An Indoor Localization System Based On Backscatter RFID Tag

Jun Wang, Yiyin Wang, Xinping Guan
Department of Automation, Shanghai Jiao Tong University
Shanghai 200240, P.R.China
Email: wangjunemse@foxmail.com, {yiyinwang, xpguan}@sjtu.edu.cn

***Abstract*—Indoor localization has been actively researched in recent years due to the increasing demand for location-awareness services. However, to balance localization accuracy and system cost is always a challenge for indoor localization systems. Radio frequency identification (RFID) is a promising technology to achieve both goals, because of its reasonable cost and reliability. In this paper, we propose a novel RFID indoor localization system based on angle of arrival (AoA) and phase of arrival (PoA) methods. This system leverages RFID's two experimental signal diffusion characteristics to estimate AoA. One is that the interrogation zone is constrained in a lobe, and only in this area the tag can be queried. The second is that there exits a stable pattern of received signal strength (RSS) on angle changes. We use the two features to find a general area and to pinpoint the AoA consecutively. This effectively narrows the sampling zone (where signal needs to be sampled), and helps to reduce computational complexity. In addition, we reduce the multipath effect on range estimation by determining the AoA and rotating the reader into the direction of the target. Moreover, we exploit two signals with a slightly different frequency to eliminate the phase ambiguity issue. Our system takes only one reader and achieves mean accuracy of 23 cm. The simplicity and effectiveness of our system make it convenient to be used in practice.**

I. Introduction

Indoor localization has attracted a great deal of attention in recent years. Many applications benefit from the location information, such as patient surveillance in hospital, senior tracking at home and quick guide in a huge shopping center. Existing researches mainly focus on technologies such as infrared, ultrasonic, ultra wideband (UWB) etc. [1], [2], [3]. For an indoor localization system, accuracy and low-cost are two principle requirements. Thus, it is critical to develop a system that satisfies both requirements.

RFID is a potential candidate to achieve economical and high accurate indoor localization, due to its reliability and low-cost. It has been widely used in logistics, goods tracking and access control, etc. Especially the passive ultra high frequency (UHF) RFID transponders in the UHF from 860 MHz to 960 MHz enlarge the operational range to tens of meters. It makes RFID sufficient for indoor localization. Nevertheless, the existing low-cost RFID systems cannot reach the accuracy requirement yet [4]. Methods need to be developed to achieve accurate localization. In recent years, different approaches have been proposed to solve this problem, including conventional time of arrival (TOA) [5], [6], [7], angle of arrival (AOA) [8], [9], [10], [4], phase of arrival (POA) [11], [12], as well as received signal strength (RSS) [13], [14], [15], [16]. The TOA-based methods measure the signal's propagation distance. It deploys no less than three anchors (nodes with known positions) to locate the target by using trigonometry. It is usually hard to accurately measure the travel time due to the multipath effect in a room. The AOA-based methods need antenna arrays or directional antennas to determine the angle, and then uses trigonometry to determine the target's location. While the POA-based methods are more promising, because it is easy to obtain the signal's phase change during the prorogation. However, it has phase ambiguity problem caused by phase wrapping. Yet another type of methods is the RSS-based ones. It is based on the statical knowledge about the distribution of RSS values. The RSS-based methods are easily affected by the signal's fluctuation.

Generally, RFID localization systems can be divided into two general categories based on the principles used by the systems. The first category is RSS-based localization systems. LANDMARC [17] is a classic method. It deploys nine readers with eight different power levels and many reference tags in advance. To locate the target tag, it compares the target's signal strength with an estimated value derived from a weighted average value of k-nearest neighbors. However, it suffers from a serious latency due to large computation. VIRE [18] uses the same method as LANDMARC. However, it improves the efficiency and accuracy by filtering some unlikely positions so that less tags need to be compared. Using the k-nearest neighbors estimation, Bekkali et al. [19] leverage Kalman filtering and probabilistic map matching to estimate location based on two readers and landmarks. It is less costly and more robust to the variations of environments. D. Katabi et al. [16] introduce a fine-grained positioning system called PinIt which exploits a tag's multipath profile rather than taking it as detrimental.

The second category is phase-based localization systems. Methods related to phase difference are commonly used to locate passive RFID tags. C. Zhou et al. propose a composite dual-frequency continuous wave and continuous-wave radar system to locate passive tags [20]. Rainer et al. set up a localization system on the principle of a phased array with electronic beam steering mechanism [10]. Zhang et al. exploit the direction-of-arrival estimation method to localize passive RFID tags [21]. Hekimian-Williams et al. use phase difference to estimate position by applying maximum likelihood method [22]. Y. Liu et al. propose a positioning technology called BackPos by using the phase difference information from the reader [23].

The focus of our work is to develop a novel system which is more economical as well as with higher accuracy. In our system, we combine the AOA and POA methods to achieve the passive tag's localization. According to our experimental results, the RSS varies along the change of angle between the tag and reader. This signal diffusion phenomena is also observed by Y. Qiu et al. They design an indoor location system by taking advantage of this feature [4]. However, their system needs two readers to work separately, we propose a more attractive solution. A system consists of only one reader without any reference tag (tag with known position). Unlike conventional systems, we divide the position evaluation process into two steps: 1) we rotate the reader to estimate the AOA by using RFID's signal diffusion characteristics; 2) we use the signal's phase difference to evaluate the range. An obvious advantage is that it reduces the sampling zone and computational complexity, making our system more efficient. Moreover, we investigate the phase ambiguity issue caused by phase wrapping and resolve it by using two signals with a slightly frequency difference.

Our system has five advantages in general. 1) It is cost-efficient since it needs only one reader. 2) It is reference-free without deploying any infrastructure in advance. Therefore, it is flexible to be used in different scenarios. 3) It exploits the received signal's in-phase and quadrature information, which is supported by a commercial off-the-shelf (COTS) reader. 4) It reduces the multipath effect by determining the direction of arrival first, then rotating the reader in the direction of the target for range estimation. 5) It exempts us from measuring the initial phase rotation since we only exploit the phase difference. All those features extend the usage scope of our system.

This paper is structured as follows. Section II introduces empirical studies and AOA estimation. Section III describes the system model and range estimation process. Section IV demonstrates the experimental results. Section V contains the conclusion.

II. AOA ESTIMATION

Our localization system consists of an antenna, RFID tags and a pan-tilt unit, as shown in Fig. 1. The antenna used in our system is a platelike RFID antenna with a frequency range from 840 MHz to 845 MHz. It has linear polarization, 12 dB gain and dimensions of $445 \times 445 \times 40$ mm. The tag attached on the target is a passive UHF tag. The reader chip is QM100 FPC MB, designed and produced by MagicRF Co., Ltd [24]. All our experiments are based on the assumption that the reader and the tag are on the same height. Therefore, the position estimation is in 2-dimensional.

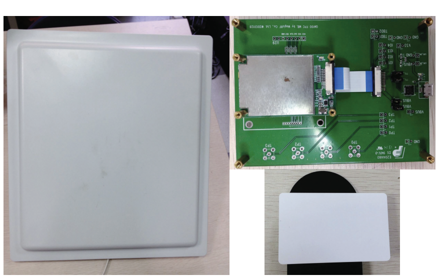

Fig. 1. RFID components, consists of a passive tag, a platelike antenna and a pan-tilt unit

Rather than applying an antenna array [25], [10] or a virtual antenna array [21] to estimate the AOA, we leverage the spacial feature of RFID reader's interrogation area. The interrogation zone of a RFID reader is actually narrowed in a lobe, and only in this are the tags can be interrogated [23], as shown in Fig. 2.

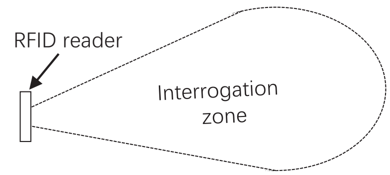

Fig. 2. Interrogation zone. It is a lobe like area, but not exactly symmetrical in practice.

In our system, the RFID reader can rotate $360°$ to detect all directions. We set a reference line as the direction of $0°$, and continuously rotate the reader. We note the angle as θ_{in} when the tag appears in the interrogation zone and the angle as θ_{out} when the tag disappears from the interrogation zone. Since the interrogation zone seems symmetrical, the angle of arrival is estimated as $\theta_e = (\theta_{in} + \theta_{out})/2$ in [4].

However, the method used in [4] does not lead to an accurate AOA estimate. It is necessary to find a more preferable way to achieve a higher estimation accuracy. According to our experiments, we find that there exits a stable pattern for RSS on direction changes. The RSS pattern changes along with AOA and always has the maximum RSS value when the antenna faces the direction of the tag. We note θ_{max} as the direction with the maximum RSS value. This experiment is conducted in a room of size 5 m$\times$ 10 m, the SNR value is 30 dB at the antenna and we sample more than 1000 values. Fig. 3 demonstrates the error CDF of these two methods. From this figure, we observe that θ_{max} is more accurate that θ_e, their mean errors are around $4°$ and $11°$ respectively.

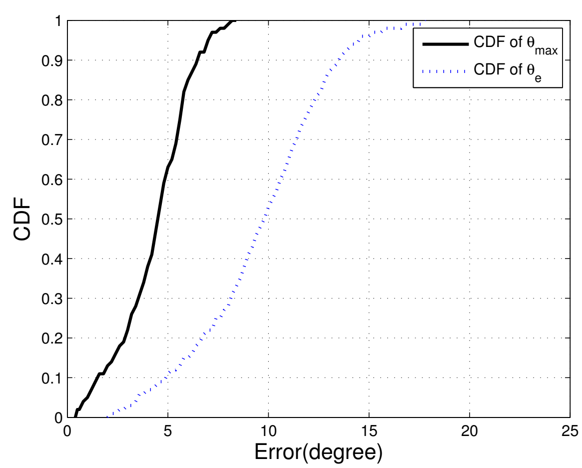

Fig. 3. CDF of errors in angles

Considering specific characteristics of these two methods, we combine them by using the interrogation zone to narrow the detection range and using the RSS pattern to pinpoint the AOA. We first obtain an approximately range, say $(\theta_e - 15°, \theta_e + 15°)$, and then sample the signal in this range to determine θ_{max}. The AOA estimate can be presented as $\theta_a = \theta_{max}$. Rather than sampling all RSS value in 360°, we decrease the sampling area to 30°. It largely reduces the computational complexity and improves the system's performance.

III. Position Estimation

A. System model

The wireless communication between the tag and the reader is a typical wireless communication system. In a RFID system with passive tags, the reader modulates the transmitter's instruction code $c(t)$ onto a carrier signal f_0, where f_0 is the frequency of the carrier signal. Thus, the transmitted signal can be written as:

$$x_t(t) = c(t)cos(2\pi f_0 t + \varphi_0) \quad (1)$$

where φ_0 is the transmitter's initial phase. While waiting for the backscatter signal from the activated tag, the transmitter needs to send the carrier signal $cos(2\pi f_0 t + \varphi_0)$ continuously to provide power for the tag. Once the tag is activated, it generates a backscattered response by changing its input impendence states. As a consequence, it creates an amplitude shift keying (ASK) modulated signal $m(t)$. The received signal for the reader could then be written as:

$$x_r(t) = K_0[1 + m(t)]cos(2\pi f_0 t + \varphi_0 - \Delta\varphi_0) \quad (2)$$

where K_0 is the channel gain and $\Delta\varphi_0$ is the propagation phase difference of the carrier signal. Note that $\Delta\varphi_0 = 2\pi f_0 2R/c$, in which R is the distance between the reader and the tag, and c is the propagation speed of light.

However, (2) represents an ideal model. In a real scenario, the difficulty of indoor localization lies in the multipath effect caused by the reflection of walls, floor and other objects in the room. Those interference signals can be divided into three catalogs: 1) the first type is the directly reflected signal without being modulated by the tag, noted as $\sum_{n=1}^{N} H_n cos(2\pi f_0 t + \varphi_0 - \Delta\phi_n)$; 2) the second type is the signal that modulated by the tag and then reflected back to the reader, which can be written as $\sum_{m=1}^{M} K_m[1 + m(t)]cos(2\pi f_0 t + \varphi_0 - \Delta\varphi_m)$; 3) the third one is Additive white Gaussian noise (AWGN) caused by the environment, represented as $w(t)$. Therefore, the received signal at the reader could be expressed as:

$$\begin{aligned} \hat{x}_r^{f_0}(t) = &\sum_{m=0}^{M} K_m[1 + m(t)]cos(2\pi f_0 t + \varphi_0 - \Delta\varphi_m) + \\ &\sum_{n=1}^{N} H_n cos(2\pi f_0 t + \varphi_0 - \Delta\phi_n) + w(t) \end{aligned} \quad (3)$$

In (3), $K_0[1+m(t)]cos(2\pi f_0 t+\varphi_0-\Delta\varphi_0)$ is the part of interest. It signifies the directly reflected backscatter signal. H_n and $K_m (m \neq 0)$ are the interference signals' path gains. $\Delta\phi_n, \Delta\varphi_m$ are the phase differences caused by multipath propagation. Their values are $2\pi f_0 \frac{D_n}{c}$ and $2\pi f_0 \frac{S_m}{c}$ respectively, where D_n is the propagation distance for the n_{th} signal of the first type interference, while S_m is the propagation distance for the m_{th} signal of the second type interference.

B. I-Q modulation analysis

For a RFID indoor localization system, the above mentioned interference signals are always the primary factors that affect the localization accuracy. The system can achieve a higher accuracy if we eliminate or reduce the multipath effect. In the following discussion, we will focus on the two kinds of interference signals, and elminate AWGN from (3) to simplify the deduction process.

The received signal is amplified and down-converted to baseband by the reader. The baseband signal is represented by the in-phase and quadrature components, denoted as $I(t)$ and $Q(t)$ respectively. Since the received carrier signal and the local carrier at the reader have the same frequency f_0 and initial phase φ_0, both in-phase and quadrature are constant, depending only on the phase shift of carrier signal. $m(t)$ depends on the tag and is the same for in-phase and quadrature. The waveforms at the reader can be presented as

$$I(t) = \sum_{m=0}^{M} A_m[1 + m(t)]cos(\Delta\varphi_m) + \sum_{n=1}^{N} B_n cos(\Delta\phi_n) \quad (4)$$

$$Q(t) = \sum_{m=0}^{M} A_m[1 + m(t)]sin(\Delta\varphi_m) + \sum_{n=1}^{N} B_n sin(\Delta\phi_n) \quad (5)$$

where A_m and B_n are the received signal magnitudes. $A_m = K_m G$, $B_n = H_n G$ and G is the gain in I-Q decomposition process. $\Delta\varphi_0$ is the wanted phase shift of the carrier signal during the propagation. The tag's modulated signal $m(t)$ can be viewed as a composition of multiple sinusoidal signals whose basic frequency is the modulate frequency, $m(t) = \sum_{l=0}^{L} a_n cos(2\pi f_l t)$. As a result, the first type of interference signal can be filtered by a DC blocking filter. Then we obtain the signals as:

$$\hat{I}(t) = \sum_{m=0}^{M} A_m m(t) cos(\Delta\varphi_m) \quad (6)$$

$$\hat{Q}(t) = \sum_{m=0}^{M} A_m m(t) sin(\Delta\varphi_m) \quad (7)$$

From (6) and (7), we see that there still exist two non-negligible factors. They are the second type of interference signal and the phase ambiguity caused by the phase wrapping. We will discuss the solutions to these problems in the following part.

C. Range estimation

To degrade the multipath effect to minimum, we choose to decrease the effect from the beginning, rather than dealing with it in the computational process. We divide our position estimation process into two stages. First is to find the direction of the target and rotate the reader into this direction. Second is to estimate the range from the target to the reader. The advantage is that the direct backscatter signal is much stronger than the second type interference signal in this condition, thus the interference signal is ignorable and the received signal approximately equals to the directly backscattered signal. We conduct experiments to validate this approxim in a room of 5 m $\times$10 m with objects inside. The distance is set as 3 m and SNR is 30 dB, and use the least-square method for fitting analysis.

For n pairs of observed data (x_1, y_1) (x_2, y_2) ... (x_k, y_k) ... (x_n, y_n), we define the equation as $y = ax + b$. The principal of least-square is to find parameter a and b to minimum $\sum (ax_k + b - y_k)^2$. To get the minimum value of $\sum (ax_k + b - y_k)^2$, we let the partial derivative of a and b to be 0 and have $\sum (b + ax_k - y_k) = 0$ and $\sum x_k(b + ax_k - y_k) = 0$. Thus, we resolve the equations and obtain $a = [n \sum (x_k y_k) - (\sum x_k \sum y_k)]/[n \sum ({x_k}^2) - (\sum x_k)^2]$, $b = (\sum y_k)/n - a(\sum x_k)/n$.

The fitting line and theoretical line are illustrated in Fig. 4. We take $\Delta\varphi = \arctan \frac{\hat{Q}(t)}{\hat{I}(t)}$ as our estimated phase and sampled around 1000 values for calculation. The actual phase shift is $2k\pi + \theta_0$, where θ_0 is in $[0, 2\pi)$ and k is an integer. Since k does not affect the phase difference tendency, we take θ_0 to represent phase difference in this figure.

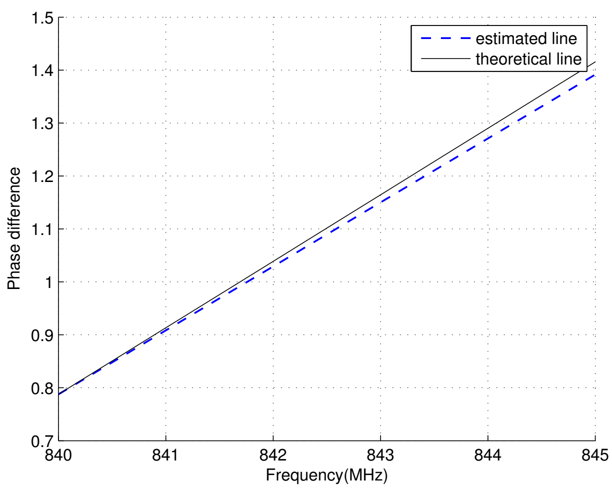

Fig. 4. Phase difference trend on different frequencies

From Fig.4, we observe that the estimated phase shift tendency is close to theoretical one, with slope of 0.1208 and 0.1256 respectively. In other words, the interference signal in (6) and (7) is negligible compared the direct backscatter signal when the antenna of the reader faces the direction of the tag. Otherwise the phase difference would be irregular to frequency change. Consequently, the in-phase and quadrature components in (6) and (7) can be approximated as

$$\hat{I}_0(t) = A_0 m(t) cos(\Delta\varphi_0) \tag{8}$$

$$\hat{Q}_0(t) = A_0 m(t) sin(\Delta\varphi_0) \tag{9}$$

The waveforms received at the reader, as given in (8) and (9) allow a straightforward estimation for the phase difference. That is, at time t, the phase difference could be evaluated as $\Delta\hat{\varphi}_0 = \arctan \frac{\hat{Q}_0(t)}{\hat{I}_0(t)}$. Therefore, the straightforward range estimation is

$$\hat{R} = \frac{\Delta\hat{\varphi}_0 \cdot c}{4\pi f_0} \tag{10}$$

We notice that $\Delta\hat{\varphi}_0$ is periodic with a period of 2π, which causes the phase ambiguity problem. That is, the maximum accurate range estimation is $R_m = 2\pi c / 4\pi f_0 = \lambda_0/2$. Abiding by the UHF Gen 2 protocol [26], the frequency range of RFID is from 860 MHz to 960 MHz, corresponding a maximum accurate range from 15.6 cm to 17.4 cm. This limitation sharply restricts its application scope.

D. Phase ambiguity issue

Phase ambiguity is a common problem due to phase wrapping. To resolve this problem, we let the reader alternatively send two carrier signals with a slightly frequency difference, saying f_0 and f_1 respectively. For each signal, we obtain its phase difference by using the precedent method. Denote the two values as

$$\Delta\varphi_{00} = 2\pi f_0 \frac{2R}{c} \tag{11}$$

$$\Delta\varphi_{10} = 2\pi f_1 \frac{2R}{c} \tag{12}$$

By applying subtraction operation to $\Delta\varphi_{00}$ and $\Delta\varphi_{10}$, we get a quadratic phase difference $\Delta\hat{\varphi} = \Delta\varphi_{00} - \Delta\varphi_{10} = 2\pi\Delta f \frac{2R}{c}$. Consequently, the estimated range is

$$\hat{R} = \frac{\Delta\hat{\varphi} \cdot c}{4\pi\Delta f} \tag{13}$$

Since we can choose f_0 and f_1 freely under the UHF Gen 2 protocol, the maximum unambiguous range could be adapted by modifying the value of Δf, according to our demand. For example, if we want to locate a target in a range less than 12 m, then a Δf of 10MHz is more than enough, with a corresponding maximum unambiguous range of 15 m. This method enlarges its usage scope and enhances the system's flexibility as well. The following experimental results demonstrate its validity and effectiveness.

IV. Experimental Results

Our experiment is designed towards measuring the position accuracy. It is performed in a room whose size is 5m $\times$ 10m. Three tags are deployed at coordinates A1 (0, 3.5), A2 (-2, 2), A3 (3, 3) respectively and the reader is deployed at coordinate O (0, 0.3), as shown in Fig. 5. The frequencies used are 840.125 MHz and 844.875 MHz, corresponding to an maximum resolvable range of 31.5 m. SNR is 30 dB at the antenna and the experiment is repeated 100 times for each coordinate. The real position is marked as "$\triangle$" in this figure. Note that the positions are not symmetrical in order to make this experiment more general.

From Fig. 5, we observe that the error has a little difference among the positions. That is, the points closer to the antenna has a smaller error compared with the farther ones. Because the signals from farther away tags have a lower SNR, leading to a larger error. We also plot the error CDF of these positions in

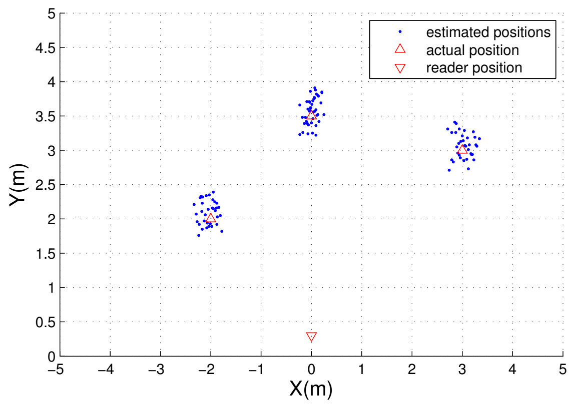

Fig. 5. Positioning results

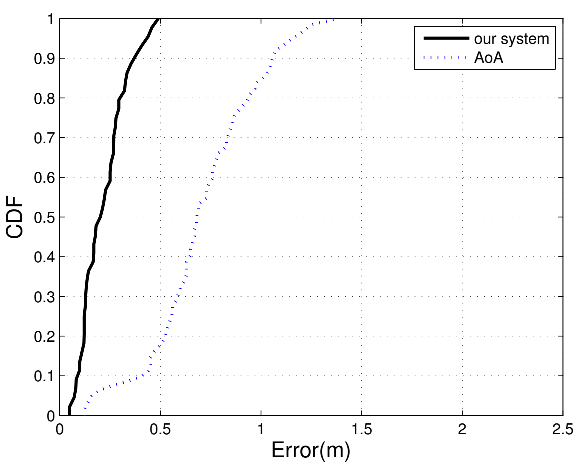

Fig. 6. CDF of position errors

Fig. 6. The error is defined as the Euclidean distance between the measured position and the real position. From this figure, we observe that our system is indeed much better than AOA-based method [4]. The AOA-based method has a 90th percentile accuracy of 106 cm, while ours is 37 cm. The mean error of our system equals to 23 cm while the AOA-based method's mean error is around 70 cm. Generally speaking, our system achieves a high accuracy in a cost-effective way.

V. Conclusion

A prototype indoor localization system has been presented in this paper. It is made up of COTS RFID reader and passive RFID tag, and it achieves a high precision at low cost (both in system price and computational price). The key innovation in our system is to take advantage of the RSS pattern on direction change and the characteristics of interrogation zone to accomplish accurate AOA estimation, then rotate the reader into the direction of the tag to eliminate the multipath effect. The experimental results demonstrate the advantages of combining AOA and POA methods for accurate localization. As the features we used in our system is universal for all RFID systems and that the system is cost-effective. It shows the potential prospect for other application scenarios.

We notice that the antenna in our system is not practical for real applications and that the system need to rotate 360° for AOA estimation. Thus we should test the system's performance with smaller antennas and continue to improve AOA estimation efficiency. Our future work is to resolve the issues discussed above and further adapt this system for motion tracking.

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