A Coalitional Graph Game for Device-to-Device Data Dissemination with Power Budget Constraints

Yiming Zhao and Wei Song
Faculty of Computer Science
University of New Brunswick, Fredericton, Canada
Email: {ym.zhao, wsong}@unb.ca

***Abstract*—With the evolution of wireless networks and pervasive mobile devices, device-to-device (D2D) communications have been envisioned as an effective means for data dissemination, *e.g.*, in disaster alerts and event notifications. As mobile devices are battery-powered, it is essential to save power when scheduling D2D links for data dissemination. Also, users are generally more willing to forward data to others with social connections. In this paper, we take into account two important aspects, *i.e.*, D2D users' social incentive constraint and power budget constraint, to enable more practical data dissemination. It is found that it is very difficult to obtain an optimal solution that minimizes the total power consumption while satisfying such constraints. Therefore, we propose a coalitional graph game based approach, which iteratively derives a transmission graph to reach every interested user. Simulations are conducted to compare the proposed approach with the optimal solution and two other reference schemes. The simulation results demonstrate the high performance of our approach in various scenarios with different network scales and social connections.**

***Index Terms*—Data dissemination, D2D communications, power constraints, social networks, coalitional graph game.**

I. Introduction and Related Work

Data dissemination aims at delivering information to a group of target users in a geographical region. It has a wide range of applications in disaster alert, event notification, and advertisement distribution. With the proliferation of mobile devices and evolution of wireless networks, device-to-device (D2D) communications offer promising paradigms for energy-efficient data dissemination.

In [1], Sun *et al.* propose a coalitional graph game for D2D data dissemination among socially connected users to maximize system sum rate. In [2], Xu *et al.*propose an analytical model through ordinary differential equations to mimic epidemic information dissemination in mobile social networks and validate the model by trace-driven simulation. A novel content delivery framework is proposed in [3] to distribute content to moving vehicles via both parked vehicles and roadside units (RSUs). A Stackelberg game is formulated to determine where to obtain the requested content, while each party of the Stackelberg game obtains the maximum utility with the optimal price during the content delivery. In [4], we propose an energy-efficient D2D dissemination approach based on minimum spanning tree. This approach mainly addresses two key problems in a two-phase procedure, i.e., initial seed selection and subsequent transmission scheduling, aiming to achieve a good balance between total energy consumption and transmission completion time. A three-phase approach is further investigated in [5,6] for D2D-based data dissemination to address user mobility and exploit opportunistic forwarding.

In this work, we focus on two important factors which are insufficiently addressed in previous works for data dissemination in wireless networks, *i.e.*, users' incentive constraint and power budget constraint. As data dissemination consumes energy and bandwidth resources, people are generally more willing to share data with friends. Therefore, to meet the users' incentive constraint, many works limit the scope of D2D transmission to users with social ties, assuming that every user is able to disseminate data to all its friends within the D2D transmission range [1,4]. In fact, as portable wireless devices are battery-powered and users generally expect that their devices can operate for a long time to handle daily activities, people often set a power budget and only contribute limited power for data dissemination. Hence, we take into account both social and budget constraints of D2D users to enable more practical data dissemination. Particularly, given these constraints, we propose a coalitional graph game to coordinate data transmission of D2D users to save power consumption in data dissemination. The simulation results confirm the effectiveness of our proposed approach.

The remainder of this paper is organized as follows. In Section II, we give the system model for social-aware data dissemination via D2D communications with power budget constraint. Section III presents our proposed coalitional graph game. Simulation results are shown in Section IV followed by conclusions in Section V.

II. System Model and Problem Formulation

A. Data Dissemination Model

Consider a data dissemination scenario depicted in Fig. 1. The base station (BS), b, is requested to disseminate some data to a set of n users in an area, denoted by N. The BS first chooses a subset of those users as *seeds*, denoted by $M \subset N$, and then multicasts the data to the selected seeds at an authorized frequency channel. After that, the seeds forward the data to other users by D2D communications underlaying

This research was supported in part by Harrison McCain Foundation and Natural Sciences and Engineering Research Council (NSERC) of Canada.

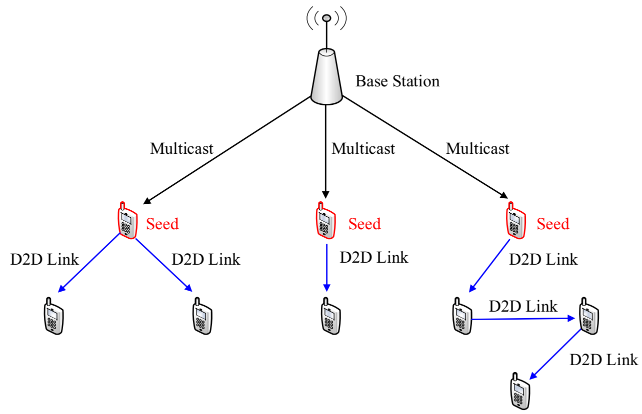


Fig. 1. System model.

the cellular network, while any user that receives the data can further disseminate the data to others similarly via D2D links.

To reduce co-channel interference, the D2D links share the uplink spectrum of cellular users. When the D2D underlay link from i to j shares the uplink channel of cellular user ℓ, there exists interference between D2D user j and cellular user ℓ. Then, the received signal at D2D user j can be written as

$$y_j = \sqrt{P_{t,i}} h_{ij} x_i + \sqrt{P_{t,\ell}} h_{\ell j} x_\ell + n_j \tag{1}$$

where x_i and x_ℓ are the signals from i and ℓ transmitted with power $P_{t,i}$ and $P_{t,\ell}$, respectively, h_{ij} and $h_{\ell j}$ are the channel responses of links from i to j and from ℓ to j, respectively, and n_j is the additive white Gaussian noise (AWGN) at j. The second term in (1) is the interference from ℓ to j. Thus, the channel rate of the D2D link from i to j is given by

$$R_{ij} = B_{ij} \cdot \log_2 \left(1 + \frac{P_{t,i} \cdot |h_{ij}|^2}{P_{t,\ell} \cdot |h_{\ell j}|^2 + |n_j|^2}\right) \tag{2}$$

where B_{ij} is the bandwidth of the resource blocks consumed by the D2D link from i to j. Here, we consider a Rayleigh fading channel model with log-distance path loss. In addition, we assume that a message of size F is transmitted in one time slot of length τ. Then, the data rate demand for the message is a constant, *i.e.*, $R_{ij} = F/\tau \triangleq \gamma$. Accordingly, we can obtain the required transmit power from i to j, $P_{t,i}$.

B. Social Network Model

Let f_{ij} denote whether user i and user j are socially connected. To accommodate user incentive constraint, we assume that D2D data dissemination only occurs between two users if they are socially connected, and their physical distance and D2D channel conditions can meet the data rate requirement, and the resulted power consumptions of users' devices satisfy the budget constraints. To characterize the social relationships among D2D users, we use *the caveman model*, and it has been proved in [7] that social networks based on this model are very close to real ones. The caveman model starts with K isolated complete graphs, also known as *caves*, in which every vertex is adjacent to every other vertex. Then in a rewiring stage, every edge of a cave in the original network is randomly rewired by pointing to a node in another cave with probability p. The rewiring procedure intends to establish random interconnections between individual nodes of different caves.

C. Design Objective

Given the system model in Section II-A, we can model the transmission from the BS to D2D users and the D2D communications among the users with social connections as a *directed* graph $G(V, E, w)$, where V is the set of the BS (b) and D2D users (N), *i.e.*, $V = \{b\} \cup N$, E denotes the links from the BS to D2D users and the available D2D links between D2D users, and each edge is labeled by weight $w(e_{ij})$, which gives the transmit power for the corresponding transmission from node i to node j. Let $E' \subseteq E$ denote the set of selected links for data dissemination, where $E' \subseteq E$ implies that each node in N only forwards data to its socially connected users. Here, we aim to design a data dissemination solution, which can properly coordinate the data transmission of the BS and D2D users so as to minimize the total power consumption of data dissemination while satisfying each user's power budget constraint, *i.e.*,

$$\min_{E' \subseteq E} \sum_{e_{ij} \in E'} w(e_{ij}) \tag{3}$$

$$\text{s.t.} \quad \sum_{j \in S_i} w(e_{ij}) \leq B_i, \forall i \in N \tag{4}$$

$$\{j : \forall e_{ij} \in E'\} = N \tag{5}$$

where S_i is the set of users that receive data from user i, or in other words, the head endpoints of the outgoing edges of node i in E', and B_i is the power budget of user i. Constraint (4) requires that the power budget of each user be respected. Constraint (5) indicates that each user in N should receive the disseminated data.

III. Coalitional Graph Game Solution

As for problem (3) formulated in Section II, it is essentially to construct a minimum spanning tree of the directed graph G with the BS as the root node, which satisfies the power budget constraint of each node. Correspondingly, the child nodes of the BS in the generated tree will be the seeds. In fact, it is very complex to obtain the optimal solution to this problem. A straightforward approach is to first enumerate all the spanning trees of graph G, *e.g.*, using the algorithm in [8], then find the feasible spanning trees that satisfy the node budget constraints, and last return the feasible spanning tree with the minimum total power consumption. Instead of directly applying such a costly centralized approach, we propose a distributed solution based on a coalitional graph game, which is preferable for the wireless network with limited power.

A. Design Rationale

As discussed in Section I, users are generally willing to share data with their friends as long as the power consumption does not exceed their limited power budgets. Hence, this forms a coalitional group among the socially connected users and the BS in the network. Moreover, in data dissemination, a user needs to first receive data from a source node and then transmit the data to some other users. Thus, the transmission links among the nodes in the network, *i.e.*, the coalition structure, are very important. Based on these insights, we design a *coalitional graph game* for the formulated problem to coordinate the transmission among the nodes in the network.

During the process of data dissemination, the result of interactions among the nodes can be represented by a directed transmission graph $G^*(V, E^*)$, in which a directed edge $e^*_{ij} \in E^*$ indicates that there is a link to transmit data from node i to node j. Similar to [1], we assume that each user device is equipped with a single antenna. Thus, the maximum number of links from or to node i at any moment is limited to 1. Letting d_i^{in} and d_i^{out} denote the in-degree and out-degree of node i in graph G^*, we have $d_i^{\text{in}} \in \{0, 1\}$ and $d_i^{\text{out}} \in \{0, 1\}$ at any snapshot of the evolving transmission graph.

As for the coalitional graph game, an important component is the definition of utility function. Here, we define the utility function with respect to the transmission graph $G^*(V, E^*)$ as

$$U(G^*) = \sum_{e^*_{ij} \in E^*} (P^*_{\max} - P_{t,i}) \tag{6}$$

$$P^*_{\max} = \max_{e_{ij} \in E} \{w_{ij}\} + \epsilon \tag{7}$$

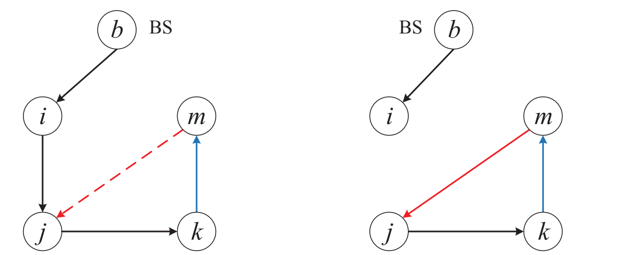
where $P^*_{\max}$ is the largest power consumption of all links in graph $G(V, E, w)$ plus a small constant value ϵ, and $P_{t,i}$ is the transmit power of user i to forward data to user j. This utility definition can be interpreted as follows. At a starting point, suppose that every node $i \in N$ in the network can only receive data from a virtual source node x, which transmits data to node i with transmit power $P^*_{\max}$. Following the starting point, a node i takes allowed actions iteratively and switches to a different source under certain conditions. Accordingly, the transmission graph G^* is updated. The more the power reduced from the initial choice, the higher the utility resulting from the new transmission graph.

B. Solution Details

Given a transmission graph $G^*(V, E^*)$ in a certain iteration, the state of any node i in graph G^* is represented by (a_i, b_i, c_i), which indicates that node $i \in V$ receives data from $a_i \in V$ (the upstream node of i) and transmits shared data to $b_i \in N$ (the downstream node of i). For notation simplicity, let $a_i = i$ when $d_i^{\text{in}} = 0$ and $b_i = i$ when $d_i^{\text{out}} = 0$. In order to track the state of nodes and transmission links, we include c_i to record the node that has promised to transmit shared data to node i, *i.e.*, the actual transmission source to node i.

With a current transmission graph $G^*(V, E^*)$, we consider that node i can do nothing in an iteration or take an allowed action among the following or certain combinations:

- Offer to establish new link(s) e^*_{ij}, where $j \neq i$ and $f_{ij} = 1$ (*i.e.*, $e_{ij} \in E$), if $d_i^{\text{out}} = 0$, which *intends* to add to E^* new *outgoing* links from node i;
- Accept to establish a new link e^*_{ji}, if $d_i^{\text{in}} = 0$ and $f_{ij} = 1$, which adds to E^* a new *incoming* link to node i; and
- Break an existing link $e^*_{ij} \in E^*$ from i to j, if $d_i^{\text{out}} = 1$.



(a) After node m accepts the transmission request from node k, it sends transmission request to node j.

(b) Assuming $P_{mj} < P_{ij}$, node j chooses to receive data from node m instead of i. Thus, a cycle without a source is formed.

Fig. 2. An illustrative example on how a cycle without a source is formed.

Here, the accept-link action of node i is accompanied by an offer-link action to establish a new link to each node that is socially connected with i. That is, after a node receives data from a newly established link, it will immediately request to transmit data to other nodes. Besides, the break-link action of node i for an outgoing link is combined with an offer-link action to establish a link to a different downstream node.

It is worth emphasizing that a node can transmit shared data to only one node in each round, due to the single antenna constraint. In order to explore more potential receivers, a transmitter i needs to first break its transmission link to the current receiver j to reset d_i^{out} to 0 (*i.e.*, b_i is set i), so as to offer another node a new link. Simultaneously, the state of node j is synchronized to $d_j^{\text{in}} = 0$ and $a_j = j$, so that j can accept the request from a better source. Since the break-link action is tentative for searching better options, c_i in the new state is not simultaneously reset with the break-link action but only updated when a better link is established. As seen, c_i is mainly for backtracking purpose to reconstruct the entire transmission graph. Hence, we define an *available strategy* of node i by $\langle a_i, b_i \rangle$, which indicates the immediate result relevant to node i in the new graph due to its action. Then, the strategy space of node i is denoted by $S_i = \{s_i = \langle a_i, b_i \rangle \mid a_i \in V, b_i \in N\}$.

According to [9], an available strategy is *feasible* if and only if the utility of the new graph resulting from the strategy is not less than that of the current transmission graph. In our scenario of data dissemination, this definition is likely to result in a cycle without a valid source. Fig. 2 shows such an example. As seen, originally, there is a transmission path from the BS to node k, $b \to i \to j \to k$. Then, node m accepts the offer from node k and establishes the transmission link from k to m. After that, node m offers to transmit data to node j. Assuming that the transmission link from m to j consumes less power than the link from i to j, node j will choose to receive data from m instead of i. As a result, a cycle $j \to k \to m \to j$ is formed. Obviously, such a cycle without a valid source is infeasible, since none in the cycle is associated with a transmission link from the BS and thus cannot start the data dissemination. In addition to avoiding cycles, a feasible strategy also needs to respect the nodes' power budget constraints. Therefore, we extend the definition of feasible strategies as follows.

Algorithm 1: A coalitional graph game based approach for D2D data dissemination.

Input: $G(V,E)$, $P^*_{\max}$, $\gamma = F/\tau$, $B_i, \forall i \in V$, $|h_{ij}|^2$, $d_{ij}, \forall e_{ij} \in E$

Output: $G^*(V,E^*)$

1 **begin** Calculate power consumption of possible transmission links

2 **foreach** $e_{i,j} \in E$ **do**

3 Calculate $P_{t,i}$ with respect to receiver node j according to Eq. (2) such that $R_{ij} \geq \gamma$

4 **begin** Form transmission graph iteratively

5 $t \leftarrow 0$ *// Initialize iteration counter*

6 Initialize $G^*_t(V,E^*_t)$, where $E^*_t \leftarrow \varnothing$, and $U(G^*_t) = 0$

7 **foreach** $i \in V$ **do** *// Initialize states of nodes in V*

8 **if** $i = b$ **then**

9 Set $a_i = b_i = c_i = b$

10 **else**

11 Set $a_i = b_i = i, c_i = x$

12 **while** G^*_t *is not a local Nash network* **do**

13 Randomly select node $i \in V$

14 Request necessary information from BS for node i and calculate its set of feasible strategies S^*_i

15 Choose node i's local best response $s^*_i = \langle a^*_i, b^*_i \rangle$

16 Construct new transmission graph to $G^*_{t+1}(V,E^*_{t+1})$ according to s^*_i, where $E^*_{t+1} = (E^*_t \setminus \{e_{a_i i}, e_{ib_i}\}) \cup \{e_{a^*_i i}, e_{ib^*_i}\}$ *// Update c^*_i according to best response $\langle a^*_i, b^*_i \rangle$*

17 **if** $a^*_i \neq i$ **then**

18 $c^*_i \leftarrow a^*_i$

19 **else**

20 $c^*_i \leftarrow c_i$

21 $(a_i, b_i, c_i) \leftarrow (a^*_i, b^*_i, c^*_i)$ *// Update node i's state*

22 $t \leftarrow t+1$

23 Reconstruct final transmission graph $G^*(V,E^*)$ according to c_i in the state of node i, $\forall i \in V$

24 Return $G^*(V,E^*)$

Definition 1: An available strategy $s_i = \langle \tilde{a}_i, \tilde{b}_i \rangle \in S_i$ is *feasible* for user $i \in V$ with state (a_i, b_i, c_i) if and only if $U(\tilde{G}^*) \geq U(G^*)$, and this strategy will not lead to a cycle without a source, and the resulted power consumption of each user satisfies its corresponding budget constraint, where $G^*(V,E^*)$ is the current transmission graph and $\tilde{G}^*(V,\tilde{E}^*)$ is the consequent transmission graph following strategy s_i. The set of feasible strategies of node i is denoted by S^*_i.

The most popular approach to solving a coalitional graph game is to iteratively play *myopic best-response dynamics*. In our case, a node is randomly selected in each round and plays a feasible strategy, which will not decrease the utility of the transmission graph, *i.e.*, not increase the total power consumption. Furthermore, as the game aims to gradually increase the utility and approach the optimum, the node is supposed to choose among all feasible strategies the one that maximizes the current utility. This is defined as the *local best response*, which is the feasible strategy that maximizes the utility given that the other nodes maintain their strategies [9]. Thus, the nodes in the proposed coalitional graph game keep playing their best responses unilaterally to explore more efficient transmission links for increasing the network utility. As a result of the nodes' iterative actions, the network utility tends to be maximized, while the total power consumption is converged to the minimum. To ensure that the transmission graph G^* reaches a steady state, we consider the notion of *local Nash network*, in which no node can improve the utility $U(G^*)$ by a unilateral change in its feasible strategy [9], *i.e.*, the graph finally converges to a local Nash network.

Alg. 1 gives the details of the proposed coalitional graph game. As seen, in Lines 1-3, we first need to calculate the required transmit power for all possible transmission links in graph $G(V,E)$ to meet the rate requirement. Then, in the main block (Lines 4-23), we iteratively build the transmission graph $G^*_t(V,E^*_t)$ by randomly selecting a node in each round t and applying its best response. Once $G^*_t(V,E^*_t)$ converges to a local Nash network, the iterations terminate and the final transmission graph $G^*(V,E^*)$ is reconstructed according to the node state information $c_i, \forall i \in V$.

IV. Simulation Results

To evaluate the performance of our proposed approach, we conduct computer simulations with a 200m×200m square region, in which the BS is located at the center point, and the cellular users and D2D users are uniformly distributed. The number of cellular users is fixed at 150, while the number of D2D users varies in the simulations. Each D2D user is assigned an arbitrary cellular uplink channel for its D2D communications. The D2D transmission range is set to 100m. We use the caveman model with different rewiring probabilities to generate the social relationships among the D2D users. In order to specify a user's power budget constraint, we define a factor called *budget ratio*, which is the ratio of the power that a user would spend in transmitting data to its friends within the D2D communication range over its potential total power.

A. Convergence Performance

First, we show the convergence performance of our proposed coalitional graph game for the network with 15 (n) D2D users. The social relationships are modeled by the caveman model. Here, we set the number of caves to 3, the size of each cave to 5, and the rewiring probability p to 0.1. The budget ratio of each user is set within the range of $(0.5, 1]$. Fig. 3 shows the network utility and total power consumption of the proposed approach versus the iterations respectively. As observed, the network utility first increases rapidly and then converges gradually. Meanwhile, we can see that the corresponding total power consumption decreases gradually and finally reaches a low value. This is because our definition of utility is inversely proportional to the total power

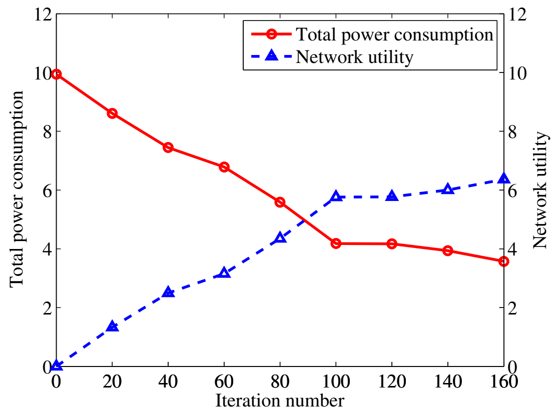


Fig. 3. Convergence performance of the proposed coalitional graph game with $n = 15$.

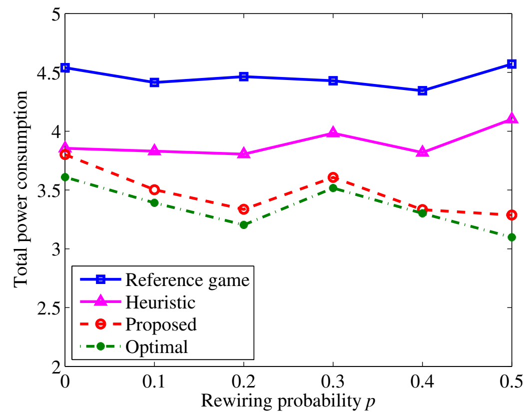


Fig. 4. Comparison of data dissemination schemes with different social structures and $n = 15$.

consumption, such that as the utility increases, the total power consumption decreases correspondingly.

B. Comparison of Different Solutions

Next, we compare our proposed approach with three reference schemes. The first reference scheme is introduced at the beginning of Section III which can find an optimal solution to problem (3). The second scheme is a distributed heuristic approach, in which one of the nodes that have received data is randomly selected in each iteration and the node transmits data to the feasible receiver which consumes the lowest power. This approach iterates until all nodes in the network have received the data. Third, we consider a different coalitional graph game that extends the basic idea of [1] to problem (3). In [1], the BS is regarded as the initial source, and a transmission graph $\hat{G}(V, \hat{E})$ coordinating the data dissemination is built from the initial directed graph $G(V, E)$ via a coalitional graph game. Here, the utility function is defined similarly as $U(\hat{G}) = \sum_{e_{ij} \in \hat{E}} (m_i - m_j)(w_{\max} - w(e_{ij}))$, where m_i (resp. m_j) is binary indicating whether i (resp. j) has possessed the data, and $w_{\max}$ is the maximum weight of edges in E.

First, we run simulations with relatively small-scale networks and different social connection structures. Here, all the parameter settings are the same as those specified in the previous simulation with 15 D2D users, except that the rewiring probability p ranges from 0 to 0.5 to generate social networks of different characteristics. Fig. 4 shows the total power consumption with different social structures. As seen, the total power consumption of our approach is fairly close to that of the optimal solution with different social relationships. The total power consumptions of the two reference schemes are both higher than that of our approach, among which the scheme based on a different coalitional graph game has the highest power consumption. In this scheme, after a node receives data from another node, it cannot accept any link request from a more efficient source, since accepting such a request means the term $(m_i - m_j)$ in the utility function will be zero and thus cannot increase the utility. This design is to aggressively avoid forming a cycle without a source, even though not every such request will lead to an undesired cycle. By contrast, our proposed coalitional graph game relaxes this limitation and allows nodes to accept the requests from other nodes for establishing more efficient links as long as no cycle without a source will result from such actions.

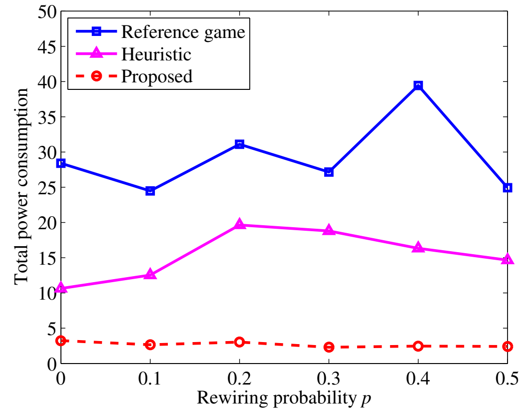
C. Scalability to Large Networks

In the following, we run simulations with larger-scale networks. As mentioned in Section III, it is very difficult to obtain the optimal solution to problem (3). Especially, with a larger network scale, the search space of the graph becomes much broader. As a consequence, it becomes extremely difficult to obtain the optimal solution. Therefore, in the following simulations, we only compare our solution with the heuristic approach and the other coalitional graph game based approach. Here, we consider networks with 50 and 100 D2D users, while the number of caves is set to 5 and 10, respectively, given that the cave size is fixed at 10. The budget ratio of each user is set within the range of $(0.5, 1]$ and the rewiring probability p varies from 0 to 0.5.

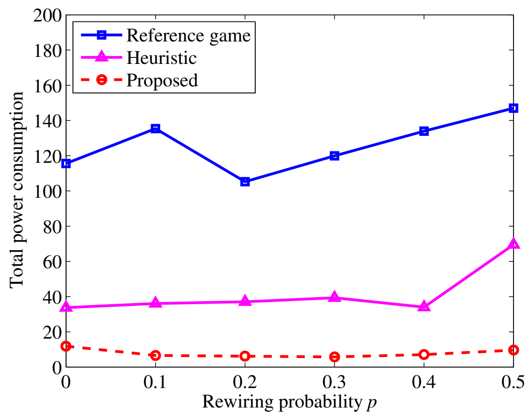
Fig. 5 shows the total power consumption of three data dissemination schemes with different network scales. As seen in both Fig. 5(a) and Fig. 5(b), the total power consumption of our solution is always lower than that of the two reference schemes. It is worth noticing that, when the network scale increases, the gap between our solution and the reference schemes becomes more significant. This demonstrates that our approach is more adaptive to networks of different sizes, and especially more scalable to large networks. Meanwhile, it can be observed in both scenarios that, with the increase of the rewiring probability, the total power consumption of our solution fluctuates within a narrower range while the two reference schemes fluctuate more dramatically. This indicates that our approach is also more adaptive to different social connection structures and power budget constraints.

D. Impact of Power Budget Constraint

Last, we test the impact of users' power budget constraints on the performance of data dissemination. Here, we use similar settings as the simulation with 15 D2D users in Section IV-A.



(a) $n = 50$.



(b) $n = 100$.

Fig. 5. Comparison of data dissemination schemes with large D2D networks.

The rewiring probability p is set to 0.5, while the cave size remains to be 5 and there are 3 caves. In order to reflect the impact of users' power budget constraint, we assume the same budget ratio for each user and vary the ratio from 0.2 to 1.

Fig. 6 shows the total power consumption and the BS's power consumption versus the budget ratio. As seen, the power consumption of our approach is fairly close to that of the optimal solution in all cases with various power budgets. Besides, as expected, the power consumption decreases with a larger budget ratio. In particular, when the budget ratio increases from 0.2 to 0.4, the power consumption of the BS is reduced substantially. This is because the larger power budget allows users to contribute more energy in transmitting data to their friends within the D2D communication range. Thereby, more efficient D2D links can be utilized to offload data transmission from the BS. Furthermore, when the budget ratio exceeds certain threshold (say, 0.6), the power consumption becomes more stable. This is because after certain point most efficient D2D links have already been selected. Even when the users would like to contribute more energy, the selected D2D links will rarely change.

V. Conclusions and Future Work

In this paper, we investigate how to explore D2D communications and social connections for energy-efficient data dissemination. To enable data dissemination in practice, we take into account both social incentive constraint and power budget constraint of D2D users. As it is computationally difficult to obtain an optimal solution to the formulated data dissemination problem, we propose a coalitional graph game to approach the optimal solution. The simulation results show that the power consumption of our proposed approach is fairly close to that of the optimal solution in a small-scale D2D network. Moreover, our approach outperforms two other reference schemes in various cases with different network sizes and social structures. We also demonstrate the effect of users' power budgets on the performance of data dissemination. An interesting extension direction is to enhance data dissemination of multi-class contents [10] by exploiting an integrated environment with heterogeneous wireless networks.

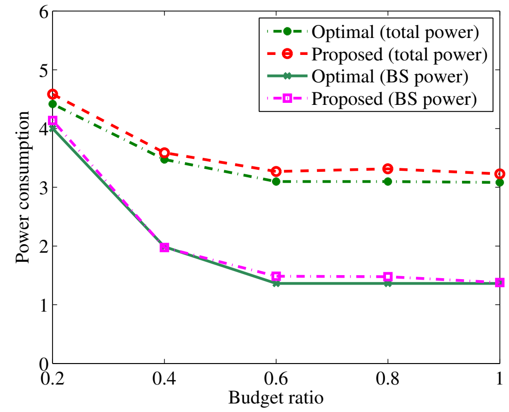


Fig. 6. Impact of users' power budget constraint on data dissemination performance with $n = 15$.

References

[1] Y. Sun, T. Wang, L. Song, and Z. Han, "Efficient resource allocation for mobile social networks in D2D communication underlaying cellular networks," in *Proc. IEEE ICC*, 2014, pp. 2466–2471.

[2] Q. Xu, Z. Su, K. Zhang, P. Ren, and X. Shen, "Epidemic information dissemination in mobile social networks with opportunistic links," *IEEE Trans. Emerg. Topics Comput.*, vol. 3, no. 3, pp. 399–409, 2015.

[3] Z. Su, Q. Xu, Y. Hui, M. Wen, and S. Guo, "A game theoretic approach to parked vehicle assisted content delivery in vehicular ad hoc networks," *IEEE Trans. Veh. Technol.*, 2016, to appear.

[4] Y. Zhao and W. Song, "Social-aware energy-efficient data dissemination with D2D communications," in *Proc. IEEE VTC Spring*, 2016.

[5] Y. Zhao and W. Song, "Social-aware data dissemination via opportunistic device-to-device communications," in *Proc. IEEE VTC Fall*, 2016.

[6] Y. Zhao, W. Song, and Z. Han, "Social-aware data dissemination via device-to-device communications: Fusing social and mobile networks with incentive constraints," *IEEE Trans. Services Comput.*, 2016, to appear.

[7] D. J. Watts, *Small Worlds: The Dynamics of Networks Between Order and Randomness*. Princeton University Press, 1999.

[8] H. N. Gabow and E. W. Myers, "Finding all spanning trees of directed and undirected graphs," *SIAM Journal on Computing*, vol. 7, no. 3, pp. 280–287, 1978.

[9] W. Saad, Z. Han, M. Debbah, A. Hjørungnes, and T. Başar, "Coalitional game theory for communication networks," *IEEE Signal Processing Magazine*, vol. 26, no. 5, pp. 77–97, 2009.

[10] W. Song and W. Zhuang, "Multi-class resource management in a cellular/WLAN integrated network," in *Proc. IEEE WCNC*, 2007, pp. 3070–3075.