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Cross-Layer Optimization for Cooperative Content Distribution in Multihop Device-to-Device Networks

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***Abstract*—With the ubiquity of wireless network and the intelligentization of machines, internet of things (IoT) has come to people's horizon. Device-to-device (D2D), as one advanced technique to achieve the vision of IoT, supports a high speed peer-to-peer transmission without fixed infrastructure forwarding which can enable fast content distribution in local area. In this paper, we address the content distribution problem by multi-hop D2D communication with decentralized content providers locating in the networks. We consider a cross-layer multi-dimension optimization involving frequency, space, and time, to minimize the network average delay. Considering the multicast feature, we first formulate the problem as a coalitional game based on the payoffs of content requesters, and then, propose a time-varying coalition formation based algorithm to spread the popular content within the shortest possible time. Simulation results show that the proposed approach can achieve a fast content distribution across the whole area, and the performance on network average delay is much better than other heuristic approaches.**

***Index Terms*—cross-layer optimization, device-to-device, content distribution, multihop transmission, coalition formation game.**

I. Introduction

A. Background and Motivation

BASED on the requirements of network ubiquity and machine intelligence in future economic production and life, the concept that internet of things (IoT) has come to people's horizon [1], and the interconnection of all things has boosted the development of quite a number of techniques [2]. Device-to-device (D2D) communication, as one of the critical components for the next generation mobile networks, supports a high speed peer-to-peer transmission without fixed infrastructure data forwarding [3]. Due to the flexibility of network deployment, the advantage of proximity connection on data rate, and the capability of cellular data offloading, D2D has also been considered as one advanced technique to achieve the vision of IoT [4], [5].

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One distinct advantage of D2D communication is that it can dramatically improve the spectrum efficiency and network throughput by reusing cellular radio resources [6]–[9]. Based on the data analysis report provided by Cisco [10], the wireless data traffic is mainly distributed in local hotspots, where it exists an extremely high user density, e.g., a playground, a public transport, a conference hall, and so on. In such areas, high volumes of data traffic always lead to network congestion and user interruption [11]–[14]. Actually, a situation occurred frequently that most of users in the hotspots request for the same content. For instance, visitors attempt to download the electronic map or other multimedia information of a playground. In a traditional way, the content has to be transmitted repeatedly from a fixed infrastructure to each visitor, which seriously degrades the system performance [15]. Therefore, D2D technique can be applied to distribute the popular content from the content holder to interested users directly via single-hop or multihop transmission, offloading large amounts of data from infrastructures [16].

Some existing works have paid attention to content distribution through D2D communications [17]–[21]. Most of these researches consider a centralized content provider, i.e., the base station (BS), who pushes the requested content to a set of selected users as seeds first, and then the seed users transmit the content to others in their multicast group by D2D links. In such case, the BS cannot completely separate itself from data downloading process, which still places a burden of data traffic on the BS. Therefore, we put emphasis on content distribution problem with some decentralized content providers locating in the hotspot, which have already acquired the content from the BS or other fixed infrastructures.

The above mentioned scenario brings large challenges to the system. Firstly, the locations of content holders (transmitters) are random and uncertain, which makes it difficult to determine the multicast group. Especially for the users with terrible channel conditions from any transmitter, they may need multihop transmissions to obtain the data, and thus, the routes of content distribution need to be optimized. Secondly, average transmission delay is one of the most important indicators used to measure the network performance, and there is a tradeoff between a single-hop and a multihop link on minimizing the network average delay. In addition, since the D2D links reuse the cellular spectrum that brings co-channel

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interference to both cellular and D2D layers, an efficient resource allocation scheme for D2D multicasting is required to further optimize the system performance. Based on these considerations, the core objective of our work is to spread the popular content that initiated from decentralized content holders within the shortest possible time.

B. Contributions

In this paper, we study a cross-layer optimization method for cooperative content distribution by combining media access control (MAC) layer and network layer involving three dimensions, i.e., frequency, space, and time. Considering the cooperative relationship among D2D users, we employ cooperative game [22] to solve the content distribution problem. Specifically, we model the process of multicast group establishment as a coalition formation game [23], in which players form coalitions to improve their own profits. Some works have used the coalition formation game for content downloading in vehicular networks [24] and spectrum sharing in D2D underlay networks [25]. In our problem, the cooperator locations, multihop routes, and co-channel interferences should be jointly considered. The main contributions are summarized as below:

- We investigate a cross-layer design for content distribution to completely offload the cellular data from the BS by multihop D2D networks. We propose a coalition formation game to determine the multicast group. In the game, the minimization of network average delay is formulated as the utility function, which is transferred to each D2D user's payoff. Moreover, cellular users are selfless to join in coalitions and share their spectrum resources with D2D links.
- We design a multihop routing scheme when the channel condition between the content requester and the content holder cannot support a direct single-hop link. Jointly considering the coalition formation and the multihop scenario, we propose a multi-dimension optimization algorithm to solve the content distribution problem with the purpose of minimizing the network average delay.
- The proposed coalition formation is proved to converge to a Nash-stable equilibrium, and complexity of the whole algorithm is analyzed theoretically. In the simulation, we provide a comparison of the proposed cooperative game based approach, a non-cooperative approach and the random access approach. Numerical results show that the proposed approach achieves a considerable performance gain in the network average delay.

The rest of this paper is organized as follows. In Section II, we introduce some related works and discuss the differences between them and our work. Section III provides the system model including channel model and content distribution model, and Section IV gives the optimization problem with objective function of minimizing the network average delay. In Section V, we first reformulate the content distribution problem as coalition formation games within multiple time slots, and then describe the game-theoretical algorithm with relevant concepts and analysis. The numerical results and discussions are provided in Section VI. Finally, we conclude the paper in Section VII.

II. Related Works

The purpose of this work is to investigate a cross-layer solution for content distribution through D2D communications. Especially, due to the terrible direct channel conditions, multihop transmissions should be taken into account, and routing selection naturally becomes a key problem [26]–[28]. In [26], the authors proposed a multihop cooperative routing path selection algorithm, which simultaneously improves the throughput of primary users and the success possibility of secondary users who opportunistically exploit the licensed spectrum preoccupied by primary users. The authors in [29] investigated a scenario that mobile devices have the same demand toward a common content and cooperatively download the content through multihop D2D link. Three greedy algorithms with different grouping strategies were proposed to investigate the tradeoff between performance and complexity. In [30], the authors proposed a novel framework to enable devices to form multihop D2D connections, and maintain sustainable communication in the presence of device mobility. A tractable theoretical framework was proposed in [31] to analyze the performance of D2D in the co-channel interference scenario. The shortest-path-routing algorithm was used for both uplink and downlink multihop D2D transmission. In [32], D2D communication was employed to extend the coverage area of active base station, which significantly improves both the energy and spectral efficiency performance compared to conventional cellular networks.

Previous works mentioned above have solved the multihop D2D routing problem. However, most of them have not taken co-channel interference into consideration. Although the co-channel interference was considered in [31], it has not involved content distribution problem and transmission delay minimization through the whole network.

Coalition game is a powerful tool which attracts intensive attentions [33]–[37] from both academia and industry. The authors in [33] proposed an coalition formation algorithm which enables the users to autonomously decide whether to join or leave a coalition based on the rule of minimizing their average download delay. In [38], the optimization problem of multi-hop D2D communication was formulated as a coalition graph game, then a dynamic algorithm based on local best response and a near-optimal algorithm based on switching operation were proposed to solve the problem. The authors in [39] proposed a cooperative approach using coalitional graph game to establish a peer-to-peer vehicular network, and adopted the cognitive radio technique to implement vehicle-to-vehicle transmissions.

Although the coalition game has been used to solve the content distribution and multihop routing problems in some works, none of them have ever taken both of the two problems into consideration simultaneously. In [39], the coalition game was used to reduce the transmission delay of content distribution, but the authors just considered the scenario that only one transmitter is allowed to transmit the content in each time slot, which means that the resource allocation problem has not been involved.

By taking the multihop D2D communication and the resource allocation into consideration, the content distribution problem in this paper can be highly complex, which is difficult to solve in a direct way because it involves multi-dimension optimization, i.e., frequency, space, and time. In order to reduce the average delay of D2D content requesters receiving the content, and improve the efficiency of content distribution, we formulate the route selection and resource allocation problem as a cooperative game, and then propose a coalition formation algorithm to solve the problem.

There are some previous studies which solved content distribution problem by applying similar approaches to this paper [22], [23]. The authors in [22] formulated the energy-efficiency content dissemination problem as a nontransferable utility game, and solved it by applying a distributed coalition formation algorithm. The optimization objective of this work is energy efficiency while our work focuses on minimizing the average delay of content distribution, which is definitely different. Moreover, multihop transmission scheme and resource allocation have not been involved in [22]. In [23], the authors investigated relay-based schemes in cellular systems, and they proposed a cooperative content uploading scheme to reduce the content upload delay. The key issue considered in this work is to employ multihop D2D communication to upload contents to the eNodeB, which is totally different from our work.

III. System Model

In this paper, we consider a hotspot area with one serving BS, multiple traditional cellular users (CUEs), and other users who request for the same popular content. Each user can obtain the content from either the BS, or another user via direct D2D links. Here, we assume that the cellular system is fully loaded, and thus new content requests need to be responded by D2D communications. The users who have already obtained the content can act as transmitters, and they transmit the content to their neighbour content requesters (CRs) by multicast mode. There exist three key problems in this scenario: 1) Given some random locations of transmitters, how to determine the multicast group so that the network average delay can be minimized; 2) How to design a resource allocation scheme for D2D multicast to improve the system performance; 3) For the users with bad channel conditions from any transmitter, how to design a multihop routing scheme to optimize the average delay.

As illustrated in Fig. 1, the requested popular content has already been obtained by part of users named original content holders (OCHs), which are randomly distributed in the hotspot. The CRs can receive data from the decentralized OCHs by D2D multicast transmissions reusing the uplink cellular resource blocks (RBs). Each CUE in the system occupies one orthogonal RB, which can be reused by at most one D2D multicast group within one time slot, and meanwhile, each multicast group can only use one RB for content distribution.

We assume that there are C cellular users, and M D2D users including K original content holders and $M-K$ ($M>K$) content requesters. All the cellular users are randomly distributed in the cell, and the OCHs and the CRs are randomly distributed in the hotspot. The sets of D2D users and cellular users are denoted by $\mathcal{M}=\{1,2,\cdots,M\}$, $\mathcal{C}=\{1,2,\cdots,C\}$, respectively. We use m_t to denote a D2D transmitter, i.e., content holder (CH) who broadcasts the content in a multicast group, m to denote a CR in the group, and c to denote a CUE and the corresponding RB. We have $\forall m, m_t \in \mathcal{M}$, $\forall c \in \mathcal{C}$. It is noted that when some of D2D receivers (CRs) finish the content reception, they would transform into transmitters and multicast to other users without content, i.e., once the CRs receive the content from the OCHs, their roles would be turned into CHs. This process continues until all the CRs obtain the content, and as a consequence, the number of D2D transmitters (CHs) and receivers (CRs) in the network is not fixed and it varies over time. As shown in Fig. 1, when CR2 receives the content from OCH2, it will transform into CH3 and broadcast the content to CR3 and CR4 in the next time interval.

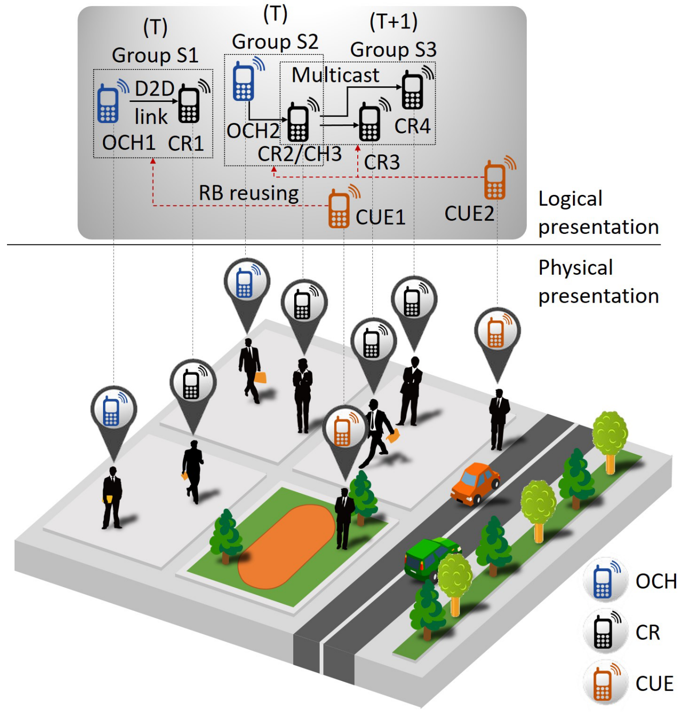

Fig. 1. System model of content distribution in multihop D2D networks.

For the channel model, the Rayleigh fading is used to model the small-scale fading, and the free space propagation path-loss is used to model the large-scale fading. Considering the co-channel interference, if CR m receives signal from CH m_t on RB c, it receives interference from CUE c, and meanwhile the BS is exposed to interference from CH m_t. Thus, the signal to interference plus noise radio (SINR) at CR m on RB c can be expressed as

$$\gamma_{m_t,m}^{c}=\frac{P_D h_{m_t m}^2}{P_C h_{cm}^2+N_0}=\frac{P_D d_{m_t m}^{-\alpha} h_{s,m_t m}^2}{P_C d_{cm}^{-\alpha} h_{s,cm}^2+N_0}, \qquad (1)$$

where P_D and P_C denote the transmit power of D2D users

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and cellular users, respectively. $h_{m_t m}$ is the channel response of D2D link while h_{cm} is the channel response of interference link from the CUE. $d_{m_t m}$ denotes the transmission distance between D2D transmitter m_t and receiver m, and d_{cm} is the distance between cellular user and D2D receiver. α is the large-scale fading path-loss exponent of the transmission channel. $h_{s,m_t m}$ and $h_{s,cm}$ denote the small-scale fading (Rayleigh) channel coefficients, which obey the complex Gaussian distribution $\mathcal{CN}(0,1)$. N_0 is the one-sided power spectral density of the additive white Gaussian noise (AWGN).

Similarly, the SINR received by the BS on RB c is

$$\gamma_c^{m_t} = \frac{P_C h_{cB}^2}{P_D h_{m_t B}^2 + N_0} = \frac{P_C d_{cB}^{-\alpha} h_{s,cB}^2}{P_D d_{m_t B}^{-\alpha} h_{s,m_t B}^2 + N_0}. \quad (2)$$

Here, h_{cB} represents the channel response of cellular link, and $h_{m_t B}$ represents the channel response of interference link from D2D transmitter to the BS. d_{cB}, $d_{m_t B}$ denote the distance between CUE c and the BS, the distance between D2D transmitter m_t and the BS, respectively. $h_{s,cB}$ and $h_{s,m_t B}$ are the corresponding small-scale fading channel coefficients.

In the process of content distribution, the network average delay is the key indicator to measure the system performance. The popular content should be transmitted in priority through a high quality channel with a high transmission rate. By giving the SINR of D2D receivers, the transmission rate of D2D link can be obtained by

$$r_{m_t,m}^c = \log_2(1+\gamma_{m_t,m}^c) = \log_2(1+\frac{P_D d_{m_t m}^{-\alpha} h_{s,m_t m}^2}{P_C d_{cm}^{-\alpha} h_{s,cm}^2 + N_0}). \quad (3)$$

Thus, the transmission delay from CH m_t to CR m reusing RB c can be expressed as

$$t_{m_t,m}^c = \frac{A}{W r_{m_t,m}^c} = \frac{A}{W \log_2(1+\frac{P_D d_{m_t m}^{-\alpha} h_{s,m_t m}^2}{P_C d_{cm}^{-\alpha} h_{s,cm}^2 + N_0})}. \quad (4)$$

Here, A represents the size of popular content in $bits$, and W denotes the bandwidth of RB in Hz.

IV. Problem Formulation

The purpose of this work is to achieve content distribution within possible minimum network average delay by multihop D2D communications so that the BS can be completely separated from data transmission. According to the optimization objective, the users who have already obtained the content should multicast to its neighbour CRs that have not obtained the content as long as there are reusable RBs (can be occupied by one CUE). Hence, we need to consider a multi-dimension optimization problem involving frequency, space, and time. Fig. 2 shows a timeline of content distribution process, where "E_i" ($i = 1, 2, \cdots$) denotes the event that a D2D multicast group has finished the content distribution. The entire time is divided into consecutive time slots, which keeps synchronized with the cellular system. At the beginning of any time slot, a CH starts to transmit the content in its multicast group. Note that "S_i" ($i = 1, 2, \cdots$) represents a multicast group, and the figure illustrates the transmit durations of some multicast groups. We set the length of time slot as T_s.

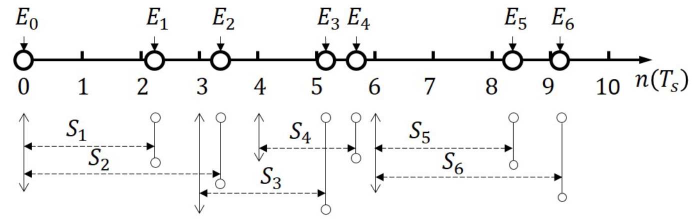

Fig. 2. Timeline of content distribution process.

In the multihop transmission scenario, the time for a CR to obtain the requested content includes two parts, the delay of its content provider (transmitter) receiving the data and the transmission delay from the transmitter to the CR. For simplicity, we ignore the processing delay. Based on the system synchronization, the transmission should start at the initial time of any time slot. Thus, the delay of CR m obtaining the content can be expressed as

$$T_{m_t,m}^c = n_{m_t} T_s + t_{m_t,m}^c, \quad (5)$$

where n_{m_t} represents the number of time slots that CH m_t spends in obtaining the content. $t_{m_t,m}^c$ is the transmission delay of CR m receiving the requested content from CH m_t on RB c defined in (4).

To minimize the network average delay, we need to design a cross-layer optimization mechanism for deciding the content provider for CRs and allocating the RBs to the multicast groups. We use binary variables $x_{m_t,m,c}$ ($\forall m_t, m \in \mathcal{M}, c \in \mathcal{C}$) to formulate the decision results. $x_{m_t,m,c} = 1$ represents that CR m receives data from CH m_t reusing RB c. Based on these settings, our work is to design the binary decision variables $\{x_{m_t,m,c}\}$ to minimize the average delay of the whole system. Therefore, the problem can be formulated as a mixed integer nonlinear programming (MINLP)

$$\begin{aligned} \min_{\{x_{m_t,m,c}\}} \quad & \frac{1}{M-K} \sum_{m\in\mathcal{M}} \sum_{m_t\in\mathcal{M}} \sum_{c\in\mathcal{C}} x_{m_t,m,c} T_{m_t,m}^c \\ \text{s.t.} \quad & C1: \ \gamma_{m_t,m}^c \ge \gamma_{min}^D, \forall m_t, m \in \mathcal{M}, c \in \mathcal{C}, \\ & C2: \ \gamma_c^{m_t} \ge \gamma_{min}^C, \forall c \in \mathcal{C}, m_t \in \mathcal{M}, \\ & C3: \ x_{m_t,m,c} \in \{0,1\}, \forall m_t, m \in \mathcal{M}, c \in \mathcal{C}, \\ & C4: \sum_{m_t\in\mathcal{M}, c\in\mathcal{C}} x_{m_t,m,c} \le 1, \forall m \in \mathcal{M}, \end{aligned} \quad (6)$$

where $C1$ and $C2$ guarantee the QoS requirements of transmission links. γ_{min}^D and γ_{min}^C denote the SINR threshold of D2D links and cellular links, respectively. The inequalities in $C4$ ensure that each CR can obtain the content from at most one CH, that is, join in one multicast group, while reusing at most one cellular RB.

V. Coalition Formation Game based Content Distribution Approach in Multihop D2D Networks

Considering the multicast feature of content distribution, we introduce a coalition formation game based approach to solve the cross-layer optimization problem in this section. First, we formulate the original problem as a coalitional game by defining an utility function for each multicast group. Then, we give some concepts of coalition formation. At last, we describe the details of content distribution algorithm.

A. Coalitional Game

In the proposed content distribution problem, we consider the performance of the average delay experienced by all the CRs in the network. For a D2D multicast group, there exist one CH, multiple CRs, and only one RB is reused for multicast transmissions. We define the utility function of multicast group S_{m_t} as the average transmission delay of all the CRs in the group, and given by

$$U(S_{m_t}) = -\frac{1}{|S_{m_t}|} \sum_{m \in S_{m_t}, c \in S_{m_t}} t^c_{m_t,m}. \tag{7}$$

Here, $|S_{m_t}|$ denotes the number of CRs in the group S_{m_t}. Note that the negative sign indicates that the utility of a multicast group is inversely proportional to the average delay.

As the content is transmitted in multicast groups, we can formulate the content distribution problem as a coalitional game, and each group constitutes a coalition. In the coalition game, each user acts as a game player and tends to join in a coalition so that it can receive the content and minimize its delay, and meanwhile, do not increase the average delay of CRs in the group, i.e., have a positive effect on the utility of the coalition. We define the coalitional game as $(\mathcal{G}, V)$, where $\mathcal{G}$ denotes the set of users who participate in the game, and V is the value of a coalition. In this paper, we naturally treat the utility function in (7) as the value function, thus it has

$$V(S_{m_t}) = \begin{cases} U(S_{m_t}), & \text{if } S_{m_t} \neq \emptyset, \\ 0, & \text{otherwise.} \end{cases} \tag{8}$$

where $S_{m_t} \subseteq \mathcal{G}$. In the formulated game, each coalition contains one CH, multiple CRs and one CUE who shares its RB for D2D multicast communications. We use m_t as the subscript to identify coalitions.

For each CR, it tends to seek for its ideal CH and RB (provided by cooperative CUE) to obtain the content with minimum transmission delay. When the content has been received by all the CRs in a coalition, the RB is released, and the CRs can immediately transform into CHs and provide the content for other CRs in the next-hop transmission. Therefore, each coalition tends to reduce the average delay as much as possible. Whether a CR can be allowed to join in a coalition depends on its contribution to the coalition value, i.e., a CR may be refused if it seriously increases the average delay of a multicast group. Thus, the payoff of each CR in a coalition is defined as the individual contribution to the coalition value. Hence, we can derive the payoff of CR m, $\forall m \in \mathcal{M}$, in coalition S_{m_t} as

$$\phi^{m_t}_m = V(S_{m_t} \cup \{m\}) - V(S_{m_t}), \tag{9}$$

where $S_{m_t} \cup \{m\}$ denotes that CR m joins in the coalition S_{m_t}.

In the game, CUEs join in the coalitions to provide their RBs for the multicast transmissions. Since one RB can only be reused by one coalition for the content distribution, we must guarantee that there only exists one CUE in each coalition. As the spectrum resources are controlled by the system, we assume that CUEs are selfless and willing to share its RB, thus the payoff of each CUE in a coalition is defined as the coalition value. The payoff of CUE c joining in coalition S_{m_t} can be given by

$$\phi^{m_t}_c = V(S_{m_t} \cup \{c\}). \tag{10}$$

A CUE selects to join in the coalition who gives a highest payoff to it, but only the CUE has the highest payoff can join in the coalition selected by multiple CUEs.

B. Coalition Formation Concepts

Next, we introduce a coalition formation based approach to solve the proposed coalitional game. Firstly, we give several definitions as follows.

Definition 1: A collection of all coalitions is defined as a set, denoted by $\mathcal{P} = \{S_{m_t}\}$, $m_t \in \mathcal{M}$, and $S_{m_t} \subset \mathcal{G}$ denotes the mutually disjoint coalitions. A collection is an arbitrary combination of coalitions S_{m_t}. If it exists $\bigcup_{S_{m_t} \in \mathcal{P}} S_{m_t} = \mathcal{G}$, the collection $\mathcal{P}$ is regarded as a partition of $\mathcal{G}$.

For the considered scenario, there might exist CRs that cannot satisfy the D2D channel quality requirement no matter what coalition they join in, thus the collection of coalitions does not necessarily contain all the users of $\mathcal{G}$. In the process of coalition formation, the CRs are allowed to join or leave a coalition based on the defined preferences. Each CR would compare and order its potential coalition based on the payoff calculated by (9). To obtain the preferences, we introduce the concept of coalition preference as below.

Definition 2: Consider two different collections of coalitions $\mathcal{P} = \{S_1, S_2, ...\}$ and $\mathcal{Q} = \{S^*_1, S^*_2, ...\}$, both of which are partitions of the same subset of $\mathcal{G}$, i.e., $\mathcal{G}' \subseteq \mathcal{G}$. The comparison relation of any two partitions is denoted by $\succ$. For instance, $\mathcal{P} \succ_{\mathcal{G}'} \mathcal{Q}$ implies the way that $\mathcal{P}$ partitions $\mathcal{G}'$ is superior to the way that $\mathcal{Q}$ partitions $\mathcal{G}'$, i.e., $\mathcal{P}$ is preferred.

For the CRs that cannot satisfy the QoS requirement given the current geographic distribution of CHs, they have to wait for the possible next-hop transmission. Thus, the performance of previous-hop has direct influence on that of the next-hop. We consider a best-effort scheme to minimize the average delay of current participant players. During the process of coalition formation game, a CR may leave its current coalition and join in another one. Next, we give the switch operation rule.

Definition 3: Given $m \in S_{m_t} \in \mathcal{P}$, if the payoff of CR m joining in coalition $S_{m'_t}$ is larger than that in coalition S_{m_t}, i.e., $\phi^{m'_t}_m > \phi^{m_t}_m$, then CR m will perform a switch operation from S_{m_t} to $S_{m'_t}$. The comparison relation is defined as $S_{m'_t} \succ_m S_{m_t}$. After that, the current collection $\mathcal{P}$ is turned into a new collection $\mathcal{P}' = (\mathcal{P} \backslash \{S_{m_t}, S'_{m_t}\}) \cup \{S_{m_t} \backslash \{m\}, S'_{m_t} \cup \{m\}\}$.

C. Coalition Formation Algorithm

Based on the concepts of coalition formation, CRs who satisfy the signal to noise ratio (SNR) threshold can participate

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in the current coalition game to form disjoint coalitions. The SNR threshold is denoted by γ^*_{min}. Specifically, if the payoff of a CR in the current coalition is lower than joining in another coalition, it will perform a switch operation. Based on the rules mentioned above, the coalition formation algorithm can be constructed as follows.

Step 1: *Initialization of coalitions.* Based on SNR, the preference order for each CR towards all of the CHs is calculated. The preference order is in descending order of SNRs, and the first element is the most favorite choice of the CR. The SNR of CR m who chooses CH m_t as transmitter is given by

$$\gamma^*_{m_t,m} = \frac{P_D h^2_{m_t m}}{N_0} = \frac{P_D d^{-\alpha}_{m_t m} h^2_{s,m_t m}}{N_0}. \quad (11)$$

Among all of the CHs, if one of them can satisfy the SNR threshold γ^*_{min} for CR m, i.e., $\gamma^*_{m_t,m} \geq \gamma^*_{min}$, then m is added into the set $\mathcal{G}'$. Meanwhile, CR m in the set of $\mathcal{G}'$ temporally joins in the coalition S_{m_t} where m_t is in the first place of preference order.

Step 2: *Coalitions for resource allocation.* Each CUE chooses to join in its preferred coalition which brings it the highest payoff based on (10). Since there might be two or more CUEs that prefer the same coalition, it is necessary to ensure that at most one CUE would stay in one coalition. Hence, we design a strategy that only the CUE obtains the highest payoff from a coalition can join in it, while the payoffs of other CUEs choosing the same coalition are set to be a high negative value. Thus, they will give up joining in the coalition and turn to other coalitions, which avoids the conflicts.

Step 3: *Switch operation to form coalitions.* After a temporal collection of coalitions $\mathcal{P}$ is formed, CRs have opportunities to change their choices based on the payoffs defined in (9). According to Definition 3, CR m will leave its current coalition S_{m_t} and join in coalition $S_{m'_t}$ if it satisfies $\phi^{m'_t}_m > \phi^{m_t}_m$, that is, $S_{m'_t} \succ_m S_{m_t}$. For $\forall m \in \mathcal{G}'$, the system performs the leave-and-join switch operation iteratively until none of CRs in $\mathcal{G}'$ intend to leave their current coalitions and join in other ones. Then, a partition $\mathcal{P}'$ for the set $\mathcal{G}'$ is formed, which satisfies $\mathcal{P}' \succ_{\mathcal{G}'} \mathcal{P}$.

Step 4: *Final coalition formation and content distribution.* To construct the final partition, Step 2 and step 3 need to be repeated until both the CUEs and CRs will not change their choices. We call the time that final partition is formed as *the decision point*. After that, the CH in each coalition starts to broadcast data on the RB which is shared by the CUE in the same coalition. The life of a coalition ends when the requested content is distributed to every CR in the coalition.

Step 5: *Next-hop transmissions.* In the end of each time slot, the BS checks if any multicast group finishes the transmission. It is possible that multiple groups finish the content distribution in the same time slot. Then, the CRs obtained the content in current time slot will act as CHs in the next-hop transmissions. The system updates the constituent, and the algorithm turns to Step 1. It is noted that the algorithm will conclude when every CR obtains the content, or there is no CH that can satisfy the QoS of a CR.

Algorithm 1 Coalition Formation Algorithm

Input: $\mathcal{M}$, $\mathcal{C}$, T_s, M, K, N_{max}.
Initialization: $\mathcal{G}' = \emptyset$, $\Omega = \emptyset$
if Any of coalitions finishes its content distribution process **then**
  for $\forall\ m \in \mathcal{M}$ **do**
    Calculate the SNR towards every CHs and the preference order.
    if $max(\gamma^*_{m_t,m}) \geq \gamma^*_{min}$ **then**
      $\mathcal{G}' = \mathcal{G}' \cup \{m\}$, $S_{m_t} = S_{m_t} \cup \{m\}$, where $m_t = arg \max(\gamma^*_{m_t,m})$
    end if
  end for
  Set $N = 0$.
  while $N \leq N_{max}$ **do**
    Calculate the payoffs for each CUE towards each coalition.
    while $\exists c \notin S_{m_t}, \forall m_t$ and $\exists S_{m_t} \cap \mathcal{C} = \emptyset$ **do**
      for $\forall c \in \mathcal{C}$ **do**
        $S_{m_t} = S_{m_t} \cup \{c\}$, $m_t = arg \max(\phi^{m_t}_c)$
      end for
      Put the coalitions that has been chosen by multiple CUEs into set Ω.
      for $S_{m_t} \in \Omega$ **do**
        for $c \in \mathcal{C}$ **do**
          if $\phi^{m_t}_c = max(\phi^{m_t}_i)$, $\forall c \in S_{m_t}$ **then**
            CUE c will stay in S_{m_t}.
            $\forall i \in S_{m_t}, i \neq c$, $\phi^{m_t}_i$ are reset as a high negative value. Remove CUE i from S_{m_t}, and remove coalition S_{m_t} from the set Ω.
          end if
        end for
      end for
    end while
    for $m \in \mathcal{G}'$ **do**
      Calculate $\phi^{m'_t}_m$ towards its potential coalition.
      if $\exists \phi^{m'_t}_m > \phi^{m_t}_m$ **then**
        Remove CR m from S_{m_t}.
        $S_{m'_t} = S_{m'_t} \cup \{m\}$.
      end if
    end for
    Update loop index with $N = N + 1$.
  end while
end if

The proposed coalition formation algorithm is summarized in Algorithm 1.

D. Convergence and Stability

For each CR, it always looks for a better coalition by the switch operation process, but if a CR finds that there exists no better choice, it will remain in the current coalition. If all the CRs find that their current coalitions are their respective best choices, the partition structure of the player set would no longer change. Since the number of partitions for a given set is Bell number [40], the leave-and-join operation will

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terminate and the algorithm will converge to a final partition in finite iterations. Therefore, no matter what initial partition the proposed approach starts from, it will end with a final partition, defined as $\mathcal{P}_f$.

Here, the stability of the final partition can be proved by using the concept from hedonic games [41], as follows.

Definition 4: A partition $\mathcal{P}$ is Nash-stable, if $\forall m \in \mathcal{M}$, $m \in S_{m_t} \in \mathcal{P}$, it has $S_{m_t} \succ_m S_{m_k} \cup \{m\}$ for all $S_{m_k} \in \mathcal{P} \cup \{\emptyset\}$.

Proposition 1: The partition at each decision point in the proposed coalition formation algorithm is Nash-stable.

Proof: For the multihop scenario, we consider the stability of the final partition at each decision point, i.e., the time any multicast groups are initiated. Assume that the final partition $\mathcal{P}_f$ at a certain decision point is not Nash-stable, then there must exist a CR $m \in \mathcal{M}$, $m \in S_{m_t} \in \mathcal{P}_f$, and a coalition $S_{m_k} \in \mathcal{P}_f$, which satisfy $S_{m_k} \cup \{m\} \succ_m S_{m_t}$. According to the coalition formation based algorithm, CR m can perform a leave-and-join operation since it finds a better choice. However, based on the initial setting that $\mathcal{P}_f$ is a final partition, which means that there is no leave-and-join operation, it appears a contradiction. Therefore, we can conclude that any final partition $\mathcal{P}_f$ at a certain decision point in the proposed coalition formation algorithm must be Nash-stable. ∎

E. Complexity

The proposed coalition formation algorithm is performed in an iterative way. The complexity depends on the initial states of the involved users including CHs, CRs, and CUEs. Here, we consider the worst case computational complexity to identify the efficiency of the proposed algorithm.

In the initialization of coalitions, each CR detects the channel state information (CSI) towards every available CH and calculates the corresponding SNR. The computational complexity of obtaining the SNR list for each CR is $\mathcal{O}(K)$, and the complexity of obtaining preference order by sorting the SNR values for each CR is $\mathcal{O}(K\log(K))$. For the coalition formation process, the worst case is that all the CUEs choose to join in the same coalition and all the CRs also have the same choice in each switch operation process. In this paper, the objective is to minimize the network average delay, which leads to a centralized way in the coalition formation process. Therefore, the complexity of calculating the payoffs for all the CUEs are $\mathcal{O}(CK)$, and the complexity of coalition formation for resource allocation and switch operation is $\mathcal{O}(C+M)K$. In the worst case, there will be K iterations. Thus, the complexity of coalition formation process is $\mathcal{O}((C+M)K^2)$.

VI. Simulation Results and Discussions

In this section, the proposed cross-layer optimization algorithm is compared with two heuristic approaches, that is, non-cooperative approach [39], [42] and random access approach [42]. In non-cooperative approach, each CR chooses its preferred CH based on SNR maximization, and RBs are randomly allocated to the multicast groups. The random access approach is served as a lower benchmark, in which the CRs and CHs in the network form multicast groups randomly, and RBs are also allocated in a random way. Table I shows the simulation parameters.

TABLE I
Simulation Parameters.

Simulation Parameter	Value
Cell radius R	500 m
Pathloss exponent α	4
Transmit power of D2D users P_D	23 dBm
Transmit power of CUEs P_C	23 dBm
Noise power N_0	-114 dBm
Number of CRs $M-K$	$8 \sim 32$
Number of CUEs/RBs C	$6 \sim 16$
Number of OCHs K	$6 \sim 16$
SINR threshold of D2D links γ_{min}^D	25 dB
SINR threshold of cellular links γ_{min}^C	25 dB
Length of time slots T_s	1 ms
Size of a content package A	2 Mb

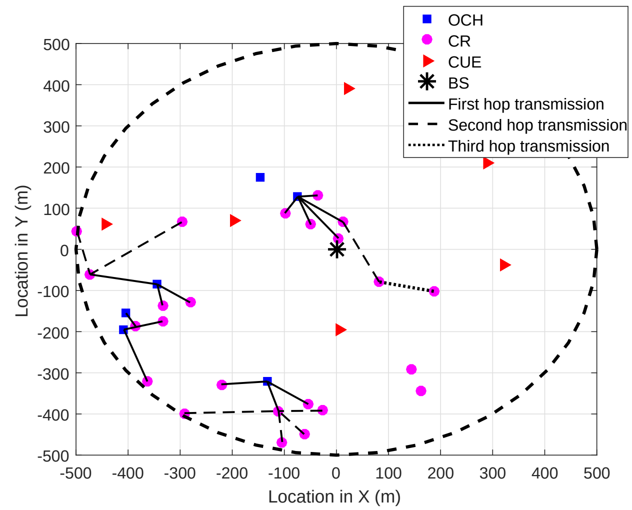

Fig. 3. An illustration of user locations and multihop D2D transmissions with K OCHs, $(M-K)$ CRs and C CUEs ($M=30, K=6, C=6$).

There are C cellular users randomly distributed in a cellular network with a radius of $R=500$ m. M D2D users, which includes K OCHs, are randomly located in a hotspot area. Fig. 3 gives an illustration of content distribution with $C=6$, $M=30$, and $K=6$. At the beginning, multiple OCHs broadcast the content to the CRs in their respective groups. After some of CRs receive the content, they continue to broadcast it to others. In this case, there exists at most a three-hop transmission link. At last, there still exist two users that cannot obtain the content by D2D multicast transmissions and have to turn to cellular mode.

Fig. 4 shows the content distribution efficiency by employing different approaches. The percentage of CHs is defined as the number of D2D users who have already obtained the content divided by the total number of D2D users. We set $C=6$, $M=30$ and $K=6$ at the beginning of the simulation. As shown in Fig. 4, the percentages of CHs achieved by all three approaches increase monotonically with time. However, the unit increments of CHs percentage per time slot decrease monotonically with time. The reason is that most

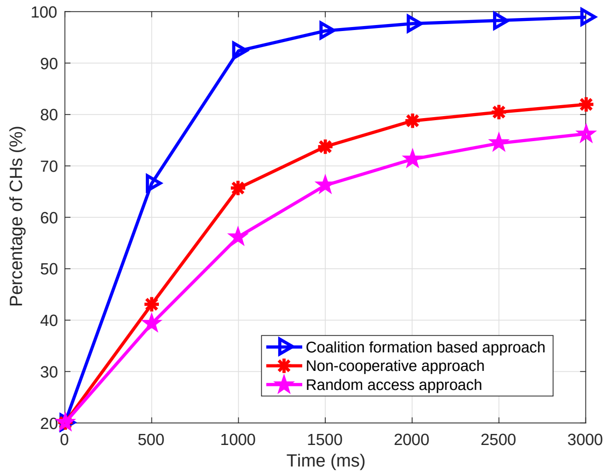

Fig. 4. Percentage of CHs vs. time ($M = 30, K = 6, C = 6$).

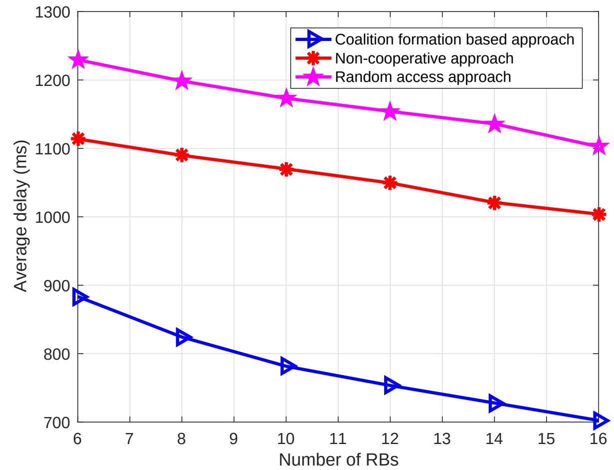

Fig. 6. Network average delay vs. number of RBs ($M = 30, K = 6$).

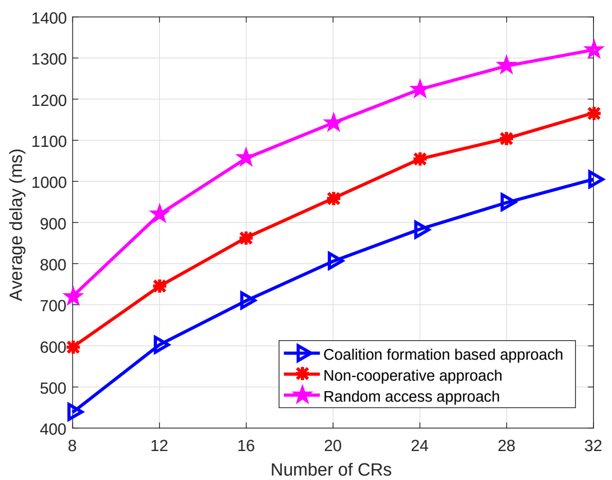

Fig. 5. Network average delay vs. number of CRs ($K = 6, C = 6$).

D2D users can obtain the content through multicast groups in the beginning time slots. It is noted that the proposed approach is able to achieve 98.6% CHs at 3000 ms. In comparison, the percentages of CHs corresponding to the non-cooperative approach and the random access approach are only 82.4% and 76.0%, respectively. In the two heuristic approaches, each CR searches for CHs in a non-cooperative way or even random way, which would not consider the quality of experience (QoE) of other users, and may lower multicast efficiency. In the proposed approach, each CR joins in a coalition to maximize its payoff, which highly depends on the average delay within the coalition. Therefore, the proposed approach results in a better performance on the transmission efficiency.

Fig. 5 shows the average delay of all the D2D users versus the number of original CRs. As the number of CRs increases, there may be more CRs that experience bad direct channel conditions from OCHs, thus have to obtain the content through multihop transmissions. Consequently, the average delay goes up monotonically with the number of CRs increasing. Moreover, we can see that the proposed approach achieves much better performance on average delay compared to the non-cooperative approach and random access approach, which can be also found in Fig. 6 and Fig. 7. The proposed approach encourages CRs to cooperate with each other to form coalitions with the objective of minimizing the average delay, so it has a better performance. In particularly, the random access approach performs worst among the three ones, since the selections of CHs and RBs are completely random.

Fig. 6 presents the average delay versus the number of RBs. It is observed that the average delay achieved by all three approaches decreases when the number of RBs increases. The reason is that a larger amount of spectrum resources supports to establish more multicast groups at the same time. As mentioned above, the proposed approach performs better than the others, and we find that the superiority becomes more obvious as the number of RBs keeps rising. When the number of spectrum resources is larger than the number of multicast groups, there will be an opportunity for the groups to access a better RB from the perspective of average delay, which is similar to the effect of multiuser diversity. In contrast, the two heuristic approaches achieve less performance gains since RBs are allocated in a random fashion. For this reason, the performance gap between the proposed approach and the other ones becomes larger with the number of RBs increasing.

Fig. 7 shows the average delay versus the number of OCHs. As is shown, when the number of OCHs is 6, the average delay achieved by the proposed approach is 883.0 ms; and when the number of OCHs reaches 16, the average delay is 652.7 ms, which decreases about 26.1%. When the number of OCHs grows, there may be more CRs that can obtain the requested content directly from single-hop transmission, thus the average delay of the network is reduced.

Fig. 8 shows the percentage of CHs versus number of OCHs under different SNR threshold. On one hand, we find that the percentage of CHs at the end of content distribution raises up when the number of OCHs increases continuously. It implies that more users provide the requested content, a

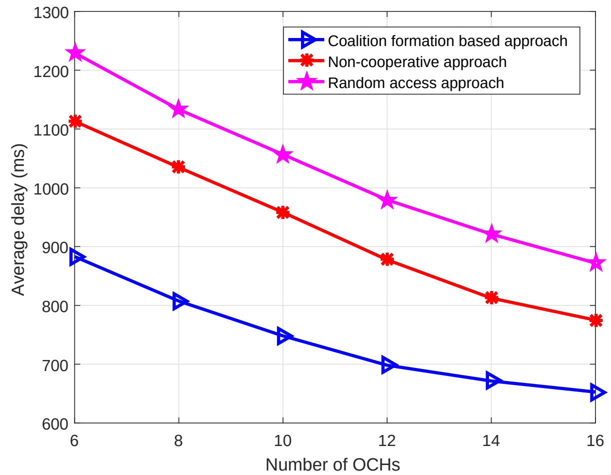

Fig. 7. Network average delay vs. number of OCHs ($M-K=24, C=6$).

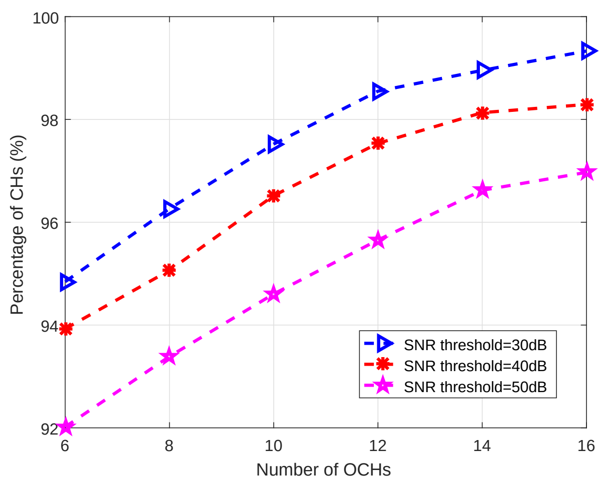

Fig. 8. Percentage of CHs vs. number of OCHs ($M-K=24, C=12$).

better distribution performance can be reached. On the other hand, the percentage of CHs decreases slightly with the SNR threshold increasing. Due to a relatively high QoS requirement, some of the CRs that experience bad channel conditions cannot join in multicast groups to obtain the content through D2D communication, thus have to switch to cellular mode instead. Therefore, as depicted in Fig. 8, both the SNR threshold of users and the number of OCHs distributed in the network have impact on the performance of the proposed approach.

VII. Conclusions

In this paper, we investigated the content distribution problem by multihop D2D communication with decentralized content providers locating in the networks. Moreover, we considered a cross-layer optimization that jointly design the route of content distribution and spectrum allocation. First, we formulated the problem as a coalitional game based on the payoffs of users. Then, we proposed a time-varying coalition formation based algorithm to solve the problem. Finally, the proposed approach was validated and compared with two heuristic approaches. Simulation results show that the game-theoretical approach effectively reduces the time spent in the content distribution and its performance on average delay is much better than that of non-cooperative approach. By incorporating more RBs into the network, the performance of the proposed approach can be significantly increased. When there exist more original content holders in the hotspot, both the percentage of users obtaining the content and the network average delay can achieve better performances. In future works, we will focus on the distributed caching schemes in multihop D2D networks.

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