Battery-Free Sensing in Industrial Environments

Junchen Guo
School of Software, Tsinghua University
gjc16@mails.tsinghua.edu.cn

Abstract

Recent advances in battery-free sensing have enabled a large quantity of cross-modal sensing applications. Due to its inviting characteristics such as the ease of deployment and the relatively low cost of maintenance, battery-free sensing is extremely welcomed in industrials environments. With our initial exploration in this field, we recognize many key challenges of building robust and practical battery-free sensing systems. In this article, we share our preliminary understandings and propose the plan for further research on battery-free sensing in industrial environments.

1 Introduction

Nowadays, due to the ever-increasing cost of human resources, modern factories are desperately seeking alternative solutions, e.g. automatic surveillance systems that are able to continuously monitor the whole life-cycle of their critical machines as well as their products. Nevertheless, traditional approaches such as embedded sensors are either hard-to-deploy (e.g. complicated wiring for power and communication), or of high maintenance cost (e.g. replacing the batteries, or temporarily removing the nodes during the maintenance time). Moreover, camera-based solutions, which benefit from the rich information contained in images and videos, could easily suffer from the None-Line-Of-Sight (NLOS) problem, require stable light conditions, and even consume heavy computation resources.

Therefore, recent innovations of battery-free sensing have shed light upon continuous cross-modal monitoring applications. In such sensing paradigm, *battery-free* sensors can harvest energy from either the dedicated readers or the ambient environment, and transmit the sensed data *wirelessly* to some remote data collectors. In such an architecture, the complicated wiring plan and laborsome battery replacement are no longer necessary. Also, due to the capability of

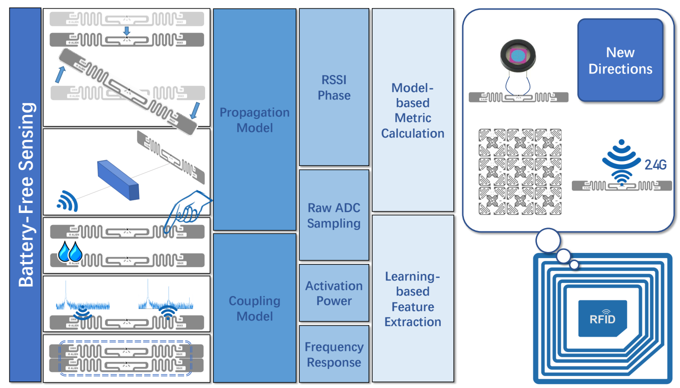

Figure 1. Roadmap of Battery-Free Sensing Research

diffraction and penetration of the wireless signal, the NLOS problem can be relieved to some extent. Last but not least, the battery-free sensors are often cheap and light-weight, which enables the plug-in-play and disposable manners.

Radio-Frequency IDentification (RFID) is one of the most common technology for battery-free sensing. A dedicated RFID reader transmits the power, sends the interrogation, and receives the reply from RFID tags. When interrogated, a battery-free RFID tag (often passive) backscatters its ID after being powered up. With the prosperity of such backscatter communication, various industrial Internet-of-Things (IoT) applications have been prompted, such as vibration sensing [9], material identification [8], product tracking [3] and human-object interaction [6]. In our industrial IoT project, Pavatar, we also deploy a eccentricity detection system for rotating machinery [10], and a liquid leakage detection system for water / lubricant recycling machines [2].

In the following sections, we investigate the-state-of-art research proposals, summarize their commonness (Sect. 2), address further challenges (Sect. 3), and propose potential research directions (Sect. 4).

2 Recent Advances

RFID or other RFID-like backscatter technologies conduct cross-modal sensing by analyzing the backscattered signal from battery-free tags. Basically, the causes of the signal variation mainly come from three folds: *the motion of the tagged objects*, *the far-field signal penetration*, and *the near-field coupling with the tags*.

The signal propagation model is often utilized to quantify the first two categories of signal variations. For in-

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stance, tracking approaches analyzing the variated distances between the reader and the tag [9][10] as well as their polarization directions [3]. In the meanwhile, the impact of signal penetration along the LOS path offers an opportunity for material and shape identification [8]. The third category, near-field coupling, is often modeled by equivalent RLC circuits. The variation of tag's impedance violates its frequency response as well as its backscattered signal [6]. To extend the sensing capabilities, the effects e.g. the mutual coupling [2] and the nonlinear harmonics [5] are also leveraged.

There are various data inputs to analyze the signal variation. For example, to measure the tiny vibration of rotating machinery, Received Signal Strength Indicator (RSSI) and phase reading provided by commercial readers [9] as well as the raw ADC sampling from Software-Defined Radio (SDR) devices [5]. Moreover, the activation power, which is the minimal power of the reader's antenna to activate the tags, is also a common metric [7]. To further process and analyze these signal inputs, model-based metric calculation [9][5], and learning-based feature extraction [6][2] are the two main strategies. Such choices are made according to the knowabilities of the parameters of their basic signal models.

3 Challenges

Although the initial steps of battery-free sensing have been made in the past few years, there still exists a huge gap towards practical applications in industrial environments. While deploying our battery-free sensing systems [10][2], we have summarized the following three key challenges.

Improving the limited sensing capability. Although the far-field propagation and near-field coupling can offer relatively rich information, there are still many critical physical metrics that do not have distinct impact on the backscattered signal, e.g. temperature and illumination intensity. How to expand RFID tags' sensing modality is very interesting but also challenging.

Expanding the limited sensing coverage. This research challenge involves two critical issues. First, the maximum interrogation power of $900MHz$ ISM band regulated by FCC strongly limits the sensing coverage of the readers. Second, the collision-avoid protocols, e.g. EPC Gen 2, abandon plenty of useful information under the dense deployment of tags. To expand the sensing coverage is extremely crucial for the promotion of battery-free sensing in practical applications.

Separating sensing from communication. Currently, the sensed data is transmitted by imposing modulations such as FSK, OOK, or other distinct signal patterns. However, such modification significantly degrades the original backscatter communication. It is extremely challenging to remain the robust communication while performing sensing tasks.

4 Research Plan

Next, we discuss our preliminary research plans.

External sensor integration. A recent work [7] explores the feasibility of appending external low-power and low-cost sensors to the passive RFID tags, which sheds light on how to expanding the sensing modalities. A dedicated model that can depict the relationship between the sensor data and the signal variation is expected. Besides, integrating passive tags with ADC components that quantify such sensor data can further decouple the data conveying from the backscatter communication.

Beyond $900MHz$ backscatter communication. Recent efforts that enable backscatter communication on $2.4GHz$ or higher frequency band [1] provide alternative choices for expanding the sensing range while reducing the device cost (e.g. no need for dedicated readers). Moreover, corresponding technologies such as Multiple Input Multiple Output (MIMO) and beamforming can be adopt to enhance the backscatter communication, and further enable the multi-hop backscatter networking.

The power of array and matrix. To overcome the limitation of one single tag, a direct solution is to consider tag arrays or matrices as an integrated sensor. For example, a recent work reconstruct the 3D shape of tagged object by modeling the geometry structure a tag matrix [4]. Apart from fusing these multiple input, another approach is to define sensor tags and communication tags, and recovery the sensed data by investigating the variation of their mutually coupled relationship.

5 Conclusion

In this abstract, we explore the recent advances in battery-free sensing for industrial applications, and discuss key challenges for this field. Our future research will explore the feasibility of tackling the above challenges, propose practical and robust solutions, and integrate them into the real-world industrial IoT systems.

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