the channel coefficient $h_{u,s}$ follows the independent complex Gaussian distribution $\mathcal{CN}(0,1)$ [51].

With the received power $P_{u,s}$, we then calculate the SINR $\gamma_{u,s}$ on link $u \rightarrow s$, which can be expressed by

$$\gamma_{u,s} = \frac{P_u^c \cdot d_{u,s}^{-a} \cdot |h_{u,s}|^2}{P_{int,s} + N_0}, \tag{3.2}$$

where $P_{int,s}$ represents the interference signal power, which is obtained by the BS and decided by the transmitted power of D2D devices assigned by the same radio resources with device u [32]. N_0 represents the thermal noise density level received by the BS.

After obtaining the SINR $\gamma_{u,s}$, we finally calculate the data rate r_u^c of device u in the cellular transmission mode, which is decided by Shannon's capacity formula [52] as follows

$$r_u^c = B_u \cdot log_2(1 + \frac{P_u^c \cdot d_{u,s}^{-\alpha} \cdot |h_{u,s}|^2}{P_{int,s} + N_0}), \tag{3.3}$$

where B_u is the radio resource of device u.

Considering D2D transmission mode, we consider that device u transmits data to the BS by device $v \in \mathcal{N}_u$. Similar to the data rate calculation method in cellular transmission mode, we first calculate the received power by device v on link $u \rightarrow v$, and then calculate SINR on link $u \rightarrow v$. Finally, the expression of the data rate of device u, denoted by r_u^d, is given by

$$r_u^d = B_u \cdot log_2(1 + \frac{P_u^d \cdot d_{u,v}^{-\alpha} \cdot |h_{u,v}|^2}{P_{int,v} + N_0}), \tag{3.4}$$

where P_u^d represents the transmitted power of device u in the D2D transmission mode. $h_{u,v}$ and $d_{u,v}$ represent the channel coefficient and the distance between device u and v, respectively. $P_{int,v}$ represents the interference signal power received by device v, which is determined by the transmitted power from D2D devices and cellular devices that are assigned the same radio resources with device u [32].

3.2.2 Data Uploading Latency Calculation

Based on the above calculated data rate, we derive the expression of the data uploading latency, which is first defined as follows [53].

Data Uploading latency: For any device, the data uploading latency is defined as the time duration from the time slot when the device starts to deliver the data packet to the time slot when the BS has received the data packet.

To calculate the data uploading latency from any device $u \in \mathcal{M}$, we take chain S with l devices as an example where $1 \leq l \leq N$ and $u \in S$. In chain S, the source device is considered as the first node (i.e., $u = 1$) and the head device is regarded as the last node (i.e., $u = l$), and we assume that device u needs to transmit a certain amount of data, denoted by $b_u \geq 0$, to the BS. According to calculation method of the channel occupation time in [25], we calculate the data uploading latency $t_u(S)$ of device u in chain S, which is expressed by

$$t_u(S) = 20/3 \cdot \sum_{i=u}^{l-1} \sum_{j=u}^{i} b_j/r_i^d + 10/6 \cdot \sum_{j=u}^{l} b_j/r_l^c, \tag{3.5}$$

where $l = 1$ represents that device u delivers data to the BS separately.

Then, the total data uploading latency $T(S)$ of chain S, which represents the sum of the data uploading latency of all devices in chain S, is given by

$$T(S) = 20/3 \sum_{i=1}^{l-1} \sum_{j=1}^{i} b_j/r_i^d + 10/6 \sum_{j=1}^{l} b_j/r_l^c. \tag{3.6}$$

Similar to the calculation method of $T(S)$, we then calculate the total data uploading latency $T(S_1), T(S_2), ..., T(S_k)$ of other chains $S_1, S_2, ..., S_k$. Considered the number of devices in different chains, i.e., $|S_1|, |S_2|, ..., |S_k|$, the expression of the average data uploading latency, denoted by T_{ave}, is given by

$$T_{ave} = \frac{T(S_1) + T(S_2) + ... + T(S)... + T(S_k)}{|S_1| + |S_2| + ... + |S|... + |S_k|}. \tag{3.7}$$

In this paper, our objective is to construct multi-hop chains for data uploading by D2D cooperation so that the average data uploading latency is reduced. Thus, we formulate the problem of cooperative D2D data uploading for cellular networks as low-latency data uploading (LLDU) problem, which is described as follows:

$$\textbf{LLDU:} \quad min\ T_{ave} = \textstyle\sum_{i=1}^{k} T(S_i) / \sum_{i=1}^{k} |S_i|,$$

$$s.t. \begin{cases} 0 < |S_i| \leq N\ and\ 1 \leq i \leq k; \\ |S_1| + |S_2| + ... + |S_k| = N. \end{cases} \tag{3.8}$$

3.3 Notations

The main notations of this thesis are summarized in Table 3.1 and 3.2.

Table 3.1: Main notations

Symbol	Definition
$\mathcal{N} = \{1, 2, ..., N\}$	The set of all devices, where N is the number of the devices.
$\mathcal{M} = \{1, 2, ..., M\}$	The set of the devices with uploading data, where $\mathcal{M} \subset \mathcal{N}$.
$G^p = \{V^p, \varepsilon^p\}$	The physical cooperative graph, where V^p is the set of vertices, and ε^p is the set of edge.
$\varepsilon^p = \{(uv) : e^p_{uv} = 1\}$	The cooperative relationship of devices u, v, where $e^p_{uv} = 1$ means that device u, v are within communication range.
$\mathcal{N}^p_u$	The physical cooperative database of device u.
$G^s = \{V^s, \varepsilon^s\}$	The social trust graph, where V^s is the set of vertices, and ε^s is the set of edge.
$\varepsilon^s = \{(uv) : e^s_{uv} = P^s\}$	The social relationship of devices u and v, where $e^s_{uv} = 1$ implies that device u and v have trustworthy relationship.

$\mathcal{N}_u^s$	The social trust database of device u.
$G = \{V, \varepsilon\}$	The physical-social graph, V is the set of vertices, and ε is the set of edge.
$\varepsilon = \{(uv) : e_{uv} = 1\}$	The physical-social relationship of devices u and v, where $e_{uv} = e_{uv}^s \cdot e_{uv}^p = 1$ implies that device u and v have the trust-based relationship and are within communicate range.
$\mathcal{N}_u$	The cooperative database of device u.
$P_{u,s}$	The received power by the BS on the link $u \rightarrow s$.
a	The path loss compensation factor.
$d_{u,s}$	The distance between device u and the BS.
P_u^c	The transmitted power of device u in cellular transmission mode.
$h_{u,s}$	The channel coefficient of link $u \rightarrow s$.
$\gamma_{u,s}$	The SINR on link $u \rightarrow s$.
$P_{int,s}$	The interference signal power received by the BS.
N_0	The thermal noise density level received by the BS.
r_u^c	The data rate of device u in the cellular transmission mode.
r_u^d	The data rate of device u in D2D transmission mode.
P_u^d	The transmitted power of device u in the D2D transmission mode.
$h_{u,v}$	The channel coefficient between device u and v.
$d_{u,v}$	The distance between device u and v.
$P_{int,v}$	The interference signal power received by device v.
$t_u(S)$	The data uploading latency of device u in chain S.
$T(S)$	The total data uploading latency of chain S.
T_{ave}	The average data uploading latency of all devices.
$\Delta t_u(S)$	The reduced latency of device u assisting other devices of chain S for data uploading.
$\Omega = \{\mathcal{N}, \mathcal{X}_{\mathcal{N}}, \mathcal{V}\}$	The coalitional game. $\mathcal{N}$ is the set of players, $\mathcal{X}_{\mathcal{N}}$ is the set of cooperative strategies, $\mathcal{V}$ is the characteristic function.

λ	The scaling factor which describes the incentive intensity.
α	The scaling factor which describes the incentive intensity.
β	The scaling factor which describes the incentive intensity.
b_u	The data amount of device u.
$C(S)$	The sum of reward received by all devices in chain S.
$\mathcal{B} = \{B_1, B_2, ..., B_M\}$	The resource set of M devices.
$\mathcal{C} = \{c_1, c_2, ..., c_N\}$	The reward set from the devices.
$\mathbf{x} = \{x_1, x_2, ..., x_N\}$	The sets of individual payoffs.
$\mathcal{S} = \{S_1, S_2, ..., S_k\}$	A coalitional structure (or a partition) of $\mathcal{N}$.
$\mathcal{A} = \{A_1, A_2, ...A_l\}$	A partition of any coalition.
d	The maximum communication distance.
$s_u(S)$	The data uploading reliability of device $u \in S$.
P_s	The probability of social relationship between any pair of devices.
$N(\mu, \sigma)$	The normal distribution with mean μ and variance σ.
$\mathcal{CN}$	The independent complex Gaussian distribution.
t_0	The tolerable latency t_0.
$e_u(S)$	The energy consumption of device u in chain S.
s_0	The tolerable reliability s_0.
$\triangleright$	The preference order.
$\not\triangleright$	The opposite rule of the preference order $\triangleright$.

Table 3.2: Main variables

Notation	Definition
k	The number of coalitions.
$\mathcal{F} = \{F_1, F_2, ...F_N\}$	The flag of all devices.
f	The cycle count.
i	The cycle count.
V	The set of selected devices.

B_{sum}	The total resources.

3.4 Summary

In this chapter, we introduced the system models of cooperative D2D data uploading for cellular networks, including network model, cooperation model, communication model, and transmission model. Then we calculated the data rate of each device under cellular transmission mode and D2D transmission mode. With the calculated data rate, we formulated the system utility in terms of the data uploading latency.

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Chapter 4

Generalized Cooperative D2D Data Uploading

In this chapter, we propose a generalized cooperative data uploading scheme which considers D2D cooperation among both the devices with and without uploading data, so that the data uploading latency can be reduced. This scheme covers the conventional schemes where D2D cooperation is only limited to devices with uploading data as special cases. In this scheme, to motivate D2D cooperation among all available devices, we organize the devices within communication range by offering them rewards to construct multi-hop D2D chains for data uploading. Specifically, we formulate the problem of chain formation among the devices for data uploading as a coalitional game. Based on merge-and-split rules, we develop a coalition formation algorithm to obtain the solution for the formulated coalitional game with convergence on a stable coalitional structure. Finally, extensive numerical results show the effectiveness of our proposed scheme in reducing the average data uploading latency.

4.1 Coalitional Game Formulation

In this section, we introduce a coalitional game to address the problem of D2D chain formation for data uploading, so that the data uploading latency is reduced. Here, coalitional game formulation for cooperative D2D data uploading is firstly presented, and then we analyze two critical properties of our formulated coalition game in terms of the characteristic form and the superadditivity.

4.1.1 NTU Coalitional Game

In our work, we cast the problem of D2D chain formation as a nontransferable utility (NTU) coalitional game [54], which is described as follows:

Definition 1 : The coalitional game with a nontransferable utility is defined by the pair $(\mathcal{N}, \mathcal{V})$, in which $\mathcal{N}$ is the set of players, and $\mathcal{V}$ is a characteristic function which is defined on the coalition $S \subseteq \mathcal{N}$, where $\mathcal{V}(S) \subseteq \mathbb{R}^{|S|}$ and $\mathcal{V}(\phi) = \phi$. $\mathcal{V}(S)$ represents a set of payoff vectors $\mathbf{x}(S)$ of all players in coalition S, where every element $x_u(S) \in \mathbf{x}(S)$ is a payoff received by player $u \in S$ through the feasible cooperation with other players of coalition S.

Remark 1: Considering the selfishness of human beings, the devices carried by human beings only consider their individual payoff rather than the coalitional payoff while participating in D2D cooperation for data uploading. Thus, we adopt game theory to formulate the problem of cooperative D2D data uploading, which can maximize the individual payoff.

In our concerned coalitional game, the players in set $\mathcal{N}$ correspond to all devices in our deployed cell, and each payoff $x_u(S)$ in the payoff vectors $\mathbf{x}(S)$ is measured by the reward $c_u(S)$ received by device u in chain S. For any device $u \in S$, its reward $c_u(S)$ is proportional to the reduced latency $\Delta t_u(S)$ created by device u assisting other devices in S for data uploading, and then is given by

$$c_u(S) = \lambda \Delta t_u(S), \tag{4.1}$$

where $\lambda > 0$ is a scaling factor and it is used for describing the incentive intensity.

To calculate the reduced latency $\Delta t_u(S)$, we consider that there have been $u - 1$ devices in chain S before the uth device participates in chain S, and the total data uploading latency of chain S is determined as $T'(S)$ according to formula 3.6. After the uth device participating in chain S, the total data uploading latency of chain S

is determined by $T(S)$ according to formula 3.6. Then the reduced latency $\Delta t_u(S)$ for device u in chain S is defined as

$$\begin{aligned}\Delta t_u(S) &= T'(S) - T(S) \\ &= 5/3\Big(\sum_{i=1}^{u-1} b_i/r^c_{u-1} - 4\sum_{i=1}^{u-1} b_i/r^d_{u-1} - \sum_{i=1}^{u} b_i/r^c_u\Big).\end{aligned} \tag{4.2}$$

Remark 2: Notice that each device consumes its own resources (e.g., time, energy, and memory) when assisting other devices or coalitions for data uploading, and thus it is often reluctant to assist other devices or coalitions in data uploading without getting payment, especially for the devices without uploading data. To encourage all available devices to cooperate with each other, we propose a new incentive mechanism, which is similar to that of [43, 45, 55]. In this mechanism, if the device u with $u \in \mathcal{N}$ can assist other devices or coalitions in data uploading and the data uploading latency of the assisted devices or coalitions can be reduced, the device u will earn a payment (e.g., credit, penalties, etc.), which is determined by the reduced latency for assisted devices or coalitions.

4.1.2 Property Analysis

Our concerned coalitional game relates to two essential properties: the characteristic form and the superadditivity [56]. For the characteristic form, the payoff vectors of the players in coalition S only depend on the feasible cooperations among all players in coalition S, with no dependence on other devices out of coalition S. Besides, the form of our concerned coalitional game is the characteristic form, which is due to the fact that the devices in the same coalition can construct a D2D chain, whereas the devices in different coalitions do not establish any cooperation. Another key property is the superadditivity, which is described as follows.

Definition 2 : A NTU coalitional game $(\mathcal{N}, \mathcal{V})$ is superadditive if any coalitions

$S_1, S_2 \subset \mathcal{N}$ with $S_1 \cap S_2 = \phi$ satisfy the following condition

$$\begin{aligned} \mathcal{V}(S_1 \cup S_2) \supset \{\mathbf{x}(S_1 \cup S_2) \in \mathbb{R}^{|S_1 \cup S_2|} | \\ x_u(S_1) \in \mathcal{V}(S_1), x_v(S_2) \in \mathcal{V}(S_2)\}, \end{aligned} \tag{4.3}$$

where $\mathbf{x}$ is a payoff vector of all devices from coalitions S_1 and S_2. If the condition of superadditivity holds, D2D cooperation among the devices is always beneficial, and thus the players can form the grand coalition due to individual payoff improvements, where all players are in a coalition. Then the following theorem holds.

Theorem 1 : Our concerned coalitional game is nonsuperadditive.

Proof: We consider any two formed coalitions $S_1, S_2 \subset \mathcal{N}$ with $S_1 \cap S_2 = \phi$ and their corresponding payoff vectors $\mathbf{x}(S_1)$ and $\mathbf{x}(S_2)$ when they do not cooperate with each other. We assume that the devices in coalitions S_1 and S_2 share resources of coalitions S_1 and S_2, respectively. Furthermore, we assume that there exists interference among the devices between coalitions S_1 and S_2. Assume that coalitions S_1 and S_2 form coalition $S_1 \cup S_2$, we can obtain $c_u(S_1 \cup S_2) < c_u(S_1), \forall u \in S_1$ and $c_v(S_1 \cup S_2) < c_v(S_2), \forall v \in S_2$ according to 4.1. As a result, the payoff $x_u(S_1 \cup S_2) < x_u(S_1), \forall u \in S_1$ and $x_v(S_1 \cup S_2) < x_v(S_2), \forall v \in S_2$ hold, which contradicts with the definition of superadditivity. Thus, our concerned coalitional game is nonsuperadditive.

Due to the nonsuperadditive, the grand coalition seldom forms. On the contrary, independent disjoint coalitions may form. Thus, we develop coalition formation algorithm to find independent and disjoint coalitions.

4.2 Coalition Formation Algorithm

In this subsection, we first introduce coalition formation theory, which is used for analyzing how to formulate independent disjoint coalitions, and then develop a merge-and-split formation algorithm to construct the multi-hop D2D chains. Finally, we analyse the property of stability and computational complexity for the proposed coalition formation algorithm.

4.2.1 Coalition Formation Theory

Coalition formation theory [56] is an important research direction in coalitional game. It mainly analyzes the formation of coalitional structure when the grand coalition does not form. To derive a feasible coalitional structure, we first give the concept of coalitional collection $\mathcal{S}$, which is defined as $\mathcal{S} = \{S_1, S_2, ..., S_k\}$ with $S_i \subset \mathcal{N}$ and $S_i \cap S_j = \phi$ for $i \neq j$. If condition $\bigcup_{i=1}^{k} S_i = \mathcal{N}$ holds, the collection $\mathcal{S}$ is regarded as a coalitional structure (or a partition) of $\mathcal{N}$.

Finding a feasible coalitional structure in $\mathcal{N}$ by exhaustive traverse of all partitions of $\mathcal{N}$ is not feasible and impractical, due to the fact that the number of partitions of $\mathcal{N}$ increases exponentially with the number of devices of $\mathcal{N}$ and is regarded as the Bell number [57], which makes this problem into a NP-complete problem [58]. To derive the optimal coalitional structure, the merge-and-split rules [59] are introduced, where the players from $\mathcal{N}$ leave or join a coalition according to the preference order [59].

Definition 3 : A preference order $\triangleright$ is defined for comparing two collections $\mathcal{S}' = \{S'_1, S'_2, ..., S'_l\}$ and $\mathcal{S} = \{S_1, S_2, ..., S_k\}$, which are two partitions for the same subset $\mathcal{A} \subseteq \mathcal{N}$. If $\mathcal{S} \triangleright \mathcal{S}'$, it implies that partition $\mathcal{S}$ of $\mathcal{A}$ is preferable to partition $\mathcal{S}'$ of $\mathcal{A}$.

A variety of well-known orders can be used as the preference order [59], where the Pareto order [59] considers the individual payoff of each player, and thus we utilize the Pareto order as the preference order. To define the Pareto order, we set two collections $\mathcal{S}$ and $\mathcal{S}'$ as a partition of $\mathcal{N}$, where the sets of individual payoffs $\mathbf{x} = \{x_1, x_2, ..., x_N\}$ and $\mathbf{x'} = \{x'_1, x'_2, ...x'_N\}$ are resulted from collections $\mathcal{S}$ and $\mathcal{S}'$, respectively. Then the definition of the Pareto order is given by

$$\mathcal{S} \triangleright \mathcal{S}' \Leftrightarrow \{x_u \geq x'_u, \forall u \in \mathcal{N} \; and \; x_u > x'_u, \exists u \in \mathcal{N}\} \tag{4.4}$$

This definition means that collection $\mathcal{S}$ outperforms collection $\mathcal{S}'$ if at least one player can obtain a payoff improvement without reducing other players' payoff when coalitional structure changes from collection $\mathcal{S}'$ to collection $\mathcal{S}$. With the defined preference order, we give the concept of merge-and-split rules [59], which are defined as follows.

- Merge Rule: Merge any set of coalitions $\{S_1, S_2, ..., S_k\}$ into a single new coalition $S' = \bigcup_{i=1}^{k} S_i$, if $S' \triangleright \{S_1, S_2, ..., S_k\}$.
- Split Rule: Split any coalition S' into multiple new coalitions $\{S_1, S_2, ..., S_k\}$, if $\{S_1, S_2, ..., S_k\} \triangleright S'$, where $S' = \bigcup_{i=1}^{k} S_i$.

The merge rule means that coalitions will merge only if the merge operation can improve the individual payoff of at least one player while other players' payoffs do not be decreased. Similarly, the split rule means that any coalition will split only if at least one player can obtain an improvement for individual payoff through the split operation, whereas other players do not suffer the payoffs reduction.

4.2.2 Merge-and-Split Algorithm

With the defined merge-and-split rules, we develop a coalition formation algorithm to implement the formulated coalitional game, as described in Algorithm 1. By starting from the set of noncooperative devices $\mathcal{N}, \mathcal{M}$ and cooperative database $\mathcal{N}_u^p, u \in \mathcal{N}$, we construct a stable coalitional structure $\mathcal{S}_{fin} = \{S_1, S_2, ..., S_k\}$ to reduce the data uploading latency. In this algorithm, we first initialize the coalition index i, the cycle count f, the set of selected devices V, the reward set $\mathcal{C}$, and apply MT scheduling policy to allocate the resources to the M devices from lines 1-4. Then in line 5, we sort the devices of set $\mathcal{M}$ in an ascending order according to their uplink CQI. Through the efficient D2D cooperation among nearby devices, we sequentially search for all feasible coalitions $(S_1, S_2, ..., S_k)$ from lines $6 - 33$. To construct each coalition S_i with $1 \leq i \leq k$, we first select a device $u \in \mathcal{M}$, which does not participate in D2D cooperation (i.e., $u \notin V$) and set it as the first device of coalition S_i (i.e., $S_i = \{u\}$) in line 7. Then from lines 8 to 31, we iteratively select next device v for the current device u from $\mathcal{N}_u^p \neq \phi$.

In each iteration, we first sort the devices from set $\mathcal{N}_u^p$ in a descending order according to their D2D CQI in line 9, and then select device v from set $\mathcal{N}_u^p$ based on merge and split operations from lines 10-30. If the selected device v does not participate in D2D cooperation, we execute Procedure 1 to evaluate if the merge operation of v and S_i can improve the individual payoff of at least one device, while other devices' payoffs do not decrease. In Procedure 1, the merge operations of both cases (i.e., best case and worst case) are considered. For the best case, we calculate the total resources B_{sum} in formulated coalition $S_i \cup \{v\}$, and then set the resources $B_j = B_{sum}$ for device $j \in S_i \cup \{v\}$. Based on formula 4.1, we calculate the reward $c_v(S_i \cup \{v\})$ received by device v in coalition $S_i \cup \{v\}$, and make a comparison between $c_v(S_i \cup \{v\})$ and c_v. In the worst case, device v can utilize the resources allocated to them in advance. Similar to the operation of the best case, we calculate the reward $c_v(S_i \cup \{v\})$ of device v, and then compare the reward $c_v(S_i \cup \{v\})$ and c_v. If $\{S_i \cup \{v\}\} \triangleright \{\{v\}, S_i\}$, we join device v into coalition S_i and update the reward of device v. Then, we set v as the current device of S_i and go to step 8 to select the next device of device v.

If the selected device v has involved in another coalition, we traverse all formed coalitions to search for coalition $S_{i'}$ with $v \in S_{i'}$, which consists of two coalitions $S_{i'1}$ and $S_{i'2}$ with $v \in S_{i'2}, v \notin S_{i'1}$ by taking into account v as the threshold device, and then execute Procedure 2 to evaluate if the formed coalition $S_{i'}$ can split. In Procedure 2, we consider the split operation of both case (i.e., best case and worst case). For the best case, we calculate the total resources B_{sum} in formulated coalition $S_{i'2} \cup S_i$, and then set the resources $B_j = B_{sum}$ of device $j \in S_{i'2} \cup S_i$. Based on formula 4.1, we calculate the reward $c_j(S_{i'2} \cup S_i)$ received by device j with $j \in S_{i'2} \cup S_i$, and make a comparison between the reward $c_j(S_{i'2} \cup S_i)$ and c_j for device $\forall j \in S_{i'2} \cup S_i$. In the worst case, the devices $j \in S_{i'2} \cup S_i$ can utilize the resources allocated to them in advance. Similar to the operation of the best case, we calculate the reward $c_j(S_{i'2} \cup S_i)$ of device $j \in S_{i'2} \cup S_i$, and then compare the reward $c_j(S_{i'2} \cup S_i)$ and c_j of device $j \in S_{i'2} \cup S_i$. If $\{S_{i'1}, S_{i'2} \cup S_i\} \triangleright \{S_{i'}, S_i\}$, we split coalition $S_{i'}$ into coalitions $S_{i'1}, v \notin S_{i'1}$ and $S_{i'2}, v \in S_{i'2}$ by taking v as the threshold device, and then merge coalitions S_i and $S_{i'2}$ into coalition S_i. Finally, we update the rewards of all devices in coalition S_i, and search for the next device in current coalition $S_{i'1}$ by jumping into step 8. The iteration procedure repeats until no feasible device $v \in \mathcal{N}_u^p$ can help device u (i.e., $f = |\mathcal{N}_u^p|$), and then coalition S_i forms. Once coalition S_i forms, we search for the next coalition S_{i++}. After finishing the loop from lines $6 - 33$, we can obtain a stable coalitional structure S_{fin}.

Remark 3: Notice that the proposed coalition formation algorithm is implemented by the BS in the centralized manner, which is similar to that of [60]. Preliminarily, the BS collects all the required information about channel gains, traffic demand, and the device SINRs of both cellular and D2D links, and then calculates and distributes the resources to the devices with uploading data according to MT scheduling policy. Moreover, a merge and split coalition formation algorithm is executed under the assistant of the BS, which is summarized in Algorithm 1. In Algorithm 1, each device first performs peer discovery to obtain cooperative candidates, and then constructs multi-hop D2D chains by D2D cooperation with cooperative candidates. When the stable coalitional structure $\mathcal{S}_{fin} = \{S_1, S_2, ..., S_k\}$ forms, the BS will be in charge of propagating the message of coalitional structure to all devices using the channel-aware random access manner, which has been adopted in [38]. Under the execution process, the head device of each coalition first sends the collected message of coalition (i.e., device number, device ID, and device location) to the BS, and then the BS broadcasts the received message to all devices over the channel via a random access manner. Finally, through the formulated paths, the devices apply the half-duplex decode-and-forward (DF) relaying protocol to transmit data to the BS. The information overhead for the centralized algorithm [60] is realistic for a small or medium-sized network in which changes in traffic demand are not very fast. In our proposed centralized algorithm, the information overhead involves three parts (i.e., collecting the required information, allocating the resource and sending the algorithm message), and the amount of the overhead depends on the size of our deployed network that is very small. Therefore, the information overhead of Algorithm 1 can be restricted to a tolerable level for a practical system.

4.2.3 Algorithm Analysis

In this subsection, we analyse the property of stability and computational complexity for the proposed coalition formation algorithm. Firstly, our proposed algorithm converge to a stable coalitional structure which consists of disjoint coalitions (the proof of stability is similar to that in the works [41], [61]).

Then, we analyze the other property of our proposed algorithm, i.e., computational complexity, which is decided by the number of merge-and-split iteration operations in Algorithm 1. In this Algorithm, to search the number of all feasible coalitions from lines 6 to 33, the iteration is executed at most M times in the worst case, i.e., M devices with uploading data form M singleton coalitions. From lines 8 to 31, as we require to search all devices from the set $\mathcal{N}$ to construct a coalition in the worst case, the complexity of this operation is at most N. In addition, to select the cooperative device for each device u, the time of iteration from lines 10 to 30 is at most $|\mathcal{N}_u^p|$. The reason is that device u has at most $|\mathcal{N}_u^p|$ feasible cooperative devices within its communication range, and thus device u requires to make $|\mathcal{N}_u^p|$ attempts to guarantee the maximum cooperation in the worst case. As a result, the computational complexity of Algorithm 1 is at most $O(M \times N \times |\mathcal{N}_u^p|)$. Furthermore, since $M \leq N$ and $|\mathcal{N}_u^p| \leq N$. Thus, our proposed coalition formation algorithm has a computational complexity of $O(N^3)$.

Remark 4: Notice that in our proposed algorithm, the computational complexity is determined by the number of iteration of merge-and-split operations. For the merge operation, each device needs to make the merge attempts with other devices in $\mathcal{N}$ for guaranteeing the maximum cooperation, and thus the number of merge operations will be $O(N^3)$ in the worst case. For the split operation, it involves finding all possible partitions of the formed coalitions, and thus splitting a coalition S requires to make $O(2^{|S|})$ attempts in the worst case, which is restricted to the size of the formed coalitions. In practice, due to the limitation of D2D communication range, the size of the formed coalitions is quite small, and thus the complexity of the split operation can be neglected. As a result, our proposed algorithm has a computational complexity of

$O(N^3)$. Compared to the conventional works [25, 51] that apply the merge-and-split rules to implement coalition formation algorithm, the computational complexity of our proposed algorithm is at the same level with that of [25, 51].

4.3 Numerical Results

In this section, we evaluate the performance of our proposed generalized data uploading scheme. The evaluating settings, the impact of D2D cooperation and the performance comparison with other uploading scheme are presented as follows.

4.3.1 Evaluating Settings

In the performance evaluations, we carry out the simulations in a network scenario of disaster recovery communication (e.g., earthquake, hurricane or flood) that has been widely adopted in previous studies [3, 62, 63], where power failures and damaged communication infrastructures caused by disasters leave the affected area cut off from the outside and hinder the rescue operations. To accelerate rescue operations, the devices of trapped survivors that are unable to move need to send out the amount of message from surrounding environments to rescue crews, even with best effort service and even without acknowledgment.

In the network simulation, we consider a 1000 $m \times 1000$ m square area with the BS in the center, where N devices within the number range of $0 \sim 50$ are randomly scattered within the coverage of the BS, and $M \leq N$ devices are willing to upload data to the BS. To derive the amount of uploaded data of M devices, we adopt the real datasets from [64] that matches the practical network scenarios, where the uploaded data is comprised of a lot of video clips and the video file size corresponds to the amount of uploaded data. In addition, we assume that the locations of all devices fix during a D2D communication scheduling period, and the maximum communication distance between arbitrary two devices is set as $d = 100$ m. We execute 500 simulations, and then the data uploading latency is obtained by the average of all simulation results.

The main parameters used in our simulation are described as follows: we consider a 10 MHz spectrum band shared by the devices under cellular transmission mode and D2D transmission mode that operate at 2.5 GHz carrier frequency. For cellular transmission model, the transmission power P_u^c for any device u is set as 23 dbm, whereas its transmission power P_u^d is set as -19 dbm in D2D transmission model. In particulary, the thermal noise density level N_0 of both transmission models is set as -174 dbm/Hz. To depict the incentive intensity and the path loss compensation factor, we set λ as 10 and a as 2, respectively.

As discussed earlier in the paper, we adopt TDD mode to reallocate the uplink resources to all devices from the same coalition, where the devices share the same radio resources of coalition. However, the above allocation mode can lead to mutual interference among the devices in the same coalition. To avoid mutual interference among these devices, we consider resource allocation of the best case and the worst case, and analyze both cases in this work which correspond to the upper and lower bounds and the other cases of resource sharing fall between them.

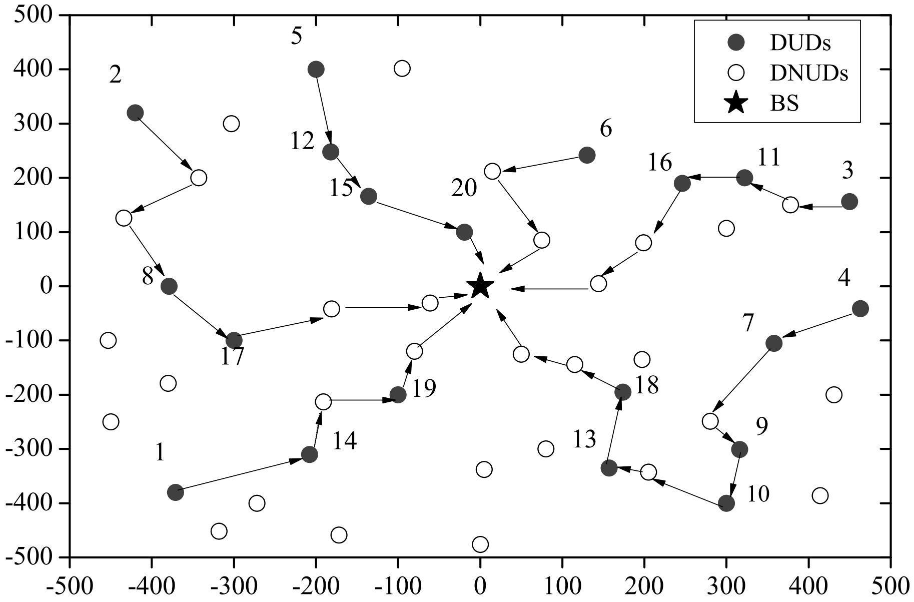
The performance evaluation focuses on the average data uploading latency. To evaluate the efficiency of our proposed generalized data uploading scheme denoted by GDUS, we compare the performance among our proposed GDUS, the constrained coalition formation scheme (CCFS) proposed in [25] and the non-cooperative uploading scheme(NCUS), where the data is directly uploaded by the devices to the BS.

4.3.2 Performance Gain by D2D Cooperation

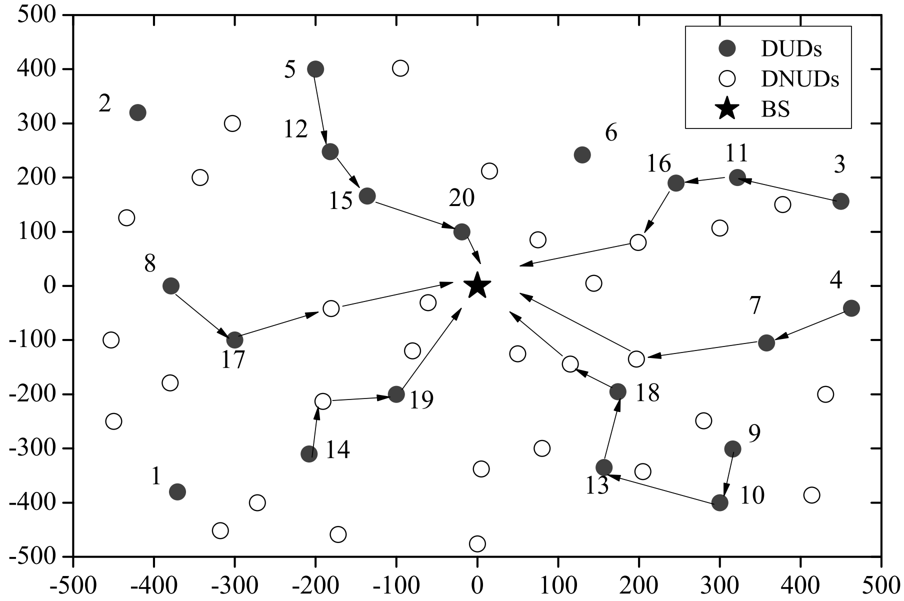
We focus on a sample scenario of the stable coalitional structure formed by D2D cooperation in which two cases (i.e., best case and worst case) are considered. The objective is to analyze coalition formation process, and then compare the data uploading latency under the NCUS, best case (GDUS-BC) and worst case (GDUS-WC) in our proposed GDUS.

Figure 4-1 shows the sample of the formed coalitions with $N = 50, M = 20$ and $d = 100$ m under the best case and the worst case, in which the base station, the devices with uploading data (DUDs) and the devices without uploading data

(DNUDs) are labelled as solid star, solid circle and hollow circle, respectively. Each formed coalition based on D2D cooperation is connected by arrow line. In addition, the devices with uploading data are marked as the numbers from 1 to 20.



(a) Best case



(b) Worst case

Figure 4-1: Sample of a stable coalitional structure resulting from our scheme for (a) best case and (b) worst case with $N = 50, M = 20$ and $d = 100\ m$.

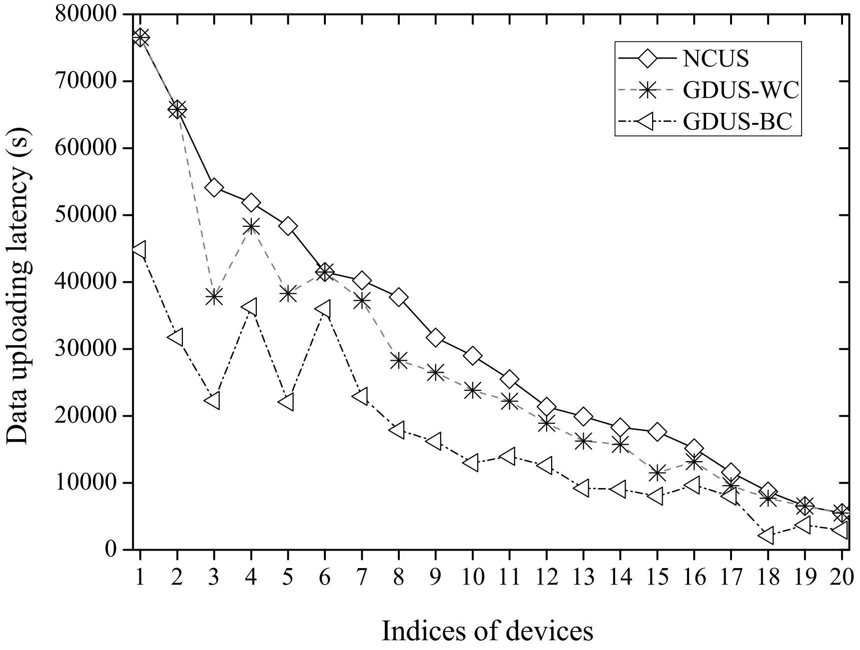
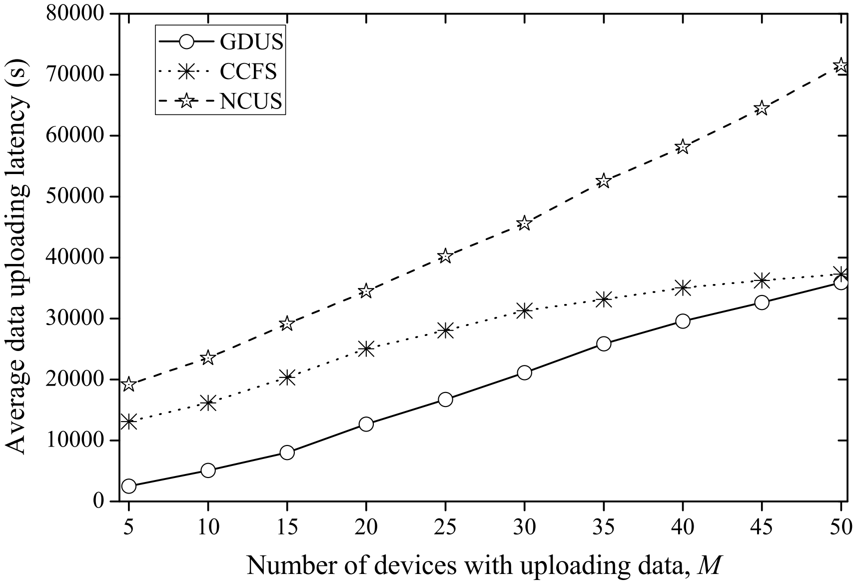


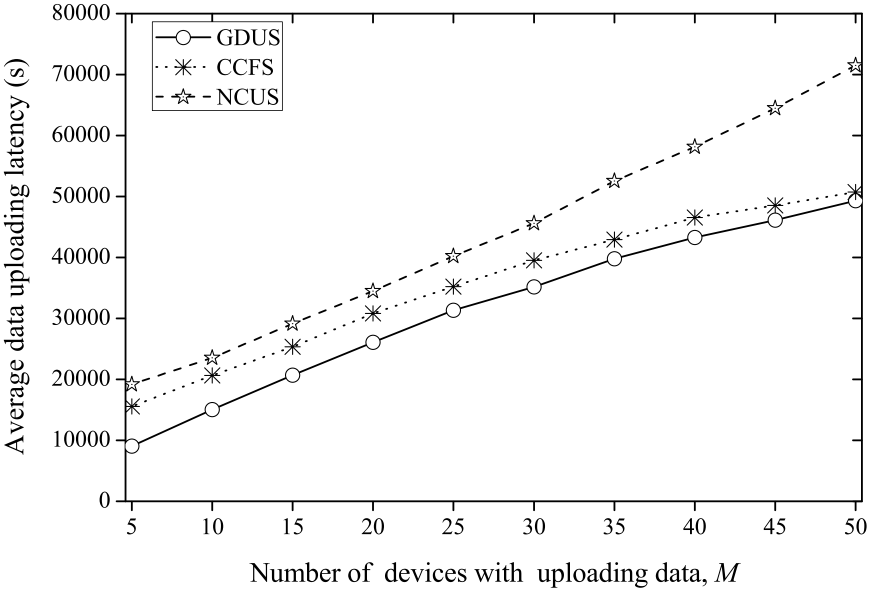
Figure 4-2: Data uploading latency under NCUS, best case (GDUS-BC) and worst case (GDUS-WC) in Figure 4-1.

As depicted in Figure 4-1(a), we can see that all DUDs and most of DNUDs participate in D2D cooperation under the best case. This is because that the best case considers no interference among simultaneously transmitting devices in the same coalition, and then each device in the coalition can share the radio resource with the other devices in the coalition, which increases the cooperative opportunities among the devices and leads to more devices (i.e., partial DNUDs and all DUDs) taking part in D2D cooperation.

In the worst case, due to the interference among simultaneously transmitting devices in the same coalition, each device only utilize the allocated radio resources in advance, which reduces the cooperative possibilities among the devices. Therefore, we can find from Figure 4-1(b) that some DUDs do not participate in any coalition and the data from those devices is directly uploaded to the BS (e.g., device 1, 2, 6). For each device with uploading data in Figure 4-1, the data uploading latency under the best case (GDUS-BC) and the worst case (GDUS-WC) is obtained based on our proposed scheme and the NCUS in Figure 4-2. We can note that the data uploading latency is minimum under the GDUS-BC.

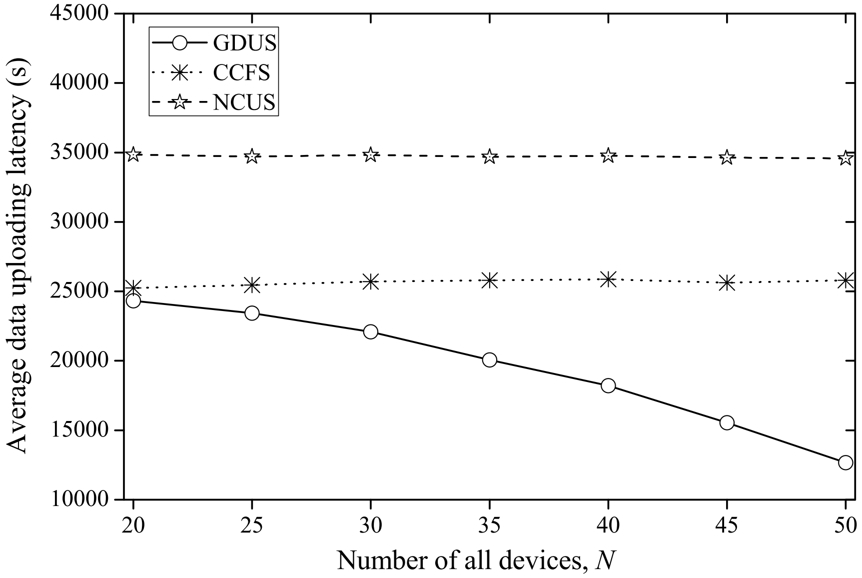


(a) Best case

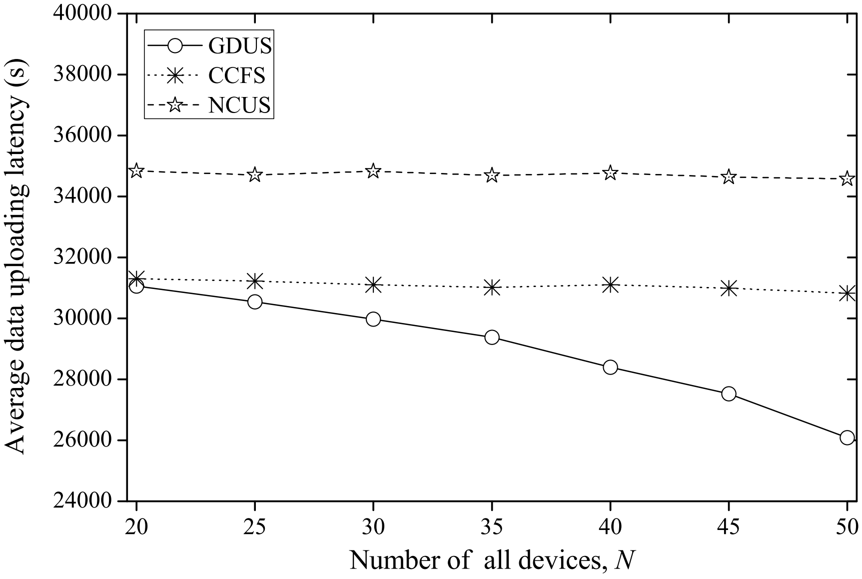


(b) Worst case

Figure 4-3: Average data uploading latency versus the number of devices with uploading data using NCUS, GDUS and CCFS for (a) best case and (b) worst case with $N = 50, d = 100\ m$.



(a) Best case



(b) Worst case

Figure 4-4: Average data uploading latency versus the number of all devices in deployed cell using NCUS, GDUS and CCFS for (a) best case and (b) worst case with $M = 20, d = 100\ m$.

4.3.3 Performance Gain of Our Scheme

In this subsection, we give the comparisons on the average data uploading latency obtained by GDUS, NCUS and CCFS for best case and worst case. In Figure 4-3, we show the average data uploading latency with $N = 50$ and $d = 100$ m for different number of DUDs (M). From Figure 4-3, we can see that the average data uploading latency increases with the increase of number of DUDs, and that our proposed GDUS outperforms the other two schemes (i.e., NCUS and CCFS). Moreover, we can also observe that when the number of DUDs reaches to the maximum value 50, the result achieved by the GDUS is similar to that achieved by CCFS. This is because that in this case, all devices in our deployed cell need to upload data, which is a scenario considered by CCFS, and thus our proposed GDUS can cover the CCFS as a special case.

Figure 4-4 shows the average data uploading latency with $M = 20$ and $d = 100$ m for different number of all devices (N) in the deployed cell. We can find that the average data uploading latency from our proposed GDUS decreases with the increase of number of devices, whereas that for NCUS and CCFS changes in a small scale. This is because, as the number of all devices (N) increases, the DUDs can cooperate with more DNUDs to upload data in GDUS and thus the average data uploading latency is reduced. Since NCUS and CCFS only focus on cooperative data uploading among the DUDs without consideration of D2D cooperation from the DNUDs, the time is not related to the value of N when M is fixed.

4.4 Summary

In this chapter, a generalized data uploading scheme was proposed by leveraging D2D cooperation among all available devices to reduce the average data uploading latency. In this scheme, the devices within communication range were rewarded to establish D2D cooperation and then form the multi-hop D2D chains for data uploading. Specifically, a coalitional game was introduced to formulate the problem of cooperative D2D data uploading, and then we devised a merge-and-split formation algorithm to obtain the solution for the formulated coalitional game. Simulation results showed that our proposed scheme outperforms the state-of-the-art schemes.

Algorithm 1 Coalition formation algorithm for cooperative D2D data uploading:

```
Input:
    The set of devices $\mathcal{N}, \mathcal{M}$ and cooperative database $\mathcal{N}_u^p, u \in \mathcal{N}$.
Output:
    A stable coalitional structure $\mathcal{S}_{fin} = \{S_1, S_2, ..., S_k\}$
    (each $S_i$ denotes a coalition for $1 \leq i \leq k$).
 1: Initialize coalition index $i = 1$ and cycle count $f = 0$;
 2: Initialize the set of selected devices $V = \phi$;
 3: Initialize the reward set $\mathcal{C} = \{c_1, c_2, ..., c_N\} = \phi$;
 4: Allocate $\mathcal{B} = \{B_1, ..., B_M\}$ according to MT scheduling policy;
 5: Sort devices $\forall u \in \mathcal{M}$ with an ascending order of their uplink CQI;
 6: for $u \in \mathcal{M}$ and $u \notin V$ do
 7:     Set $V = V \cup \{u\}$ and $S_i = \{u\}$ ;
 8:     while $\mathcal{N}_u^p \neq \phi$ and $f \neq |\mathcal{N}_u^p|$ do
 9:         Sort devices $\forall v \in \mathcal{N}_u^p$ in a descending order of their D2D CQI;
10:         for $v \in \mathcal{N}_u^p$ do
11:             if $v \notin V$ then
12:                 Execute Procedure Merge operation;
13:                 if $\{S_i \cup \{v\}\} \triangleright \{\{v\}, S_i\}$ then
14:                     Set $S_i = S_i \cup \{v\}$ and $V = V \cup \{v\}$;
15:                     Update the reward of devices $v$;
16:                     Set $v$ as the current device of $S_i$ and go to step 8;
17:                 end if
18:             end if
19:             if $v \in V$ then
20:                 Traverse all formed coalitions to search for $S_{i'}, v \in S_{i'}$;
21:                 Take $v$ as the threshold point to divide coalition $S_{i'}$ into two coalitions
                    $S_{i'1}$ and $S_{i'2}$ with $v \in S_{i'2}, v \notin S_{i'1}$;
22:                 Execute Procedure Split operation;
23:                 if $\{S_{i'1}, S_{i'2} \cup S_i\} \triangleright \{S_{i'}, S_i\}$ then
24:                     Set $S_{i'} = \{S_{i'1}, S_{i'2}\}$,$S_i = S_i \cup S_{i'2}$, $S_{i'} = S_{i'1}$;
25:                     Update the rewards of the devices in coalition $S_i$;
26:                     Set $S_{i'1}$ as the current coalition and go to step 8;
27:                 end if
28:             end if
29:             Set cycle count $f = f + 1$;
30:         end for
31:     end while
32:     $i = i + 1$ and search for the next coalition $S_i$;
33: end for
```

Procedure 1 Merge operation:

```
Set the sum of radio resources $B_{sum} = 0$;
if Best Case then
    Calculate the total resources $B_{sum} = \sum_{j \in S_i \cup \{v\}} B_j$ in set $S_i \cup \{v\}$;
    Set the resource of each device $B_j = B_{sum}, \forall j \in S_i \cup \{v\}$;
    Calculate the reward $c_v(S_i \cup \{v\})$ based on (4.1);
    Compare the reward $c_v(S_i \cup \{v\})$ and $c_v$;
end if
if Worst Case then
    Calculate the reward $c_v(S_i \cup \{v\})$ based on (4.1);
    Compare the reward $c_v(S_i \cup \{v\})$ and $c_v$;
end if
```

Procedure 2 Split operation:

```
Set the sum of radio resources $B_{sum} = 0$;
if Best Case then
    Calculate the total resources $B_{sum} = \sum_{j \in S_{i'2} \cup S_i} B_j$ in set $S_{i'2} \cup S_i$;
    Set the resource of each device $B_j = B_{sum}, \forall j \in S_{i'2} \cup S_i$;
    Calculate the reward $c_j(S_{i'2} \cup S_i), \forall j \in S_{i'2} \cup S_i$ based on (4.1);
    Compare the reward $c_j(S_{i'2} \cup S_i)$ and $c_j$ for $\forall j \in S_{i'2} \cup S_i$;
end if
if Worst Case then
    Calculate the reward $c_j(S_{i'2} \cup S_i), \forall j \in S_{i'2} \cup S_i$ based on (4.1);
    Compare the reward $c_j(S_{i'2} \cup S_i)$ and $c_j$ for $\forall j \in S_{i'2} \cup S_i$;
end if
```

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Chapter 5

Social-aware Cooperative D2D Data Uploading

The social-aware data uploading study of D2D enabled cellular networks is critical for supporting their applications. This chapter extends the previous works on cooperative D2D data uploading with full trust and no trust to the more real social network scenario, and investigates the problem of cooperative D2D data uploading with the consideration of the impact of human social relationships on cooperation behaviors. Specifically, we introduce the human social relationship to provide the trustworthy assistance for D2D cooperation, where the nearby devices with mutual trust can build D2D cooperative relationships. To model D2D cooperation, a coalition game is then developed, and we devise a coalition formation algorithm to implement the formulated coalitional game, where the devices with the poor uplink channel quality are first considered to join D2D cooperation and the bottom to top mode is adopted to construct the D2D chains. Simulation results show that our proposed approach can effectively reduce the average data uploading latency compared with the state-of-the-art approaches under the real network scenario.

5.1 Human Social Relationship

To guarantee the data uploading reliability, human social relationship is provided as the trustworthy assistance for D2D cooperation among devices. To describe the cooperative relationships among devices, we introduce the social trust graph $G^s = \{V^s, \varepsilon^s\}$ [39]. Here V^s is the set of vertices to denote the set of devices, and $\varepsilon^s = \{(uv) : e^s_{uv} = 1, \forall u, v \in \mathcal{N}\}$ is the set of edge, where $e^s_{uv} = 1$ if and only if device u and device v have the trustworthy relationship (i.e., family member, friend and colleague). Based on G^s, each vertex (i.e., device) u can build its social trust database $\mathcal{N}^s_u = \{v : e^s_{uv} = 1, \forall v \in \mathcal{N}\}$.

Based on the physical cooperative graph and the social trust graph mentioned above, we introduce the physical-social graph $G = \{V, \varepsilon\}$. Here V is the set of vertices to denote the set of devices, and $\varepsilon = \{(uv) : e_{uv} = e^s_{uv} \cdot e^p_{uv} = 1, \forall u, v \in \mathcal{N}\}$ is the set of edge, where $e_{uv} = 1$ if and only if device u and device v have the trust-based relationship and are within communicate range. Based on G, each device u can build its cooperative database $\mathcal{N}_u = \{v : e_{uv} = 1, \forall v \in \mathcal{N}\}$. Clearly, all devices in $\mathcal{N}_u$ can help device u. For simplicity, we generalize the cooperative database of device u as $\mathcal{N}_u \cup s$, where s represents the BS. If device u chooses s as the cooperator, it means that device u uploads data directly to the BS.

5.2 Coalitional Game Formulation

In this work, our objective is to construct multi-hop chains for data uploading by D2D cooperation so that the data uploading latency is reduced. Thus, a key challenge is how to efficiently divide the devices into multiple chains. Taking the basic concepts into consideration from [54], we formally define a coalitional game $\Omega = \{\mathcal{N}, \mathcal{X}_{\mathcal{N}}, \mathcal{V}\}$ to solve the chain formation problem, where

- The set of players $\mathcal{N}$ is the set of all devices.
- $\mathcal{X}_{\mathcal{N}} = \{(v_u)_{u \in \mathcal{N}} : v_u \in \mathcal{N}_u \cup s, \forall u \in \mathcal{N}\}$ is the set of cooperative strategies for all players. Here, it represents the set of possible cooperators for all devices based

on their cooperative database.

- $\mathcal{V}(S) = \{(v_u)_{u\in\mathcal{N}} \in \mathcal{X}_{\mathcal{N}} : \{v_u\}_{u\in S} = \{w\}_{w\in S}$ and $\{v'_u\}_{u'\in\mathcal{N}\setminus S} = \{w'\}_{w'\in\mathcal{N}\setminus S}\}$ is the characteristic function which is defined on the coalition $S \subseteq \mathcal{N}$. Here the condition $\{v_u\}_{u\in S} = \{w\}_{w\in S}$ represents the feasible cooperation among all devices in coalition S, the condition $\{v'_u\}_{u'\in\mathcal{N}\setminus S} = \{w'\}_{w'\in\mathcal{N}\setminus S}$ represents other devices out of coalition S do not take part in any cooperation in S.

The critical mechanism in coalition game formation is to enable the player to join or leave a coalition based on the well-defined preference. Here, we introduce the concept of preference order $\triangleright_u$ [65] for player u as follows.

Definition 1 : For each player $u \in \mathcal{N}$, the preference order $\triangleright_u$ is defined as a complete, reflexive, and transitive binary relation on the set of all coalitions that player u can possibly form.

In our formulated coalition game, each device can select its potential cooperators according to its preference order. For device u, $v \triangleright_u v'$ means that u prefers to cooperate with v than v', where $v, v' \in \mathcal{X}_u \cup s$. Considered low-latency data uploading problem, we construct the preference order in terms of the data uploading latency. As a result, each device $u \in \mathcal{N}$ can select a preference cooperator $v = argmin_{v\in\mathcal{N}_u\cup s} T_u(S)$ with $|S| \geq 1$ as the preference order to cooperate in uploading data.

5.3 Coalition Formation Algorithm

In this section, we first introduce the definition of core, which is used to assess the stability of coalition structure, and then devise a coalition formation algorithm to construct multi-hop chains for data uploading. Finally, we analyze the time complexity of our proposed algorithm.

5.3.1 The Definition of Core

The solution of coalition game formation is to search the set of feasible coalitions which guarantee that devices do not have incentives to leave a given coalition and then join another coalition according to the preference order. This condition is described as coalition structure stability. The core [56] is used to assess the stability of coalition structure, which is defined as follows.

Definition 2 : The core is the set of cooperative strategy ($\mathbf{x}(\mathcal{N}) \in \mathcal{V}(\mathcal{N})$ for which there is no coalition S and S-feasible cooperative strategy ($\mathbf{y}(S) \in \mathcal{V}(S)$) so that $y_u(S) > x_u(\mathcal{N})$.

In other words, the core guarantees that no coalition can leave the formed coalition structure and provide a better allocation for all members by deviating the formed coalition structure.

5.3.2 Coalition Formation Algorithm

To obtain the solution of core, we construct trust-ware assisted coalition formation algorithm, as summarized in Algorithm 1. By starting from noncooperative device set $\mathcal{N}$ and cooperative strategy $\mathcal{X}_{\mathcal{N}}$, the execution process is divided into two phases: the prepared stage and the formation stage. In prepared stage, we initialize the flag set $\mathcal{F} = \{0\}$ of all devices and coalition number $k = 1$, and then sort all devices in a ascending order of CQI.

In formation stage, we search all feasible coalitions to form a stable coalition structure $\mathcal{S}_{fin}$ from lines 4-21. For each formation coalition S_k, we first select a device u from $\mathcal{N}$ which does not join any coalitions and needs to upload data to the BS, and then join device u into coalition S_k in lines 5-8. Form lines 9 to 19, we iteratively select a cooperator v for the current device u from $\mathcal{X}_u$ with the preference order to construct the coalition S_k.

Once device u is joined into coalition S_k, we sort the cooperative strategy $\mathcal{X}_u$ of device u with the preference order, and then successively select a cooperator v for the current device u from $\mathcal{X}_u$ to join coalition S_k until no preferable device $v \in \mathcal{X}_u$ can help device u. The coalition S_k forms and the iterative procedure repeats until M devices with data uploading have involved in the formed coalitions. Finally, a stable coalition structure S_{fin} forms.

Algorithm 1 Trust-ware assisted coalition formation algorithm:

```
Require:
    $\mathcal{N} = \{1, 2, ..., N\}; \mathcal{X}_{\mathcal{N}} = \{(v_u)_{u \in \mathcal{N}} : v_u \in \mathcal{N}_u \cup s\}$.
Ensure:
    A stable coalition structure $\mathcal{S}_{fin} = S_1 \cup S_2 \cup ... \cup S_k$.
 1: Set the flag $\mathcal{F} = \{F_u : F_u = 0, u \in \mathcal{N}\}$;
 2: Initialize coalition number $k = 1$;
 3: Sort $\mathcal{N}$ in a ascending order of CQI;
 4: while $u \in \mathcal{N}$ do
 5:     if $F_u = 1$ and $v = u$ then
 6:         continue;
 7:     end if
 8:     $S_k \leftarrow u, F_u = 1$;
 9:     repeat
10:         Sort $\mathcal{X}_u$ with the preference order;
11:         while $v \in \mathcal{X}_u$ and $v \neq u$ do
12:             if $F_v = 1$ then
13:                 continue;
14:             else
15:                 $S_k \leftarrow v, F_v = 1$;
16:                 Set $v$ as the current device, break;
17:             end if
18:         end while
19:     until $v \neq u$
20:     $k = k + 1$ and search the next coalition $S_k$;
21: end while
22: return $\mathcal{S}_{fin} = S_1 \cup S_2 \cup ... \cup S_k$.
```

5.3.3 Algorithm Analysis

Here, we analyze the time complexity of Algorithm 1. In this algorithm, for searching all feasible coalitions, the iteration from lines 4 to 21 is executed at most N times, i.e., we consider the scenario of worst case that N devices forms N singleton coalitions. For selecting all devices of each coalition, the iteration from lines 9 to 19 is executed at most N times, i.e., we need to traverse all devices in $\mathcal{N}$. For searching the cooperators for each device of each coalition, the iteration from lines 11 to 18 is executed at most N times, i.e., the worst case is that each device has N cooperators. Thus, the algorithm has a computational complexity of $O(N^3)$. Notice that our proposed algorithm can converge to a stable coalition partition (i.e., the stability). The proof of the stability of our proposed algorithm is similar to the proof of the stability in [37].

5.4 Numerical Results

In this section, we evaluate the performance of social-aware cooperative D2D data uploading. We first set some simulation parameters, and then evaluate and compare the average data uploading latency of our proposed approach and other approaches.

5.4.1 Simulation Settings

In the performance evaluations, we consider a radius of 500 m round area with the BS in the center, where $N = 50$ devices are randomly scattered within the coverage of the BS, and M devices need to upload data to the BS. To derive the data amount of M devices, we adopt the real datasets from [64] that matches the practical network scenarios. We assume that the locations of all devices are fixed during a D2D communication scheduling period, and the maximum communication distance between arbitrary two devices is denoted by d. In addition, a $10MHz$ spectrum band that operates at $2.5GHz$ carrier frequency is considered. The thermal noise density of both channels is $-174dbm/Hz$. Over the cellular channel, the transmit power of each device is $23dbm$, and the D2D channel transmit power is $-19dbm$.

We evaluate and compare the average data uploading latency of constrained coalition formation algorithm (CCFA) proposed in [25] and our proposed trust-aware assisted coalition formation algorithm (TCFA). We consider three different trust degrees to evaluate the average uploading latency, namely, no trust, partial trust and complete trust. In the first case, there is no social trust between any two devices. In the third case, there is complete trust between any two devices. In the second case, only partial devices are provided with the trust relationship. To describe partial trust, we assume that social edge e^s_{uv} exists between any user u and v with probability P_s, and the parameter value P_s is set as 0.8.

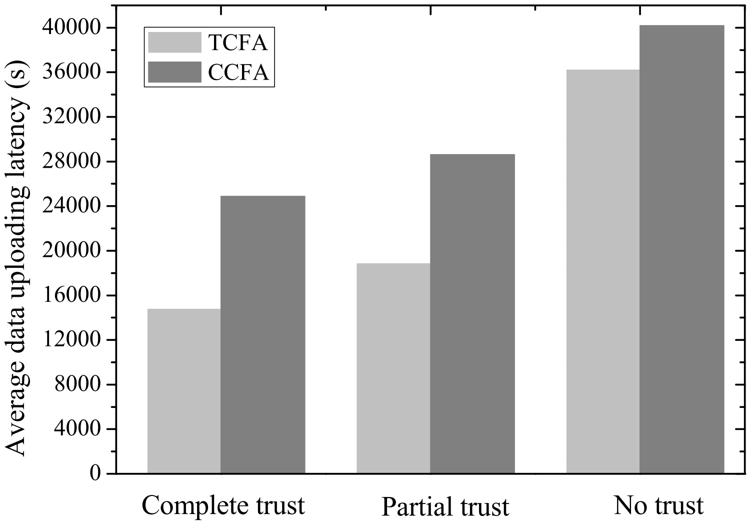

Figure 5-1: Comparison on the average data uploading latency between TCFA and CCFA for different trust degrees with $d = 100\ m,\ N = 50$ and $M = 30$.

5.4.2 Performance Analysis

In Figure 5-1, we compare the average data uploading latency using TCFA and CCFA with $N = 50, M = 30$, $d = 100m$ for different trust degrees. We observe that TCFA outperforms CCFA. Such behavior can be attributed to the reason that the devices without uploading data have occupied some radio resources in CCFA, but do not join any coalition. For our proposed TCFA, we only allocate radio resources to the devices with uploading data, and the devices without uploading data attend coalition formation if they can reduce the data uploading latency of other devices.

We also observe that, for different trust degrees, using complete trust is better than other two trust degrees for both algorithms (i.e.,TCFA and CCFA)). It is because that the devices with complete trust have more chances to participate in cooperation relationship compared to ones with partial trust. Under the case of no trust case, all devices need to directly upload their data to the BS, so they need more time to uploading data to the BS.

Figure 5-2 compares the average data uploading latency using TCFA and CCFA

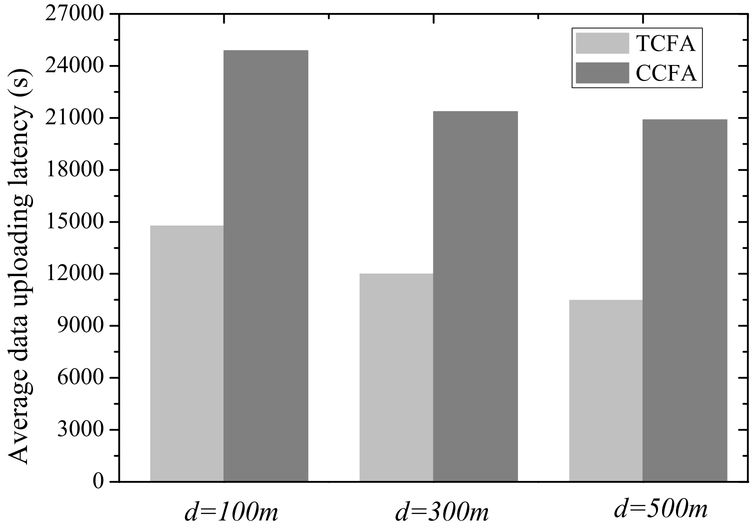

Figure 5-2: Comparison on the average data uploading latency between TCFA and CCFA for different communication ranges with $N = 50$, $M = 30$ and complete trust.

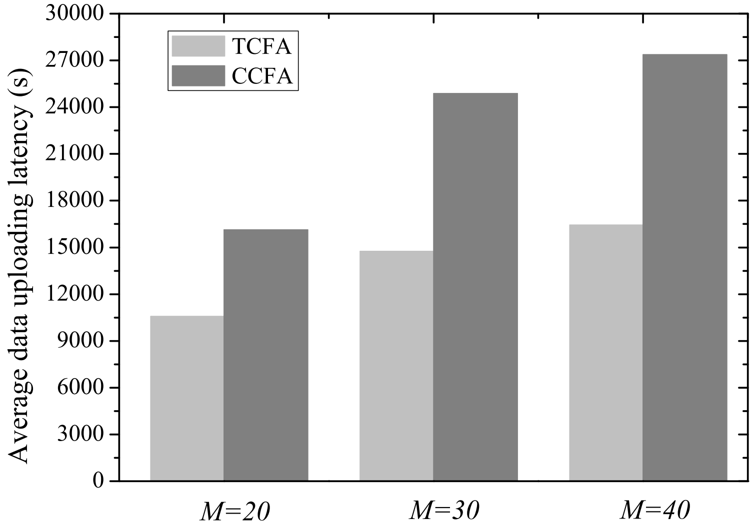

Figure 5-3: Comparison on the average data uploading latency between TCFA and CCFA for different number of devices with $d = 100\ m$, $N = 50$ and complete trust.

for $d = 100m$, $300m$, $500m$ with $N = 50$, $M = 30$ and complete trust among all devices. From the results in Figure 5-2, we can observe the similar conclusions as that in Figure 5-1. It is notable that, in both algorithms, the average data uploading latency decreases with the increase of communication distance d. This is due to the facts that more devices participate in cooperation with the increase of communication distance d. After the communication distance d increases to a certain value, the number of formed coalitions will not increase, and thus the average data uploading latency does not decrease even if the communication distance d increases.

To better understand the impact of M, we evaluate the average data uploading latency using TCFA and CCFA for $M = 20$, $M = 30$, and $M = 40$ with $d = 100m$, $N = 50$ and complete trust among all devices. As depicted in Figure 5-3, we can observe that the average data uploading latency in our proposed TCFA is greatly reduced compared to CCFA. We also observe that the average data uploading latency increases with the increase of device numbers M. This is because that more devices have more data amount.

5.5 Summary

This chapter investigated the impact of human social relationships on cooperative behaviors. A coalition game was then adopted to formulate the problem of D2D cooperation for data uploading. Based on formulated coalition game, we devised a coalition formation algorithm to construct D2D chains by adopting the bottom to top mode. Simulation results showed our proposed approach outperforms the state-of-the-art approaches under the real network scenario.

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Chapter 6

Social-aware Cooperative D2D Data Uploading with Incentive Mechanism

Under the social network scenario, this chapter proposes an incentive mechanism to motivate more devices to participate in D2D cooperation, such that data uploading latency can be reduced and data uploading reliability can be enhanced. With this incentive mechanism, the nearby devices can obtain rewards such that they are willing to construct a multi-hop D2D chain to assist the other devices in data uploading. To this end, we adopt coalitional game to formulate the D2D chain with careful consideration of social-aware data uploading, where each device acts as a player and the individual reward is modeled as the utility function. We further design a coalition formation algorithm with merge-and-split rules to determine the solution for formulated D2D chain. Extensive simulations are conducted to illustrate that the performance gain of our incentive mechanism outperforms that of non-incentive mechanism.

6.1 Design of Incentive Mechanism

Mobile devices exert their effort levels (e.g., the amount of energy and time spent) to perform data uploading tasks, and then the crowdsourcer can offer the virtual rewards (e.g., credit, penalties, etc.) to the devices for their contribution in return, which is called incentive mechanism. In our incentive mechanism, the reward received by device is determined by two factors: the data uploading latency and the data uploading reliability. The former represents the time duration from the beginning to the end of data delivery, while the latter which is used for assessing safety of data received by the BS is measured by trustworthy relationship. In the following part of this section, we take chain S with $1 \leq l \leq N$ devices as an example to calculate the reward of each device. First, we obtain the data uploading latency calculated by Chapter 3, and then we define and calculate the data uploading reliability. Finally, we provide a reward to devices which participate in cooperative D2D data uploading.

Considering the calculation method of the data uploading latency in Chapter 3, we obtain the data uploading latency from device $u \in S$, which is given by

$$t_u(S) = 20/3 \cdot \sum_{i=u}^{l-1} \sum_{j=u}^{i} b_j / r_i^d + 10/6 \cdot \sum_{j=u}^{l} b_j / r_l^c. \tag{6.1}$$

Since multiple devices are recruited to perform the same data uploading task in D2D cooperation, we define the data uploading reliability as a joint trustworthy relationship among multiple devices. This definition is realistic and general, and has been adopted in [66]. Here, the data uploading reliability of device $u \in S$, denoted by $s_u(S)$, can be expressed by

$$s_u(S) = \prod_{i=u}^{l-1} e_{u(u+1)}^s. \tag{6.2}$$

Corresponding the data uploading latency $t_u(S)$ and data uploading reliability $s_u(S)$ of device $u \in S$, the reward $c_u(S)$ offered by the crowdsourcer, which is inversely proportional to the data uploading latency $t_u(S)$ and directly proportional to the data uploading reliability $s_u(S)$, is defined by

$$\begin{aligned} c_u(S) &= \alpha/t_u(S) + \beta s_u(S) \\ &= \alpha/(\frac{20}{3}\sum_{i=u}^{l-1}\sum_{j=u}^{i}\frac{b_j}{r_i^d} + \frac{5}{3}\sum_{j=u}^{l}\frac{b_j}{{r_l}^c}) + \beta\prod_{i=u}^{l-1} e_{u(u+1)}^s, \end{aligned} \tag{6.3}$$

where $\alpha > 0$ and $\beta > 0$ are regarded as the scaling factors, which are used for describing incentive intensity.

When all devices of chain S achieve data uploading, the BS can offer the rewards, denoted by $C(S)$, to all members of chain S, which is defined by

$$\begin{aligned} C(S) &= \sum_{i=u}^{l} c_u(S) \\ &= \sum_{u=1}^{l}(\alpha/(\frac{20}{3}\sum_{i=u}^{l-1}\sum_{j=u}^{i}\frac{b_j}{r_i^d} + \frac{5}{3}\sum_{j=u}^{l}\frac{b_j}{{r_l}^c}) + \beta\prod_{i=u}^{l-1} e_{u(u+1)}^s). \end{aligned} \tag{6.4}$$

Then, the next step is how to construct multi-hop D2D chains to effectively distribute the rewards $C(S)$ to all members of each chain according to their individual contributions, so that the corresponding reward received by any device can be maximized. As a result, we employ a coalitional game to solve this issue and the details will be discussed in the followings.

6.2 Coalitional Game Formulation

In this section, we first introduce a nontransferable utility (NTU) coalitional game to formulate the problem of cooperative D2D chain formation under social-aware data uploading, and then analyze two essential properties of our concerned coalitional game: the superadditivity and core.

6.2.1 NTU Coalitional Game

In our work, the key issue is how to improve the rewards of the entire chain by D2D cooperation, and then effectively distribute the rewards to all members of the chain according to their individual contributions. Therefore, we employ a nontransferable utility (NTU) coalitional game to address this problem. For the sake of completeness, we first give a brief introduction to the NTU coalitional game [54], which is defined as follows.

Definition 1 : The NTU coalitional game is represented by the pair $(\mathcal{N}, \mathcal{V})$, where $\mathcal{N}$ is the set of players, and $\mathcal{V}$ is a characteristic function for each nonempty coalition $S \subseteq \mathcal{N}$ with $\mathcal{V}(S) \subseteq \mathbb{R}^{|S|}$. $\mathcal{V}(S)$ describes a set of payoff vectors $\mathbf{x}(S)$ of all players in coalition S, in which each element $x_u(S)$ of the vector $\mathbf{x}(S)$ is a payoff that player $u \in S$ can obtain through the feasible cooperation with other players in coalition S.

In our concerned coalitional game, $\mathcal{N}$ is the set of all devices in deployed area, which corresponds to game players. The payoff $x_u(S)$ of each player u in coalition S is measured as the reward $c_u(S)$ received by device u in chain S. To calculate the reward $c_u(S)$ received by device $u \in S$, we consider chain S with $u-1$ devices before the *uth* device participates in S, and the total reward of $u-1$ devices is labelled as $C'(S)$, which is obtained by formula (6.4). After the *uth* device participates in S, the total reward of u devices is determined as $C(S)$ by formula (6.4). Then the reward $c_u(S)$ received by device $u \in S$ is defined by

$$c_u(S) = C(S) - C'(S) = \textstyle\sum_{f=1}^{u}(\alpha \frac{t'_f - t_f}{t_f t'_f} + \beta(s_f - s'_f))$$

$$s.t. \begin{cases} t'_f = \frac{20}{3}\sum_{i=f}^{u-2}\sum_{j=u-1}^{i}\frac{b_j}{{r_i}^d} + \frac{5}{3}\sum_{j=f}^{u-1}\frac{b_j}{{r_{u-1}}^c}; \\ t_f = \frac{20}{3}\sum_{i=f}^{u-1}\sum_{j=u}^{i}\frac{b_j}{{r_i}^d} + \frac{5}{3}\sum_{j=f}^{u}\frac{b_j}{{r_u}^c}; \\ s_f = \prod_{i=f}^{u-1} e^s_{f(f+1)}; \\ s'_f = \prod_{i=f}^{u-2} e^s_{f(f+1)}. \end{cases} \tag{6.5}$$

In addition, each device u needs to consume its energy when it delivers data (its own and the received one) to the next device, and thus we calculate the energy consumption $e_u(S)$ of device u according to the calculation method in [25]. As we know, no feasible device is willing to receive a negative utility. That is to say, the reward $c_u(S)$ received by device $u \in S$ should satisfy following condition: $c_u(S) > e_u(S)$.

Considering the basic concepts from [54] and the device utility calculated above, we cast the chain formation problem for social-aware data uploading as a NTU coalitional game, which is represented by a triple $(\mathcal{N}, \mathcal{X}_{\mathcal{N}}, \mathcal{V})$, and then we formally depict the formulation of this game as follows.

- *Player.* The set of players $\mathcal{N}$ is the set of all devices.
- *Cooperative strategy.* The set of cooperative strategies $\mathcal{X}_{\mathcal{N}} = \{\mathcal{N}_u^p : \forall u \in \mathcal{N}\}$ represents the set of possible cooperators for device $u \in \mathcal{N}$ based on their cooperative database $\mathcal{N}_u^p$.
- *Characteristic function.* The characteristic function $\mathcal{V}(S)$ is the value for every coalition $S \subseteq \mathcal{N}$. It is a nontransferable payoff considering the reward $c_u(S)$ for any device $u \in S$, which depends on the feasible cooperations among all devices in S, without relationship on other devices out of S.

6.2.2 Property Analysis

Our concerned coalitional game refers to two essential properties: the superadditivity and core [56]. Then, we introduce the concept of superadditivity in the following.

Definition 2 : A NTU coalitional game $(\mathcal{N}, \mathcal{V})$ is said to be superadditive if for any two coalitions $S_1, S_2 \subset \mathcal{N}$ and $S_1 \cap S_2 = \phi$, the following condition holds

$$\begin{aligned} \mathcal{V}(S_1 \cup S_2) \supset \{&\mathbf{x}(S_1 \cup S_2) \in \mathbb{R}^{|S_1 \cup S_2|} | \\ &x_u(S_1) \in \mathcal{V}(S_1), x_v(S_2) \in \mathcal{V}(S_2)\}, \end{aligned} \tag{6.6}$$

where $\mathbf{x}(S_1 \cup S_2)$ is a payoff vector for coalition $S_1 \cup S_2$. Due to superadditivity, cooperation is always beneficial, and the players have an incentive to form the grand coalition where all players are in a coalition. Then we have the following theorem.

Theorem 1 : Our concerned coalitional game is nonsuperadditive.

Proof: Consider two disjoint coalitions S_1 and S_2 in cellular network with their corresponding payoff vectors $\mathbf{x}(S_1)$ and $\mathbf{x}(S_2)$ when they do not cooperate with each other. Here, we consider two cases to prove the nonsuperadditive of our concerned coalitional game. The first case is when the devices of coalitions S_1 and S_2 are without communication range with each other, and then coalitions S_1, S_2 can not construct coalition $S_1 \cup S_2$ by D2D cooperation. Therefore, the payoff vectors $\mathbf{x}(S_1 \cup S_2)$ obtained by coalition $S_1 \cup S_2$ is equal to the payoff vectors $\mathbf{x}(S_1)$ and $\mathbf{x}(S_2)$. The second one is that all devices of coalition $S_1 \cup S_2$ are within mutual communication range. We assume that the devices of coalitions S_1 and S_2 share all radio resources of coalitions S_1 and S_2, respectively. Furthermore, we assume that there exists interference among mobile devices between coalitions S_1 and S_2, and thus $t_u(S_1 \cup S_2) > t_u(S_1), \forall u \in S_1$ and $t_v(S_1 \cup S_2) > t_v(S_1), \forall v \in S_2$ according to the formula (6.1). In addition, we assume that $e^s_{uv} = 0$ for $\forall u \in S_1, v \in S_2$. Under the above confined conditions, if coalitions S_1 and S_2 can form coalition $S_1 \cup S_2$, we can obtain $c_u(S_1 \cup S_2) < c_u(S_1), \forall u \in S_1$ and $c_v(S_1 \cup S_2) < c_v(S_1), \forall v \in S_2$ according to (6.5). Therefore, $x_u(S_1 \cup S_2) < x_u(S_1), \forall u \in S_1$ and $x_v(S_1 \cup S_2) < x_v(S_2), \forall v \in S_2$, which is inconsistent with the definition of superadditivity. Thus, our concerned coalitional game is nonsuperadditive. As another key property, the core is defined as follows.

Definition 3 : The core of NTU coalitional game $(\mathcal{N}, \mathcal{V})$ is the set of payoff vector $(\mathbf{x}(\mathcal{N}) \in \mathcal{V}(\mathcal{N})$ where there is no coalition S and S-feasible payoff vector $(\mathbf{x}'(S) \in \mathcal{V}(S))$ so that $x'_u((S)) > x_u(\mathcal{N})$.

In other words, the core guarantees that no coalition S has incentives to leave the formed grand coalition and provides a better payoff for all members by deviating the formed grand coalition. Therefore, the formed grand coalition is stable if one can find a feasible payoff vector that lies in the core.

Theorem 2 : In general, the core of the grand coalition is empty.

Proof: In our concerned coalitional game, the devices in the same coalition may share same radio resources to maximize the system resource utilization. If there exists interference among simultaneously delivering devices in the formed grand coalition, the devices without uploading data deviate from the grand coalition as those devices are not allocated resources and do not share resource with other devices due to interference. Consequently, the payoff vector that lies in the core cannot be found, and the grand coalition is unstable as the core of our concerned coalitional game is empty. As a result, due to the nonsuperadditive, the grand coalition cannot form and the grand coalition is unstable as the core is empty. Instead, independent disjoint coalitions may form. Thus, we devise a coalition formation algorithm to find independent and disjoint coalition partitions.

6.3 Coalition Formation Algorithm

In this section, we first introduce coalition formation theory, which is used for analyzing how to formulate independent disjoint coalitions, and then develop a merge-and-split formation algorithm to determine the solution for D2D chain formulation.

6.3.1 Coalition Formation Theory

Coalition formation theory [56] has been an important research direction in coalitional game. It mainly analyzes the formation of coalitional structure when the grand coalition does not form. To describe coalitional structure, we introduce the concept of coalitional collection $\mathcal{S}$, which is defined as the set $\mathcal{S} = \{S_1, S_2, ..., S_k\}$ of mutually disjoint coalitions in $\mathcal{N}$ (i.e., $S_i \subset \mathcal{N}$ and $S_i \cap S_j = \phi$ for $\forall i, j$). If $\bigcup_{i=1}^{k} S_i = \mathcal{N}$, the collection $\mathcal{S}$ is called a coalitional structure (or a partition) of $\mathcal{N}$.

For finding a feasible coalition structure, we need to search all partitions of the set $\mathcal{N}$. The number of partitions of set $\mathcal{N}$ grows exponentially with the device number in set $\mathcal{N}$ and is given by a value known as the Bell number [57]. However, this approach for exhaustive search is an NP-complete problem [58], and thus it is not feasible. To derive the feasible coalitional structure, we introduce simple merge-and-split rules [59], which enable players of set $\mathcal{N}$ to join or leave a coalition based on the well-defined preferences. In other words, the player decides to join a coalition if it can increase own utility by this coalition. Likewise, the player considers leaving a coalition if it reduces individual utility from this coalition. To describe merge-and-split rules, we first introduce the concept of preference relation [59] for collection comparison.

Definition 4 : A preference relation $\triangleright$ is defined for comparing two collections $\mathcal{S} = \{S_1, S_2, ..., S_k\}$ and $\mathcal{S}' = \{S'_1, S'_2, ..., S'_l\}$ that are partitions of the same subset $\mathcal{A} \subseteq \mathcal{N}$. If $\mathcal{S} \triangleright \mathcal{S}'$, it implies that the partitions $\mathcal{S}$ of $\mathcal{A}$ is preferable to the partitions $\mathcal{S}'$ of $\mathcal{A}$.

Various well known orders can be used as preference relations [59]. These orders are split into two categories: coalition value orders and individual value orders. Coalition value orders compare two collections (or partitions) using coalition value. Individual value orders perform the comparison using the individual payoffs. In our work, we define the preference relation using individual value orders, due to the fact that our objective in coalitional formation is to increase the utility of each device. Let collections $\mathcal{S}$ and $\mathcal{S}'$ be the partition of $\mathcal{N}$, where the sets of individual payoffs $\mathbf{x}(\mathcal{S})$ and $\mathbf{x}'(\mathcal{S}')$ are resulted from the collections $\mathcal{S}$ and $\mathcal{S}'$, respectively. The preference relation for our concerned coalitional game is defined as follows

$$\mathcal{S} \triangleright \mathcal{S}' \Leftrightarrow \{x_u(\mathcal{S}) \geq y'_u(\mathcal{S}'), \forall u \in \mathcal{N} \quad and \quad x_u(\mathcal{S}) > x'_u(\mathcal{S}'), \exists u \in \mathcal{N}\} \tag{6.7}$$

This definition implies that collection $\mathcal{S}$ is preferred over collection $\mathcal{S}'$, if at least one player can improve its individual payoff without hurting other players' profits when coalitional structure changes from $\mathcal{S}'$ to $\mathcal{S}$. Based on our defined preference relation, we then introduce the merge-and-split rules [59], which are described as follows

- Merge Rule: Merge any set of coalitions $\{S_1, S_2, ..., S_k\}$ into a single new coalition $S' = \bigcup_{i=1}^{k} S_i$, if $S' \triangleright \{S_1, S_2, ..., S_k\}$.
- Split Rule: Split any coalition S' into multiple new coalitions $\{S_1, S_2, ..., S_k\}$, if $\{S_1, S_2, ..., S_k\} \triangleright S'$, where $S' = \bigcup_{i=1}^{k} S_i$.

The merge rule means that at least one player can improve its individual payoff while other players' payoffs do not be decreased through merge operation. Similarly, the split rule means that at least one player can obtain an increase for individual payoff through split operation, whereas no other players suffers decreasing on the payoffs.

6.3.2 Merge-and-Split Algorithm

Algorithm 1 Merge-and-split formation algorithm:

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1.  Initialize the set of the devices $\mathcal{N} = \{1, 2, 3, ..., N\}$ and $\mathcal{M} = \{1, 2, 3, ..., M\}$;
2.  Set the initial coalition structure $\mathcal{S}_{ini} = \mathcal{N}$ and the current coalition structure as
    $\mathcal{S}_{ini} \rightarrow \mathcal{S}_{cur}$.
3.  repeat
4.      Randomly select any two coalitions $S$ and $S'$ with communication range after
        merging;
5.      Calculate the utility of any device under coalition $S \cup S'$ and $\{S, S'\}$ according
        to (6.5);
6.      if $S \cup S' \triangleright \{S, S'\}$ then
7.          Merge $S$ and $S'$ into $S \cup S'$;
8.          Update the current partition $\mathcal{S}_{cur}$;
9.      end if
10.     Randomly select one feasible coalition $S = S_1 \cup S_2$ after splitting;
11.     Calculate the utility of any device under coalition $S$ and $\{S_1, S_2\}$ according
        to (6.5);
12.     if $\{S_1, S_2\} \triangleright S$ then
13.         Split $S$ into $S_1$ and $S_2$;
14.         Update the current partition $\mathcal{S}_{cur}$;
15.     end if
16. until A stable coalition structure $\mathcal{S}_{fin}$ forms.
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Based on merge-and-split rules, we devise a coalition formation algorithm to obtain the solution for the formulated coalitional game, as summarized in Algorithm 1. In this Algorithm, we first initialize the system by $\mathcal{N}$, $\mathcal{M}$, $\mathcal{S}_{ini}$, $\mathcal{S}_{cur}$ in lines 1-2, where we assume that all devices in set $\mathcal{N}$ are noncooperative, and then we iteratively construct a stable coalition structure $\mathcal{S}_{fin}$ from lines 3-16. In each iteration, we randomly select any two coalitions S and S' with mutual communication range, and then calculate the utility of any device under coalition $S \cup S'$ and $\{S, S'\}$ according to (6.5). If $S \cup S' \triangleright \{S, S'\}$, we merge coalitions $\{S, S'\}$ into a single new coalition $S \cup S'$, and update the current coalition structure $\mathcal{S}_{cur}$. Otherwise, it remains unchanged. The merging procedure repeats until no couple of coalitions can be merged. Similarly, we randomly select one feasible coalition $S = S_1 \cup S_2$, and then calculate the utility of any device under coalition S and $\{S_1, S_2\}$ according to (6.5). If $\{S_1, S_2\} \triangleright S$, we split coalitions S into two coalitions S_1 and S_2, and update the current coalition structure $\mathcal{S}_{cur}$. Otherwise, it remains unchanged. The splitting procedure repeats until no coalition can be split. If all coalitions from the current coalition structure have been checked through merging or splitting and no one coalition structure is most preferable, the procedure is terminated and a stable coalitional structure S_{fin} forms.

6.4 Algorithm Analysis

In this subsection, we investigate three important properties of the proposed coalition formation algorithm in terms of convergence, stability and computation complexity. As coalition formation algorithm constructed by merge-and-split rules can converge, which is proved by [59], and thus we give corresponding analysis for stability and computation complexity as follows.

6.4.1 Stability Analysis

In our work, we prove theoretically that our proposed coalition formation algorithm converges to a stable coalition structure with disjoint coalitions by adopting the defection function $\mathbb{D}_{hp}$ [59], [61], which is mainly used for assessing the partition stability resulting from the merge-and-split rule, and is defined in [41].

Definition 5 : A coalition structure $\mathcal{S}$ is $\mathbb{D}_{hp}$-stable if no players in $\mathcal{S}$ benefits from leaving current $\mathcal{S}$ and forming other coalition structures of $\mathcal{N}$ by executing a merge or a split operation.

Obviously, a coalition structure $\mathcal{S} = \{S_1, S_2, ..., S_k\}$ is $\mathbb{D}_{hp}$-stable if and only if the following two conditions are satisfied [61].

- For any $i \in \{1, 2, ..., k\}$ and the partition $\{A_1, A_2, ...A_l\}$ of any coalition S_i, $\{A_1, A_2, ...A_l\} \not\triangleright S_i$, where $\not\triangleright$ is the opposite rule of the preference order $\triangleright$.

- For each $W \subseteq \{1, 2..., k\}$ and $u \in \bigcup_{i \in W} S_i$, $\bigcup_{i \in T} S_i \not\triangleright \{S_i | i \in W\}$.

With the definition of $\mathbb{D}_{hp}$-stable, we prove our formed coalition structure $\mathcal{S} = \{S_1, S_2, ..., S_k\}$ is $\mathbb{D}_{hp}$-stable according to Theorem 3.

Theorem 3: Every the outcome of iteration from our proposed merge-and-split formation algorithm is $\mathbb{D}_{hp}$-stable.

Proof: After every iteration of merge-and-split algorithm, every device cannot leave the current coalition structure through merge or split operation without increasing its utility. Therefore, the formed coalition structure $\mathcal{S}$ cannot further merge or split. We assume that $\mathcal{S} = \{S_1, S_2, ..., S_k\}$ is the coalition structure resulting from our proposed merge-and-split formation algorithm. If for the partition $\{A_1, A_2, ...A_l\}$ of any coalition $S_i \in \mathcal{S}$, we have $\{A_1, A_2, ...A_l\} \triangleright S_i$, so the coalition S_i can perform a split operation, which contradicts with our formed coalition structure $\mathcal{S}$ resulting from merge-and-split iterations. Therefore, the first $\mathbb{D}_{hp}$ stability condition is verified. In addition, the similar method can prove the second $\mathbb{D}_{hp}$ stability condition. When the above conditions hold, we prove that our formed coalition structure $\mathcal{S}_{fin}$ obtained from Algorithm 1 is $\mathbb{D}_{hp}$-stable.

6.4.2 Complexity Analysis

We consider the computational complexity of our proposed coalition formation algorithm. The complexity of this algorithm is determined by the number of iteration of merge-and-split operations. In the deployment scenario, the system consists of N non-cooperative devices. In order to guarantee maximizing cooperation with each other, each device needs to make a merge operation with other devices in $\mathcal{N}$. In the worst case, the first device needs $\frac{N \cdot (N-1)}{2}$ merge operations, the second needs $\frac{(N-1) \cdot (N-2)}{2}$ operations and so on. The total number of merge operations will be $O(N^3)$. In practice, the merge process requires the rather less number of operations. The three reasons are illustrated as follows: once two devices merge, it does not require to go through other merge operations, and thus the number of merge operations will decrease. Moreover, each device only attempts to merge the devices with communication range. Finally, after the first merge-and-split iteration, most of devices merge to form larger coalitions, the number of the rest devices which makes the subsequent iteration is much smaller than N.

In addition, we analyze the complexity of the split operation. Generally speaking, the split operation involves finding all possible partitions of each coalition in formed coalition structure. In the worst case, splitting a coalition S requires to make $O(2^{|S|})$ attempts. In practice, this split operation is restricted to the formed coalition structure. Combined the individual utility with communication range of the device, the size of the coalitions is quite small. Thus the complexity of the split operation is reduced. Moreover, once a coalition finds a split operation according to preference relationship, this coalition will split and the further split operation is not required. Therefore, this complexity is further reduced. In other words, the complexity of split operation can be neglected. Finally, our proposed coalition formation algorithm has a computational complexity of $O(N^3)$.

6.5 Numerical Results

In this section, we provide simulation results to evaluate the performance of our proposed incentive mechanism. The evaluating settings, the impact of different parameters and the performance comparison with non-incentive mechanism are presented as follows.

6.5.1 Evaluating Settings

We carry out the simulations in a 1000 $m \times 1000$ m square area within the base station in the center, in which N mobile devices within the number range of $0 \sim 50$ are randomly distributed within the coverage of the BS. In our simulation, we assume that $M \leq N$ devices need to upload data to the BS and data amount b_u for each device u is uniformly generated according to the real datasets from [64], which is assessed by the MPEG-2 encoding standard [67]. Since we use such a random approach to distribute all devices, we assume that the locations of all devices remain unchanged

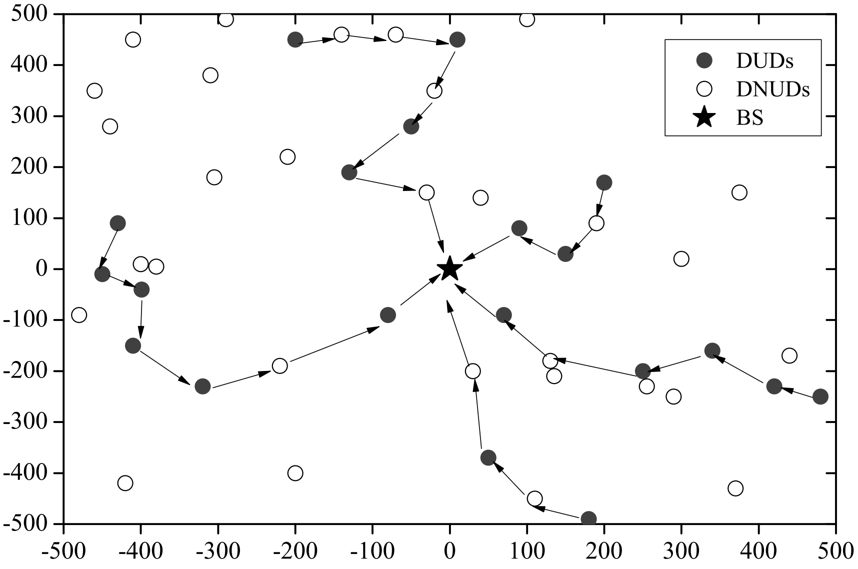


Figure 6-1: Sample of a stable coalitional structure resulting from our scheme with $N = 50$, $M = 20$.

under each simulation scenario and communication distance between any two devices is set 100 m. To obtain the average of simulation results, we execute the simulations by 500 times, and each time with random-generated locations.

As an illustration for sample scenario in the simulation, we randomly generate the positions of the BS, the devices with uploading data (DUDs) and the devices without uploading data (DNUDs) in Figure 6-1. In this figure, the BS, the DUDs and DNUDs are represented as solid star, solid circle and hollow circle, respectively. Additionally, we also show the snapshot of the final coalition structure formed by our proposed algorithm under the above simulation scenario, where all devices form 5 coalitions by D2D cooperation, and each formed coalition is connected by arrow line.

To describe social relationships among different users holding these mobile devices, we construct social relationship graph G^s by adopting the Erdós-Rényi (ER) graph model [68], where social edge exists between each pair of users with probability P_s. If social edge between any user u and v exists, social trust e^s_{uv} between them follows a normal distribution $N(\mu, \sigma)$ with mean μ and variance σ [69]. We set the parameter values of social networks as follows: $P_s = 0.8, \mu = 4$, and $\sigma = 2$.

In our simulation, we assume that the uplink channel for cellular transmission mode and D2D transmission mode is modeled as the Rayleigh fading channel [32], which takes the large-scale shadowing and the small-scale fading into consideration. Additionally, we assume that the path losses of uplink channels with both transmission modes are calculated based on the free space propagation loss model [50], where the channel coefficient h_{uv} on link $u \rightarrow v$ follows the independent complex Gaussian distribution $\mathcal{CN}(0, 1)$, and the path loss compensation factor is 2. We consider a 10 MHz spectrum band used by cellular transmission and D2D transmission mode that operates at 2.5 GHz carrier frequency. Over the cellular transmission, the transmission power of any device is 23 dbm, whereas the transmission power is -19 dbm for D2D transmission. Both transmissions are with the thermal noise density level -174 dbm/Hz. To depict the different incentive intensity, we assume that the scale factor α varies within a range of $0 \sim 1000$, and the scale factor β varies from 0 to 1000.

As discussed by previous section, we adopt TDD mode to reassign radio resources to all devices of the same chain, where the devices in the same chain share either the same or different resources according to the interference level experienced on simultaneously delivering devices. In our work, we consider two extreme resource sharing modes: one is the best case and the other is the worst case. The former means no interference among simultaneously delivering devices in the same chain, where all radio resources of the chain can be shared on the D2D uplink. The latter corresponds to interference among all simultaneously delivering devices in the same chain, and thus the allocated resources of each device in advance are used on the D2D uplink. We analyze the above two cases which represent the lower and upper bounds and all other cases of radio resource sharing in the chains fall on them.

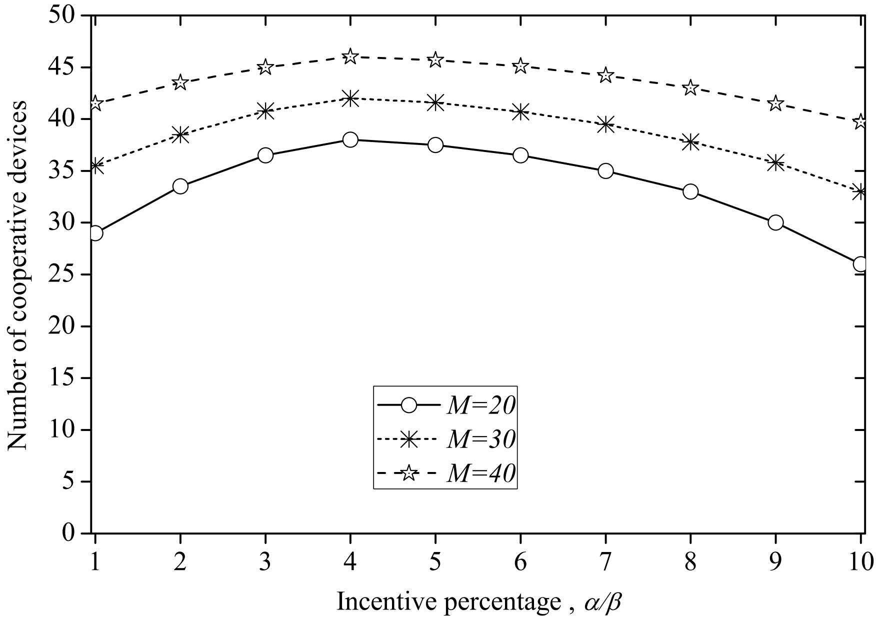
To show the efficiency of our incentive mechanism with social-aware data uploading denoted by SDUM, we compare the performance of our proposed SDUM with generalized data uploading scheme (GDUS) proposed by [70]. As discussed by Chapter 4, our work is different from the previous one, which focuses on cooperative D2D data uploading without consideration of incentive mechanism. However, our current work achieves cooperative D2D data uploading with consideration of the impact of incentive mechanism. In our simulations, we take the following three evaluation metrics into consideration:

- Number of cooperative devices, which is the number of participators that assist in delivering data.
- System sum utility, which is the aggregated utility obtained by all participating devices according to (6.5), i.e., $\sum_{u=1}^{N} c_u$
- Successful ratio, which is the ratio between the number of data packet uploaded successfully by cooperative devices and the total number of data packet generated by all devices. Here, a successfully data uploading means that the data uploading latency is no larger than the tolerable latency t_0, and the data uploading reliability is no less than the tolerable reliability s_0.

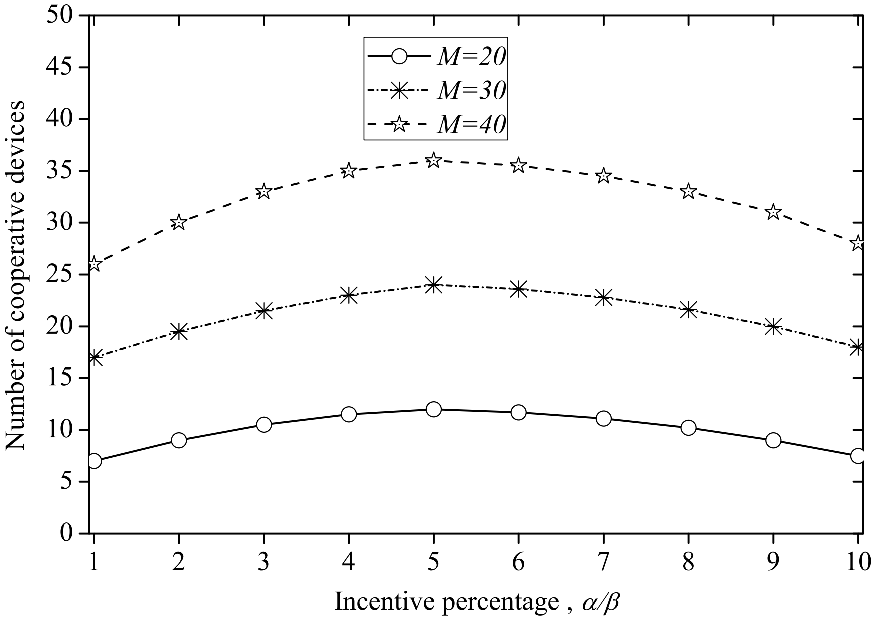
6.5.2 Impact of Different Parameters

To better understand the performance of our proposed SDUM, we next conduct a series of sensitivity experiments by adjusting various system parameters. Firstly, we analyze how to select scale factors α and β to maximize the number of cooperative devices, and then evaluate the impact of scale factors α and β on system sum utility.

Figure 6-2 shows number of cooperative devices as a function of the value of incentive percentage, defined as the scale factor α divided by the scale factor β, under $M = 20, 30, 40$. To better understand the impact of scale factor α and β, both best case and worst case are considered and compared. From the curves in Figure 6-2(a), we see that there exists a best value of α/β which makes number of cooperative devices reach the peak value. As mentioned in Section 6.1, the value of scale factor α and β reflect incentive intensity and are used for motivating devices to participate in D2D cooperation. When α is too small or β is too big, the incentive mechanism does not work effectively since the devices are not willing to participate in D2D cooperation with such a low payoff. When α is too big or β is too small, the number of cooperative devices is seriously affected by the data uploading latency so



(a) Best case



(b) Worst case

Figure 6-2: Number of cooperative devices versus incentive percentage under $M = 20, 30, 40$ for (a) best case and (b) worst case.

that it neglects the incentive impact of data uploading reliability. Therefore, there exists one optimal value of incentive percentage, i.e., $\alpha/\beta = 4$, with which the most devices can be motivated to participate in D2D collaboration. From Figure 6-2(b), we can see that the best value of incentive percentage for the worst case is 5.

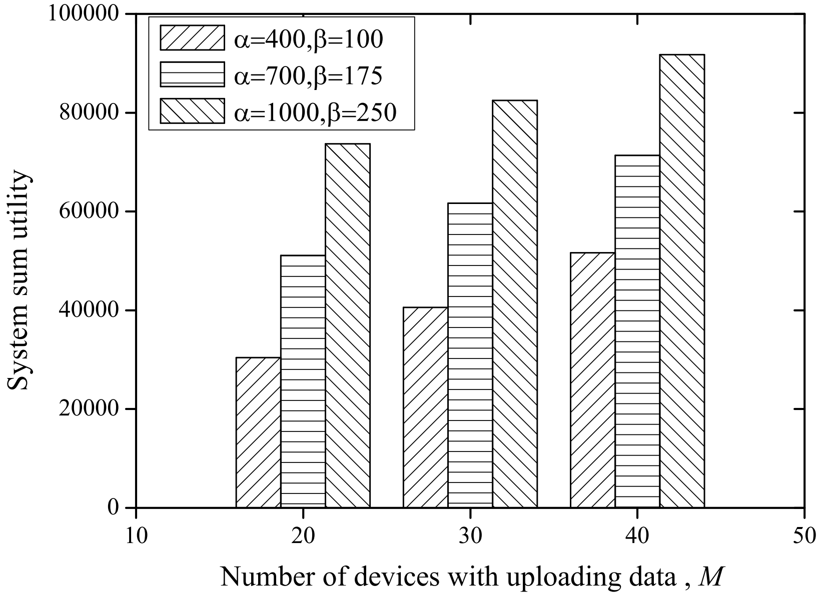
Additionally, from both Figure 6-2 (a) and (b), we also observe that one bigger M can lead to that more devices take part in constructing D2D cooperation chain. Such behavior can be attributed to the reason that bigger M means the data uploading tasks are more in the network. Therefore, in order to gain more payoffs from the publicized tasks, more devices are inclined to participate in uploading the tasks by cooperating with others.

We plot Figure 6-3 to show the effect of the different number of devices with uploading data (i.e., $M = 20, 30, 40$) on the system sum utility under both the best and worst cases. Form Figure 6-3, we can observe that adopting more devices can improve the system sum utility. Furthermore, we can also note that as the scale factor α and β increases, system sum utility can be further improved for any device number M, which can be proved by formula 6.5. While α and β increasing for either the best case or worst case, the reward that each device received by participating in data uploading will increase, and improve the system sum utility.

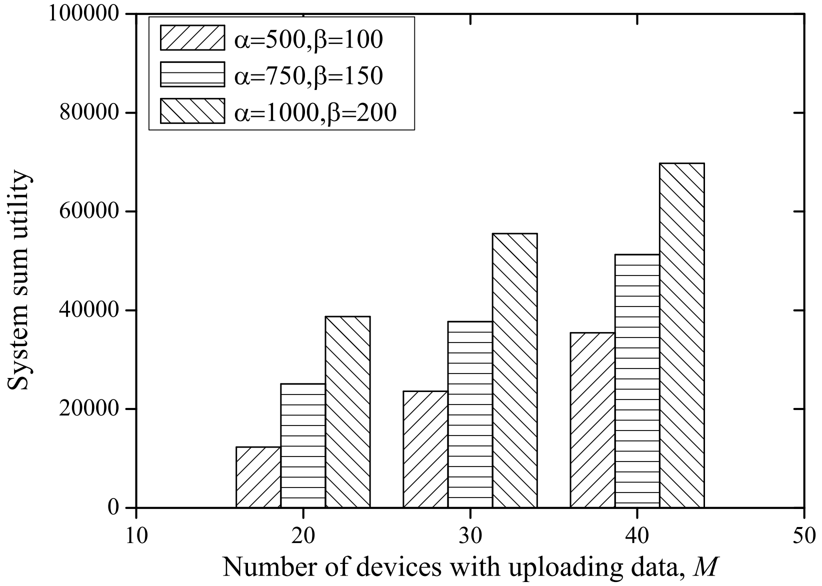
6.5.3 Comparison with Other Uploading Scheme

To demonstrate the effectiveness of the proposed SDUM, we evaluate the performance of the GDUS and the SDUM on successful ratio in terms of the tolerable latency t_0, the tolerable reliability s_0 and the number of the devices with uploading data M. In the performance comparison, we implement the experiments with $M = 50$, the default threshold $t_0 = 3000$ and $s_0 = 3$. The default optimal value under best case and worst case are given as $\alpha = 1000, \beta = 250$ and $\alpha = 1000, \beta = 200$, respectively.

Figure 6-4 presents the successful ratio with the variations of tolerable latency t_0 and tolerable reliability s_0 under best case and worst case. From Figure 6-4, we can see that as the tolerable latency t_0 increases and the tolerable reliability s_0 deceases, the successful ratio increases. This result is consistent with our expectation. Besides,

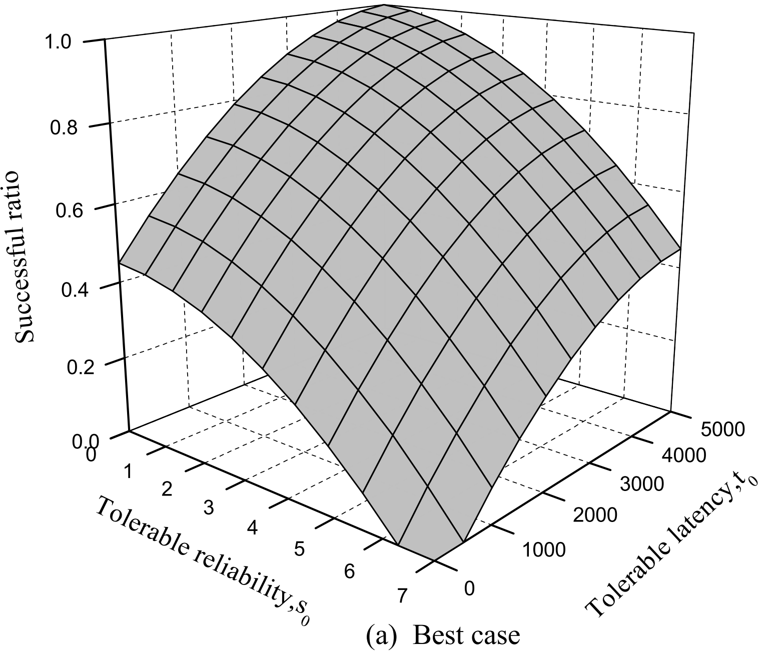


(a) Best case

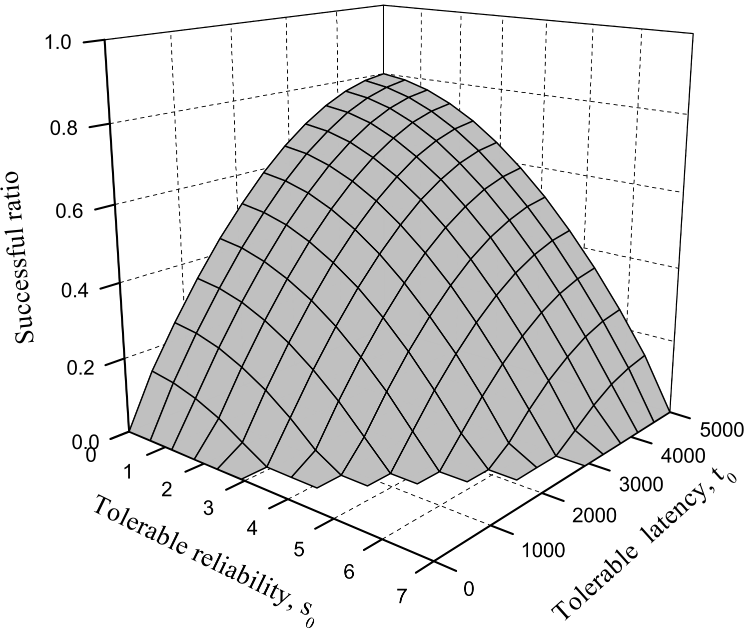


(b) Worst case

Figure 6-3: System sum utility versus number of devices with uploading data under different incentive intensity α and β for (a) best case and (b) worst case.



(a) Best case



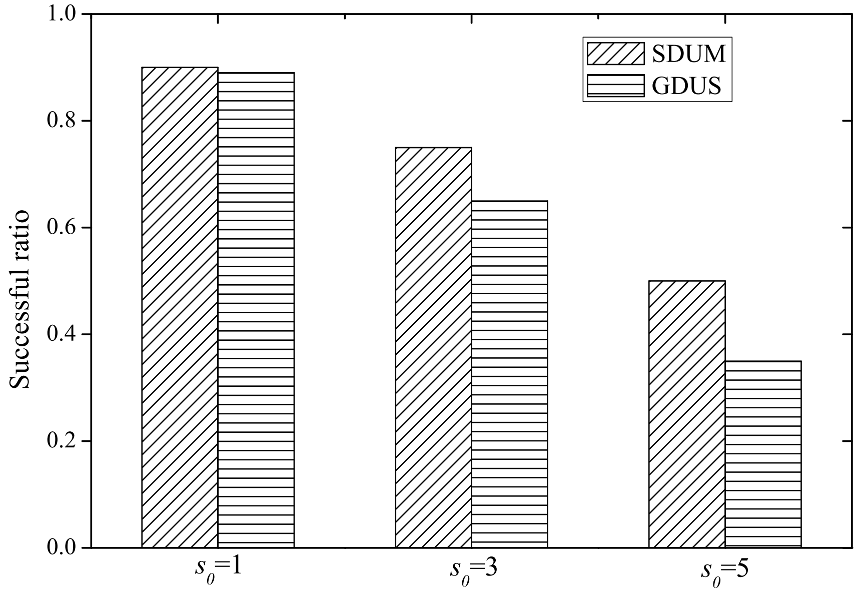
(b) Worst case

Figure 6-4: Successful ratio from our scheme versus the tolerable latency t_0 and the tolerable reliability s_0 for (a) best case and (b) worst case.

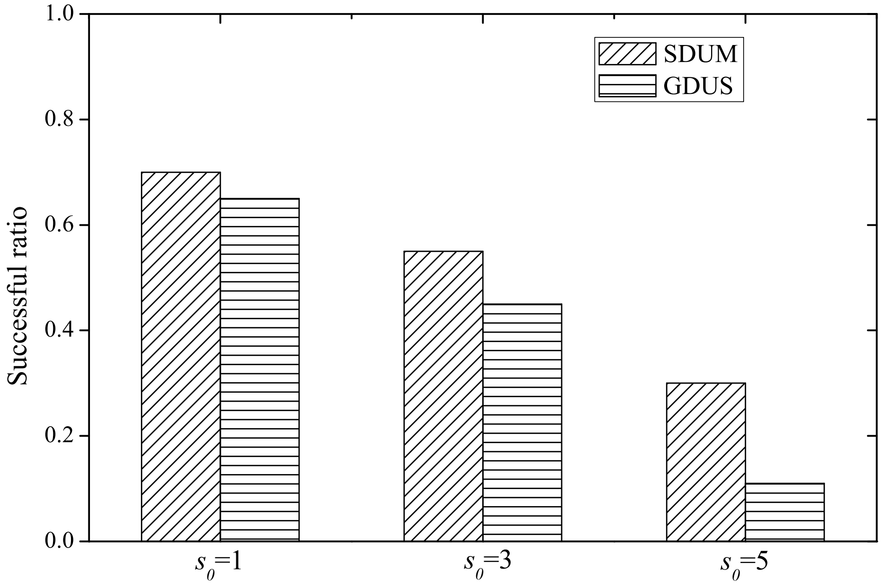
we also see that the successful ratio of worst case is smaller than that of best case under the same parameter setting. This is because in worst case, in order to avoid the interference among simultaneously delivering devices in the same coalitions, each device of coalitions utilizes allocated orthogonal resources in advance, which reduces data uploading latency of each device of coalitions. While the best case considers no interference among simultaneously delivering devices in the same coalitions, and then mobile device in the same coalitions can share the radio resource with each other, which increases data uploading latency of each device of coalitions. However, there is no decrease on data uploading reliability for each device, and thus, successful ratio of best case is better than that of best case.

Considering the result in Figure 6-4, we select the three groups of typical threshold s_0, t_0 and then compare and evaluate successful ratio of SDUM and GDUS using three groups of typical threshold s_0, t_0. Figure 6-5 shows successful ratio versus the tolerable reliability s_0 and tolerable latency t_0 using SDUM and GDUS for best case and worst case. From Figure 6-5, we note that the trends of the GDUS are similar with those of SDUM. but the gaps between both approaches become widen as the tolerable reliability s_0 increases. This is because the incentive cost of data uploading reliability is not considered by GDUS, while our SDUM considers the incentive impact of data uploading reliability on motivating D2D cooperation among devices, and thus, we can find from Figure 6-5 that the influence of s_0 on successful ratio for GDUS is higher than our SDUM. Similar analysis stands for the curves in Figure 6-6, in which the gaps between both approaches become narrowed as the tolerable latency t_0 increases.

Figure 6-7 shows successful ratio as a function of the number of the devices with uploading data using SDUM and GDUS. In the performance comparison, best case and worst case are considered. From Figure 6-7(a), we can note that the successful ratio of both SDUM and GDUS increases as the number of the devices with uploading data M increases, and turn out to be diminishing returns, which can be explained as below. As the number of the devices with uploading data is becoming more, there are more data uploading tasks in the deployed area, so more devices are inclined to participate in uploading tasks since there is more opportunity for them to gain high

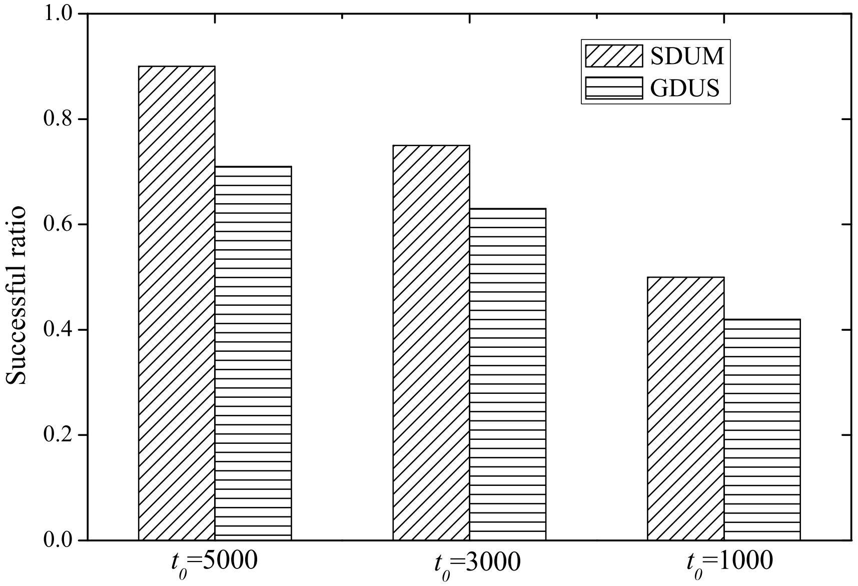


(a) Impact of reliability under best case

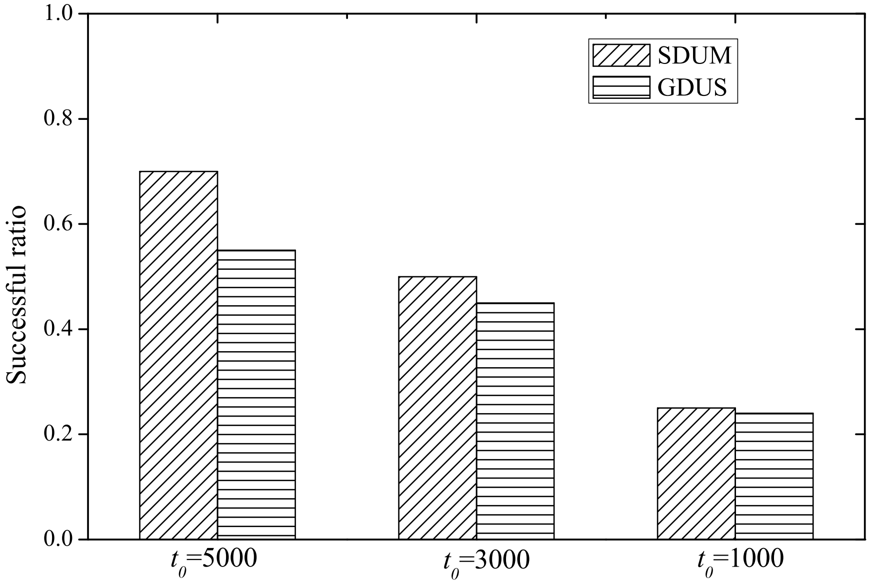


(b) Impact of reliability under worst case

Figure 6-5: Successful ratio for SDUM and GDUS using three typical tolerable reliability s_0 for best case and worst case.

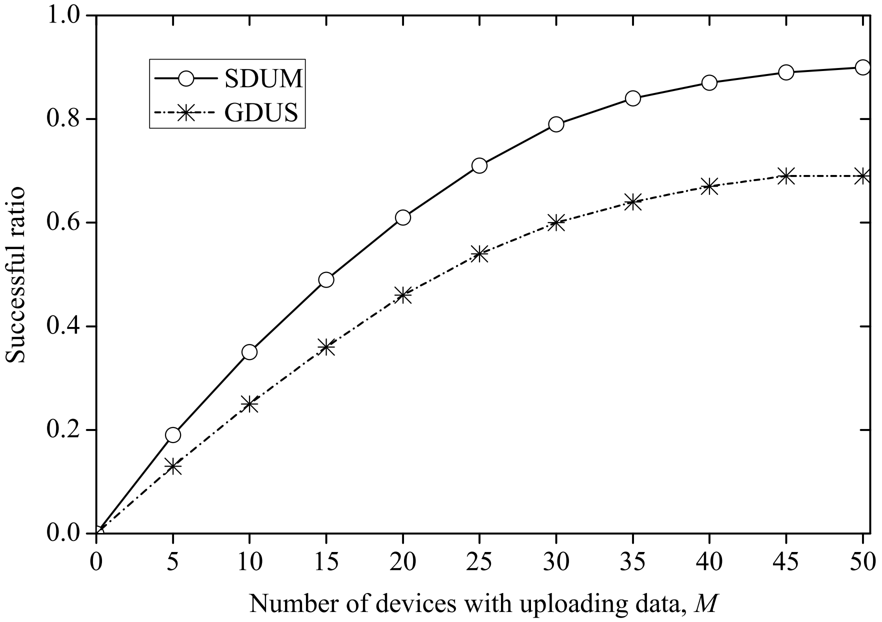


(a) Impact of latency under best case

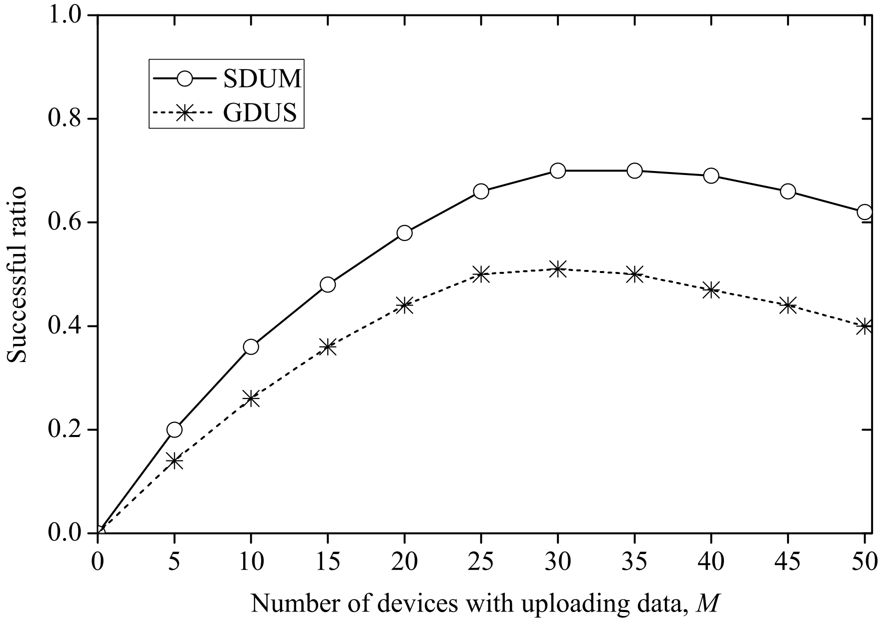


(b) Impact of latency under worst case

Figure 6-6: Successful ratio for SDUM and GDUS using three typical tolerable latency t_0 for best case and worst case.



(a) Best case



(b) Worst case

Figure 6-7: Successful ratio versus number of the devices with uploading data using SDUM and GDUS for (a) best case and (b) worst case.

profits from those newly publicized tasks. However, each device only participates in one coalition, when there are too many tasks in the networks, D2D cooperation between devices become saturated, and thus the successful ratio increases to reach a stable value, which leads to the diminishing returns of the curves.

Besides, we also note from Figure 6-7(b) that when M is small for the worst case, the trends of SDUM and GDUS are similar with those of best case. However, when M is large, successful ratio with both schemes will decrease as the number of the devices with uploading data M increasing. Due to the fact that the total radio resource keeps unchanged, but the allocated radio resource of each device becomes less with increase of device number M, which leads to a higher data uploading latency. Therefore, there must exist a optimal M with which the successful ratio reaches the maximum value, i.e., the trade-off between the allocated radio resource and data uploading tasks can be achieved. In both cases, as the number of the devices with uploading data M increases, the gap between SDUM and GDUS becomes bigger and bigger, such behavior can be attributed to the incentive impact of data uploading reliability on successful ratio, which makes the SDUM perform better than the GDUS.

6.6 Summary

In this chapter, we studied social-aware data uploading underlaying cellular networks with consideration of D2D communications. A new incentive mechanism was proposed to compensate the resource consumption of devices on data uploading. To maximize the individual reward, the devices in proximity were willing to construct a multi-hop D2D chain to assist the other devices for data uploading. After that, we introduced coalitional game to formulate the problem of social-aware data uploading based D2D cooperation among devices, and then devised a merge-and-split formation algorithm to obtain the solution for formulated D2D chain. Through extensive simulations, we obtained the optimal scale factor α and β for best case and worst case, and then we provided numerical results to demonstrate the effectiveness of the proposed SDUM in terms of successful ratio by comparison with the GDUS.

Chapter 7

Conclusion

This chapter summarizes our contributions and discusses the future research directions.

7.1 Summary of the Thesis

In this thesis, we studied the low-latency data uploading in D2D-enabled cellular networks with the help of device cooperation, human social relationship and incentive mechanism. First, we considered D2D cooperation among both the devices with uploading data and the ones without uploading data and proposed a generalized cooperative data uploading scheme to reduce data uploading latency. Considering the data uploading reliability, we further investigated the impact of human social relationships on cooperative behaviors, where the nearby devices with mutual trust can build D2D cooperative relationships. Under this social network scenario, an incentive mechanism was finally proposed to motivate more devices to participate in the D2D cooperation, such that the data uploading latency can be further reduced and data uploading reliability can be enhanced. The main contributions of this thesis are summarized as follows.

- For generalized cooperative data uploading scheme, we introduced a NTU coalitional game to formulate the problem of D2D cooperation among the devices.

Then we devised a merge-and-split formation algorithm to obtain the solution for the formulated coalitional game, where the devices within communication range were rewarded to establish D2D cooperation and then formed the multi-hop D2D chains for data uploading. It is expected that our proposed scheme can effectively reduce the average data uploading latency compared to the existing schemes.

- For cooperative D2D data uploading with the consideration of human social relationship, we investigated the impact of human social relationships on cooperative behaviors, and then formulated the problem of D2D cooperation as a coalitional game. Based on the formulated coalitional game, we further devised a chain formation algorithm to implement D2D chain construction, where the devices with the poor uplink channel quality were first considered to join D2D cooperation and the bottom to top mode was adopted to construct the D2D chains. The numerical results demonstrated that the average data uploading latency can be futher reduced by adopting our proposed algorithm.
- In Chapter 6, we investigated cooperative D2D data uploading in social network scenario. An incentive mechanism was then adopted to motivate more devices to participate in the D2D cooperation. With this incentive mechanism, the nearby devices can obtain reward such that they were willing to construct a multi-hop D2D chain to assist the other devices for data uploading. To this end, we adopted coalitional game to formulate the D2D chain with careful consideration of social-aware data uploading, and then designed a coalition formation algorithm with merge-and-split rules to determine the solution for formulated D2D chain. Extensive simulation results indicated that the performance gain of our incentive mechanism outperforms ones with non-incentive mechanism.

7.2 Future Work

We summarize the future interesting directions as follows.

- In this thesis, we study the data uploading in cellular networks with the consideration of D2D cooperation among static devices, one interesting future direction is to further explore the impact of device mobility on cooperative behaviors, which has been largely neglected in most literature.

- We only focus on how to forward data to the BS with high-reliability and low-latency, another interesting direction is how to recruit the devices to collect data by leveraging D2D cooperation while satisfying the coverage probability over the field of interest. It is also interesting to guarantee reliable service quality and wide-area coverage.

- It is notable that our studies in this thesis consider cooperative D2D data uploading in 4G LTE cellular networks, so that the data uploading latency can be greatly reduced. Another interesting direction is to further extend the current 4G cellular system to the fifth generation (5G) communication system, which can provide high data rates, high resource utilization, low latency, high system capacity and quality of service (QoS). Thus, it will be interesting topic to develop cooperative D2D data uploading scheme in 5G cellular networks, and really worth making progress step by step.

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