FEATURE ARTICLE

GreenCrowd: Toward a Holistic Algorithmic Crowd Charging Framework

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Crowd charging represents an alternative peer-to-peer energy replenishment option for mobile users to align with the circular economy paradigm. Following this option, users bound by finite resource capacity utilize the energy from external to the crowd wireless or wired energy sources (such as shared chargers), and internal to the crowd energy sources (such as mobile devices, via wireless power transfer). If designed carefully, such utilization can boost the energy availability of users and provide energy ubiquitously to their devices for making them functional for longer. This article proposes the GreenCrowd framework, introducing a privacy-by-design in the digital domain crowd charging process, the architecture of which incorporates multiple crowd-* components, such as online social information exploitation, algorithmic battery aging mitigation, user reward mechanisms, and advanced decision making. The primary aim of article is to present the technological and applicative requirements and constraints of GreenCrowd, and provide practical evidence on its feasibility.

Mobile portable devices such as smartphones, tablets, and wearables play a crucial role in the field of pervasive computing and to the integration of technology into every aspect of our daily lives, so it is everywhere and always available. Mobile portable devices are essential in this respect because they allow individuals to access and utilize technology from anywhere and at any time. This increased availability of technology has revolutionized the way we live and work, providing us with new opportunities and possibilities.

The energy reserves of mobile portable devices are a particularly essential resource in modern cultures; fast battery depletion is an issue that billions of smartphone and wearable device users worldwide face on a daily basis. Unfortunately, the residual energy supplies of these devices are limited and dependent on their battery power, which directly affects their usability. Individual users in a social crowd are constrained by restricted resource capacity, and it is difficult to provide energy directly to their devices to keep them working for an extended period of time. If shared, the spare capacity or resources of other users in the crowd may be employed to satiate varying demand.

By using the energy from external to the wireless network energy sources, such as shared chargers, or energy sources within the network, such as other mobile devices via wireless power transfer (WPT), it is now possible to extend the lifetime of such networks. Energy sharing techniques, either by wired or wireless medium, have made this possible. Although there have been some recent, isolated works on this type of energy sharing, to the best of our knowledge, none of the related works has presented a holistic framework that takes into account all the technological and applicative requirements and constraints. Peer-to-peer (P2P) crowd charging has recently emerged as an alternative energy replenishment option. Specifically, although innovation and research initiatives have targeted at improving the technological properties of WPT or at profiling the individual user aspects for optimized usage, there has never been a holistic, network-wide charging optimization framework which focuses on battery aging mitigation, considers both the wired and the wireless energy medium, takes into account

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the opportunistic nature of human contact networks, the cooperation opportunities among the network nodes, as well as privacy and incentivization aspects.[1]

To this end, in this article we introduce GreenCrowd: A holistic algorithmic crowd charging framework, which (unlike recent, mainstream opportunistic charging visions which focus on the optimization of individual devices/users for solely stationary wired charging) introduces ubiquitous intelligence and network-wide user profiling for both stationary wired charging and cooperative P2P-WPT, with a goal of rendering the crowd charging process more circular and sustainable. GreenCrowd aims at advancing the state-of-the-art compared to the traditional i) crowd sensing systems, ii) wireless powered networks, and iii) battery aging mitigation techniques, providing the following novelties:

1) GreenCrowd chooses to consider significant characteristic phenomena in the algorithmic modeling process related to fine-grained battery aging properties, such as state-of-charge (SOC), state-of-health (SOH), and CC-CV protocol curves, as opposed to,[2] which enforces some simplifications in the representation of the underlying phenomena in the interest of reducing the complexity of network modeling.
2) GreenCrowd naturally considers the fundamental human element of the opportunistic setting and addresses the socio-technical dimension by meeting the user QoE expectations with respect to the utility and enjoyment of the wi-enabled cooperative charging service, in contrast to mainstream crowd charging services that concentrate on solving emerging technical problems (such as Shamsa et al.[3]).
3) Unlike traditional participatory,[4,5] or opportunistic[6] mobile crowd sensing situations, which frequently take users' set incentives into account, GreenCrowd focuses on offering novel and dynamic reward systems, which allow users to remain anonymous in the system, and do not keep track of user rewards but rather task rewards.
4) It is apparent that user privacy must also be considered because gathering vast amounts of data that may contain sensitive information may reveal users' private routines and habits. In privacy related designs, such as Ni et al.[7] and Yan et al.[8] the emphasis is on masking user IDs with hashes during data collection or purely anonymizing them, hence eliminating the correlation between sections of various metrics. Such approaches prevent measurement correlation and does not permit ranking users based on their prior behavior, an ability better represented by the architecture suggested by GreenCrowd.[9]
5) Existing methodologies presuppose that nodes would trade energy with other nodes whenever possible, independent of the social situation. A few strategies also unreasonably assume that every node is open to exchanging energy with every other node. The duration of the energy exchange in such approaches is likewise considered not constrained by the time between meetings of the associated users.[10] However, in practice, and according to GreenCrowd design, each node may only interact with a portion of the crowd while moving, and choices are also influenced by the crowd's social dynamics.

THE PROPOSED FRAMEWORK

The basic conceptual building block on which the GreenCrowd framework is based is the recent concept of P2P energy sharing,[11] which has been gaining more and more attention lately. In this energy sharing paradigm, users from the crowd are able to share (transmit and receive) energy with other mobile devices in the surroundings, either via P2P interactions with WPT, or via centralized shared energy pools. The energy sharing use case can be participatory, where the user consciously opts to meet an application request thanks to incentivization techniques, or opportunistic, where the user might not be aware of the active applications. Indicative applications span crowded areas from offices or trains to airports or cities.

Motivated by these considerations, the reference structure of the scenario considered by the GreenCrowd proposal are sketched in Figure 1. The crowd realm is tessellated in three domains; the device domain, the physical domain, and the online social domain. Each domain contains the corresponding elements that perform interactions: the device domain includes the portable devices which can exchange energy, along with their batteries, the physical domain includes the users which are engaged in interactions in the physical world, and the online social domain in which users connect and interact virtually. All three domains of the crowd realm are intertwined through the GreenCrowd privacy-by-design in the digital domain framework into an architecture that incorporates user rewards, battery aging mitigation, online social information management, and energy sharing decision making. Clearly, users will eventually have to meet to exchange energy, therefore identifying their peer. Thus, GreenCrowd keeps the identity of the users private until they have to meet, hence in the digital domain.

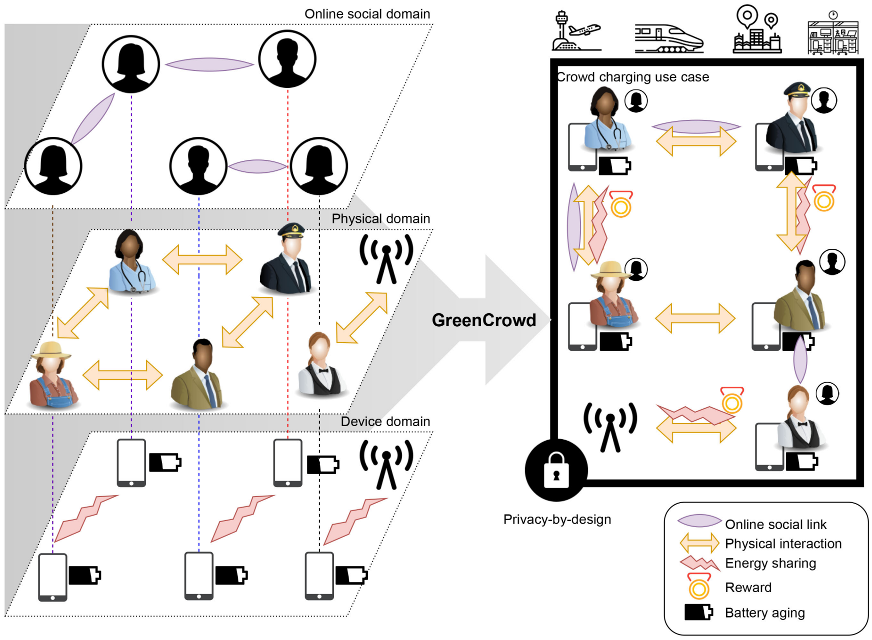

FIGURE 1. Proposed GreenCrowd framework.

To highlight a potential scenario in which GreenCrowd can be applied, we present a possible interaction between two GreenCrowd users. Alice goes in a stadium to watch a match, but her phone is low on battery. She wants to record and send photos and videos to her friends, but the battery is too low to perform such actions, since she also needs to save some for the way back home, and there are now power plugs available to do so. Alice then uses GreenCrowd, and finds users which are at the stadium with her with more battery energy than what they need, hence they are glad to sell some of it. Bob replies to the request made by Alice, and GreenCrowd provides guidance on how to meet, so that Bob can transfer part of his energy to Alice, which can now use again her phone while watching the match. We also want to not how similar scenarios can be found for instance at train stations while waiting for a train, on a bench in a public park, or in an airport lobby if no power plugs are available.

Objectives and Methodologies

The proposed GreenCrowd design aims at:

- Basing the framework on innovative system modeling by realizing scientific breakthroughs in a set of complementary use case paradigms (e.g., opportunistic, participatory, ad hoc) and energy sharing settings (e.g., P2P, centralized, mixed) to pave the way toward the full exploitation of crowd charging capabilities for fully resilient and sustainable use cases.
- Exploiting the technological breakthroughs to provide the framework with a groundbreaking algorithmic toolkit, which will include dedicated operational components (namely, reward, online social information, battery aging mitigation, privacy-by-design in the digital domain, decision components).
- Facilitating an efficient exploration of standardized crowd charging's full potential toward applied energy circularity by validating the GreenCrowd's framework in real-world settings via emulated use cases in the lab and/or human-generated datasets.

In order to achieve the intended sustainable goals, the GreenCrowd development strategy utilizes a novel interplay of rigorous principles that emerge from a combination of ICT methodologies. Table 1 provides a summary of GreenCrowd's primary research questions and proposed methods to address them.

The technological implementation of crowd charging calls for a wide range of theoretical and practical instruments as it reflects the originality of GreenCrowd. However, the specifics of electromagnetism and electronics must be modeled. The network-wide

TABLE 1. The greencrowd methodologies.

No.	Research question	Tackling method
RQ1	How to tackle battery aging and ensure device longevity?	Network-wide parameter optimization of SOC, SOH, and QoE
RQ2	How to leverage user social links to improve the crowd charging process?	Fine-grained online social info, and socially-aware energy sharing
RQ3	How to provide a reward to contributors proportional with the system state and users requests?	Variable rewarding with different compensations, as per user density and access requests
RQ4	How to improve user trust toward a crowd charging framework?	Privacy-by-design architecture which guarantees user anonymity
RQ5	How to deliver a holistic crowd charging process to the users?	Combine RQ1-RQ4 methods to an architecturally solid, validated decision-making framework
RQ6	How to evaluate a crowd charging framework?	Layered evaluation approach: simulations, social human-trace datasets, lab

strategy combines aspects of distributed and decentralized computing. Selected concepts from computer–human interaction are utilized in the socio-technical extensions.

The GreenCrowd design is omnipresent, which calls into question the fairness of the quality of experience (QoE) considerations that may be made to maintain the user's fair and sufficient satisfaction. Instead of using traditional quality of service metrics, which are unable to reflect the actual provided QoE, energy resources, and energy services can be controlled to ensure certain QoE levels. By evaluating how users now perceive the battery aging mitigation service, this socio-technical management strategy can be QoE-aware-by-design and provide GreenCrowd the option to reduce energy flows by providing just the resources necessary to maintain a particular level of user happiness.

According to CC-CV protocol,[12] each individual device's charging implementation pattern is often followed, similar to what we display in Figure 2. The device is first charged with constant current (CC) to a specific threshold voltage, after which the voltage is maintained throughout the constant voltage (CV) phase, during which the current is gradually decreased until full charge is obtained. If the device remains

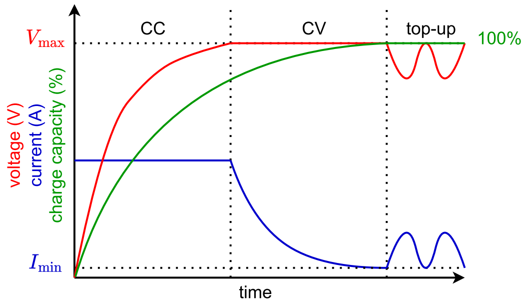

FIGURE 2. Typical charging curve of CC-CV protocol.

plugged, then self-discharge is compensated when the SOC falls below a specified threshold, leading to the top-up phase, in which the battery health further deteriorates. These particular charging curves can be described analytically and act as separate fundamental component of the GreenCrowd development methodology.

Key Functional Components

The standardized collaboration approach toward a multilevel crowd charging framework delivers a clear roadmap for an innovative framework composition from the two different partners with a common goal toward socio-technical crowd charging. The main outcome of this offering focuses on the creation of complementary components, facilitating circular driven innovation for multiple stakeholders. In more detail, as shown in Figure 3, this collaboration line will comprise:

1) A "reward component," forming a set of smart incentive mechanisms.
2) An "online social information component," which fuses and exploits the ubiquitous social information.
3) A "battery aging mitigation component," which employs innovative methods for improving the battery health status.

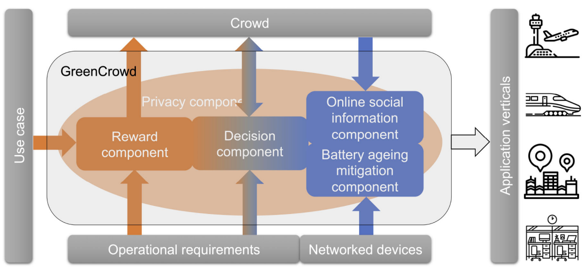

FIGURE 3. GreenCrowd key functional components.

4) A "privacy component," which ensures the obedience of the framework to the user privacy requirements and constraints and will apply the privacy-by-design in the digital domain approach.
5) A "decision component," which is eventually making real-time decisions on how to share the energy supplies among the users in the crowd, taking also into account the WPT-incurred energy loss.

These components can be exploited based on innovative collaboration models, facilitated by circular-related standards (such as the Qi standard) further enhanced by distributed computing principles, which are considered as a critical modern asset toward decentralization and circularity.

The developed framework incorporates a reward component for crowd charging, which will truly empower users with different opportunities to participate in energy sharing tasks. Specifically the dynamic reward component takes into account a series of parameters, some of them which can be input by the user requesting a service, some which are computed by the component. These include, from the requesting user perspective: 1) the amount of charge required, 2) the maximum amount of time which can be spent in the same location, 3) the device wear and, 4) the reward willing to be given to the service provider. From the component point of view, the respective reward can be enriched by the number of users available in the area, and the previous number of tasks already required in the same area. Practically, the reward is given in the form of tokens to use GreenCrowd, which can be redeemed when requesting a charge from other users, or exchanged for a monetary prize.

The user can have the possibility from its own application to request a specific service and to input the required parameters, depending on the user specific needs. No parameter is mandatory, so that users can simply configure anything which is mandatory for them and let the component decide the rest. While the user parameters are updated, a constant feedback mechanism with the server will also compute dynamically the expected time of delivery for the service requested, according to the component parameters. For instance, if there are several tasks already requested with a higher pay than the one offered by the requesting user, the component advises the user to either increase the payment amount, or to extend the deadline, in order to meet the service provider expectations. It is also important to note that the component's scope can be easily generalized to other crowd-* systems.

Although innovation and research initiatives have targeted at improving the technological properties of batteries or at profiling the individual user aspects for optimized usage, to the best of our knowledge, there has never been a network-wide charging optimization framework like GreenCrowd, which focuses on battery aging mitigation, considers also the wireless energy medium, and takes into account the opportunistic nature of human contact networks, the cooperation opportunities among the network nodes, as well as emerging energy sharing socio-technical breakthroughs such as wireless social crowd charging.[13] The current literature includes works solely in 1) the domain of battery aging mitigation for individual devices and without any wireless power capability, and, 2) the domain of wireless crowd charging (usually targeting network energy balance and WPT-incurred energy loss management) but without any battery aging mitigation mechanisms. The GreenCrowd approach in this respect combines the two concepts by assigning a dedicated component to battery aging mitigation and incorporating the energy loss management in the decision component, so as to explore the tradeoffs between charging efficiency and battery longevity.

IT IS ALSO IMPORTANT TO NOTE THAT THE COMPONENT'S SCOPE CAN BE EASILY GENERALIZED TO OTHER CROWD- SYSTEMS.*

Users' social connections and interests can have an impact on both their mobility and the flow of energy between them. The current techniques of crowd charging do not take into account the dual issue of energy exchange brought on by the user's inescapable mobility and the impact of sociality on the latter. The energy balance attained by these works is slowed down by computation with imperfect information and is hampered by energy loss for the crowd. Currently, only coarse-grained social information is used. In this regard, the GreenCrowd method, for the first time, provides a component with fine-grained social data that can produce outcomes which are expected to be more accurate in this respect, borrowing features from social psychology. In the physical world, reciprocal interactions—which have been demonstrated to be a powerful altruism-inspiring factor,[14] can influence users to choose friends over strangers when giving resources, especially if the cost of sharing is expensive. Similar trends may be seen for social reciprocity in cyberspace, where online communities share many structural traits with real-world face-to-face networks.[15] An increase in an online social user's reciprocity value has been shown empirically to boost the reciprocity responses from her nearby online social graph.[16] By utilizing the data accessible on online social networks, those social features can assist us in adding a social component to the energy sharing process.

ASSESSMENT OF GREENCROWD'S POTENTIAL

To assess the potential of GreenCrowd in a real scenario, we leverage the dataset presented in Sapiezynski et al.[17] that reports human contacts between hundreds of users. The dataset is built with traces from more than 700 students on a 4 week period, and the data have been collected with smartphones, which record their RSSI with respect to other nearby smartphones. It is then a well built dataset to explore the social interactions among users and the time in which they are in contact through a whole day, hence it poses the following key questions:

- What is the percentage of users in a given area which can leverage the services offered by the GreenCrowd platform?
- How much charge could they get depending on their mobility patterns?
- How many contacts take place between (online social) friends?

To answer these questions, we analyze the data studied in Sapiezynski et al.[17] which spans over 28 days, assuming a real world deployment of GreenCrowd. Specifically we consider users moving freely in a campus, and which may access the GreenCrowd platform when in range of other users for at least a minimum time of contact. In our study, we conservatively set this minimum time to 15 min. In other words, users which are not in contact for at least 15 consecutive minutes of time are not willing to exchange energy, due to too much overhead in accessing the platform, finding the other device and performing the wireless charge.

Figure 4 reports our findings related to the first research question. We analyzed for each user how many charging opportunities she may have in the 28 days in which the data were recorded. We consider a minimum contact of at least 15 min with another device at different distances. For our study, we considered three different RSSI levels for the Bluetooth, which are: −**73 dBm**, which corresponds to roughly 1.5 m and reflect users already being close to each other, −**80 dBm**, which corresponds to roughly 3.5 m and reflect users which may be in the same room, and −**89 dBm**, which corresponds to roughly 10 m and reflect users which may be in adjacent rooms.

From Figure 4, we can see that a large portion of users have plenty of opportunities for recharging, even with devices which are already standing close to them. We also note that typically any kind of device needs to be charged a maximum of 1-2 times per day, hence a value of 28 means that the users has on the average a charging opportunity per day. Allowing to query farther users increase this value beyond several opportunities per day, confirming the availability of users which may offer additional charging when needed.

The second analysis we performed is pictured in Figure 5, where it is possible to see the amount of

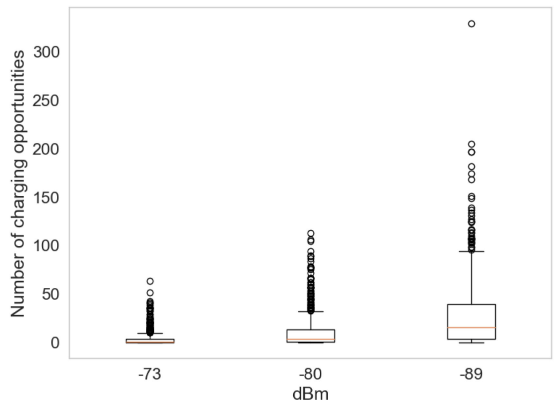

FIGURE 4. Daily charging opportunities for each user in a given area, which can leverage the services offered by the GreenCrowd framework.

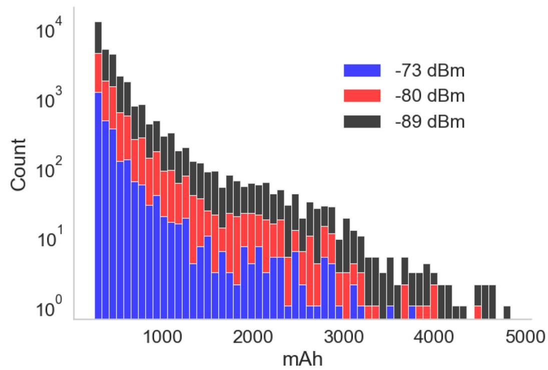

FIGURE 5. Charge that users can get from the GreenCrowd framework, depending on their mobility patterns.

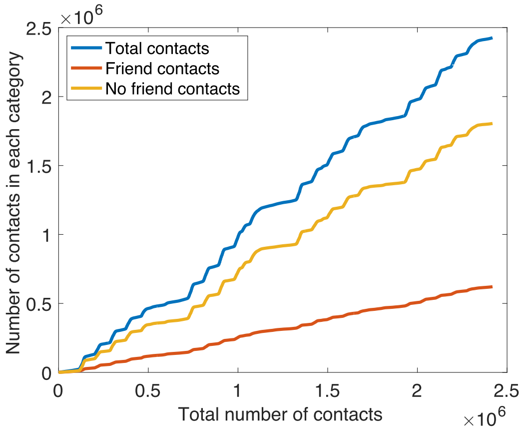

FIGURE 6. Number of contacts for each category of users over time (the blue plot's values equal to the sum of the rest of the plots' values).

charge users can get leveraging the GreenCrowd platform. To perform this analysis, we considered a conservative maximum rate of charge of 1 Ah, although faster and more efficient wireless charging technologies do exist. Again, we test this for different proximity with other users, and the results confirm that a vast majority of users can recharge a considerable amount of charge, with some of them which are also able to recharge up to 5Ah, which correspond to some of the smartphone with the largest batteries available at the time of writing.

Next, we obtain some insight about the useful online social information with respect to the pattern of the contacts of pairs of "online friends." Given that in this case we consider very limited Facebook status data exchanges (which can be performed over long distance in minimal time instead), we take into account all the contacts of the users, regardless of their RSSI levels or time of contact. The trend of the increase of contacts over time is displayed visually in Figure 6. The results demonstrate that, after taking into account the entire number of contacts, out of 2.418.901 contacts, a significant portion of 25.68% took place between online friends. This finding of a significant amount of contacts that took place "online friends" strengthens the motivation behind GreenCrowd's approach toward fusing the crowd charging process with the abundant available online social information for better fine-tuning the energy sharing functions.

As a final note, we also want to state that these results were obtained without considering any voluntary movement from users. In other words, we have derived this number considering the usual mobility of the users, without any deviation from their original journey or habits. Clearly the introduction of a reward system as part of the GreenCrowd platform will likely increase the user willingness to participate in the wireless charging task. Also, as we have shown in our previous work,[18] the careful battery aging mitigation can have a positive effect on the battery health of mobile peers.

CONCLUSION

By leveraging social, reward, privacy, battery, and decision-making functional components, the GreenCrowd framework can be customized to suit various use cases. This flexibility creates new opportunities for reducing the dependence on nonrenewable energy sources and encourage a shift toward a more sustainable and equitable energy distribution approaches. Moreover, our proposed framework has the potential to reduce e-waste by extending the life of existing energy storage systems and extending the lifetime of single-use batteries. This shift will contribute to reducing the carbon footprint and enhancing environmental sustainability, eventually promoting a more sustainable and circular approach to resource consumption. The increased engagement of the crowd has the potential to lead to a more informed and involved community that is better equipped to address the challenges of energy sustainability, which might in turn lead to more effective data collection, analysis, and dissemination, further supporting the sustainability of the broader pervasive computing sector.

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