RFID Indoor Localization Based on Doppler Effect

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Abstract

Internet of Things (IoT) incorporates concepts from pervasive computing and enables iteration between people and objects. Location service is one of the primary services of IoT. However, existing techniques for indoor localization either have low accuracy or are too complex, requiring a high investment. This paper presents a technique of RFID indoor localization based on an analytical model of the Doppler Effect. From the Doppler frequency, due to the relative motion between the reader antenna and the tag, it is possible to estimate the spatial position of the reader antenna. Test results show the technique provides the location of the reader antenna with high accuracy and meets the requirements of low complexity and cost.

Keywords

RFID, Indoor Localization, IoT, Doppler Effect

1. Introduction

Location service is one of the primary services of the Internet of Things (IoT) and accuracy in location is a key piece [1]. The RFID (Radio Frequency Identification) is one of the main technologies that enable this service. It allows the identification, location and tracking of an RFID tag attached to a person or object. However, due to its high sensitivity to interference, its use in indoor environment is dramatically affected by the problems inherent in electromagnetic propagation in indoor environment [2]. Thus, a novel and robust location technique to meet indoor environment requirements is needed.

Most RFID indoor localization techniques are based on either the RSSI (Received Signal Strength Indicator) or the phase of the received signal. In case of RSSI, the signal transmitted by the tag (signal backscatter) depends on the antenna gain in the tag. It also depends on the reflection coefficient of the backscatter modulator and its relative change. Another problem is that the incident power on the tag influences the reflection coefficient and the backscattered power. Moreover, techniques based on the phase location of the received signal are strongly influenced by the multipath effect. The methods based on round-trip-time will also fail due to high jitter in the response time of the tag [3].

Addressing the problems discussed and what the IoT needs for an accurate service location, this paper presents a new location technique based on the Doppler Effect and an analytical model to determine the position of the reader antenna using the Doppler frequency on the tag movement.

The remainder of this paper is organized as follows: Section 2 shows a summary of related work. The Doppler model proposed for RFID indoor localization is described in Section 3. Section 4 shows the test environment. Section 5 demonstrates the test results and finally, Section 6 shows the conclusion and the future works.

2. Related work

There are many works on RFID indoor localization; most of them are based on RSSI [4] and on the phase of the received signal [5].

In [4], a survey on main localization techniques based on RSSI is presented. These techniques take advantage of the signal strength value that decreases as the distance increases. In most of them, in order to predict the target position, reference tags in known locations are deployed and arrays of antennas are used.

A survey on localization techniques based on phase difference of arrival (PDOA) is presented in [5]. Time domain (TD), frequency domain (FD) and spatial domain (SD) works are examined and details on how phase is measured by the reader are shown.

In [6] is proposed an RFID localization algorithm based on the characteristic of receiving signal of mobile reader and time-frequency change caused by relative movement between reader antenna and tags. Doppler frequency is estimated by sectioned linear fitting and parameter estimation in linear frequency modulation (LFM) methods. From the estimated frequency, the Levenberg-Marquardt algorithm is used to obtain the velocity and initial position of the target. Based on this information and the time operation of the algorithm, the current position of the target is estimated. For testing, reader and antenna was mounted on a moving target and tags fixed to the side of the path traveled by the reader, where each tag had its unique identifier and spatial coordinates. This algorithm had a good performance and the localization error reached the centimeter-level. This model requires a preconfigured environment and reference tags, which are its limitations with respect to applicability.

3. Doppler model

Most RFID readers can measure both the received signal strength and the phase of the tag [5]. The phase of the received tag signal can be written as:

$$\theta = \theta_{prop} + \theta_o + \theta_{BS} \tag{1}$$

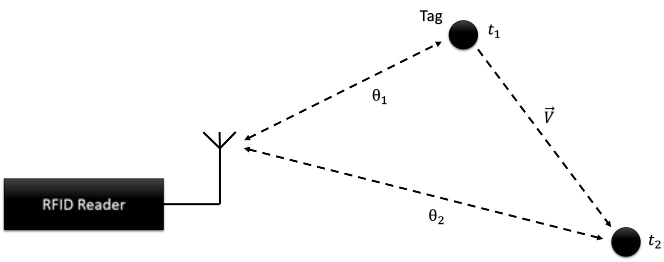
where θ_{prop} is the phase accumulated due to electromagnetic wave propagation, θ_o is the phase offset, which includes phases of the cables and other reader and antenna components, and θ_{BS} is the backscatter phase of the tag modulation.

RFID readers can measure the Doppler frequency by reading the phase tag on two distinct moments, as shown in Fig. 1. From the phase shift, caused by the tag motion and the time elapsed between two time points, the Doppler frequency can be written as:

$$f_D = \frac{\Delta\theta}{4\pi\Delta T} \tag{2}$$

where $\Delta T = t_2 - t_1$ is the time elapsed and $\Delta\theta = \theta_2 - \theta_1$ is the phase shift between time points t_1 and t_2.

Figure 1: Doppler frequency measured from phase shift.



The influence of velocity and transmitter–receiver space location on the value of Doppler frequency is presented in [7] [8]. From the electric field analysis, and taking into account the signal source motion, the Doppler frequency is expressed as:

$$\begin{aligned} f_D(X,t) &= f(X,t) - f_0 = \\ &\frac{k}{1-k^2}\left(k + \frac{x - vt}{\sqrt{(x-vt)^2 + (1-k^2)(y^2+z^2)}}\right) f_0 \end{aligned} \tag{3}$$

where f_0 is the transmitted signal frequency, $X = (x, y, z)$ are the spatial coordinates of signal source, v is the receiver velocity, and $k = v/c$, where c is the speed of light. According to (3), the Doppler frequency depends not only on signal source velocity and carrier frequency, but also on the space location of the signal source and the receiver.

Thus, considering one known signal source spatial coordinate and a fixed travel speed for the receiver, the individual spatial coordinates (x, y, z) of the signal source can be estimated after the elementary transformation of (3) for two moments t_1 and t_2 . Formulas describing the coordinates follow [9]:

$$\begin{cases} x = v\dfrac{t_1 A(t_1) - t_2 A(t_2)}{A(t1) - A(t2)} \\ y = \pm\sqrt{\dfrac{\left[\dfrac{v(t_1-t_2)A(t_1)A(t_2)}{A(t_1)-A(t_2)}\right]^2}{1-k^2} - z^2} \\ z = \pm\sqrt{\dfrac{\left[\dfrac{v(t_1-t_2)A(t_1)A(t_2)}{A(t_1)-A(t_2)}\right]^2}{1-k^2} - y^2} \end{cases} \tag{4}$$

where $A(t) = \dfrac{\sqrt{1-F^2(t)}}{F(t)}$ and $F(t) = \dfrac{f_D(t)}{f_0}\dfrac{1-k^2}{k} - k$.

The technique presented in this paper is based on (4). The spatial location of the RFID reader antenna is estimated using the Doppler frequency related to tag motion. The model has two constraints: (i) travel speed of the tag must be constant; (ii) one of the reader antenna spatial coordinates must be known.

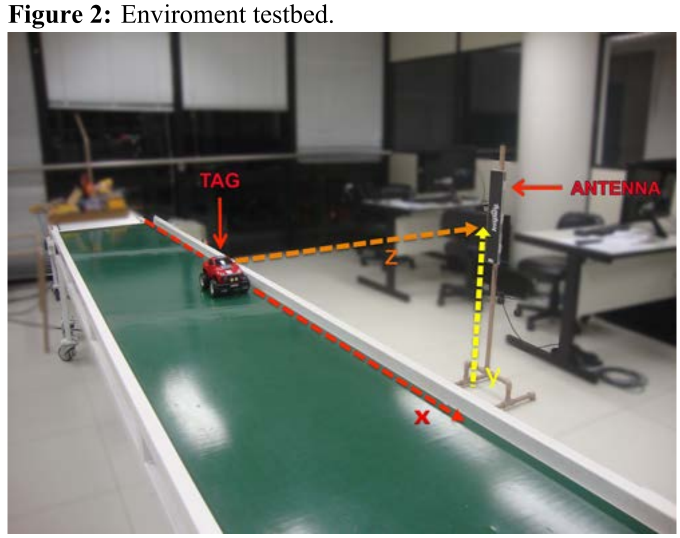
4. Environment

A Speedway Revolution R420 RFID reader and a Threshold RFID antenna, both from Impinj manufacturer, are used in the experiments. Threshold is a far-field antenna, which operates in a frequency range of $902 - 928$ MHz. Its maximum power is 30 dBm and it provides a maximum gain of 5 dBi. The RFID tag used is a RafSec DogBone Wet Inlay, which operates in the frequency range of $860 - 960$ MHz. The connection between reader and antenna is made by a coaxial cable of 3.05 m using BNC connectors.

The reader estimates the Doppler frequency as shown in Section 3, but it calculates the Doppler frequency over the duration of a single packet and not on two reading intervals over distinct moments [10]. This feature avoids many of the pitfalls inherent in using the RF phase from two different packets, like stochastic inventory protocol, antenna switching and channel hopping. However, the time aperture of a single packet places limits on the range of Doppler frequency estimates.

The environment testbed is presented in Fig. 2. In the environment, there is a conveyor belt of 3.90 m (x axis) along which the RFID tag moves. The distance between the antenna and the tag (z axis) is 1.275 m. The tag is fixed at position $z = 0.0$ m and the reader antenna at $z = 1.275$ m. On the y axis (height), the center of the reader antenna is at position $y = 0.98$ m, measured from the floor ($y = 0.0$ m). On the x axis, the reader antenna is located at position $x = 1.742$ m.

Figure 2: Enviroment testbed.



Although the conveyor belt is 3.90 m in length, the range used in the experiments was 3.6925 m. This adjustment was made in order to make the object positioning over the conveyor belt easier.

Eqn. 4 was applied to estimate the reader antenna position. As at least one of the reader antenna spatial coordinates is required to be constant, coordinate z was fixed in order to obtain the coordinate y and coordinate y was fixed to calculate the coordinate z.

In attendance to federal regulations, like FCC (USA) and ANATEL (Brazil), UHF RFID equipments cannot stay in the same frequency for more than 0.4 seconds in a 10 seconds interval [11]. In order to meet this constraint, RFID readers hop on to each available 250 KHz channel, limiting the possibility of testing on a fixed frequency. Because of this, in these experiments, the regulatory region was set to a frequency range of $923-925$ MHz.

In experiments, two different scenarios were deployed: tag motion in slow speed (Scenario 1), and tag motion in fast speed (Scenario 2).

In Scenario 1, the RFID tag was fixed to a paper box and the paper box positioned over the conveyor belt (Fig. 3). From the conveyor belt movement, the paper box travelled 3.6925 m in 9.15 s, at an average speed of $0.4035\,\mathrm{m/s}$. The height between floor ($y=0$) and tag was 0.98 m ($y=0.98$).

Figure 3: Paper box and RFID tag.

In Scenario 2, the RFID tag was fixed in a radio-controlled (R/C) model car (Fig. 4). The conveyor belt was turned off and the car positioned over it. The height between floor and tag was 0.95 m ($y=0.95$). In experiments, the car travels 3.6925 m in 1.79 s, at an average speed of $2.06\,\mathrm{m/s}$.

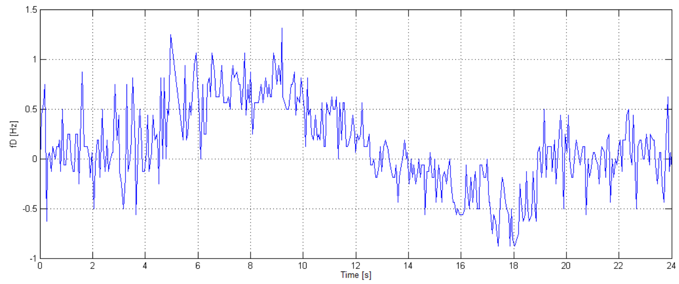
Figure 4: R/C car and RFID tag.

Five samples were collected for each scenario. As the obtained data was similar, one random sample of each scenario were chosen in order to run the model.

5. Results

For Scenario 1, the variation of Doppler frequency versus time is shown in Fig. 5. The tag is stopped between time instants $t=0$ s and $t=4$ s, and from $t=20$ s to $t=24$ s. Between time instants $t=4$ s and $t=9$ s, and from $t=18$ s to $t=20$ s, the tag is in the process of acceleration and deceleration, respectively. The movement of constant speed occurs between time instants $t=9$ s and $t=18$ s.

Figure 5: Doppler frequency versus time for Scenario 1.



As shown in Table 1, the largest (0.559 m) and smallest (0.268 m) errors are in axes x and z, respectively. The error for axis y is 0.390 m.

Table 1: Scenario 1 results.

Axis	Real value (m)	Estimated value (m)	Error (m)
x	1.742	2.302	0.560
y	0.980	0.589	0.391
z	1.275	1.006	0.269

In Scenario 1, tag motion speed does not cause a meaningful variation of Doppler frequency and this can influence the location error. Although variation in Doppler frequency is small, the time interval where the motion has constant speed is noticeable.

In Scenario 2, tag motion speed is significant, which results in a larger variation in Doppler frequency. Fig. 6 shows Doppler frequency versus time for Scenario 2. Acceleration and deceleration occurs between time instants $t=14.55$ s and $t=14.59$ s, and from $t=16.8$ s to $t=16.97$ s, respectively. The motion has constant speed between time instants $t=14.95$ s and $t=16.75$ s.

Figure 6: Doppler frequency versus time for Scenario 2.

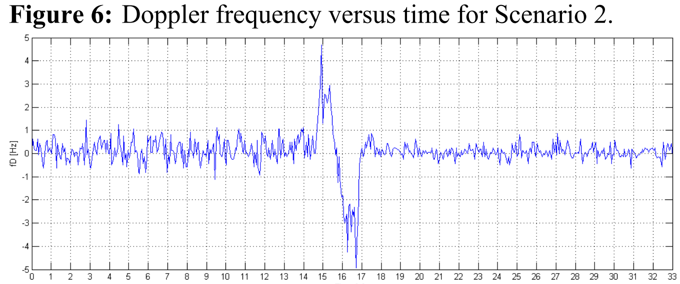


Table 2 presents results for axis x, y and z. The error for Scenario 2 is much smaller than that for Scenario 1. Axis y presents the largest error (0.042 m). Errors are 0.024 m and 0.016 m for axis z and x, respectively.

Results for Scenario 2 are better than those for Scenario 1. The error reaches up to a few centimeters, which is as expected for a high accuracy localization technique. Error reduction in Scenario 2 can be assigned to the higher speed of the tag. Tag motion exceeds the minimum speed threshold; hence, the Doppler frequency increases the localization accuracy significantly.

Table 2: Scenario 2 results.

Axis	Real value (m)	Estimated value (m)	Error (m)
x	1.742	1.725	0.017
y	0.980	0.937	0.043
z	1.275	1.250	0.025

In both scenarios, it is possible to observe an ideally symmetrical arrangement, where the direction of motion and the point that intersects the tag antenna are easily discriminated by the sign of the received Doppler frequency.

To better illustrate the effectiveness of the proposed location technique, in Table 3 is made a comparison between this technique, considering the results obtained in Scenario 2, and other localization techniques based on phase difference of arrival. The localization error shown is measured in terms of mean absolute error (MAE) or root mean square error (RMSE). For the proposed technique, the Euclidean distance is used in three-dimensional space as from average absolute error for each axis.

Table 3: A localization error comparison between the proposed technique and other techniques based on the phase difference of arrival.

Localization technique	Error	Measuring error method
Proposed technique	0.052 m	MAE
TD-PDOA [12]	1.3 m	MAE
SD-PDOA [13]	3.3°	RMSE
FD-PDOA [14]	0.14 m	MAE

6. Conclusion

This paper presented a novel RFID indoor localization technique based on the Doppler Effect and an analytical model to determine the position of the reader antenna, using the Doppler frequency due to the tag movement.

The technique has wide applicability and low cost as it does not require reference tags and several readers or antennas. Also, it can be used in almost any environment, without the need for prior preparation.

One drawback of this technique is that the tag must remain in the range of the reader antenna long enough for reading at least two packets, at different moments. Another drawback is that the speed needs to be high enough to cause a significant variation in the Doppler frequency and exceed the threshold of the minimum frequency at which this technique can be applied. These drawbacks are not relevant, since the time and the minimum threshold are feasible to be achieved in almost any practical scenario.

Future works can verify the range of Doppler frequency for which this technique can be applied, along with the relationship between the error and the increase in distance between reader antenna and tag.

7. References

[1] Z. Chen, F. Xia, T. Huang, F. Bu, and H. Wang, "A Localization Method for the Internet of Things," The Journal of Supercomputing, vol. 63, no. 3, pp. 657–674, Sep. 2011.

[2] E. Berz, F. Hessel, M. de Azambuja, and J. Ody, "Prediction of RFID Systems Coverage Applied to Smart Cards Scenario," in Personal Indoor and Mobile Radio Communications (PIMRC), 2012 IEEE 23rd International Symposium on, Sep. 2012, pp. 1484–1490.

[3] T. Faseth, M. Winkler, H. Arthaber, and G. Magerl, "The Influence of Multipath Propagation on Phase-Based Narrowband Positioning Principles in UHF RFID," in Antennas and Propagation in Wireless Communications (APWC), 2011 IEEE-APS Topical Conference on, Sep. 2011, pp. 1144–1147.

[4] L. Ni, D. Zhang, and M. Souryal, "RFID-Based Localization and Tracking Technologies," Wireless Communications, IEEE, vol. 18, no. 2, pp. 45–51, Apr. 2011.

[5] P. Nikitin, R. Martinez, S. Ramamurthy, H. Leland, G. Spiess, and K. V. S. Rao, "Phase Based Spatial Identification of UHF RFID Tags," in RFID, 2010 IEEE International Conference on, Apr. 2010, pp. 102–109.

[6] J. Yu, K. H. Liu, and P. Luo, "A Mobile RFID Localization Algorithm Based on Instantaneous Frequency Estimation," in Computer Science Education (ICCSE), 2011 6th International Conference on, Aug 2011, pp. 525–530.

[7] J. Rafa and C. Ziółkowski, "Influence of Transmitter Motion on Received Signal Parameters – Analysis of the Doppler Effect," Wave Motion, vol. 45, no. 3, pp. 178 – 190, 2008.

[8] C. Ziolkowski, J. Rafa, and J. Kelner, "Practical Aspects of the Doppler Effect in Mobile Communication Systems," in Microwaves, Radar and Wireless Communications, 2008. MIKON 2008. 17th International Conference on, May 2008, pp. 1–4.

[9] P. Gajewski, J. M. Kelner, and C. Ziółkowski, "Subscriber Location in Radio Communication Nets," Journal of Telecommunications and Information Technology, pp. 88–92, 2008.

[10] Impinj, "Speedway Revolution Reader Application Note - Low Level User Data Support," pp. 1–16, 2012.

[11] R. R. d. F. Dias, H. E. Hernandez-figueroa, and L. R. Costa, "Analysis of Impacts on the Change of Frequency Band for RFID System in Brazil," RFID-Technologies and Applications (RFID-TA), 2013 IEEE International Conference on, pp. 4–5, 2013.

[12] B. Kusy, A. Ledeczi, and X. Koutsoukos, "Tracking mobile nodes using RF Doppler shifts," Proceedings of the 5th international conference on Embedded networked sensor systems - SenSys '07, p. 29, 2007.

[13] C. Angerer, R. Langwieser, and M. Rupp, “Direction of arrival estimation by phased arrays in RFID,” in Proceedings of the third international EURASIP workshop on RFID technology, Spain, 2010.

[14] A. Povalac and J. Sebesta, “Phase difference of arrival distance estimation for RFID tags in frequency domain,” 2011 IEEE International Conference on RFID-Technologies and Applications, no. 1, pp. 188–193, Sep. 2011.