2020 16th International Conference on Distributed Computing in Sensor Systems (DCOSS)

Social-Aware Energy Balancing in Mobile Opportunistic Networks

Eyuphan Bulut and Aashish Dhungana
Department of Computer Science, Virginia Commonwealth University
401 West Main St. Richmond, VA 23284, USA
{ebulut, dhunganaa}@vcu.edu

***Abstract*—Thanks to the recent advances in wireless power transfer technology and its adoption in mobile portable devices (e.g., smartphones), an alternative energy replenishment option for users has emerged through peer-to-peer energy sharing among devices. Such a notion of energy sharing among nodes in a mobile opportunistic network can help balance the energy levels of nodes and can keep them connected, prolonging the lifetime of the network. Existing works studying the energy balancing problem mainly focus on decreasing of the energy difference among nodes as fast as possible, thus consider sharing of the energy among meeting nodes equally. However, in an opportunistic network consisting of mobile devices carried by people (i.e., also called mobile social network), due to the underlying social relations between people, there will be multiple social groups affecting the contact relations between nodes. While nodes in the same group interact more often, the nodes in different groups interact less frequently. Moreover, there is usually a smaller number of nodes from different groups that interact (i.e., bridge nodes), providing limited opportunity for energy transfer between groups. In this study, we look at the energy balancing problem considering the underlying social network structure and present a two-stage social-aware energy balancing protocol for a fast balancing process. To this end, we integrate the roles of nodes (e.g., bridge/non-bridge node) as well as the average energy differences between different groups to determine the amount of energy transfer between meeting nodes. Through simulations, we demonstrate that the proposed social-aware energy balancing protocol performs better than the state-of-the-art.**

***Index Terms*—Energy balancing, social network structure, wireless energy transfer, opportunistic network, crowd charging.**

I. Introduction

Wireless charging based energy replenishment of battery-powered devices has recently attracted a lot of attention thanks to recent advances in the technology and its convenience. While most of the earlier studies have focused on the wireless rechargeable sensor networks [1] and considered the charging of sensor nodes from mobile charger vehicles, there is a growing number of interesting research studies that utilize wireless charging for the energy management and replenishment of various types of mobile devices (e.g., Internet of Things [2]) and vehicles (e.g., electric vehicles [3]).

One recent research problem that utilize wireless charging is the energy balancing problem [4]–[6] which aims to equalize the energy levels of nodes through peer-to-peer energy sharing and minimize the sum of the differences of their energy from the average energy in the network as much as possible. In scenarios where there is no external mobile charger device can be used due to environmental restrictions and operational costs, such an energy balancing process indeed offers a solution to prolong the network life time which is usually defined as the time until the first node in the network dies.

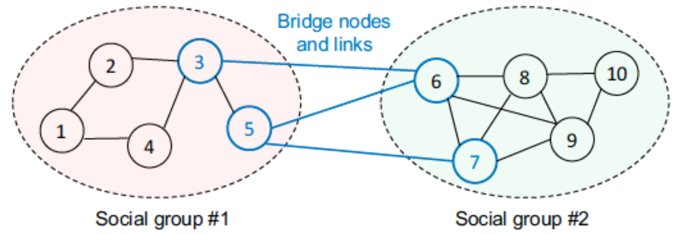


Fig. 1: An example contact graph in a mobile opportunistic network with two social groups. Bridge nodes are the only nodes that can help transfer energy between different groups.

Depending on the network application considered, an energy balancing process comes with several challenges. For example, in a static network consisting of nodes at fixed locations [6], the selection of nodes that will harvest energy from others who will also need to adjust their power levels will be critical. Similarly, in an opportunistic network, as the energy exchanges can only happen during non-deterministically occurring meetings of nodes, for an efficient and fast balancing process, the amount of energy that will be shared among nodes at every meeting opportunity has to be determined carefully [4], [5].

Thanks to the recent adoption of wireless charging technology in smartphones and its bidirectional consideration (e.g., research prototypes [7], [8], and products in market such as Samsung Galaxy S10), an energy balancing problem has been recently considered under the concept of crowd charging [9]. Mobile users who are friends of each other or have been provided some sort of incentive, charge the other users' devices from their own devices during their encounter times so that they continue to be functional. While the existing energy balancing protocols proposed for opportunistic networks can be used for such crowd charging scenarios, they will have a slow balancing process as they do not take into account the underlying social relations between the peers. These relations however determine the intermeeting times of nodes and the energy exchange opportunities between nodes.

Consider the example provided in Fig. 1. The ten nodes in

2325-2944/20/$31.00 ©2020 IEEE
DOI 10.1109/DCOSS49796.2020.00064

an opportunistic network is divided into two social groups or communities due to their contact relations. The nodes in each group opportunistically meet with each other more often, even though not each pair meet, and the nodes in different groups meet less frequently. We call the nodes that connect the nodes of two groups as *bridge* nodes and they are the only nodes that can realize the energy transfer between these two groups. As existing solutions [4], [5], [10]–[12] solely focus on the reduction of energy difference between nodes, they suggest an energy exchange between the nodes in the opposite sides of the average energy in the network. However, for example, if the current average energy levels of nodes within these two social groups are different than each other, in the meeting of, say, node 5 and node 6, if the energy levels of these nodes are closer to each other and they have both less or more than the average energy in the network (i.e., at the same side with respect to average energy), they will miss the opportunity to transfer energy from one group to another, while this could be a very rare opportunity. In this paper, we address this issue through a new energy balancing protocol.

Our goal in this paper is to develop an energy balancing protocol among a population of mobile nodes that interact opportunistically under their socially defined relationships. We target a fast energy balancing process while trying to reduce the energy difference between the nodes in the network. To this end, we consider the underlying social groups between the nodes that affect their contact patterns in the design of the energy sharing protocol and propose a two-stage approach. In the first stage, we aim to equalize the average energy levels of different groups through energy exchanges between bridge nodes, which is also supported by maximum possible energy transfers from/to bridge nodes to/from non-bridge nodes within groups. In the second stage, we target an internal energy balancing process within each group. Through simulations, we evaluate the performance of the proposed social-aware energy balancing protocol and compare with a state-of-the-art protocol which does not take into account the social component. The results show that the proposed approach can reduce the energy difference among nodes faster especially when the initial average energy levels of different groups are different.

The rest of the paper is structured as follows. In Section II, we provide an overview of the literature that study energy balancing problem leveraging peer-to-peer energy sharing. In Section III, we present the system model together with the assumptions made and the description of the problem. In Section IV, we give the details of the proposed social-aware energy balancing protocol. Section V presents the simulation settings used and provides the performance evaluation and comparison of the proposed approach with the existing work. Finally, we end up with conclusion in Section VI.

II. Related Work

Peer-to-peer wireless energy sharing [13] has recently attracted a lot of attention by researchers and several problems have been studied for various application scenarios [14]–[21]. These include energy balancing among nodes, incentivizing nodes for relaying of messages from other nodes, finding crowd charging peers and skipping of charging sessions. Particularly, in energy balancing studies [4], [5], [10] the goal is to exploit opportunistic node meetings to let the nodes exchange energy towards balancing the energy levels of all nodes in the network. However, these studies assume that all nodes are interacting with each other and at each meeting of nodes at opposite sides (i.e., one node having less energy than the average energy and the other node having higher energy than the average energy), they share their total energy equally (or in a weighted manner depending on the significance of each node [4]). This indeed causes an unnecessary energy loss, thus in [12] a loss-aware sharing protocol is proposed using the final expected average energy in the network, instead of the current average, to decide opposite side nodes. Energy amount shared is also decided based on the closeness of energy levels of the nodes to this final average instead of blindly equalizing the energy levels of nodes. On the other hand, that study also assumes that the contact graph among nodes is a complete graph. However, not all nodes in an opportunistic network interact with each other. Such heterogeneous contact relations among nodes have been considered in [11] and the final optimal achievable average energy is found via a Mixed Integer Linear Programming (MILP) based solution and the corresponding energy exchanges between nodes are defined deterministically.

Despite these various studies looking at energy balancing problem, none of them considers the underlying social group structure inside an opportunistic network which has a key role in the contact relations among nodes. To the best of our knowledge, there is only one recent study [9] that considers the social component in the design of a peer-to-peer energy sharing or wireless crowd charging scenario. The study simply considers self reported friendship relations of users in an online social network as well as their social groups to decide if an energy exchange between users will happen. While the results provided in this study show that crowd charging process is influenced by these online social network relations, it does not provide any conclusion and does not propose any new energy sharing protocol that will improve the process. Moreover, the study mostly focuses on the online social network structure among the users in the opportunistic network. Contrary to this study, in this paper, we study the impacts of social group structure integrated in the opportunistic physical contact relations among users. Thus, the social component part we study is different than how it is considered in this previous work. Moreover, we propose a new energy sharing protocol that takes into account the roles of users in the social network model as well as the differences of average energy levels in different groups.

III. System Model

A. Assumptions

We assume that there is a set of mobile nodes , each having a limited battery capacity, and

TABLE I: Notations

Notation	Description
	Number of nodes in the network.
	Interaction protocol between nodes for energy exchange.
	Energy loss rate.
	Transferred energy.
	Energy of user 's device at time .
	Average intermeeting rate between nodes in group .
	Average intermeeting rate between a node in group and a node in group .
	Neighbors of node in the contact graph.
	Social group of node .
	Represents if the node is bridge node (1) or not (0).
	Average energy in the network at time .
	Average energy in the group of node
	Total variation distance between two distributions, , .

equipped with necessary hardware for energy sending and receiving. When two nodes meet opportunistically, they exchange energy according to an energy sharing protocol . The energy of a node at time is denoted by . Each node belongs to a social group denoted by , which is predetermined through a social network analysis on the contact relations between nodes. We assume each pair of nodes, ( ), interacts in an exponentially distributed manner, with an average rate of for each pair of nodes within group and with a rate of for nodes from group and group . The energy loss rate due to wireless charging technology used is denoted by , which is assumed to be a constant in . That is, when two nodes and interact at time and node transfers energy to node , node will receive energy and their new energy levels will be:

We denote the set of neighbors of a node in the contact graph by and define the *bridge* nodes as the nodes that have at least one neighbor node from a different group. That is, for a node :

if

otherwise.

As in previous work [4], [5], [10]–[12], for simplicity, we assume that there is no or minimal energy loss that can be neglected due to mobility or other activities of the nodes, as this is beyond the focus of the current paper. We also assume that each node knows the average energy level in the network and within their own group, which can be realized via cellular communication with a central server. Note that as these values only change when nodes interact and exchange energy, which happens rarely in an opportunistic network, such a communication overhead will be low. The notations used throughout the paper are summarized in Table I.

B. Problem Description

The goal is to achieve a fast energy balancing among a set of nodes with as low variation as possible. We define the energy difference among nodes using the total variation distance from probability theory as in [4].

Let P, Q be two probability distributions defined on a sample space . The total variation distance is calculated as:

(1)

Here, we do not divide the sum by two to keep the actual differences. At any time, we define the energy distribution on a sample space by

where, (2)

for any . We also define the average energy in the network at time as

(3)

The objective, by any time , can then be formally defined as:

(4)

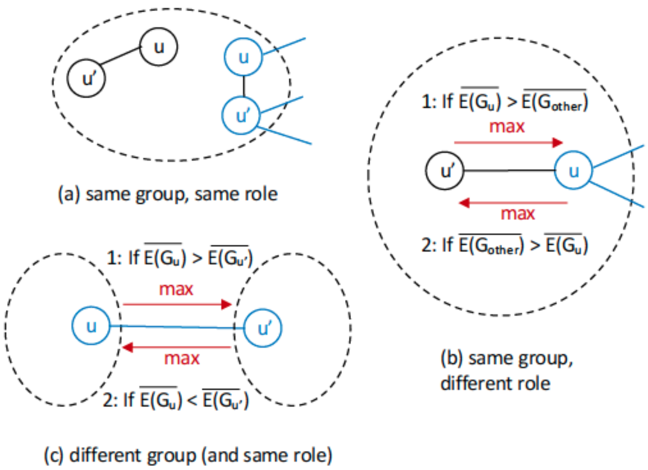
where denotes the uniform energy distribution on (i.e.,).

IV. Social-Aware Energy Balancing

In this section, we give the details of the proposed social-aware crowd charging process that aims to balance the energy levels of nodes in the network. In particular, we target speeding up the balancing process thus consider the underlying social group structure among the nodes in the network and take into account their roles in the energy exchange protocol.

As the nodes within the same social group or community interact more often compared to the nodes in different groups, the energy balancing process can be slow if there is a remarkable difference in the average energy levels of different groups. To this end, we propose a two-stage approach where we apply different rules of energy exchange at different stages.

In the first stage, our goal is to equalize the average energy levels of nodes in different groups. The energy exchange between groups can only happen at the meetings of nodes from each group called bridge nodes. However, these inter-group meetings happen less frequently compared to intra-group meetings of nodes. Thus, each of such meeting opportunity should be benefited at maximum capacity. To address that, we adjust the energy levels of bridge nodes during their intra-group meetings. Consider the different cases of node meetings in Fig.2. If the meeting nodes are in the same group and have the same role (i.e., both bridge or non-bridge node), any potential energy exchange between nodes will not help increase the amount of energy shared between groups. However, if one node ( ) is a bridge node and the other one ( ) is a non-bridge node as in Fig.2b, adjusting the energy level of would help in inter-group energy exchanges. If the group of these nodes has more average energy than the other group's average, maximizing node 's energy level will lead to more energy exchange opportunity to other group. Similarly, if



(a) same group, same role

(b) same group, different role

(c) different group (and same role)

Fig. 2: Different cases of node meetings require different energy sharing procedures in different stages.

node u's group has lower energy than other group's energy, it can minimize its energy by transferring energy to node u'. This provides node u more space to receive energy from the nodes of other group in case they meet and can potentially reduce the average energy difference between groups quickly. When the nodes from different groups meet (both will be bridge nodes), they also exchange energy from the node with higher average group energy to the node with lower average group energy but this should not be more than needed. Once the two groups' average energy levels are equalized, they should stop sharing further and second stage starts.

The second stage stops the interaction of nodes from different groups. It targets intra-group meetings and let the nodes exchange energy if they are at different sides of the average energy. Note that this is necessary in order to make sure that energy variation distance in the network decreases [4], [5], [10]. Here, in order to prevent unnecessary losses during intra-group meetings and energy exchanges, we adopt the opportunistic closer protocol [11] in this stage. That is, if one node has more energy than the average energy and the other one has less than the average energy, they first compute their energy difference from average energy and make the closer one reach the average energy through a sufficient amount of energy exchange (i.e., sending or receiving) with other node.

Algorithm 1 shows the interaction process of this *F*irst *G*roup *T*hen *I*ndividual protocol, or $\mathcal{P}_{FGTI}$ in short. In the first stage, if the nodes in the same group meet (lines 2-8), we allow an energy exchange only if their roles are different i.e., case b in Fig. 2. To this end, we first find the average energy level in the meeting nodes' group and check if it is more than any other group's average energy (lines 5-7). If it is the case, the bridge node should receive as much energy as possible from the non-bridge node so that when it meets a node from the other group it can share energy to that node with a maximum capacity. Similarly, if other group has more energy, then the bridge node should send maximum possible energy to non-bridge node so that bridge node will have enough space when it meets a node from the other group. If the nodes from different groups meet (lines 10-17), in the first stage they find the maximum possible energy sharing between nodes towards

Algorithm 1: FirstGroupThenIndividual (u, u', t)

Input: (u, u'): Interacting nodes
t: Time of interaction

1 **if** Stage $= 1$ **then**
2 **if** $\mathrm{G}_u = \mathrm{G}_{u'}$ **then**
3 **if** $\mathcal{B}_u \neq \mathcal{B}_{u'}$ **then**
4 $(u_b, u_r) \leftarrow (\mathcal{B}_u = 1\ ?, (u, u'), (u', u))$
5 $(u^+, u^-) \leftarrow$ $(\mathrm{E}(\mathrm{G}_{u_b}) > E(\mathrm{G}' \neq \mathrm{G})\ ?(u_r, u_b), (u_b, u_r))$
6 $m = \min\{\mathrm{E}(u^+)(1-\beta),\ 100 - \mathrm{E}(u^-)\}$
7 $\mathcal{P}_{FGTI}(E_{t-1}(u^+), E_{t-1}(u^-))$ = $(E_{t-1}(u^+)$ - $m/(1-\beta),\ E_{t-1}(u^-) + m)$
8 **end**
9 **else**
10 $(u^+, u^-) \leftarrow$ $(\mathrm{E}(\mathrm{G}_u) > \mathrm{E}(\mathrm{G}_{u'})\ ?(u, u'), (u', u))$
11 E_{dif} = $|\mathrm{E}(\mathrm{G}_u) - \mathrm{E}(\mathrm{G}_{u'})|$
12 $m = \min\{\mathrm{E}(u^+)(1-\beta),\ 100 - \mathrm{E}(u^-),\ \frac{\mathrm{E}_{dif}}{(1+\beta)}\}$
13 $\mathcal{P}_{FGTI}(E_{t-1}(u^+), E_{t-1}(u^-))$ = $(E_{t-1}(u^+)$ - $m/(1-\beta),\ E_{t-1}(u^-) + m)$
14 **if** $m = \frac{\mathrm{E}_{dif}}{(1+\beta)}$ **then**
15 Stage $= 2$
16 **end**
17 **end**
18 **else**
19 **if** $\mathrm{G}_u = \mathrm{G}_{u'}$ **then**
20 **if** *(*$E_{t-1}(u) > \overline{E}_{t-1}$ ***and*** $E_{t-1}(u') < \overline{E}_{t-1}$*)* **then**
21 $(u^+, u^-) \leftarrow (u,\ u')$
22 **else**
23 **if** *(*$E_{t-1}(u) < \overline{E}_{t-1}$ ***and*** $E_{t-1}(u') > \overline{E}_{t-1}$*)* **then**
24 $(u^+, u^-) \leftarrow (u',\ u)$
25 **end**
26 **end**
27 **if** (u^+, u^-) *is set* **then**
28 $\delta_{t-1}(u^+) = E_{t-1}(u^+) - \overline{E}_{t-1}$
29 $\delta_{t-1}(u^-) = \overline{E}_{t-1} - E_{t-1}(u^-)$
30 **if** $\delta_{t-1}(u^+)(1-\beta) > \delta_{t-1}(u^-)$ **then**
31 $\mathcal{P}_{FGTI}(E_{t-1}(u^+), E_{t-1}(u^-))$ = $(E_{t-1}(u^+)$ - $\frac{\delta_{t-1}(u^-)}{(1-\beta)},\ \overline{E}_{t-1})$
32 **else**
33 $\mathcal{P}_{FGTI}(E_{t-1}(u^+), E_{t-1}(u^-))$ = $(\overline{E}_{t-1},$ $E_{t-1}(u^-)$ + $(1-\beta)\delta_{t-1}(u^+))$
34 **end**
35 **end**
36 **end**
37 **end**

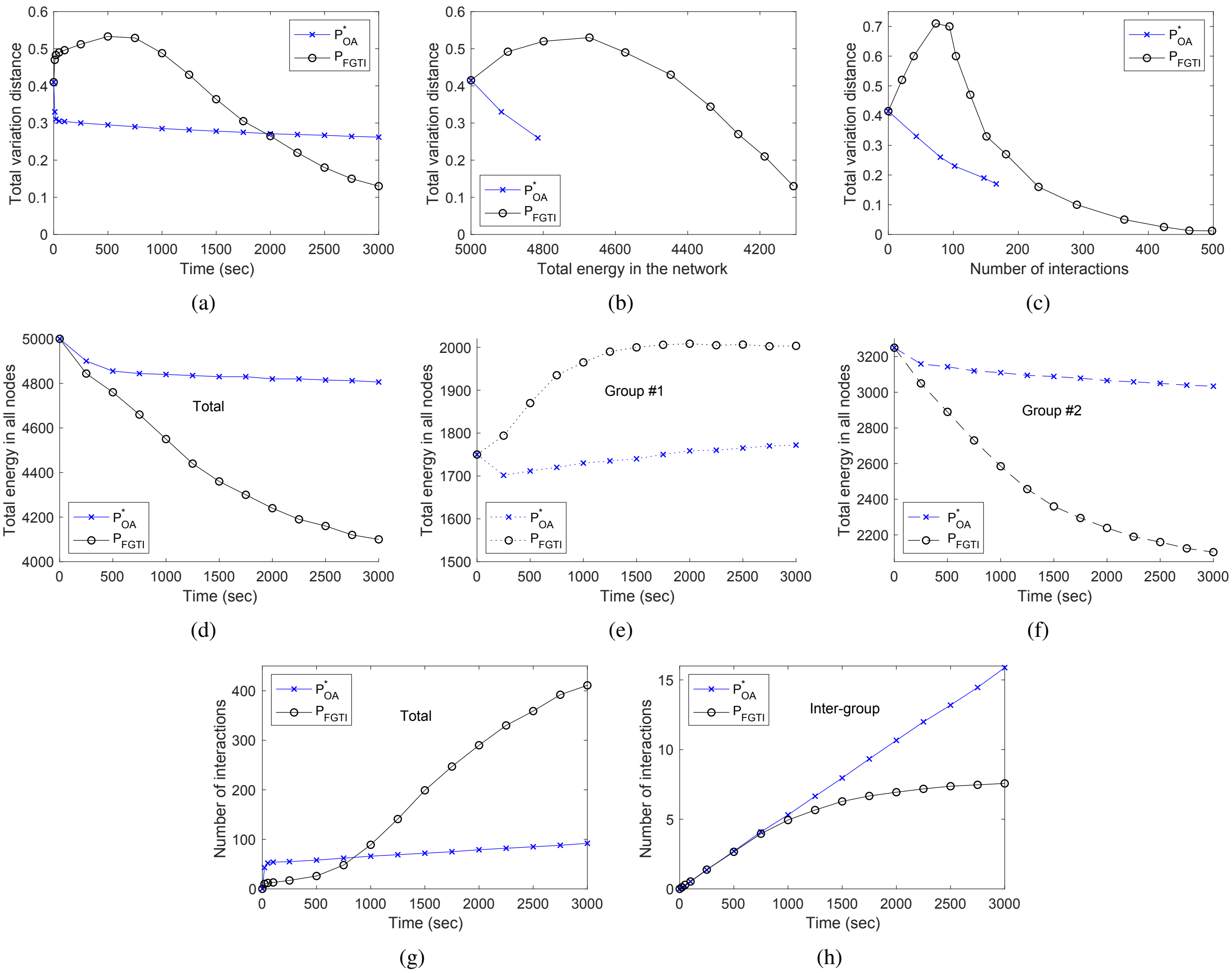


Fig. 3: Comparison of proposed social-based algorithm with the state-of-the-art algorithm in terms of (a) variation distance, (b) variation distance at each total energy level, (c) variation distance at each total number of interactions, (d) total energy remaining in the entire network, (e) total energy remaining in group 1, (f) total energy remaining in group 2, (g) total number of interactions, and (h) total number of inter-group interactions.

equalizing the average energy levels of groups and apply that. If the energy shared is equal to the amount that will equalize different group's average energies, the second stage starts. In the second stage (lines 19-37), we allow only the nodes in the opposite sides of the average energy in the network share energy. The actual amount of energy shared is defined by the node whose energy is closer to the current average in the network.

V. Simulations

In this section, we present the results of our evaluation through simulations. We generate a network of nodes and split them equally into two groups. In order to introduce a difference in the initial average energy levels of groups, we assign an energy in [0, 70] units randomly for the nodes in the first group and in [30, 100] units randomly for the nodes in the second group. For the nodes in the same group, we generate a meeting pattern using exponential distribution with a rate, , randomly selected from 200 sec to 400 sec. Similarly, for the nodes in different groups, we generate a meeting pattern using exponential distribution with a rate, , randomly selected from 700 sec to 1200 sec. However, we only allow 0.2% of node pairs from different groups interact.

From the beginning of the simulation, we let the devices interact and exchange energy based on the characteristics of each protocol proposed. We then compare the proposed social-aware protocol with a state-of-the-art protocol called [4], [5], [10], in terms of several metrics. Note that in the original , each node locally estimates the average energy level in the network using the ratio of the total energy seen in the encountered nodes to the number of encountered nodes. For a fair comparison, we assume that each node has the global information and knows the exact average energy in the network in that protocol too, thus name this version as . Note that performs better than . We repeat each simulation

1000 times for statistical smoothness. Error bars are not shown as the results were highly concentrated around the mean. We also use an energy loss rate, , of 0.2.

In Fig. 3a, we first show the total variation distance comparison for these two protocols. While causes an increase initially due to the energy exchanges in the first period, which does not worry about balancing individual node energies but focus on balancing the group level average energies, it provides a smaller variation distance than the eventually. Variation distance at a given energy available in the network as well as at each total number of interactions are also shown in Fig. 3b and Fig. 3c, respectively. The results show that can achieve better variation distance that is not possible by , but at some earlier times, its performance is not as good as due to its two-stage design. Looking at the total energy available in the network shown in Fig. 3d, we see that there is more loss in . However, this is expected and if reducing the variation distance is the priority, this additional loss could be justified. Note that as shown in Fig. 3e, the total energy level (as well as average energy level as each group has equally 50 nodes) increases in the earlier times (i.e., first stage) with , while can only increase it slowly. Similarly, as shown in Fig. 3f, second group's energy decreases faster with thanks to its design in the first stage.

The number of total interactions with an energy exchange between nodes, as shown in Fig. 3g, also shows that causes more interactions initially which are mostly intra-group meetings. However, once the nodes in each group reaches its best energy level within the constraints of node meetings, the only interactions for energy exchange happen between nodes in different groups. But due to the greedy energy sharings in earlier times, the inter-group interactions and their contribution to the reduction of variation distance is very slow. On the contrary, allows limited but critical interactions at first, then through intra-group interactions it achieves balancing in each group. As shown in Fig. 3h, we also see that after certain time inter-group interactions stop for the proposed approach while they continue for .

VI. Conclusion

In this paper, we study the energy balancing problem in opportunistic networks considering the underlying social network structure in their contact graph. We aim a fast balancing process towards minimization of variation distance of energy levels of nodes in the network. We propose a two-stage protocol where we aim to balance average energy levels between groups in the first stage and then aim to balance individual energy levels in the second stage. Our simulation results show that the proposed algorithm can indeed achieve a better variation distance however, it comes with some additional energy loss which could be justified if variation distance reduction is the priority. In our future work, we will consider more than two groups and extend the proposed solution to such general social network structures. Moreover, we will focus on reducing the energy loss while still achieving a better energy balance.

Acknowledgement

This material is in part supported by the U.S. National Science Foundation (NSF) under Grant CNS1647217.

References

[1] C. Lin, Y. Zhou, H. Dai, J. Deng, and G. Wu, "MPF: Prolonging network lifetime of wireless rechargeable sensor networks by mixing partial charge and full charge," in *Proc. of SECON*, 2018, pp. 1–9.

[2] X. Fan, H. Ding, S. Li, M. Sanzari, Y. Zhang, W. Trappe, Z. Han, and R. E. Howard, "Energy-ball: Wireless power transfer for batteryless internet of things through distributed beamforming," *Proc. of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies*, vol. 2, no. 2, p. 65, 2018.

[3] D. Kosmanos, L. A. Maglaras, M. Mavrovouniotis, S. Moschoyiannis, A. Argyriou, A. Maglaras, and H. Janicke, "Route optimization of electric vehicles based on dynamic wireless charging," *IEEE Access*, vol. 6, pp. 42 551–42 565, 2018.

[4] S. Nikoletseas, T. P. Raptis, and C. Raptopoulos, "Wireless charging for weighted energy balance in populations of mobile peers," *Ad Hoc Networks*, vol. 60, pp. 1–10, 2017.

[5] S. Nikoletseas, T. Raptis, and C. Raptopoulos, "Energy balance with peer-to-peer wireless charging," in *MASS*. IEEE, 2016, pp. 101–108.

[6] Z. Gao, D. Chen, and H.-C. Wu, "Energy loss minimization for wireless power transfer based energy redistribution in WSNs," *IEEE Transactions on Vehicular Technology*, vol. 68, no. 12, pp. 12 271–12 285, 2019.

[7] P. Worgan, J. Knibbe, M. Fraser, and D. Martinez Plasencia, "Powershake: Power transfer interactions for mobile devices," in *CHI Conf. on Human Factors in Computing Systems*. ACM, 2016, pp. 4734–4745.

[8] E. Bulut, S. Hernandez, A. Dhungana, and B. K. Szymanski, "Is crowdcharging possible?" in *27th International Conference on Computer Communication and Networks, ICCCN*, 2018, pp. 1–9.

[9] T. P. Raptis, "When wireless crowd charging meets online social networks: A vision for socially motivated energy sharing," *Online Social Networks and Media*, vol. 16, p. 100069, 2020.

[10] S. Nikoletseas, T. P. Raptis, and C. Raptopoulos, "Interactive wireless charging for energy balance," in *36th International Conference on Distributed Computing Systems (ICDCS)*. IEEE, 2016, pp. 262–270.

[11] A. Dhungana and E. Bulut, "Mobile energy balancing in heterogeneous opportunistic networks," in *Mobile Adhoc and Sensor Systems (MASS), 2019 IEEE 16th International Conference on*, 2019, pp. 1–9.

[12] A. Dhungana and E. Bulut, "Loss-aware efficient energy balancing in mobile opportunistic networks," in *IEEE Global Telecommunications Conference (GLOBECOM) 2019*, 2019, pp. 1–6.

[13] A. Dhungana and E. Bulut, "Peer-to-peer energy sharing in mobile networks: Applications, challenges, and open problems," *Ad Hoc Networks*, vol. 97, p. 102029, 2020.

[14] D. Niyato, P. Wang, D. I. Kim, W. Saad, and Z. Han, "Mobile energy sharing networks: Performance analysis and optimization," *IEEE Trans. on Vehicular Technology*, vol. 65, no. 5, pp. 3519–3535, 2016.

[15] E. Bulut, M. E. Ahsen, and B. K. Szymanski, "Opportunistic wireless charging for mobile social and sensor networks," in *2014 IEEE Globecom Workshops (GC Wkshps)*. IEEE, 2014, pp. 207–212.

[16] D. Niyato, P. Wang, D. I. Kim, and W. Saad, "Finding the best friend in mobile social energy networks," in *Communications (ICC), 2015 IEEE International Conference on*. IEEE, 2015, pp. 3240–3245.

[17] E. Bulut and B. K. Szymanski, "Mobile energy sharing through power buddies," in *Wireless Communications and Networking Conference (WCNC), 2017 IEEE*. IEEE, 2017, pp. 1–6.

[18] D. Niyato, P. Wang, D. I. Kim, and Z. Han, "Content messenger selection and wireless energy transfer policy in mobile social networks," in *Communications (ICC), IEEE Inter. Conf. on*, 2015, pp. 3831–3836.

[19] A. Dhungana and E. Bulut, "Energy sharing based content delivery in mobile social networks," in *IEEE 20th International Symposium on "A World of Wireless, Mobile and Multimedia Networks"(WoWMoM)*, 2019, pp. 1–9.

[20] A. Dhungana, T. Arodz, and E. Bulut, "Charging skip optimization with peer-to-peer wireless energy sharing in mobile networks," in *IEEE International Conference on Communications (ICC)*, 2018, pp. 1–6.

[21] A. Dhungana , T. Arodz, and E. Bulut, "Exploiting peer-to-peer wireless energy sharing for mobile charging relief," *Ad Hoc Networks*, vol. 91, p. 101882, 2019.