

Fast Localization and Sensing with Passive Backscattering IoT Devices

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Abstract

This paper presents an autonomous network of Internet of Things (IoT) battery-free devices for environmental monitoring activities based on Radio Frequency IDentification (RFID) communications at Ultra High-Frequency (UHF) band. A mobile robot enables continuous and automated communication with passive RFID sensor tags, collects useful data by accessing sensor data, and calculates accurate tag location thanks to a fast synthetic aperture phase-based localization algorithm, reliable with respect to both multipath and channel fading. The proposed architecture efficiently obtains a digital twin of the monitored area (e.g., a large warehouse or store). A working prototype that demonstrates the proposed system is also presented.

1 Introduction

Internet of Things (IoT) concept aims at creating networks of sensors, actuators, and wireless devices to create a digital twin of the physical world. Passive backscattering systems like Radio Frequency IDentification (RFID) ones are considered key enablers of the IoT [1] thanks to the battery-less, low-cost, and low-maintenance properties of the tags, and their scalability as well. RFID labels can also host on-tag low-power sensors that could operate passively, [2, 3]. Another relevant feature of RFID transponders is the capability of enabling high-accuracy localization, as it is done leveraging the Synthetic Aperture Radar (SAR) principle [4, 5, 6]. When a moving antenna detects a tag multiple times from different locations, multiple phase measurements (one for each RFID data packet) are available. Such information can be combined with accurately measured antenna locations to get RF images of the surrounding environment, from which tag location can be extracted. The synthetic aperture approach mitigates the multipath effect thanks to spatial averaging and overcomes blind spots in the communication channel enhancing tag detection. In this paper, we propose a system grounding on the Integrated Sensing And Communication (ISAC) [7] concept and add the localization feature with a fast RFID-SAR method based on phase unwrapping and cost-efficient convex optimization based on gradient descent. A combination of localization and sensing with RFID passive backscattering devices has been studied in [8] and is herein extended to a moving wheeled robot-based implementation. The architecture of the system is presented in Fig. 1, where an automatic

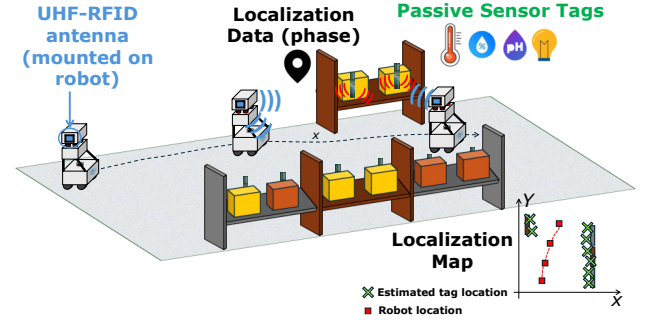


Figure 1. Architecture of the proposed system for Integrated Sensing, Communication and Localization.

robot equipped with RFID hardware - reader and antenna(s) - travels in a warehouse or large store, detects and localizes RFID sensor tags by simultaneously retrieving useful environmental information such as temperature or relative humidity (without loss of generality, temperature only is measured within this work). The integration of these features enables a digital replica of the facility carried out efficiently and without human intervention. Potential applications range from drug stocking monitoring, safety in industrial settings (e.g., gas presence detection, high-temperature environments [9]), or the food industry [10]. The paper is organized as follows: Section II presents the localization algorithm. Section III describes the experimental activity and results. Section IV draws some conclusions.

2 Localization algorithm

Synthetic array-based localization of passive RFID tags has been carried through many algorithmic variants. Herein we propose a fast technique involving phase-unwrapping and a search of the tag location through a gradient-descent optimization of a convex cost function [11, 12]. We consider the moving reader antenna installed at the robot (constant height z_{ant} and a RFID sensor tag placed at $\mathbf{p}_{tag} = [x_{tag}, y_{tag}, z_{tag}]^T$, being detected N_r times by the traveling reader antenna, at the location $\mathbf{p}_k = [x_k, y_k, z_{ant}]^T$ with $k = [0, \dots, N_r - 1]$, with k being the timestep index. The traveling antenna describes a synthetic array whose sizes on the three space directions are L_x , L_y , and L_z , respectively. Large aperture in a given direction brings to accurate spatial resolution thanks to a larger array and to an averaging of multipath effect on each tag reply. At the k -th timestep, the reader an-

tenna gathers a phase sample $\hat{\phi}_k$ affected by thermal noise as follows:

$$\hat{\phi}_k = \text{mod} \left(\frac{-2\pi 2d_k}{\lambda_0} + \phi_{off} + w_k, 2\pi \right), \quad (1)$$

where $d_k = \|\mathbf{p}_k - \mathbf{p}_{tag}\|_2$ is the antenna-tag distance, λ_0 is the carrier wavelength, ϕ_{off} is a phase offset accounting for cables, antenna polarization and tag circuitry, and it is here assumed as nearly constant. w_k is the measurement noise. Since the phase is a periodic quantity, the reader can detect it only with a 2π -periodicity. To be free of phase offset term ϕ_{off} , a phase variation with respect to the first available sample ($k = 0$) is computed by the following $\Delta\hat{\phi}_k = \hat{\phi}_k - \hat{\phi}_0$. The normalized phase $\Delta\hat{\phi}_k$ is then unwrapped to get $\Delta\hat{\phi}_k^u$. The localization approach requires a phase-unwrapping and a successive minimization of the hypothetical tag location-dependent cost function $\mathbf{J}(\mathbf{p}_{tag})$, as follow. For each hypothetical tag location within the considered search space $\mathbf{p}_{tag}$, the unwrapped noiseless theoretical model of $\Delta\hat{\phi}_k^u$ is calculated and denoted $\Delta\phi_k^u(\mathbf{p}_{tag})$. Finally, the cost function is computed as:

$$\mathbf{J}(\mathbf{p}_{tag}) = \sum_{k=1}^{N_r} (\Delta\hat{\phi}_k^u - \Delta\phi_k^u(\mathbf{p}_{tag}))^2, \quad (2)$$

which is a convex function [11] and can be expanded as:

$$\mathbf{J}(\mathbf{p}_{tag}) = \sum_{k=1}^{N_r} \left[\Delta\hat{\phi}_k^u + \frac{2\pi 2(d_k(\mathbf{p}_{tag}) - d_0(\mathbf{p}_{tag}))}{\lambda_0} \right]^2. \quad (3)$$

Where the term $d_0(\mathbf{p}_{tag})$ is due to phase normalization. The estimated tag location $\tilde{\mathbf{p}}_{tag}$ is:

$$\tilde{\mathbf{p}}_{tag} = \arg \min_{\mathbf{p}_{tag}} \mathbf{J}(\mathbf{p}_{tag}), \quad (4)$$

The minimization of the function can be therefore done with gradient-descent methods or, as in this case, with a properly sized Levenberg-Marquardt (LM) method. It is required that two consecutive antenna positions are spaced less than $\lambda_0/4$ to satisfy the sampling theorem and avoid unwrapping failures, happening with a phase difference greater than π . The phase model could include polarization-caused phase variations [13].

3 Experimental Activity

3.1 Experimental setup

Fifteen RFID sensor tags (models: Asygn AS3213C.4, Farsens EVAL02-Hygro-Fenix-RM, Farsens EVAL02-Fenix-Vortex-RM) were deployed in a large indoor room characterized with multipath conditions, arranged on three tripods as shown in Fig. 2. An automatic robot with on-board RFID equipment starts from the origin $O(x, y, z)$ of a designed reference frame and run several inventory rounds. The robot is equipped with an Impinj R420 RFID reader and a Times-7 A5020C Left Hand Circular Polarization

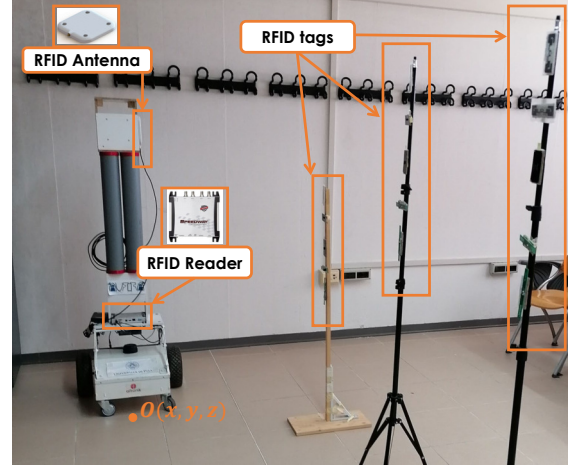


Figure 2. Experimental setup.

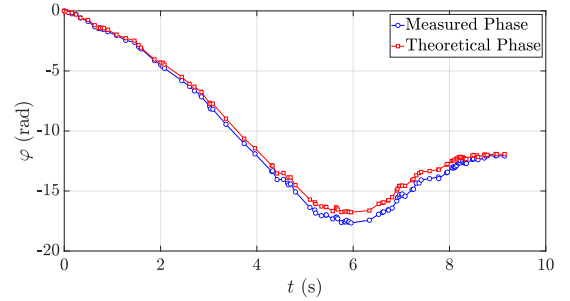


Figure 3. Sample test-case of an unwrapped measured phase (blue circular markers) and theoretical phase (red squared markers).

(LHCP) RFID antenna at a height of $z_{ant} = 1.46$ m, connected through a coaxial cable. The reader transmits a 30 dBm carrier sine-wave at a frequency of 865.7 MHz. The antenna has a gain of 5.5 dBi and a Half-Power Beam Width (HPBW) of 105° . The robot travels with a 10 cm/s speed while collecting phase and temperature data from RFID tags. A Slamtec RP3 2D LiDAR (Light Detection And Ranging) is used to reconstruct its trajectory, fundamental to measure the location $\mathbf{p}_k$ of each antenna location building the synthetic array.

3.2 Experimental Results: localization

A trajectory sample when the reader antenna detects a tag at $\mathbf{p}_{tag} = [0.8, 1.2, 0.94]^T$ m is taken in account. The RFID reader collects $N_r = 122$ tag phase replies which can be used for localization. The unwrapped measured phase is represented in Fig. 3 together with the theoretical one for the selected trajectory. The synthetic apertures along the three directions are $L_X = 0.95$ m, $L_Y = 0.82$ m, and $L_Z = 0$ m (no motion for vertical coordinate). The spatial sampling was kept below $\lambda_0/4 = 8.66$ cm. Without loss of generality, a 2D localization problem is initially considered. The 2D Cost Function on the xy -plane when $z = z_{tag}$ is shown in Fig. 4. The green cross represents

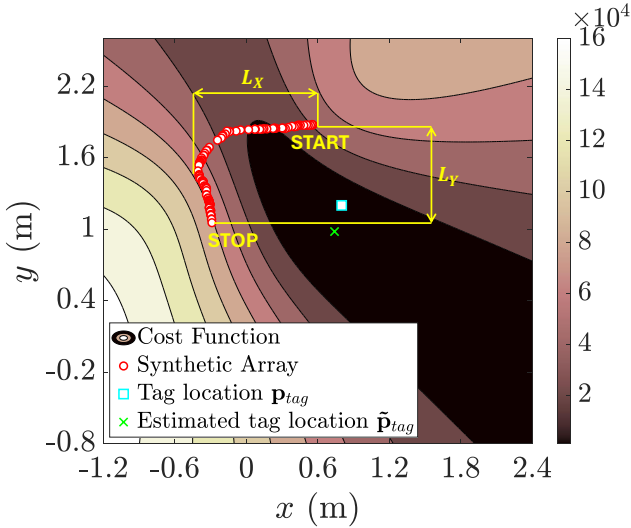


Figure 4. Cost Function for the considered test case with measured phase in Fig. 3.

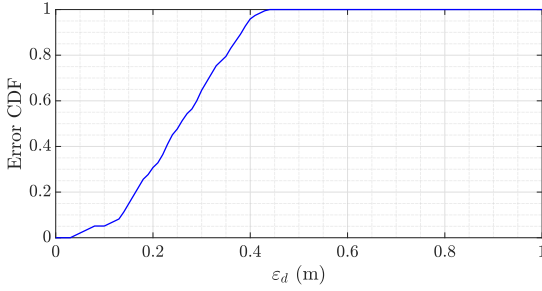


Figure 5. Cumulative Distribution Function of the 3D distance localization error ϵ_d .

the solution of the optimization through the LM method, converging in 14 ms. The estimated 2D tag location is $\hat{\mathbf{p}}_{tag} = [0.74, 0.98]^T$ m, leading to a 23 cm localization error. Now, we consider 3D localization. The Cumulative Distribution Function of the distance localization error in the 3D domain (the z -coordinate of the tag is estimated either) is shown in Fig. 5 for 391 test cases. It can be seen that all the errors are below 0.43 m, which is a suitable performance for wide area warehouses or stores.

3.3 Experimental Results: sensing

The memory of the passive RFID tags is queried to retrieve the room temperature data. Temperature data usually appear as bit-string values and must be converted in Celsius degrees. Measured temperature data is shown in Fig. 6 in a histogram form concerning 107 data samples. The room temperature was 24.2°C according to a ground truth calibrated Pt100 temperature sensor. Measured data from RFID sensor tags are consistent with this value (mean 25.01°C and standard deviation 0.473°C).

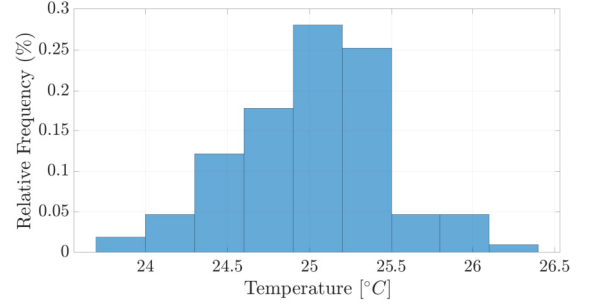


Figure 6. Histogram of the Temperature measured by the RFID sensor tags.

4 Conclusion

In this work a position-aware mobile robot-based system for integrated communication and sensing of environmental information based on passive RFID sensor tags at UHF band was presented. An experimental setup was installed to verify the system effectiveness in realistic conditions. The robot carries the RFID reader and antenna to detect RFID sensor tags in the surroundings. Its trajectory is accurately measured thanks to a 2D LiDAR. Phase delay of each exchanged RFID data packet is used to perform fast SAR localization of tags by implementing phase unwrapping and convex optimization to pinpoint tag location. The 3D localization error reaches a 0.43 m upper bound, whereas the standard deviation of the measured temperature is below 0.5°C. Shown performance are therefore suitable for environmental monitoring in a manifold of applications.

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