Is Crowdcharging Possible?

Eyuphan Bulut*, Steven Hernandez*, Aashish Dhungana* and Boleslaw K. Szymanski†
*Dept. of Comp. Science, Virginia Commonwealth University, Richmond, VA 23284
†Dept. of Computer Science, Rensselaer Polytechnic Institute, Troy, NY 12180
Email: {ebulut, hernandezsm, dhunganaa}@vcu.edu, szymab@rpi.edu

***Abstract*—Limited battery capacity has been the main bottleneck for smartphones. Users are required to charge their smartphones frequently to keep them alive. Access to a charging facility, however, may not be possible especially when users are outside. This has caused users to charge their devices at every opportunity with as much power as possible. While this results in overcharging of devices unnecessarily, it might have brought an opportunity for the realization of power sharing among mobile devices. In this paper, we introduce the concept of *crowdcharging* which aims to provide mobile users with ubiquitous power access through crowdsourcing. We first discuss the feasibility of crowdcharging from users' perspective and present some analysis and survey results showing the interest and need. We then look at the software and hardware challenges to build such a system. To this end, we have developed a mobile app that builds a mobile social network environment among the users and manages the entire process of power sharing between the mobile devices. We present the software implementation details using P2P wireless energy sharing and provide initial lab results with actual wireless charging hardware.**

I. Introduction

Advanced software capabilities and complicated applications running on smartphones have increased the quality of life for users. However, the charge on most smartphones lasts about one day with average usage, or less with intensive usage (e.g., social sensing [1]). As a result, users are required to charge their devices frequently. The most common practice for users is to charge their phones by connecting them to a wall outlet through charging cables. This requires users to carry a charging cable and find an outlet, which is mostly available indoors. Thus, the charging process can potentially be irritating and sometimes infeasible. With the integration of built-in wireless charging capability in recent phones (including iPhone 8 and X [2]), users are relieved from the need to carry charging cables but the current application of wireless charging is very limited as it requires not the phone but the charging mat to be connected to an outlet.

An organized user adopting regular daily charging habits (e.g., charging at home/work) and practicing several ways of power saving (e.g., dimming brightness, shutting down background apps) can mitigate the risk of facing a depleted battery situation. However, the current charging behavior of most users is to charge their devices opportunistically (i.e., with short durations and more frequently) and try to keep them with as much power as possible [3]. This is due to the anxiety of losing power in the middle of a critical task especially when they do not have an easy access to a power outlet.

Finding a power outlet for charging purposes can be challenging especially when users are outside. Users sometimes take the advantage of being in public venues such as libraries, coffee shops, malls, and subway to charge their phones using freely available charging ports. However, other outdoor locations such as streets, parks, and beaches are comparably less equipped with charging port. At airports, sometimes users find a business-sponsored power kiosk mostly around boarding gates but they are quickly occupied by other travelers. In response to the need of finding an outlet, some apps (mostly working through crowdsourcing) are built to find out the nearest available plugs (e.g., ChargeItSpot [4], Airport Power [5]).

Alternative solutions to charging through a power outlet include carrying additional batteries, external power banks, solar chargers [6] or other eco-friendly chargers like mobile hand generators [7]. However, the need for carrying an accessory still stays there and only limited power could be supplied.

In this paper, we explore the concept of *crowdcharging*, which aims to provide mobile users with ubiquitous power access through crowdsourcing. As it is very unlikely that all mobile devices in the vicinity will deplete their battery at the same time, such a power sharing solution could be a promising remedy especially in emergency situations in which even a small amount of charge could be sufficient to perform the task and life saving. Our aim in this paper is to discover the feasibility of the crowdcharging from (i) users', (ii) software and (iii) hardware perspective. We first discuss the results of a survey we conducted regarding the current charging behavior of users and the interest and need for peer-to-peer (P2P) energy sharing. We also analyze the current user mobility behavior for the opportunity of energy sharing among peers. We then look at the software and hardware challenges to build such a system. We have developed a mobile app that builds a social network platform among the users and manages the entire process of power sharing between the mobile devices. We present the software implementation details using P2P wireless energy sharing and provide initial lab results with actual wireless charging hardware.

The rest of the paper is structured as follows. In Section II, we look at the feasibility of crowdcharging from users'

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TABLE I: Survey results.

Survey Question	A	B	C	D
1. Do you carry a charging cable with you? A) Always, B) Most of the time, C) No, I borrow from friends	32%	23%	45%	N/A
2. How many charging cables do you have? A) 1, B) 2, C) 3, D) More	45%	32%	13%	9%
3. How do you charge your phone? (Select all that apply) A) Using power outlets at walls with a cable, B) Using my laptop's usb port with a charging cable, C) Using wireless charging pad/mat, D) From portable battery packs	100%	45%	6%	3%
4. If your phone could be equipped with a wireless power transfer equipment and an app that would let you do P2P charge sharing (in the amount controlled by you), would you be interested in having it? A) Yes, B) No	68%	32%	N/A	N/A
5. For which purposes, would you consider using the power sharing app A) Only to receive charge from others, B) Only to send charge to the others, C) Both for sending and receiving, D) None	6%	0%	71%	23%
6. If you would consider using it to share charge with others, which of the following(s) applies to you? A) With people that I know (e.g., friends/family) and without risking my own charging needs, B) With anybody who needs, C) Only if they pay me, D) Only among my own devices	77%	26%	16%	42%
7. What distance of wireless charging would be sufficient for you to use it? A) Current technology (<1cm), B) 1-10cm, C) 10-30cm, D) More	33%	25%	13%	29%
8. What charging efficiency of wireless charging would be sufficient for you to use it? A) Current technology (50-70%), B) Lower efficiency is also ok if charging at longer distances could be provided, C) 90% efficiency (regardless of distance), D) More	33%	16%	36%	15%

perspective and provide some analysis and survey results regarding its potential. In Section III, we discuss the software implementation details of an app that manages energy sharing between two smartphones. In Section IV, we discuss the P2P power sharing hardware technologies and their applicability with current smartphones. Then, in Section V we describe a small wireless charging based lab set up integrated with our app and present some preliminary results. Finally, we discuss related work in Section VI and end up with conclusion in Section VII.

II. User Aspect: Interest and Opportunity

In this part, we investigate the feasibility of (wireless charging based) crowdcharging from users' perspective. The capability of power sharing between the batteries of phones indeed transforms power to a tradable commodity and can incentivize users for sharing. Users could be concerned though about effects of power transfer on human health and safety [8]. The idea that power is transferring through the air or is buzzing around can worry people about possible radiation. Yet, the most common form of wireless charging, inductive charging, is indeed very safe to use. Several studies have been done to determine the safety limits (through several metrics such as Specific Absorption Rate (SAR), and current density) of human exposure to electromagnetic (EM) fields (created by inductive charging) by several agencies including WHO and ICNRP [9]. The reports from these studies show that there is no evidence showing that human exposure to radio frequency (RF) electromagnetic fields causes cancer, as long as they stay in given limits defined by these agencies. That's why one needs to follow these guidelines while developing new wireless charging products. Current commercially available Qi wireless chargers use low power (e.g., 5 watts) and operate at the frequencies between 110 and 205 kHz [10] which are already considered to be within these safety limits.

Another concern could be regarding the privacy of users. Thus, the most practical application scenario could be between the people who know and trust each other (e.g., friends and families). It could still be possible to have strangers share energy if incentives are provided, however, this is outside the scope of this paper. Moreover, ideal application of crowdcharging could be in passive mode with minimal intrusion to users (i.e., without changing their current charging and mobility habits). While crowdcharging could be realized with active participation [11] of users in which they will need to change their current charging habits and mobility while being compensated for their sharing, we think passive mode application (similar to crowd GPS [12]) could motivate more users to participate. Thus, in this paper, we are interested in the analysis of current user behaviors to explore if it can be leveraged to realize crowdcharging.

Is there an interest from users in P2P wireless energy sharing? We did a survey (among VCU engineering students) to understand the current charging related habits of users and to see if there is an interest in P2P energy sharing and crowdcharging. Table I shows the summary of responses from the survey. While most of the students said they have more than one charging cable, 45% of them said they rarely carry a charging cable and borrow one from their friends, when needed. In terms of the current charging habits, we observe that charging from wall outlets or from laptop's usb port are the two main ways used. Current wireless charging equipments are used by very few students. However, when we asked about the interest in being able to do P2P energy sharing, 68% said they would be interested in having that sharing functionality in their phones and all of those said they would consider using it as a receiver and sender. However, even though around a quarter of them said they would be open to share with anybody, 77% of those said they would exchange charge with the people they know, and 44% said they would only do it among their own devices. This is somewhat expected due to the aforementioned privacy concerns. We also asked what charging efficiency and distance would be sufficient for their adoption of this technology. While around 33% of users said they would be fine with current efficiency, 51% of them said they would look for higher efficiency. Interestingly, 16% of the students said they would be fine with an efficiency lower than current if longer distance charging could be provided. For distance, 33% of users said they would be fine with current distance (i.e., very close or touching) and 29% of users said they would see benefit only if over 30cm the wireless energy transfer could be achieved. As a summary of these results, we

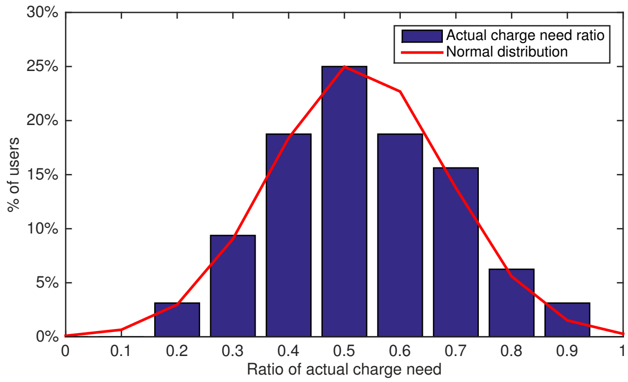

Fig. 1: Percentage of actual energy needs within total energy gained in current charging behavior.

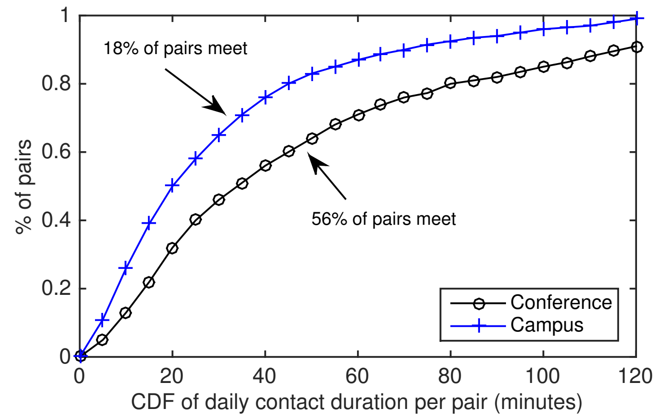

Fig. 2: CDF of daily total contact duration of (meeting) pairs in two different environments.

observe that majority is interested in P2P energy sharing but they look for charging with better efficiency and at somewhat longer distances. While the current technology is not there yet, there are some breakthroughs in the literature which could lead to progress in these aspects of wireless charging. In Section V, we discuss in more detail the long distance wireless charging efforts in the literature.

Is there a room in users' current charging behavior to share energy with others? We analyzed [13] the battery usage and charging patterns of 100 same brand (i.e., Nexus) smartphones from DeviceAnalyzer dataset [14] to understand how efficiently their batteries are charged. We have calculated the amount of energy that has been received throughout the chargings of the device and divided by the energy that could have been sufficient for the device if it were to be able to use a perfect charging schedule. Here, perfect charging schedule is defined as the charging of the device from 0% to 100% with the average charging rate and discharging of it from 100% to 0% with the average discharging rates [13]. It will not be practical for a user to adopt a perfect charging behavior, but this ratio can help us understand the tolerance of users to energy losses due to the sharing with others.

Fig. 1 shows the distribution of the actual charge need ratio among the 100 devices analyzed. On average, we observe that users could have survived with around 50% of the energy they gained through their current charging habits. There are users who are charging their devices unnecessarily very often and could even consider sharing more energy without sacrificing their own usage. From these results, we observe that there is definitely a room for users to share some of the energy on their devices' batteries with others without risking their usage based on their current charging habits. However, this has to be predicted and arranged carefully to avoid ending up with a device with a depleted energy.

Do current mobility patterns provide opportunity for energy sharing? As we investigate the potential of non-intrusive and passive mode crowdcharging, we analyzed the current meeting patterns of users to understand the level of opportunities for users to share energy. Mobile devices should be in close proximity or even touching in current form to be able to achieve wireless power transfer. The mobility of people possessing these devices will then be the key factor that will determine the opportunities for energy sharing. In Delay Tolerant Networks (DTN) and Mobile Social Networks (MSN) domain, there have been many datasets produced [15] to understand the encounter patterns of users in a community for designing efficient routing algorithms. We have analyzed two of these datasets which contain the logs of device-to-device (D2D) interactions (mainly achieved by Bluetooth, which has short range) between the wireless devices carried by people on a campus and in a conference environment, respectively. Conference data consists of the pairwise relations of 36 users, while the campus data includes pairwise relations for 99 users. Note that due to the small number of users involved and the environment in which the logs are collected, these datasets could represent a community of users that know each other, making the energy sharing application a reasonable scenario. The devices in the Bluetooth range could still be considered far from each other to achieve power transfer even with cables but these are the moments that most probably the users see each other and talk as well, thus, users can potentially leverage such periods for energy exchanges.

Fig. 2 shows the CDF of daily meeting durations of pairs that at least meet once in the entire dataset. In the conference environment, 56% of all possible pairs are meeting, while around 18% of pairs in the campus environment meets. The results show that there is a wide range of meeting durations between pairs in both environment. The average durations are 22 min and 27 min, respectively. While these numbers depend on lots of factors including the number of users in the dataset, the density of users, and degree of nodes, we can still observe the opportunity for energy sharing for a good amount of energy exchange. For example, assuming a 50% charging efficiency for wireless charging (e.g., using Qi standard), an average of 10-12% charge can potentially be exchanged daily between the devices of these users. However, this is between the user devices that meet. As the number of pairs meeting in campus

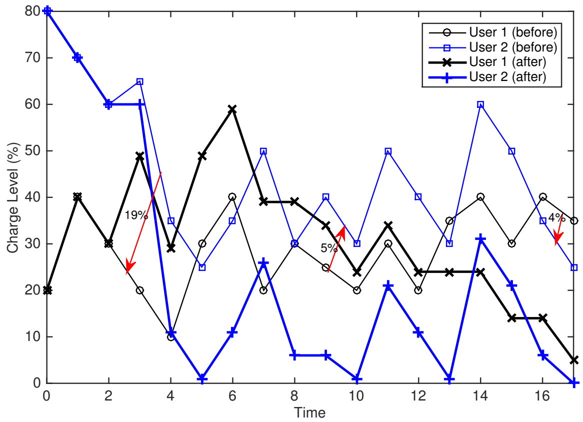

Fig. 3: Charging patterns of two nodes before and after P2P energy exchange.

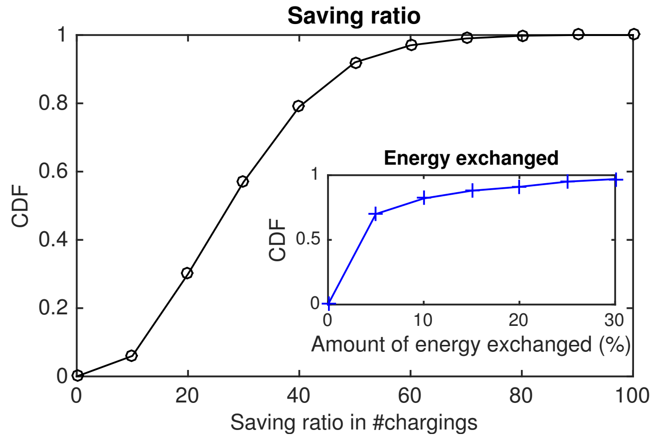

Fig. 4: Distribution of saving ratio in the number of charging times among all possible pairs after P2P charge sharing, and the distribution of energy amounts exchanged during these sharing process among peers.

dataset is small compared to the conference environment, the overall opportunity in the network for energy sharing will be lower than it is in conference environment. Yet, as one may only want to consider the sharing/receiving of energy with only a few known people (e.g., best friend [13], [16]), energy sharing could still be considered as a viable alternative to traditional charging from wall outlets in such an environment.

To what extent mobile users could relieve from traditional cord charging through collaborative charge sharing?

While it has been shown above that the opportunity for energy sharing is available among peers based on their meeting patterns, the charge status of the devices might limit the opportunity. A user may not continuously share energy at every meeting with others, and has to consider its own usage and device's battery status. Thus, for an accurate modeling of collaborative energy sharing among peers, both the charging and the meeting patterns of devices have to be jointly analyzed [17].

Fig. 3 illustrates an example collaborative energy sharing scenario among two user devices. The given charging patterns of the devices show that user 1 charges (with cable from a power outlet) the device 6 times while user 2 charges 5 times in the time frame considered. By taking the advantage of energy differences in the batteries of their devices, the users could exchange energy between their devices during their meetings and could have skipped some of these charging times. Using the dynamic programming algorithm presented in [17] for collaborative charging, we found the amount of energy exchanges that will maximize the skipping of charging times (with the energy received from other node). The figure shows the charging patterns before and after energy sharing between the devices. User 1 can skip 2 of its 6 charging cycles and user 2 can skip 2 of its 5 charging cycles through the sharing of energy among them and without ending up with depleted energy at any time. In the figure, when the user skips a charging, its charge level is assumed to decrease very minimally for simplicity. However, a discharge rate during the skipped charging period could be added easily for a more accurate modeling of new charge pattern. The figure also shows the amount and timing of energy exchanges that occur between the devices (with red arrows). User 2's device shares 19% of its battery energy with user 1, while user 1 skips the second charging time. This helps user 1's device not to deplete energy until the next charging time. Similarly, there are two other energy exchanges. User 1 shares 5% of its battery energy with user 2 so that user 2's device can skip its third charging time. Finally, user 1 shares 4% of its battery energy with user 2 so that user 2 can skip its last charging time.

In order to see the potential savings with the P2P energy sharing in a community of user devices, we have obtained the results of collaborative charging algorithm [17] among all possible pairs in that community. To this end, since the campus and conference datasets did not provide charging levels of users during their meetings, we used the two day charging patterns of 62 devices from DeviceAnalyzer [14] dataset and assigned them meetings from campus dataset. For each pair we then calculated the total saving ratio in the number of charging times with collaborative charge sharing.

Fig. 4 shows the distribution of these savings among all possible 1891 pairs, with some pairs benefiting up to 60% of their charging sessions. That means, if a user device had, for example, 10 charging sessions before collaborative charge sharing, it skips 6 of them through the energy received from the other device. The figure also shows some devices benefit only 10% of sessions but the average saving is around 28% of sessions among all pairs. The inner plot in Fig. 4 shows the distribution of the amount of energy exchanged during the collaborative charge sharing process of all pairs. While some devices share up to 30% energy, thanks to the longer and frequent meetings, on average around 5% energy is shared between pairs.

Considering all these results in this section, we observe that crowdcharging could help peers to manage the energy in their devices and decrease their number of traditional charging sessions. While there will be some limitations regarding crowdcharging application (e.g., will only be desired among known people's devices), the potential offered is promising.

III. Software: Mobile App Development

In this part, we present the details of our prototyping efforts for an app that aims to build a social network platform to let people find each other and share energy wirelessly.

Is it possible to leverage current mobile operating system and API capabilities to develop an app for achieving and controlling P2P power sharing? Android OS currently allows apps to control sharing power among peers. Power Sharing [18], an app developed by Samsung, was used as a reference to discover the specific calls required to enable and disable energy sharing. The Power Sharing .apk file was decompiled with an online Android APK decompiler [19] to uncover the calls.

In Android, *Intents* are simply events which can be passed from an app to the operating system or visa versa. The last three lines of code inside *onReceive()* function in Fig. 5 are all that is needed to alert the operating system to immediately enable or disable charging. This method works for both a direct connection to devices through a cable as well as through connected charging pad or wireless charging equipment. We noticed one quirk of this method however. Immediately upon inserting the cable; unless otherwise specified by the app, power sharing automatically starts. However, if an authorization is needed between the peers before they start sharing any energy, this has to be managed.

To solve this problem, the app needs to know when the power sharing cable or charging pad is connected. Android apps are able to receive an Intent from the operating system through a *BroadcastReceiver*. The app must first indicate which type of broadcasted Intents should be received. In our app, the data we are most interested in comes from the the Intent *android.intent.action.BATTERY_CHANGED*, which provides us with information whenever the battery changes for the device. Information is stored with the Intent as an "extra" value. Some examples of these extras are "voltage", "level" and "plugged". Additional extras can be found within *android.os.BatteryManager* [20]. Through decompiling the app, another extra labeled "power_sharing" was uncovered to be available through the Battery_Changed Intent. This extra returns a boolean indicating if a power sharing cable or charging pad is connected to the device.

Fig. 5 explains in detail the code necessary to define and register a *BroadcastReceiver*. Once registered, the app is immediately notified whenever a power sharing peripheral is connected. If connected, the app will alert the operating system through its own *Intent* whether to enable or disable power sharing as explained previously.

At the client side, the app is also able to detect information about the charging of the device. The code in Fig. 5 shows how it is possible to check if the device is currently plugged in. Note that the first option is *BatteryManager.BATTERY_PLUGGED_WIRELESS*. This means that the app can react to different methods of recharging as necessary.

As a result, we were able to successfully develop an app which is able to control wireless power sharing from host to client devices. The app is able to recognize whether a power sharing cable is plugged in and how to handle that situation. Thus, our app provides a reliable method for users to remain in control when sharing their energy among peers serving as the basis for a power sharing social network. Fig. 6 shows the screenshots of the app developed. The first two screenshots show the screens of a receiving and sharing device with the amount of energy sharing requested and the progress towards the expected completion time. Users can pause the transfer anytime or the transfer ends when the requested and authorized

```java
final String ACTION_POWER_SHARING = "android.intent.action.POWER_SHARING";
final String ACTION_BATTERY_CHANGED = "android.intent.action.BATTERY_CHANGED";
final String POWER_SHARING = "power_sharing";
final String POWER_SHARING_ENABLED = "power_sharing_enable";

private BroadcastReceiver broadcastReceiver;
private boolean currentConnectionState = false; // Is the power sharing cable connected?
private boolean toggled = false; // Is power sharing enabled?

// call from `onCreate` and `onResume`
private void registerReceiver() {
    this.broadcastReceiver = new BroadcastReceiver() {
        @Override
        public void onReceive(Context context, Intent intent) {
            String action = intent.getAction();

            if (action.equals(ACTION_BATTERY_CHANGED)) {
                boolean powerSharingIsConnected = intent.getBooleanExtra(POWER_SHARING, false);
                Integer pluggedStatus = intent.getIntExtra(BatteryManager.EXTRA_PLUGGED, 0);
                Integer statusExtra = intent.getIntExtra(BatteryManager.EXTRA_STATUS, 0);

                // Is the phone "plugged" in?
                switch (pluggedStatus) {
                    case BatteryManager.BATTERY_PLUGGED_WIRELESS:
                        break;
                    case BatteryManager.BATTERY_PLUGGED_AC:
                        break;
                    case BatteryManager.BATTERY_PLUGGED_USB:
                        break;
                    default:  // Battery is not plugged in or is not receiving power.
                        break;
                }

                // What is the status of the battery?
                switch (statusExtra) {
                    case BatteryManager.BATTERY_STATUS_CHARGING:
                        break;
                    case BatteryManager.BATTERY_STATUS_DISCHARGING:
                        break;
                    case BatteryManager.BATTERY_STATUS_FULL:
                        break;
                    case BatteryManager.BATTERY_STATUS_NOT_CHARGING:
                        break;
                    case BatteryManager.BATTERY_STATUS_UNKNOWN:
                    default: // Same as BATTERY_STATUS_UNKNOWN
                        break;
                }

                if (powerSharingIsConnected) {
                    // Power sharing cable is connected
                } else {
                    // Power sharing cable is not connected
                }

                // Here, we can check if the status has changed
                // from our last observation.
                if (currentConnectionState != powerSharingIsConnected) {
                    // Power Sharing status was changed here.
                    // Update UI to reflect connection status.
                    currentConnectionState = powerSharingIsConnected;
                }

                // Toggle power sharing immediately on battery_change
                // This prevents power from sharing upon first plugging
                // in the charging cable or wireless charging pad
                Intent i = new Intent(ACTION_POWER_SHARING);
                i.putExtra(POWER_SHARING_ENABLED, toggled);
                getApplicationContext().sendBroadcast(i);
            }
        }
    };

    IntentFilter filter = new IntentFilter();
    filter.addAction(ACTION_BATTERY_CHANGED);
    Intent batteryIntent = registerReceiver(this.broadcastReceiver, filter);
}
```

Fig. 5: Android code from our app for power sharing and control.

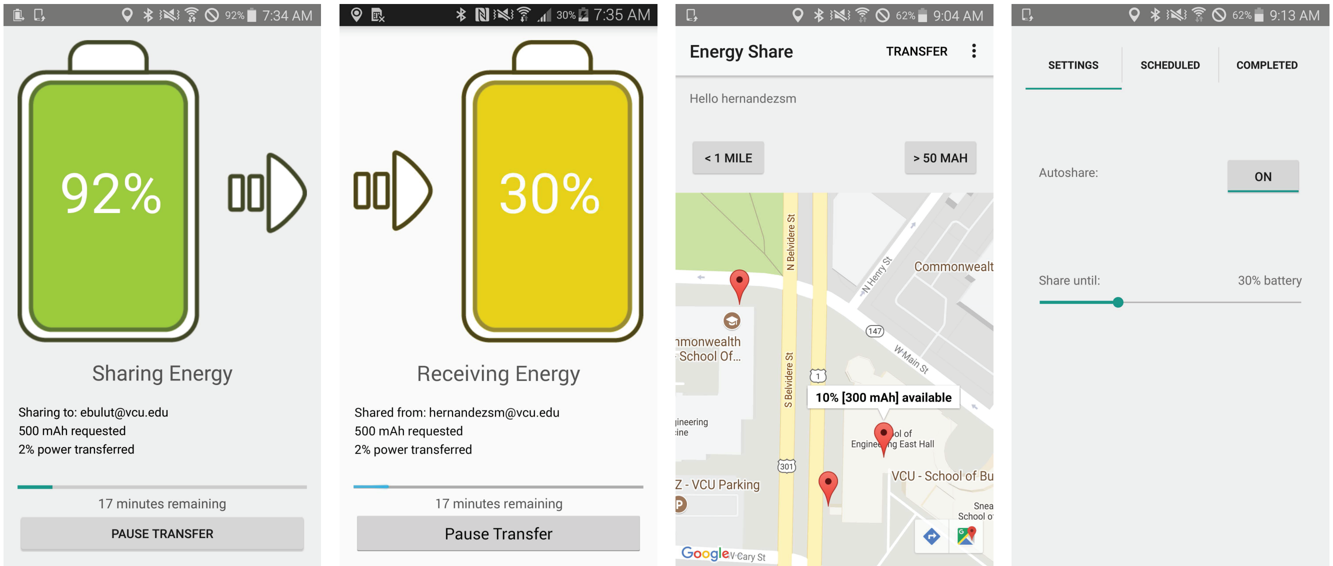

Fig. 6: Screenshots from our power sharing app.

energy amount is completely shared.

What other features must a power sharing social network have to allow users to begin social power sharing? To provide for social energy sharing, users of the system must be able to discover other users as sources of energy. To this end, the developed app provides users access to a filterable map of nearby users (third screenshot in Fig. 6). Nearby users can be filtered by distance as well as available shareable energy. Firebase [21] is used to handle authentication as well as the database backend for the app while Geofire [22] is used to enable location based queries within the Firebase database.

Users within this social network are given the option to automatically share power as well as an option to limit the amount of power to be shared (last screenshot in Fig. 6). By enabling *Autoshare*, our app only takes into account the battery level of the current device. If disabled however, the app must also take into account to whom the device is connected. Users are able to send and schedule requests for energy among peers through the map screen. Not currently implemented is a method to securely validate the receiving client device. To handle authentication of these transfers, we plan to use a pairwise authentication protocol based on Diffie-Hellman key exchanges [23] among peers without relying on certificates.

IV. Hardware: Peer-to-Peer Wireless Charging

Power sharing between mobile devices can be achieved with cables [24], gadgets (e.g., ChargeBite [25]) or wireless charging [26]. Even though the transfer efficiency is not perfect, due to it is being cable-free solution, wireless charging based power sharing could be more convenient for users and motivate more users for sharing.

There are several methods used for wireless charging including radio frequency (RF) based wireless charging [27], inductive coupling [28] and magnetic resonance coupling [29]. RF based wireless charging is radiative charging and uses electro-magnetic waves like RF waves and microwaves to deliver energy in the form of radiation. As it can be unsafe due to the RF exposure [8], [30], it is usually offered for low-power devices like sensor nodes and medical implants [31], [32]. Wireless charging products (e.g, charging pad) for smartphones in market today use inductive and/or resonant coupling [33], [34] as they are more safe (i.e. non-radiative) and comply with FCC rules [30]. Inductive coupling based charging can provide good efficiency but has a short range. Magnetic resonance coupling based wireless charging can operate at larger distances but with less efficiency.

Recently, there have been many phones manufactured with built-in wireless charging capability (including Apple's recently released iPhone X and 8 [2]). However, in its current form, users need to place their devices on a charging pad (which can be embedded in a desk [35], or cup holder [36]), which needs to be plugged to a power source. To achieve a bidirectional energy exchange between smartphones, a transmitter hardware should be embedded to the sender device during manufacturing. However, there is no phone in the market with a built-in wireless transmitter yet. Thus, in this part, we investigate the extension of smartphones with existing wireless transmitter hardware for a short-term solution. However, there are some limitations which are discussed below.

There are two sides in achieving peer-to-peer charge sharing. First, the receiver phone should have the capability of receiving the power and storing it in its battery. Second, the power sharing phone should have the necessary equipment for transmitting the power from its battery. For the former, there are many phones (e.g., Samsung, Google Nexus, iPhone 8/X) already in the market with necessary built-in hardware which can be charged wirelessly, usually by placing them on charging pads. Additionally, for the phones which do not come with such built-in feature, there are third-party accessory-based solutions which make them wirelessly chargeable easily. For example, earlier iPhone releases do not have built-in wireless

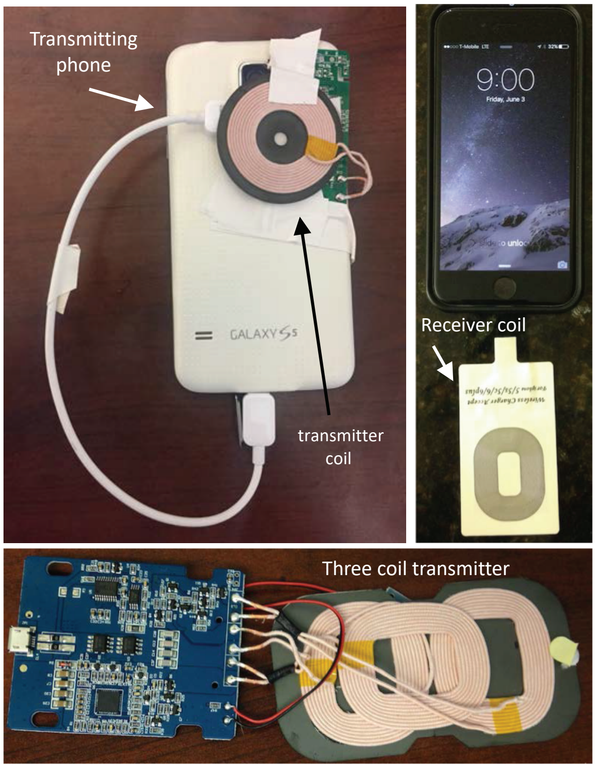

Fig. 7: Our lab setup for P2P wireless charging.

charging capability, but they can easily be made capable with a few dollar worth accessory (see Fig. 7). These accessories connect to the iPhone from lightning ports, and are flat and thin enough to be fit in between the back of the phone and an iPhone cover.

For the transmitter side, a smartphone should be able to power out from its battery. Smartphones can be easily designed and built with integrated transmitter coil hardware but current smartphones and wireless charging equipment available in the market today can be leveraged to achieve P2P wireless power sharing. A smartphone can power the transmitter coils connected to its micro-USB port as long as it supports USB OTG (USB On The Go) functionality. USB OTG is a standard that enables mobile devices to connect to one another. One device acts as a host, and allows other USB devices to be attached to it. For example, you can connect a keyboard, USB stick, or a printer to your OTG supporting smartphone and use it. Your smartphone, which acts as the host, first powers the other device and lets you access the other device features (e.g. files in the USB stick). There are many OTG supporting smartphones in the market today [37]. Thus, we use one of these smartphones for our initial lab setup.

V. Experiments

We have developed a small lab set up to show the wireless charging between two smartphones. We used one Samsung Galaxy S5, and one iPhone 5s equipped with a wireless charging receiver gadget behind it. Samsung Galaxy S5 has already a built-in wireless charging receiver however, to give it the ability to share energy with other phones, we equipped it with a wireless transmitter coil, which is connected to its charging port through a cable and taped to the back of the phone. Fig. 7 illustrates this lab set up with phones in the sharing and receiving roles. Note that the transmitter phone can also be enhanced with a three coil transmitter to achieve more flexibility with the alignment of the receiver and transmitter coils.

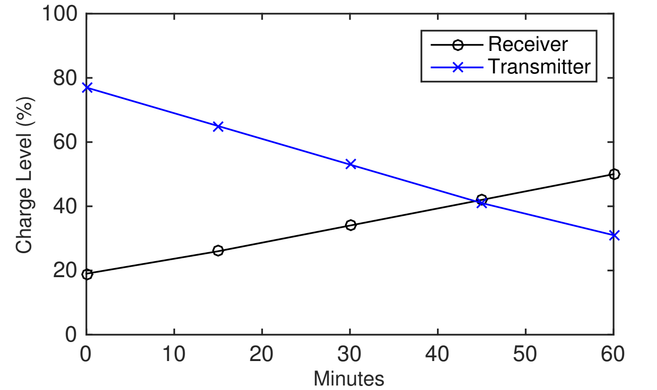

Fig. 8: Performance of P2P wireless charging experiment.

Using these phones with extended wireless charging functionality and the app developed, we then conducted a P2P power sharing experiment between these phones. To this end, iPhone 5s is located on the transmitter coils at the back of the Samsung phone and a controlled charge sharing process is started.

Fig. 8 shows the performance results from this experiment. The transmitter device's battery level and the receiver device's battery level are shown during the time of the experiment. Samsung S5 has 2800 mAh battery capacity while iPhone 5s has 1570 mAh battery capacity. This resulted in S5 battery level decrease from 77% to 31%, and iPhone S5 battery level increase from 18% to 51%. However, the actual charging efficiency is:

$$\epsilon = \frac{1570 \times 33\%}{2800 \times 46\%} \approx 40.2\%$$

This is slightly lower than the efficiency reported [33] for Qi standard (48-50%), which could be due to the distance between the coils during our setup. The loss is due to inductive conversion and transfer between the coils of receiver and transmitter sides.

This lab set up uses inductive coupling based wireless charging technology which requires pair of mobile devices touching each other. However, with recent breakthroughs in literature, it is expected that more practical wireless charging solutions at longer distances are not far. For example, Kurs et. al. [29] showed that they can achieve 90% efficiency at a distance of 0.75 meters with magnetic resonance coupling based charging. This number goes down to 30% at 2 meters. Another work [38] has shown that the magnetic wireless power transfer over a distance of 6.5 ft can deliver 10 kW of electric power with a coil-to-coil stationary efficiency of 97% (which is planned to be used for wireless charging of EVs moving on highways). The efficiency and power amount transfered in these experimental results depend on several factors like radius, size and material of coils used, however, they made a big step towards achieving long distance wireless charging (especially for smartphone's which require powers in the range of 5-10 watt hours [39]). Moreover, some very recent studies [40], [41] have shown that it is possible to charge multiple devices at a distance simultaneously by beamforming the magnetic field and the efficiency increases as the number of devices in the vicinity increases. We believe that all these efforts contribute towards more practical application of crowdcharging. Moreover, adoption of such a technology will be facilitated with the existing interest from users as shown in survey results and opportunity observed in current meeting patterns of users in a community.

VI. Related Work

Wireless power transfer (WPT), also known as wireless charging, offers a revolution in the way mobile devices are charged and brings various benefits to users such as the hassle-free charging without connecting cables [42]. Recently, this technology has attracted a great deal of interest from both academia and industry [8] due to recent breakthroughs in the area [26], [29], [40], [41]. Thanks to the convenience, flexibility and better user experience offered, it has already been proposed in a wide range of applications including sensor networks [43], smartphones [2], and medical implants [31]. Many top smartphone manufacturers have released their new devices with a built-in wireless charging capability feature. Several reports [44] published recently estimate a triple growth of this market in 4-5 years.

Impacts of P2P energy sharing in the network of mobile users have been studied by several works recently. The balancing of energy within a mobile social network through P2P energy exchanges has been studied through different sharing algorithms [45], [46]. The assignment of sharing and receiving peers based on their mobility relations has also been studied by several works [13], [16], [17], [47]. Moreover, the impact of energy sharing on network formation [48], and group based charging [49] have been studied. There are also some works [50] studying the energy sharing between electric vehicles. While all these studies provide insights on the potential benefit of sharing energy, most of them assume the existence of a software and hardware solution which can let the devices share energy. In this paper, we discuss these challenges and present results regarding the user aspects as well.

VII. Conclusion

In this paper, motivated by the recent technologies enabling wireless energy sharing between mobile devices, we discuss the feasibility of crowdcharging. Based on the findings from user data analysis and the survey as well as the Android OS implementation, we do see the user interest and opportunity for its realization. We believe this will increase interest from academia, and increase the number of current studies utilizing P2P energy transfer. However, there is also demand from users for improvements in technology for wide-spread adoption and some possible concerns (e.g., safety, privacy) that have to be addressed.

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