Energy-Aware Incentive Mechanism for Content Sharing Through Device-to-Device Communications

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Abstract—The traffic of the base station can be offloaded by content sharing through device-to-device (D2D) communications if popular on-demand contents have been cached in user devices. In D2D content sharing, the receiving user gains benefit by obtaining contents while the transmitting user has to consume the transmission energy. However, users are selfish and have no obligation to help others. To motivate user involvement in D2D content sharing, we propose an energy-aware incentive mechanism where the key idea is that physically neighboring users can form a collaborative group. In a collaborative group, a user obtains contents from other users while consuming energy on providing contents to other users. We model the problem as a coalition formation game with non-transferable utility. To solve the problem, we also propose an algorithm which is proved to be of convergence and stability. Finally, simulation results show that our proposed mechanism has significant performance gains compared with two baseline schemes.

I. INTRODUCTION

With the development of mobile devices such as smartphones and tablets, the demand for mobile traffic is growing at a tremendous rate. The huge amount of mobile data brings great pressure to cellular networks. Meanwhile, studies point out that the downloads of the same popular on-demand contents occupy a large proportion of the traffic. For example, a few popular on-demand videos are viewed by a majority of users at different times [1]. Therefore, one of the requirements of future cellular networking paradigms is to be able to deal with the vast duplicated download traffic.

Recently, content sharing through device-to-device (D2D) communications has been proposed as a promising method to offload the traffic of base stations (BSs) [2][3]. If some user devices (UEs) have cached a few popular on-demand contents, other interested neighbor UEs can reuse these contents through D2D communications, in which the contents are directly transmitted to the content requestors from the content owners [4]. Hereby, the BS would only transmit contents which are not locally available instead of transmitting the same popular contents multiple times. The traffic of the BSs is thus significantly offloaded. This operation is called as D2D content sharing in this paper. Through well-designed D2D content sharing, cellular system performance can be improved due to the short distance of D2D communication. The overall energy consumption of mobile cellular system is reduced by using D2D communications and redundant storage in [5]. In [6], the cellular network throughput gain is achieved by analyzing the optimal collaboration distance, which is crucial to the tradeoff between frequency reuse and cache hit ratio. In [7], the average caching failure rate is minimized by determining the optimal probability of storing data contents in each UEs. In [8], the amount of data traffic offloading is maximized while considering nodes with limited cache capacities and different mobility.

These distinct advantages of D2D content sharing are based on the assumption that users are willing to participate. However, users are selfish and they have no obligation to be the content providers of other users. Specifically, in a D2D communication, the receiver obtains files while the transmitter has to consume energy. There is no incentive for the transmitter to involve in D2D content sharing. Therefore, incentive mechanism is one of the critical problems in D2D content sharing.

To motivate mobile users (especially content owners) to participate in D2D content sharing, there have been a few existing incentive mechanisms [9] [10] assuming that the network operator will reward D2D users with money or virtual currencies. Besides, there are also some works using non-monetary incentive mechanisms to motivate user involvement in D2D communications, considering the fact that the users would appreciate a free and simple sharing service without complex money exchanges. In [11], the authors propose a cooperative realtime video multicast framework in which users can form coalitions to get the missed frames from other users. The incentive issue is solved by the one-helper constraint in which a user can only choose one helper and should be the helper of another user in the coalition. In [12], users can form social groups to help broadcast realtime traffic with the concept of equal-reciprocal incentive, which fairly ensures that each pair of the users in the social group share the same amount of content with each other. However, these non-monetary works focus on realtime content transmission. If they are applied into the scenario of D2D on-demand contents sharing, the one-helper constraint will dramatically decrease the cache hit ratio, and the broadcast characteristic is not suitable for asynchronous requests for on-demand contents. Moreover, the transmission energy consumption which is crucial to limited battery-powered UEs has not been considered in these works.

To this end, we are inspired to address the non-monetary incentive issues for D2D on-demand contents sharing, while considering the impact of energy consumption on user motivation. In this paper, we firstly propose a non-monetary mechanism in which UEs with different cached contents can
form collaborative groups to help each other. In a collaborative group, each user can obtain his/her interested contents from the neighbors who have exactly cached these contents. Meanwhile, each user in the group should consume transmission energy since he/she is the content provider of other users. In other words, the users bear the cost of transmission energy consumption in exchange for gaining the benefit of receiving contents. Then, we use coalition formation game to find the appropriate groups from the user perspective, in which each user aims at joining a group maximizing his/her utility. In addition, a coalition formation algorithm is proposed to get the solution of the game model.

The contributions of this paper are summarized as follows.

- We propose a non-monetary mechanism to motivate users to involve in D2D content sharing, while considering the fact that D2D users’ motivations are greatly affected by the transmission energy consumption. To the best of our knowledge, there are few literatures concentrating on non-monetary incentives for D2D on-demand contents sharing, especially when energy effect is taken into consideration.

- We formulate a coalition formation game with non-transferable utility (NTU) to solve the problem of user grouping. Moreover, a coalition formation algorithm is proposed and proved to be of convergence and stability. Numerical results show that the performance is improved by the proposed mechanism when compared with two baseline schemes.

The rest of the paper is organized as follows. Section II describes the system model. Then, we present the non-monetary mechanism in Section III. After that, Section IV proposes the coalition formation game model, algorithm and its property analysis. Next, the numerical results are shown in Section V. Finally, we give the conclusions of this paper in Section VI.

II. SYSTEM MODEL AND ASSUMPTIONS

In this section, we introduce our system model. A physical graph for D2D communication is presented, followed by some assumptions for content sharing.

A. A Physical Graph for D2D communication

We consider a cellular network where the BS serves a set \( \mathcal{N} \) of \( N \) UEs. The UEs are distributed in the cell, and they keep stationary for each duration. If the distance between two UEs is within some collaboration distance \( d_{\text{max}} \), two UEs can directly communicate with each other through a D2D communication under the control of the BS [2]. \( d_{\text{max}} \) is determined by the power level and path loss model for each transmission. Then, we denote a communication network by a physical graph \( \mathcal{G} \triangleq \{ \mathcal{N}, \mathcal{E} \} \), where the vertex set is the set of UEs \( \mathcal{N} \) and the edge set is \( \mathcal{E} \triangleq \{(i, j) : e_{i,j}^p = 1, \forall i, j \in \mathcal{N}\} \) in which \( e_{i,j}^p = 1 \) if and only if the distance \( d_{ij} \) between \( i \) and \( j \) is not longer than \( d_{\text{max}} \). We denote the neighbors of UE \( i \) as \( \mathcal{N}^i \triangleq \{ j \in \mathcal{N} : e_{i,j}^p = 1 \} \).

For simplicity, we assume that a D2D communication link is not interfered with any other links. This assumption can be justified if the D2D communications are allocated with orthogonal time-frequency resources [13]. Under this assumption, the rate of D2D link \( (i, j) \) between the receiver \( i \) and the transmitter \( j \) can be calculated as

\[
r_{ij} = B \cdot \log_2(1 + \frac{P_{ij} \cdot h_{ij}}{N_0}),
\]

where \( B \) represents the bandwidth allocated to the link, \( P_{ij} \) expresses the transmitting power at the transmitter, \( h_{ij} \) denotes the channel gain of the D2D link \( (i, j) \), and \( N_0 \) indicates the power of the noise at the receiver.

B. Assumptions for content sharing

We consider a set \( \mathcal{F} = \{ f_1, f_2, \ldots, f_m, \ldots \} \) of popular on-demand contents which have the same size of \( S \). In a duration during which the network topology keeps unchanged, a UE, say \( i \), has cached \( M_i \) popular on-demand contents in its storage, and is still in need of extra \( M_f \) contents. The set of cached contents is represented as \( \mathcal{C}_i \), with \( \mathcal{C}_i \subset \mathcal{F} \), and the set of requested contents is indicated as \( \mathcal{A}_i \), with \( \mathcal{A}_i \subset \mathcal{F} \) and \( \mathcal{A}_i \cap \mathcal{C}_i = \emptyset \). If the requested contents of UE \( i \) have been cached by another UE, say \( j (j \neq i) \), we will get \( \exists f \in \{ \mathcal{A}_i \cap \mathcal{C}_j \} \) or \( \mathcal{A}_i \cap \mathcal{C}_j \neq \emptyset \).

The receiving UEs are assumed to prefer to obtain contents through a D2D communication rather than a cellular communication, due to the lower fees charged by operators for D2D communication. For example, in the case of the out-band D2D communication [14], the UEs can acquire contents without traffic fees. Even if the D2D communication is established on the in-band frequency [14], the BS needs only undertake the task of control without consuming energy for transmission, thus reducing the serving fee of the D2D communication. In a word, we assume that the D2D communication is preferred by the receiving users. The goal of this paper is to motivate the content owners to be willing to become the transmitting users, through a non-monetary incentive mechanism.

As for the transmitting UEs, we assume that the energy consumption is solely determined by the transmission energy (we neglect the circuit energy consumed by the circuit blocks along the signal path). To guarantee the quality of D2D communication, we consider that the rate \( r_{ij} \) of D2D link \( (i, j) \) should be no less than \( r_{\text{min}} \). Then, the transmission energy consumption for transmitting a content in D2D link \( (i, j) \) is represented as

\[
E_{ij} = P_{ij} \cdot \frac{S}{r_{ij}},
\]

where \( r_{ij} \) satisfies the rate constraint, i.e., \( r_{ij} \geq r_{\text{min}} \). After putting equation (1) into equation (2), we know that the energy consumption \( E_{ij} \) is an increasing function of the transmitting power \( P_{ij} \), i.e.,

\[
E_{ij} = \frac{P_{ij} \cdot S}{B \cdot \log_2(1 + \frac{P_{ij} \cdot h_{ij}}{N_0})}.
\]
with a constraint \( P_{ij} \geq (2^{\frac{r_{\text{min}}}{r_{\text{ij}}}} - 1) \cdot \frac{N_0}{N_0} \cdot \frac{r_{\text{ij}}}{r_{\text{min}}} \). Then, the minimum transmission energy for transmitting a content is
\[
E_{\text{ij}}^m = (2^{\frac{r_{\text{min}}}{r_{\text{ij}}}} - 1) \cdot \frac{N_0 \cdot S}{h_{ij} \cdot r_{\text{min}}},
\]
when \( r_{ij} = r_{\text{min}} \). For the sake of brevity, we use \( E_{\text{ij}}^m \) to represent the energy consumed by UE \( j \) for transmitting a content through D2D link \((i, j)\) in the remaining part of this paper.

III. A NON-MONETARY INCENTIVE MECHANISM FOR D2D CONTENT SHARING

To motivate users to involve in D2D content sharing, we propose a non-monetary incentive mechanism in this section. We assume that the BS is aware of the cached contents and requested contents of UEs, as well as the channel state information of D2D links. With the help of the BS, UEs can form mutually disjoint collaborative groups. In each group, every UE is obligated to be the transmitter for providing contents to other UEs. Simultaneously, every UE also has the right to be the receiver for obtaining contents from other UEs. In addition, UEs from different groups do not share contents with each other.

A. Benefit of Joining A Group

In each group, a UE is able to gain its wanted contents as long as these contents have been cached by its physical neighbors which are also in the same group. For example, for UE \( i \) which belongs to a group denoted as \( S^i \), if its requested contents have been cached by its physical neighbors which are also in \( S^i \), UE \( i \) can directly obtain its requested contents from these neighbors through D2D communications. In other words, for UE \( i \), if there are neighbors which satisfy
\[
\exists j \in N^i \cap S^i
\]
and
\[
\exists f \in A_i \cap \mathcal{C}_j,
\]
UE \( i \) is sure to obtain content \( f \) from its group. Then, the benefit of UE \( i \) for joining group \( S^i \), i.e., the number of contents obtained by UE \( i \), is denoted as
\[
b_i = \left| A_i \cap \bigcup_{j \in N^i \cap S^i} \mathcal{C}_j \right|
\]
where \(|*|\) means the number of elements in set *.

B. Cost of Joining A Group

Besides gaining benefit by obtaining contents from the group, UE \( i \) will also have the cost of joining the group. This is due to the fact that UE \( i \) will consume energy for transmitting contents to other UEs. The question how to compute the energy consumption of UE \( i \) for joining group \( S^i \) is equal to the question how to decide which UE receives which contents of UE \( i \) in group \( S^i \). This question can be described from another perspective, there may be several UEs satisfying (3) and (4) in the same time, then which one should be selected to transmit content \( f \) to UE \( i \)? It is a question inside group \( S^i \) and is independent with other groups. The solution of this question (called as internal strategy later in this paper) decides the cost of all UEs in the group. There are many objectives for solving this question, for example, fairness in the group. In this paper, we solve the question in a way minimizing the overall cost of all UEs in the group. Taking content \( f \) which is requested by UE \( i \) as example, this problem can be formulated as
\[
\min_{j \in \mathcal{N}} E_{\text{ij}} \quad \text{s.t.} \quad C_j \cap A_i \ni f \quad j \in N^i \cap S^i.
\]

To achieve the goal of minimizing the overall cost of all UEs in a group, UE \( i \) will obtain content \( f \) from UE \( j \) which is derived from (6). Obviously, UE \( j \) has the minimum \( E_{\text{ij}}^m \) among all UE \( i \)'s neighbors which have cached content \( f \) while being in the same group \( S^i \) with UE \( i \). For simplicity, we denote the set of UE \( i \)'s physical neighbors which are also in group \( S^i \) as \( N_{S^i}^i \equiv N^i \cap S^i \), in which the elements are ranked as \( \{N_{S^i}^i, N_{S^i}^2, \ldots \} \). The \( k \)th element \( N_{S^i}^k \) is the one which has the \( k \)th small energy \( E_{\text{ij}}^m \) among all elements \( j \in N_{S^i}^i \). Additionally, we denote the cache hit contents of D2D link \((i, j)\) as the contents that are required by UE \( i \) and has been cached by UE \( j \). The key idea of (6) indicates that UE \( i \) will obtain all the cache hit contents of D2D link \((i, N_{S^i}^j)\) from UE \( N_{S^i}^j \). Then, UE \( i \) will obtain all the cache hit contents of D2D link \((i, N_{S^i}^k)\) \( (k \neq 1) \) from UE \( N_{S^i}^k \), except for the contents which have been transmitted by the first \( k - 1 \) elements of \( N_{S^i}^i \).

After the internal strategy is determined, we can represent a group as a weighted graph based on the physical graph. The nodes are the UEs in the group, the edge \((i, j)\) with a weight \( g_{ij} \) means that there are \( g_{ij} \) contents transmitted from \( j \) to \( i \). \( g_{ij} \) is computed as
\[
g_{ij} = \begin{cases} 
|C_j \cap A_i|, & \text{if } j = N_{S^i}^i, \\
\left|\bigcup_{k=1}^{n} C_{N_{S^i}^k} \right| - \left|\bigcup_{k=1}^{n-1} C_{N_{S^i}^k} \right| \cap A_i|, & \text{if } j = N_{S^i}^k, n \neq 1, \\
0, & \text{if } j \notin N_{S^i}^i.
\end{cases}
\]

Thus, the cost of UE \( i \) for joining group \( S^i \), i.e., the energy consumed by UE \( i \), is computed as
\[
c_i = \sum_{j \in S^i} g_{ij} \cdot E_{\text{ij}}^m.
\]

C. Utility Function

The utility of UE \( i \) which belongs to group \( S^i \) is defined as a function of the number of obtained contents and the energy consumption as follows
\[
u_i(S^i) = b_i - \alpha_i \cdot c_i
\]
where \( \alpha_i \) is a weighted factor of the energy consumption compared with the number of obtained contents. The value
of $1/\alpha_i$ means the upper bound of the ratio of energy consumption to the number of obtained contents allowed by UE $i$, for achieving a positive utility. Actually, the value selection for $\alpha_i$ is related to many factors such as the user preference, the remaining battery capacity, and so on. For simplicity, we assume all UEs have the same value of $\alpha_i$ in this paper. Note that increasing the value of $\alpha_i$ means greater importance of the energy consumption in the utility function, and decreasing the value of $\alpha_i$ means greater importance of the number of obtained contents.

Once a UE joins a group, its utility (9) is then determined by the membership of the group (which decides equation (5)) and the internal strategy (which decides equation (8)). Since each selfish and rational UE aims to join a group which can maximize its utility, the problem of which users join which groups is a key point for D2D content sharing. This approach will be described in the next section.

IV. USER GROUPING AS A COALITION FORMATION GAME

In this section, we use the NTU coalition formation game theory [15][16][17] to study the process of forming collaborative coalitions.

A. Coalition Formation: Model

Definition 1: A coalition formation game with non-transferable utility is defined by a triple $G=(\mathcal{N},v,\Pi)$. $\mathcal{N}$ is a fixed set $\mathcal{N}=\{p_1,\cdots,p_N\}$ of all players called as the grand coalition. A partition of $\mathcal{N}$ is a set $\Pi=\{S_1,\cdots,S_q\}$ of mutually disjoint coalitions such that $\bigcup_{k=1}^q S_k = \mathcal{N}$ and $S_k \cap S_{k'} = \emptyset$ for $k \neq k'$. $v(S) \in \mathbb{R}^{\big|\mathcal{N}\big|}$ is the coalition value of $S$ which represents the payoff vector the players in $S$ can achieve.

In our problem, a player means a UE and a coalition means a collaborative group comprising the UEs mutually sharing contents. The payoff is presented by a utility function as (9). Then, the coalition value of any coalition $S_k \subseteq \mathcal{N}$ is defined as

$$v(S_k) = \begin{cases} 0, & \text{if } S_k = \emptyset \\ \{u_j(S_k)\}_{j \in S_k}, & \text{otherwise} \end{cases}$$

where $u_j(S_k)$ equals $u_j(S^j)$ for $j \in S_k$. Note that when $|S_k| = 1$, the coalition $S_k$ contains one UE which do not share contents with others, thus $v(S_k) = (0)$. Since the objective for the players is to maximize their utilities and the utility cannot be arbitrarily apportioned among the players, we have an NTU game. Moreover, the game is in characteristic form because the utility of each player only depends on the players forming the coalition it is part of and not on the other players in the network. Specifically, this is due to that contents are not allowed to transmitted between any two players which are in different coalitions.

Definition 2: A collection of coalitions $\mathcal{X}$ is defined as a set $\mathcal{X}=\{S_1,\cdots,S_x\}$ of mutually disjoint coalitions such that $S_k \cap S_{k'} = \emptyset$ for $k \neq k'$. Particularly, when the collection contains all players in $\mathcal{N}$, i.e., $\bigcup_{k=1}^x S_k = \mathcal{N}$, the collection is a partition $\Pi$ which has been introduced in Definition 1. For any collection $\mathcal{X}=\{S_1,\cdots,S_x\}$, there exists a sequence $v(\mathcal{X}) = (v(S_1),\cdots,v(S_x))$ with $v_j(S_k) = u_j(S_k)_{S_k \in \mathcal{X}}$.

Definition 3: Collection $\mathcal{X}=\{S_1,\cdots,S_x\}$ is preferable to collection $\mathcal{Y}=\{S_1,\cdots,S_y\}$ by Pareto order, which is denoted as $\mathcal{X} \succ \mathcal{Y}$, if and only if

$$v_j(S_k) \geq v_j(S_{k'}), \forall j \in \bigcup \mathcal{X} = \bigcup \mathcal{Y} \quad (10)$$

with at least one strict inequality for some player in $\bigcup \mathcal{X}$.

The Pareto order satisfies the following two properties: (1) irreflexivity: $\mathcal{X} \succ \mathcal{X}$ never holds for any collection $\mathcal{X}$; (2) transitivity: $\mathcal{X} \succ \mathcal{Y}$ and $\mathcal{Y} \succ \mathcal{Z}$ imply $\mathcal{X} \succ \mathcal{Z}$ for any collections $\mathcal{X},\mathcal{Y},\mathcal{Z}$ with $\bigcup \mathcal{X} = \bigcup \mathcal{Y} = \bigcup \mathcal{Z}$.

B. Coalition Formation: Algorithm

Two main rules for forming and breaking coalitions, referred to as merge-and-split rules, are present in [18][19].

Definition 4: (Merge rule) Merge any collection of disjoint coalitions $\{S_1,\cdots,S_a\}$, where $\{\bigcup_{k=1}^a S_k\} \succ \{S_1,\cdots,S_a\}$, thus these disjoint coalitions $\{S_1,\cdots,S_a\}$ are merged into one coalition $\{\bigcup_{k=1}^a S_k\}$.

Definition 5: (Split rule) Split any coalition $\{\bigcup_{k=1}^a S_k\}$, where $\{S_1,\cdots,S_a\} \succ \{\bigcup_{k=1}^a S_k\}$, thus the coalition $\{\bigcup_{k=1}^a S_k\}$ is split into multiple coalitions $\{S_1,\cdots,S_a\}$.

Taking into account the purpose of maximizing the players’ utilities and the non-transferable nature of the proposed game, we introduce an algorithm for forming coalitions based on the merge-and-split rule combined with the Pareto order. In the proposed algorithm, the partition is modified over and over again by the operations of merge and split, while each operation is performed when at least one of the UEs can improve its payoff without hurting the other UEs. Details are described in Algorithm 1.

C. Coalition Formation: Property Analysis

The convergence and stability of the proposed coalition formation algorithm are analyzed as follows.

Remark 1: Starting from any initial partition, the proposed algorithm converges to a final partition $\Pi^{fin}$ of disjoint coalitions of UEs.

Proof: As definition 4 and 5, it is easily seen that every merge or split operation leads to a new partition. Note that the number of the total partitions, i.e., the Bell number, is finite. Hence, the sequence of the partitions (starting from the initial partition to the final partition), which are produced in the process of merge-and-split operations in the second phase of the proposed algorithm, will always terminate and converge to a final partition.

Definition 6: A partition $\Pi = \{S_1,\cdots,S_q\}$ of $\mathcal{N}$ is $D_{hp^*}$-stable if and only if it satisfies the following two conditions: (a) For any $T \subseteq \{1,\cdots,q\}$, $\{\bigcup_{k \in T} S_k\} \succ \{S_k|k \in T\}$ do not hold. (b) For any $k \in \{1,\cdots,q\}$ and for any partition $\{D_1,\cdots,D_l\}$ of coalition $S_k$, $\{D_1,\cdots,D_l\} \succ S_k$ do not hold.

Remark 2: Any final partition $\Pi^{fin}$ resulting from the proposed algorithm is $D_{hp^*}$-stable [17][18][19].
Algorithm 1: Coalition formation for D2D content sharing

**Phase I - Physical Neighbor Discovery and Initialization:**
- Each UE discovers its neighbors and sends feedback to the BS about the CQI of the corresponding D2D links.
- Each UE sends the requested content set $A_i$, the cached content set $C_i$, and the content-energy weighted factor $\alpha_i$ to the BS.
- Initialize the partition as $\Pi^{ini} = N = \{S_1, S_2, \ldots, S_N\}$, and set the current partition as $\Pi^{cur} = \Pi^{ini}$.

**Phase II - Coalition Formation:**
In this phase, the BS performs the coalition formation using merge-and-split operations.

repeat
  repeat
    For every coalition $S_i$ in the current partition $\Pi^{cur}$.
    - Coalition $S_i$ investigates possible merge operation using the Pareto order given in (10).
    - If a merge operation is performed, update the current partition $\Pi^{cur}$.
  until no merge occurs
  For every coalition $S_i$ in the current partition $\Pi^{cur}$.
  - Coalition $S_i$ investigates possible split operation using the Pareto order given in (10).
  - If a split operation is performed, update the current partition $\Pi^{cur}$.

until no split occurs

**Phase III - D2D content sharing:**
- The BS gets the final partition as $\Pi^{fin} = \Pi^{cur}$.
- The BS informs each UE which neighbors are in the same coalition with it.
- Each UE obtain its required contents based on the internal strategy of (6).

Proof: Assume that the final partition $\Pi^{fin}$ resulting from the proposed algorithm is not $D_{hp}$-stable. Then, the conditions (a) and (b) in definition 6 are not both satisfied for $\Pi^{fin}$. On one hand, if (a) is not satisfied, there exists a $T \subseteq \{1, \ldots, q\}$ which meets $\bigcup_{k \in T} S_k \supset \{S_k | k \in T\}$. Hence, a merge operation can be performed for $\{S_k | k \in T\} \in \Pi^{fin}$. On the other hand, if (b) is not satisfied, there exists a coalition $S_k (k \in \{1, \ldots, q\})$ whose partition $\{D_1, \ldots, D_l\}$ meets $\{D_1, \ldots, D_l\} \supset S_k$. Hence, a split operation can be performed for $S_k$ in $\Pi^{fin}$. However, whether the merge operation or the split operation can be performed for $\Pi^{fin}$, it is contrary to the fact that $\Pi^{fin}$ is the result of the convergence of the proposed algorithm (Remark 1).

V. SIMULATION RESULTS

In this section, we present simulation results to evaluate the proposed mechanism in comparison with two baseline schemes, named as the non-incentive scheme and the one-helper scheme. In the non-incentive scheme, UEs can directly get contents from its neighbors without considering the incentive for the transmitting UEs, as assumed in [7]. It means that UEs are voluntary to transmit contents to their neighbors and do not care for the energy consumption. What they care about is the number of obtained contents. To achieve the goal of maximizing the number of obtained contents for each UE, all UEs will form a grand coalition in which the internal strategy is assumed to be adopted as (6). In the one-helper scheme, UEs form social-reciprocity circles in which each UE helps transmit contents to a neighbor on the premise that the UE is helped by someone, thus solving the incentive issues by the means of achieving equivalence among helping relationships [11]. With the one-helper constraint, each UE aims to find a proper neighbor which can maximize its gain (i.e., the obtained contents in this paper), regardless of the required cost (i.e., the energy consumption of the transmitting UE in this paper). In the case that two neighbors has the same maximum number of cache hit contents, the closer one will be selected.

In the simulation, we assume a cell with a diameter of 400 m, a Poisson Point Process (PPP) distribution of UEs with an average intensity $\lambda = 0.00015$ (arrivals/m$^2$) [20], and a maximum D2D link coverage of 100 m. The channel gains of D2D links are obtained using the path loss model, i.e., $h = G \cdot d^{-\xi}$ [13]. Moreover, each D2D link is established on a bandwidth of 1 MHz frequency and limited by a minimum rate of 5 Mbps, with a noise power of $10^{-10}$ Watt, i.e., $B = 1$ MHz, $r_{min} = 5$ Mbps, $N_0 = 10^{-10}$ Watt. Besides, we assume that each UE has cached 3 contents and still needs 3 other contents, i.e. $M_c = M_r = 3$. These contents are randomly selected from a total of 10 popular on-demand contents, each of which has a size of 1 Mbit. Finally, we assume that the weighted factor $\alpha_i$ for each UE is the same.

A. A Typical Scenario

We investigate a typical scenario whose physical network topology is depicted in Fig. 1, with 15 UEs and $\alpha_i = 50$. In Fig. 1, each UE is marked by “Ui-Ai-Ci,” and any two UEs in D2D communication range are linked by an edge. Through the proposed mechanism, we obtain a final partition $\Pi^{fin} = \{\{U_1\}, \{U_2\}, \{U_3\}, \{U_4\}, \{U_5\}, \{U_6, U_{10}, U_{12}\}, \{U_7, U_{11}, U_{13}, U_{14}\}, \{U_8, U_{15}\}, \{U_9\}\}$. The coalitions with multiple users are the ones which contain the UEs involving in D2D content sharing, these coalitions are marked by ellipses with different colors in Fig. 2. Moreover, in Fig. 2, the number of contents transmitted over each D2D link, i.e., $g_{ij}$, is also marked beside the corresponding D2D link.

Note that in Fig. 2, not all the UEs can form coalitions with others due to their specific properties of locations, cached contents and required contents. However, once a UE joins a coalition with others, it will obtain a positive utility. This is an important property (for motivating users to involve in D2D content sharing), which cannot be guaranteed by the two baseline schemes. This aspect can be sustained by Fig. 3, which illustrates the individual utilities of the UEs in the typical scenario through different schemes. In Fig. 3, there are some UEs obtaining negative utilities, even though they involve in...
In the two baseline schemes, the impact of energy consumption is not taken into consideration, then different values of \( \alpha \) will not change the way in which UEs cooperate for D2D content sharing. Consequently, as the value of \( \alpha \) increases, i.e., as the energy consumption weights more, the mean individual utility through the two baseline schemes will decrease linearly, and the variance of the individual utility will increase in the form of parabola which opens upward. As for the proposed mechanism, the mean individual utility will also decrease with the increasing \( \alpha \) since the energy is being valued more. However, the downward trend is not linear, since the proposed mechanism is able to avoid the cases in which the number of obtained contents is unworthy of the energy consumption. Particularly, the proposed mechanism’s mean utility never falls below zero even if the value of \( \alpha \) grows larger and larger. These trends can be easily observed in Fig. 4 and Fig. 5.

We analyze the comparison of performance results between the non-incentive scheme and the proposed mechanism as follows. In the non-incentive scheme, all UEs form a grand coalition in which all cache hit contents will be transmitted. While in the proposed mechanism, we obtain a \( D_{hp} \)-stable partition where contents are not allowed to be transmitted between coalitions. When \( \alpha \) is small, the energy weights not much in the utility function, so the maximum number of transmitted contents can help improve the mean individual utility. Then, the non-incentive scheme which has the maximum number of transmitted contents through the grand coalition can provide a higher mean utility than the proposed mechanism, as illustrated in Fig. 4 when \( \alpha \) is smaller than the value around 40. If \( \alpha \) is big enough, some content transmission in the grand coalition becomes inefficient since the consumed energy values more than the obtained contents. So the non-incentive scheme provides a lower mean individual utility when compared with the proposed mechanism which avoids these inefficient transmissions, as illustrated in Fig. 4 when \( \alpha \) is larger than the value around 40. Besides, in the grand coalition, different UEs will have quite different values of individual utility since the impact of energy consumption is not taken into consideration. Then the variance of individual utility is larger in the non-incentive scheme than in the proposed mechanism regardless of what value \( \alpha \) equals.

As for the comparison between the one-helper scheme and the proposed mechanism, we describe the analysis as follows. In the one-helper scheme, UEs form social-reciprocity circles where each UE can only select one helper. While in the proposed mechanism, UEs have the opportunity to obtain more contents since each UE can be helped by all of its neighbors in the same coalition. Even though UEs may consume more energy in the coalition than in the circle, the coalition can efficiently exchanges the energy for contents. So the mean individual utility is higher in the proposed mechanism than in the one-helper scheme from the point of statistics. Moreover, the variance of individual utility is smaller in the one-helper scheme than in the non-incentive scheme since there is an equivalence among the helping relationships in the one-helper scheme. Furthermore, since the helping relationship does not
take into account the amount of energy consumption, the one-helper scheme will provide a larger variance of the individual utility than the proposed mechanism, when the energy weights much (i.e., $\alpha$ is larger than the value around 20 in Fig. 5) in the utility function.

Summarizing the results, the proposed mechanism results in a partition, in which a UE is guaranteed to achieve a positive utility if it involves in D2D content sharing with others. Moreover, compared with two baseline schemes, the proposed mechanism has the ability to flexibly adapt to the varying value of $\alpha$. In particular, when the UEs put more weight on energy, i.e., when $\alpha$ grows larger, the proposed mechanism can still have a good performance on the mean and variance of individual utility through the involvement in D2D content sharing.

VI. CONCLUSIONS

In this paper, we have presented an energy-aware incentive mechanism for D2D content sharing, based on forming collaborative groups where users help each other. A coalition formation algorithm is proposed to deal with the process of user grouping, which has the ability to guarantee that all users involving in D2D content sharing will achieve positive utilities. Moreover, the performance gains on the mean and variance of the utility are also achieved by using the proposed mechanism.

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