Distributed Sensing from Energy Harvesting Wireless Devices

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***Abstract*—Internet of Things (IoT) systems have been massively infiltrating in our everyday's life for various applications. One of the main constraints inhibiting the further development of these applications is the limited autonomy of present day batteries. Moreover, energy sustainability is a crucial requirement for systems employed for critical mission applications. Using renewable sources of energy might be a solution to prolong the lifetime of IoT-systems. Erratic nature of renewable energy causes several challenges, which we address in this work. In particular, we study the effect of battery imperfections on the energy harvesting wireless device operation and effective energy-balancing strategies for different system configurations.**

***Index Terms*—Energy harvesting; battery management; age of information; Internet of Things; wireless sensor network.**

I. Introduction

Wireless sensor network (WSN)-based IoT systems consist of a set of sensor nodes that use wireless communication to perform *distributed* sensing tasks. Distributed data sensing enables data collection in a more efficient way, improving delivery even if one of the nodes fails to deliver a data packet. Scalability, fault-tolerance and energy efficiency are three main requirements for designing efficient WSN [1]. In this work, we will focus on energy sustainability of such systems, since battery-powered sensors have a finite energy reserve, and even more so for tiny devices. Limited autonomy of the present-day batteries hamper the future development of the WSN applications. Hence, mechanisms to harvest energy from renewable ambient sources (solar, wind, vibration, etc.) for the battery replenishment are a further development that can significantly enhance the field of applicability of WSN [2]. However, due to the instability of energy supply from ambient energy sources, it is necessary to develop efficient policies that balance energy consumption and provide extensive sustainability for WSN systems.

II. Contribution and main results

The contribution is summarized in Fig. 1. For a single device case, we proposed different battery management solutions, such as a transmission strategy based on the study of battery imperfections [3], [4] and adaptive sampling algorithm adapted for the energy harvesting wireless sensor [5]. To investigate the multi-device case, we studied the asymmetry in energy-harvesting WSNs [6], and proposed energy cooperation as a mean of overcoming systems heterogeneity [7], [8]. Finally, we considered a special case, where the main performance metric of an energy-harvesting IoT-system is age of information (AoI) [9].

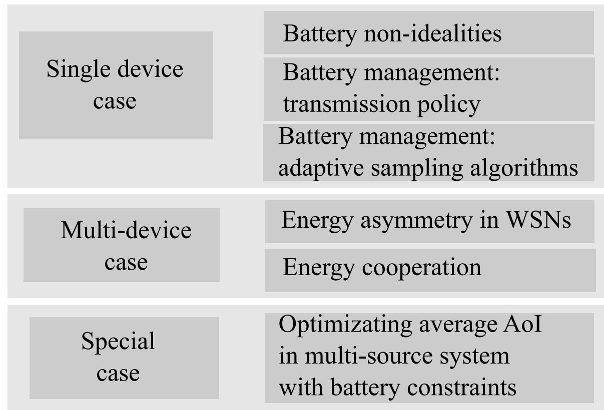

Fig. 1 – Contribution scheme

A. Single device case

Initially, we demonstrated that battery non-idealities lead to considerably different estimates of undesirable events, such as battery outage [3]. For this purpose, we introduce bi-dimensional battery value, that includes the apparent energy level, that is available at the electrodes of a battery, and the actual energy level stored in the battery. We study the effect of the so-called *charge recovery* on the battery performance analyzing such events as an apparent and real outage. We demonstrated that those battery non-idealities may lead to a heavy underutilization of the device.

For a single device case, we proposed the simplified self-control transmission management of a battery expressed by restrictions [4]. We rely on the double-queue model which includes the battery imperfections and bi-dimensional battery value. We demonstrated, that

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just tracking a few parameters, such as real and apparent energy levels, and the status of the data buffer can improve the performance of an energy-harvesting device in terms of energy sustainability. Integrating the proposed restrictions decreased the number of battery outage events up to 75%.

Another perspective of battery management of an energy-harvesting device is adaptive sampling algorithms. We proposed sampling strategies for an energy harvesting wireless device, that improve the data-driven adaptive sampling approach and balance the erratic nature of the harvested energy arrivals and energy consumption of a wireless sensor. We derive an effective and lightweight sensing/transmitting strategy that significantly decreases packet delivery failures, satisfies some industrial requirements and is computationally light to be implemented on the low complexity hardware. To test the performance of the proposed algorithms, we simulated the operation of an industrial data-logger powered with a solar panel located in Barcelona, Spain [10], relying on the enhanced state of the charge battery model. We observed, that setting threshold based rules and sampling rate limitations is justified with the prior knowledge of the environmental characteristics, which significantly increases the performance of the existing data-driven approach avoiding increasing the complexity of the algorithm [5].

B. *Multi-device case*

To begin with, we focused on the asymmetries in the nodes energetic capabilities, and how do they impact on the resulting performance [6]. We frame a problem as a repeated Bayesian game with asymmetric players and incomplete information [11], where also private information available is not symmetric. We obtained that if both sensors do not take into account the asymmetric property of the system, then the system is less balanced, meaning that the sensors are not exploited proportionally to their energy capabilities. Even if one sensor knows about the asymmetry and exploits in its strategy, then the performance of a system is more balanced.

Energy cooperation is a way to keep an IoT system energy sustainable. To do so, we considered a general framework and investigated the possibility of integrating energy cooperation within the design of energy topology, i.e., by establishing energy links between objects, in particular, wireless smart nodes powered by harvesting renewable sources [7]. For this, we constructed an optimization model, where it is guaranteed that wireless nodes will not be depleted during operation and the energy transfer does not exceed the energy demand. We demonstrated the effectiveness of energy cooperation by comparing with the system operation without optimization. In the simulated realistic scenarios, the system will have up to 30% of depleted nodes and embedded energy cooperation within smart topology decreases the amount to almost 0.

A more specific case is considered in [8], where the energy cooperation is integrated into the smart city scenario, in which we assumed the presence of the interconnected energy harvesting IoT gateways. The proposed solution entails energy transfers from energy-rich gateways to energy scarce ones. With the proposed energy allocation technique, the gateways are unlikely to run out of energy during operation. We quantified the performance of the proposed energy transfer policies as a function of network parameters, including the amount of traffic generated by sensing devices, the number of smart services in the system, and the number of gateways that are connected in the power grid. Numerical results show that, with energy cooperation, the system is fully energy sustainable, showing a substantial improvement against a scenario where cooperation is not implemented.

C. *Special case*

We investigated the optimal policy of an energy-harvesting IoT monitoring system, that with the given energy budget minimizes the average AoI of a system with a backup information source. AoI is a crucial parameter for the critical operation systems (automation, intelligent transportation and smart cities). For this problem, we formulate the scheduling of status updates from the two sources (primary and backup) as a Markov decision process and obtain a policy that decides which source to query or update from [9]. We compared the performance of the optimal policy with the so-called aggressive policy, which tries to query the most expensive source it can afford, and demonstrated that the gain from the optimal policy increases as the backup source characteristics become worse (i.e., decreasing reliability or increasing cost) or the energy harvesting rate decreases. We have also shown that employing a backup source of information is justified when the reliability of the backup source is relatively high and the cost of the information requesting is relatively low.

III. Conclusions

We considered a few strategies to improve the performance of energy-harvesting IoT systems in terms of energy sustainability. This array of strategies covers a wide range of applications, scenarios, and requirements. For instance, they can be applied to a smart city represented as a large system of interconnected smart services, or a WSN employed for critical mission applications. We demonstrated that the knowledge of battery and environmental characteristics, and the asymmetric properties of a system is beneficial for designing transmission/sensing strategies.

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