# ERCIM fellowship Programme

# Final scientific report

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# I – SCIENTIFIC ACTIVITY DURING YOUR FELLOWSHIP

During the ERCIM fellowship, we worked on devising methods for enabling Peer-to-Peer Wireless Power Transfer (P2P-WPT) over a network of users. In such scenario, it is important to achieve an energy balancing of the network where all the nodes reach an equal energy level, facilitating the nodes to extend their functional lifetime. However, in case of opportunistic mobile networks, the P2P energy exchanges can be uncertain due to various network (user mobility and social interactions) and device dynamics (heterogeneous devices and battery health) present in the scenario. In our work, we have specifically considered these aspects and devised P2P-WPT methods to mitigate the challenges. Our activities are summarized in the following:

A. **Energy balancing leveraging user mobility and social interaction:** The advancements in P2P-WPT have empowered the portable and mobile devices to wirelessly replenish their battery by directly interacting with other nearby devices. The existing works unrealistically assume the users to exchange energy with any of the users and at every such opportunity. However, due to the users' mobility, the inter-node meetings in such opportunistic mobile networks vary, and P2P energy exchange in such scenarios remains uncertain. Additionally, the social interests and interactions of the users influence their mobility as well as the energy exchange between them. The existing P2P-WPT methods did not consider the joint problem for energy exchange due to user's inevitable mobility, and the influence of sociality on the latter. As a result of computing with imprecise information, the energy balance achieved by these works at a slower rate as well as impaired by energy loss for the crowd. Motivated by this problem scenario, in this work, we present a wireless crowd charging method, namely MoSaBa, which leverages mobility prediction and social information for improved energy balancing. MoSaBa incorporates two dimensions of social information, namely social context and social relationships, as additional features for predicting contact opportunities. In this method, we explore the different pairs of peers such that the energy balancing is achieved at a faster rate as well as the energy balance quality improves in terms of maintaining low energy loss for the crowd. We justify the peer selection method in MoSaBa by detailed performance evaluation. Compared to the existing state-of-the-art, the proposed method achieves better performance trade-offs between energy-efficiency, energy balance quality and convergence time.

B. **Mitigating battery health reduction using P2P-WPT:** Battery aging is one of the major concerns for the pervasive devices such as smartphones, wearables, and laptops. Current battery aging mitigation approaches only partially leverage the available options to prolong battery lifetime. In this regard, we claim that wireless crowd charging via network-wide smart charging protocols can provide a useful setting for applying battery aging mitigation. In this paper, for the first time in the state-of-the-art, we couple the two concepts and we design a fine-grained battery aging model in the context of wireless crowd charging, and two network-wide protocols to mitigate battery aging. Our approach directly challenges the related contemporary research paradigms by (i) taking into account important characteristic phenomena in the algorithmic modeling process related to fine-grained battery aging properties, (ii) deploying ubiquitous computing and network-wide protocols for battery aging mitigation, and (iii) fulfilling the user QoE expectations with respect to the enjoyment of a longer battery lifetime. Simulation-based results indicate that the proposed protocols are able to mitigate battery aging quickly in terms of nearly 46.74-60.87 % less reduction of battery capacity among the crowd, and partially outperform state-of-the-art protocols in terms of energy balance quality.

C. **Device heterogeneity-aware energy balancing:** The recent advances in wireless energy transfer (WET) provide an alternate and reliable option for replenishing the battery of pervasive and portable devices, such as smart-phones. The peer-to-peer (P2P) mode of WET brings improved flexibility to the charging process among the devices as they can maintain their mobility while replenishing their battery. Few existing works in P2P-WET unrealistically assume the nodes to be exchanging energy at every opportunity with any other node. Also, energy exchange between the nodes is not bounded by the energy transfer limit in that inter-node meeting duration. In this regard, the parametric heterogeneity (in terms of device's battery capacity and WET hardware) among the nodes also affects the energy transfer bound in each P2P interaction, and thus, may lead to unbalanced network energy distributions. This inherent heterogeneity aspect has not been adequately covered in the P2P-WET literature so far, especially from the point of view of maintaining a balanced energy distribution in the networked population. In this work, we present a Heterogeneity-aware Wireless Energy Transfer (HetWET) method. In contrast to the existing literature, we devise a fine-grained model of wireless energy transfer while considering the parametric heterogeneity of the participating devices. Thereafter, we enable the nodes to explore and dynamically decide the peers for energy exchange. The performance of HetWET is evaluated using extensive simulations with varying heterogeneity settings. The evaluation results demonstrate that HetWET can maintain lower energy losses and achieve more balanced energy variation distance compared to three different state-of-the-art methods.

D. **Survey of WPT with UAV:** WPT techniques are emerging as a fundamental component of next-generation energy management in mobile networks. In this context, the use of UAVs opens many possibilities, either using them as mobile energy storage devices to recharge IoT nodes, or to prolong their operation time via smart charging themselves at ground stations. This paper surveys the recent literature on WPT as it applies to UAVs and identifies several open research challenges for the future. As a first step, we tessellate the related research corpus in four fundamental categories (architectures, power and communications enabling technologies, optimization with respect to spatial concepts, optimization of operational aspects). Second, for each category, we provide a critical review of the recent WPT UAV approaches with respect to the way they specialize the general concept of WPT and the extent of their applicability. The survey presents the latest advances in WPT UAV methodologies and related energy-centric services, spanning all the way from the communications aspects deep in the small- and large-scale deployments, up to the operational and applications aspects. Finally, motivated by the rich conclusions of this critical analysis, we identify open challenges for future research. Our approach is horizontal, as the selected publications were drawn from across all vertical areas of research on UAVs. This paper can help the readers to deeply understand how WPT is currently applied to UAVs, and select interesting open research opportunities to pursue.

## II – PUBLICATION(S) DURING YOUR FELLOWSHIP

1. **T. Ojha**, T. P. Raptis, A. Passarella, M. Conti, "Wireless Power Transfer with Unmanned Aerial Vehicles: State of the Art and Open Challenges," *Pervasive and Mobile Computing (Elsevier)*, 2022. (under review)
2. **T. Ojha**, T. P. Raptis, M. Conti, A. Passarella, "Heterogeneity-aware P2P Wireless Energy Transfer for Balanced Energy Distribution," in *IEEE GLOBECOM*, pp. 4123-4128, Rio de Janeiro, 2022.
3. **T. Ojha**, T. P. Raptis, M. Conti, A. Passarella, "Wireless Crowd Charging with Battery Aging Mitigation," in *Proceedings of IEEE SMARTCOMP*, pp. 142-149, Helsinki, Finland, 2022.
4. **T. Ojha**, T. P. Raptis, M. Conti, A. Passarella, "Balanced Wireless Crowd Charging with Mobility Prediction and Social Awareness," *Computer Networks (Elsevier)*, vol. 211, pages 108989, 2022.

## III – ATTENDED SEMINARS, WORKHOPS, CONFERENCES

I have attended two conferences (virtually) for presenting my work, and also attended talks and keynote sessions in these conferences.

- IEEE International Conference on Smart Computing (SMARTCOMP) at Aalto University, Helsinki, Finland during 20-24 June 2022.
- IEEE Global Conference on Communications (GLOBECOM) at Rio de Janeiro, Brazil during 04-08 December 2022.

I have presented an invited keynote talk at ICACIE 2022:

- 7th International Conference on Advanced Computing and Intelligent Engineering (ICACIE 2022) at Cuttack, Odisha, India during 23-24 December 2022.

## IV – RESEARCH EXCHANGE PROGRAMME (REP)

The REP program was not completed during the fellowship duration.