CHAPTER

LOCALIZATION IN CYBER-PHYSICAL SYSTEMS

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1 INTRODUCTION

Due to the success of cyber-physical systems (CPSs) (Lee, 2008), radio-frequency identification (RFID) technology has attracted a lot of attention from both industry and academia, e.g., smart home, Industry 4.0, object identification, and indoor localization (Finkenzeller and Waddington, 1999; Nazari Shirehjini et al., 2012; Almaaitah et al., 2010).

An RFID system consists of several readers and RFID tags. RFID tags are attached to objects of interest, and send back reply signal when they receive query signals from readers. RFID tags can be categorized as proactive and passive tags. The proactive tags are equipped with a battery and will transmit the reply signal back to the readers once it receives the query signals. The passive tags, on the other hand, are battery free and transmit the reply signal by backscattering the energy of the query signal from the reader. Although RFID technology was first proposed for identifying objects, it is now being used in localizing objects.

In early CPSs (Lymberopoulos et al., 2015), e.g., wireless sensor networks (Kuruoglu et al., 2009; Moore et al., 2004), wireless localization methods can be categorized into two groups: range-based and range-free approaches (Zhao et al., 2013).

The goal of range-based approaches is to obtain an accurate position for a target. Range-based approaches use wireless devices to measure the wireless signals transmitted from a target. Based upon the received signals, range-based approaches use signal processing techniques to obtain the angle of arrival (AoA) (Niculescu and Nath, 2003a; Xiong and Jamieson, 2013), time difference of arrival (Peng et al., 2007), and time of arrival (Hofmann-Wellenhof et al., 2012) of the received signals. Then, the Euclidean distances from the receiving devices to the target can be calculated. Finally, the target's location is computed by analyzing the geometric relation between the target and these devices.

In contrast to range-based approaches, the goal of the range-free approach, such as Niculescu and Nath (2003b), Ni et al. (2004), Wang and Katabi (2013), and Zhong and He (2009), is to find the proximity area where a target is located. The requirement of range-free approaches is that there must be anchor nodes with known positions around the target. Range-free approaches employ indirect measures, such as RSS (Ni et al., 2004), hop count (Niculescu and Nath, 2003b), and signal profile similarity Wang and Katabi (2013), to quantify the distances between anchor nodes and the target. A closer measure indicates a closer distance between an anchor node and the target. Then, the anchor node(s)

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with the closest measure will be selected. Finally, the target's location is estimated as the proximity area nearby the selected anchor nodes.

Although the principle of RFID localization system is similar to above-mentioned approaches, it differs in practical implementations and high accuracy considering the characteristics of a RFID localization system. First, the powerful signal processing capability of a RFID reader enables it to carry out complicated analysis on received signals. Therefore, in a RFID localization system, readers are able to estimate the relative positions of a target tag to the readers by analyzing the backscattered radio frequency (RF) signals from the tag. An RFID tag that passively reflects received signals, however, does not have the signal processing capability. Since most of the existing RFID localization systems employ passive tags; we will use the term tag for simplicity throughout the rest of the chapter. Second, an RFID localization system often consists of several readers and large amount of tags because readers are much more expensive than tags. What's more, RFID tags are energy efficient, especially for those passive RFID tags that work without any battery. Therefore it is possible to deploy huge amount of tags in an interested area. Third, the communication range of a regular RFID localization system is 10–20 m (Yang et al., 2014), so RFID localization systems achieve a fine-grained accuracy (error of 7 mm) (Yang et al., 2014) in an indoor environment, even in the nonline-of-sight (NLOS) scenarios (error of 11.2 cm by Wang and Katabi, 2013). Such high localization accuracy is not achievable for other CPS systems. Meanwhile, due to the above differences, the techniques used in a RFID localization system can hardly be adopted by other CPS systems.

Because of the aforementioned advantages, RFID localization is widely applied in indoor environments. It was firstly used in robotic navigation applications (Tsukiyama, 2003; Han et al., 2007; Kulyukin et al., 2004), then extended to CPS applications. For example, RFID localization is used to identify misplaced items (Liu et al., 2013; Wang and Katabi, 2013), locate the position and orientation of interested items in a NLOS environment (Wang and Katabi, 2013), and track mobile baggage (Yang et al., 2014).

As illustrated in Fig. 1, RFID localization can be better understood from two perspectives: RF signal processing and accuracy improvement. RF signal processing accounts for analyzing the backscattered RF signals and calculating the position of the target tag. It can be categorized as received signal strength (RSS)-based, phase-based, and multipath profile-based. In addition to analyzing the processed RF signals, various accuracy improvement approaches are employed improve the localization accuracy in practical implementation.

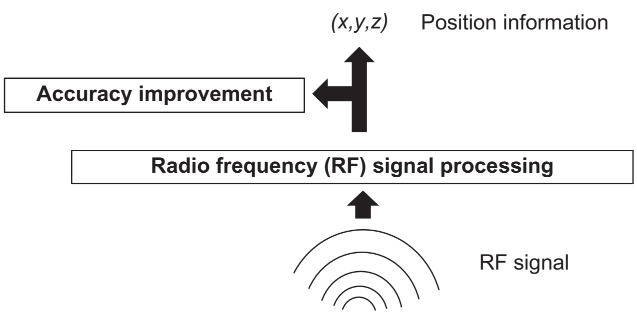

FIG. 1

Architecture of RFID localization.

Despite the variety of RFID localization approaches, there remain many research challenges in RFID localization. For example, RSS-based approaches can be easily implemented but with low accuracy. Phase-based and multipath profile-based approaches achieve higher accuracy but are time-consuming and poorly scalable.

In this chapter, we first present a review on existing RFID localization technologies, and then identify their limitations and potential improvements. The focus of this chapter will be RF signal processing in RFID localization. In addition, we will introduce various accuracy improvement techniques within different RF signal processing schemes.

2 RFID LOCALIZATION MODES

An RFID localization system can work in three different modes: (1) tag localization without reference tags, (2) tag localization with reference tags, and (3) reader localization, as illustrated in Fig. 2.

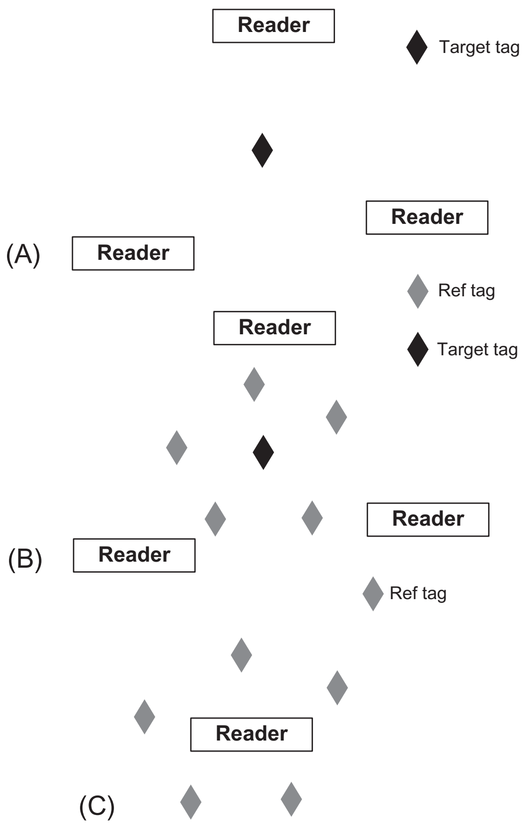

FIG. 2

Different working modes of a RFID localization system: (A) tag localization without reference tags, (B) tag localization with reference tags, and (C) reader localization.

In the first mode shown in Fig. 2A, RFID tags are attached to a target object. Localization of the target is realized by analyzing the RF signals received at the reader. In the second mode shown in Fig. 2B, extra reference RFID tags whose locations are known are deployed to assist in the localization of the target tag, such as in Ni et al. (2004). Comparing the RFID signals backscattered from the reference and the target tag, the environmental impact of the signals such as multipath effect can be eliminated. In the third mode shown in Fig. 2C, RFID tags are treat as references and the RFID reader becomes the target, such as (Kulyukin et al., 2004; Tsukiyama, 2003; Park and Lee, 2013). By communicating with these tags, the reader is able to localize itself.

3 PRINCIPLE OF RFID LOCALIZATION

In this section, we will introduce the principles of different RFID localization approaches. Existing RFID localization approaches can be categorized into three groups: RSS based (e.g., Ni et al., 2004; Bekkali et al., 2007), phase based (e.g., Li et al., 2009; Yang et al., 2014), and multipath profile based (e.g., Wang et al., 2013; Wang and Katabi, 2013). In these approaches, a reader calculates the location of the target tag(s) by analyzing the strengths, phases and multipath profiles of the received signals backscattered from the tag(s). An RSS-based approach can be easily implemented, but does not provide accurate localization results. Phase and multipath profile-based approaches offer higher accuracy but require additional hardware and/or software to perform complex signal processing tasks.

3.1 RSS-BASED RFID LOCALIZATION

The strength of a received RF signal is widely used in localizing wireless devices that send or backscatter the signal, e.g., in Bluetooth, WiFi, and cellular networks. RSS can be easily measured and usually is accessible from the physical layer. Nearly all commercial off-the-shell (COTS) RFID readers can provide RSS information in received RF signals.

The fundamental assumption of an RSS-based approach is that the strength of the received signals at a reader decreases as its distance to a tag increases, i.e., the shorter the distance, the stronger the signal strength. That is to say, RSS is an indicator of the distance between a reader and a tag. As shown in Fig. 3, the distance between a reader and a tag can be estimated based on the RSS of received signals.

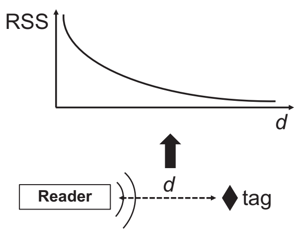

FIG. 3

Principle of RSS-based localization approaches.

The RSS of backscattered signals measured at a reader can be expressed as:

$$\mathrm{RSS}[dB] = P_{\mathrm{L}}(d_0)[dB] - 10n\log_{10}\left(\frac{d}{d_0}\right) + S,$$

where d is the distance between the tag and reader, $P_{\mathrm{L}}(d_0)$ is the path loss along a reference distance d_0, which is usually set as 1 m, n is an empirical constant depending on the signal propagation environment, S is the shadowing factor—a random variable follows the Gaussian distribution. From this equation, we can get the target tag's distance d to the reader as:

$$d = d_0 \times 10^{\frac{P_{\mathrm{L}}(d_0) - \mathrm{RSS} + S}{10n}}.$$

Integrating the distances calculated from multiple readers, the location of the target tag can be calculated.

RSS-based localization approach can be easily implemented on COTS RFID readers given the RSS of received RF signals are provided. In Hightower et al. (2000), an empirical equation is derived to reveal the relationship between distance and RSS. In Ni et al. (2004), differences of RSS from reference tags are captured to estimate the relative distances between a reader and tags. Since RSS can be significantly affected by the communication environment, e.g., multipath effects and reflections, it is often inaccurate in estimating the distance between a reader and tags.

3.2 PHASE-BASED RFID LOCALIZATION

Currently, many COTS RFID readers provide not only RSS but also phase information of received RF signals. Phase information can be used to compute the target tag's location by calculating the distances between the target tag and different readers or a reader's different antennas. Since phase information is resilient to the effects of various communication environments, it offers higher accurate localization results than RSS-based approaches.

To obtain the phase information of backscattered RF signals, received signals are first converted to baseband signals. The baseband signal can be represented by the in-phase (I) and quadrature (Q) components. Ideally, the phase of a received signal can be computed by

$$\varphi = \arctan\frac{Q(t)}{I(t)}$$

The phase offset of a received RF signal on a reader includes three components: (1) the phase offset φ_{prop} generated by the round-trip signal propagation between the reader and the tag, (2) the phase offset $\varphi_{\mathrm{reader}}$ introduced by the RFID reader when it processes the signal, and (3) the phase offset φ_{tag} caused by the tag when it backscatters the signal. Thus, the total phase offset of the received RF signal on the reader is

$$\varphi = \varphi_{\mathrm{prop}} + \varphi_{\mathrm{reader}} + \varphi_{\mathrm{tag}} \tag{1}$$

where φ_{prop} can be used to calculate the distance from the reader and tag(s). The relationship between φ_{prop} and the distance d can be expressed as:

$$\varphi_{\mathrm{prop}} = 2d \times k = 2d \times \frac{2\pi}{\lambda} = 2d \times \frac{2\pi f}{c} \tag{2}$$

where $2d$ is the distance that the RF signal traverses, λ is the signal's wave length, f is the signal's frequency, c is the speed of light. The above equation indicates that phase offset increases linearly as the distance increases, however, it returns to zero periodically. In fact, phase information can be used to calculate not only the target tag's location but also its velocity if it is on a moving object. Next, we will introduce several phase-based RFID localization methods.

3.2.1 Time domain phase difference of arrival (TD-PDOA)

Phase difference of RF signals received at different times can be used to estimate the velocity of a moving tag/target (Yanakiev et al., 2007; Nikitin et al., 2010). As shown in Fig. 4, a reader receives two signals at times t_2 and t_1 when the distances from the tag to the reader are d_1 and d_2, respectively. We use V_r to denote the velocity on the direction from the reader to the tag, and V_t for the velocity orthogonal to V_r. Then, V_r can be expressed as the derivative of the distance to time:

$$V_\mathrm{r} = \lim_{\Delta t \to 0} \frac{\Delta d}{\Delta t} = \lim_{\Delta t \to 0} \frac{d_2 - d_1}{t_2 - t_1}.$$

Multiplying $2k$ on both sides, we have

$$V_\mathrm{r} \times 2k = \lim_{\Delta t \to 0} \frac{2k \times d_2 - 2k \times d_1}{t_2 - t_1}.$$

According to Eq. (1), the above equation can be rewritten as:

$$V_\mathrm{r} \times 2k = \lim_{\Delta t \to 0} \frac{(\varphi_{\mathrm{prop}2} + \varphi_{\mathrm{reader}} + \varphi_{\mathrm{tag}}) - (\varphi_{\mathrm{prop}1} + \varphi_{\mathrm{reader}} + \varphi_{\mathrm{tag}})}{t_2 - t_1}.$$

Since the phase offsets $\varphi_{\mathrm{reader}}$ and φ_{tag} are the same for signals received at times t_2 and t_1, the radial velocity V_r can be computed from

$$V_\mathrm{r} = \lim_{\Delta t \to 0} \frac{\varphi_{\mathrm{prop}2} - \varphi_{\mathrm{prop}1}}{t_2 - t_1} \times \frac{1}{2k} = \frac{\partial \varphi}{\partial t} \times \frac{c}{4\pi f}.$$

The TD-PDOA method can only estimate the radial velocity V_r, and has no way to find the tangent velocity V_t, thus limits its application in tracking moving tags.

3.2.2 Frequency domain phase difference of arrival (FD-PDOA)

Phase difference of RF signals received at different frequencies can be used to estimate the distance between a reader and a tag (Li et al., 2009; Nikitin et al., 2010). As illustrated in Fig. 5, a reader transmits RF signals on two different frequencies f_1 and f_2.

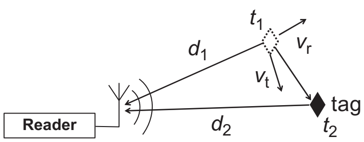

FIG. 4

Phase information is used to estimate the velocity of a moving tag.

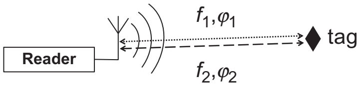

FIG. 5

Phase information is used to estimate the distance from a reader to tag.

Since different frequency means different wavelength, the phases of received signals backscattered from a tag will be different on the reader. Therefore the distance d can be calculated by comparing the phase difference in received signals. According to Eq. (2), we have

$$\varphi_{\text{prop1}} = d \times \frac{4\pi f_1}{c},$$

$$\varphi_{\text{prop2}} = d \times \frac{4\pi f_2}{c},$$

where d is the distance between the tag and RFID reader. Subtracting the above equations, we have

$$\varphi_{\text{prop2}} - \varphi_{\text{prop1}} = \varphi_2 - \varphi_1 = d \times \frac{4\pi}{c}(f_2 - f_1).$$

It is correct because the phase offsets φ_{reader} and φ_{tag} are the same in φ_{prop1} and φ_{prop2}. Therefore, the distance d from the reader to the tag can be calculated as:

$$d = \frac{c}{4\pi} \times \frac{\varphi_2 - \varphi_1}{f_2 - f_1} = \frac{c}{4\pi}\frac{\partial\varphi}{\partial f}.$$

To apply the FD-PDOA method, a reader should be capable to quickly adjust its transmission frequencies, which is not available on COTS RFID readers.

3.2.3 Space domain phase difference of arrival (SD-PDOA)

Phase difference of received signals on different antennas can be used to estimate the direction of arrival of received signals (Azzouzi et al., 2011; Nikitin et al., 2010). As illustrated in Fig. 6, a reader transmits an RF signal to a target tag. We also assume that there are at least two receiving antennas on the reader. In fact, the reader can use an antenna array to achieve higher localization accuracy.

The relationship between the signal's direction θ, also called arrival of angel (AoA), and the distance difference that the signal travels to reach antennas Rx1 and Rx2 is

$$\sin\theta \approx \frac{d_2 - d_1}{a}, \tag{3}$$

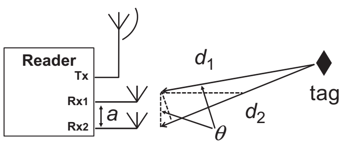

FIG. 6

Phase information is used to estimate the direction of a tag.

where a is the distance between these two antennas, d_1 and d_2 are the distances from the tag to antenna Rx1 and Rx2, respectively. The phase changes from the tag to the reader's antennas are

$$\varphi_{\text{prop1}} = kd_1,$$

$$\varphi_{\text{prop2}} = kd_2,$$

where $k = 2\pi f/c$ is the wave vector that is proportional to the frequency. Rewriting these equations, we obtain the distances from the tag to the antenna Rx1 and Rx2 as:

$$d_1 = \frac{\varphi_{\text{prop1}}}{k},$$

$$d_2 = \frac{\varphi_{\text{prop2}}}{k}.$$

Subtracting these two equations, we have

$$d_2 - d_1 = \frac{\varphi_{\text{prop2}} - \varphi_{\text{prop1}}}{k} = \frac{\varphi_2 - \varphi_1}{k} = \frac{c}{2\pi f}(\varphi_2 - \varphi_1). \tag{4}$$

Substituting Eq. (4) into Eq. (3), we get

$$\sin\theta \approx \frac{c}{2\pi f}\frac{(\varphi_2 - \varphi_1)}{a}.$$

Finally, the signal's AOA can be calculated by the following equation:

$$\theta = \arcsin\left[\frac{c}{2\pi f}\frac{(\varphi_2 - \varphi_1)}{a}\right].$$

The SD-PDOA method can accurately locate the direction of a tag. Compared to other phase-based methods, SD-PDOA requires an RFID reader to be equipped with multiple antennas. However, SD-PDOA cannot handle the NLOS scenarios.

3.2.4 Hologram

Instead of using only one reader, the holographic localization method (Parr et al., 2013; Yang et al., 2014) makes use of multiple RFID readers to calculate the location of a tag by analyzing the phase information in received signals on all readers.

The phase information of a received RF signal at a certain reader can be expressed as:

$$\varphi = \left(\frac{2\pi}{\lambda}2d\right) \bmod 2\pi = \left(\frac{4\pi}{\lambda}\sqrt{(x_0 - x)^2 + (y_0 - y)^2}\right) \bmod 2\pi, \tag{5}$$

where (x_0, y_0) and (x, y) denote the coordinates of the reader and the tag λ is the wavelength of the carrier signal and d is the distance from the reader to the tag. According to Eq. (5), a phase value measured by a reader implies multiple possible distances from itself to the tag. In particular, the possible locations inferred by a reader lay on multiple concentric circles around it as shown in Fig. 7.

Based on different phase values measured at several readers, an image consisting of multiple overlapped circles can be constructed. By splitting the image into squares, a hologram is formed in the way that any square is assigned a weight that is proportional to the number circles crossing this square. The weight of a square actually represents the likelihood of the tag being located there.

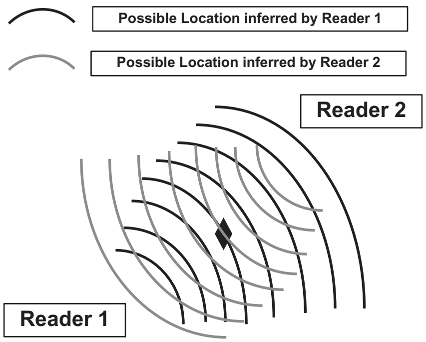

FIG. 7

Possible locations inferred by different readers.

The hologram can therefore be viewed as a likelihood distribution of the target tag's possible positions. In a hologram, the weight of a square located at (x_i, y_i) can be expressed as:

$$A(x_i, y_i) = \left| \sum_{m=0}^{n} A_m e^{j\left(\frac{4\pi d_{im}}{\lambda} - \varphi_m\right)} \right|,$$

where d_{im} denotes the distance between the square and a reader m, φ_m denotes the phase value of the signal received by reader m, and A_m is the strength of the signal received at reader m.

In summary, TD-PDOA, FD-PDOA, and SD-PDOA archive high accuracy in localization; however, TD-PDOA, FD-PDOA are too complex to be implemented on COTS RFID readers. TD-PDOA requires an RFID reader to perform multiple phase measurements within a short period of time (e.g., 1 ns), while FD-PDOA requires an RFID reader to transmit signals of multiple frequencies. Although SD-PDOA is applicable on COTS RFID readers, it cannot handle NLOS scenarios. In the end, the hologram technique can be implemented on any COTS RFID reader that provides phase information and achieves higher accuracy (Yang et al., 2014) than other phase-based approaches; it, however, requires many readers being deployed in the target area, i.e., it is not always applicable in practical real-world applications. Worse still, the hologram technique cannot handle NLOS scenario.

3.3 MULTIPATH PROFILE-BASED RFID LOCALIZATION

RSS- and phase-based localization techniques only work in the line-of-sight scenarios, where no obstacles exist between readers and tags. In many RFID localization applications, however, NLOS situations are expected. To realize RFID localization in an NLOS environment where signal reflections and multipath effects exist, multipath profile-based approaches (Wang et al., 2013; Wang and Katabi, 2013) make use of signals' profiles, such as multipath profiles, to estimate the location of RFID tags.

The outline of a multipath profile-based RFID localization approach (Wang and Katabi, 2013) can be seen in Fig. 8, where the third localization mode (tag localization with reference tags) is used. In Fig. 8, an RFID reader (with one antenna) moves along a track and keeps transmitting and receiving RF signals to emulate an antenna array. When a backscattered signal is received, the reader conducts a high

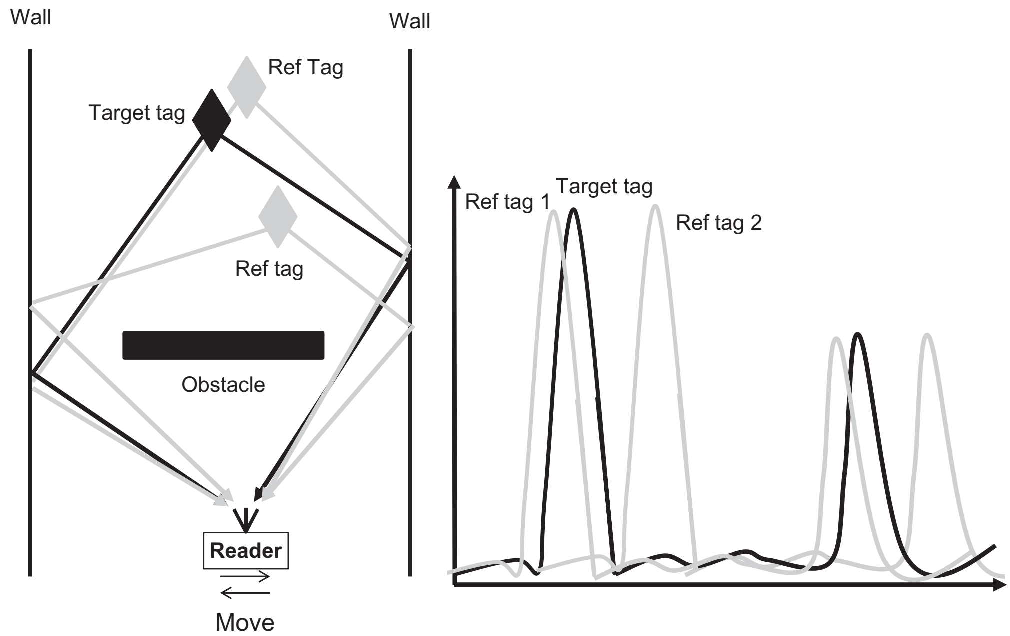

FIG. 8

Principle of a multipath profile-based RFID localization.

speed omnidirectional scan to measure the signal strength of signals from various directions. This is achieved by the reader continuously adjusting its phase controller.

For a signal reflected by a certain tag, its signal strength on direction with angle θ can be expressed as:

$$B(\theta) = \left| \sum_{k=0}^{K-1} w(k,\theta) \cdot s(t_k) \right|^2$$
$$w(k,\theta) = \mathrm{e}^{-j\frac{2\pi}{\lambda} t_k v \cos\theta}, \tag{6}$$

where t_k is the kth time instance, $s(t_k)$ is the received signal at t_k, v is the antenna's moving speed, $w(k,\theta)$ is the complex weight assigned to $s(t_k)$ when the antenna scanning is steered to the direction θ, λ is the wavelength of the carrier. Eq. (6) indicates that at time t_k, the received signal $s(t_k)$ can be considered as the signal received at the antenna located at position $t_k v$.

With the emulated antenna array, the reader can measure the signal strength on different directions, where a profile of the received signals' strength on various directions can be plotted, as shown in Fig. 8. The spikes on the left indicate the reader strong signals reflected off the left wall, and those on the right correspond to signals reflected off the right wall. We can see that the tags close to each other will have similar multipath profiles. Therefore, it is possible to find the reference tag that is the closest to the target tag by comparing their multipath profiles. The position of the reference tag is then considered the target tag's location.

In summary, the multipath profile-based approach outperforms the RSS and phase-based approaches in NLOS scenarios. However, it requires an RFID reader to quickly scan the signals received from various directions. This is not applicable to most COTS RFID readers. In addition, it requires a large amount of reference tags to be deployed.

4 CASE STUDIES

In this section, we introduce three classic RFID localization systems as case studies to further explain how the RSS, phase and multipath profile-based approaches are implemented in real applications. We also use Table 1 to present a comparison among several popular RFID localization systems.

4.1 LANDMARC

LANDMARC is one of the earliest RFID localization system (Ni et al., 2004), which adopts an RSS-based scheme and thus can be easily implemented. Most importantly, it inspired the research community to use RFIDs to localize objects rather than to identify objects. As seen in Fig. 9, LANDMARC in the second mode with reference tags assistance in localizing the target tag.

Readers in LANDMARC do not measure the exact RSS of signals backscattered from tags. Instead, it uses eight levels to represent the RSS of received signals, and each level corresponds to a distance. The LANDMARC system consists of two networks, a RFID network that tracks tags, and a wireless network that forwards tracking results to the Internet. Based on the RSS of signals backscattered from the reference and target tags, k nearest reference tags (to the target tag) can be identified. The location of the target tag can be expressed as:

$$(x, y) = \sum_{i=1}^{k} w_i (x_i, y_i),$$

where w_i is a weight assigned to each identified reference tag. The weight is quantified by the RSS difference between the reference tag i and the target tag. The smaller the difference, the larger the weight is. Experiment results show that LANDMARC's localization error is around 1 m.

Table 1 A Comparison of Several RFID Localization Systems

System	Deployment	Technique	Accuracy (m)
SportOn, Hightower et al. (2000)	Readers	RSS	3
LANDMARC, Ni et al. (2004)	Readers/ref tags	RSS	1
Tagoram, Yang et al. (2014)	Readers	Phase	0.007
New Measurement, Nikitin et al. (2010)	Readers	Phase	0.21
RF-Compass, Wang et al. (2013)	Readers	Multipath profile	0.03
PinIt, Wang and Katabi (2013)	Readers/ref tags	Multipath profile	0.11

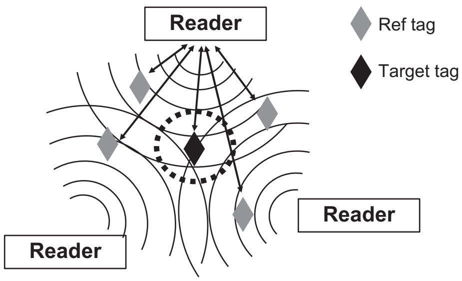

FIG. 9

Illustration of the LANDMARC RFID localization system.

4.2 TAGORAM

Tagoram is a phase-based localization scheme that employs the hologram technique (Yang et al., 2014). It achieves high localization accuracy (with an error of 7 mm) in an indoor environment. It also works well in a fast-changing environment, i.e., it can be used to track moving objects. Tagoram is tested not only in a laboratory environment, but also in real experiments—baggage tracking in three airports. Both laboratory and real-world experiments show that Tagoram is an efficient and accurate RFID localization method.

As shown in Fig. 10, two readers in the Tagoram system are placed beside a target tag. When the tag is moving, e.g., on a conveyor, the readers receive signals from different directions. If we look at the system from the tag's perspective, there are more than two virtual readers deployed along the path along which the tag is moving. With several readers in place, a hologram can be drawn based on the phase information contained in received signals on virtual readers. The phase information measured on each reader can be represented as:

$$\theta = \left(\frac{2\pi}{\lambda} \times 2d + \theta_t + \theta_r + \theta_{\text{tag}}\right) \bmod 2\pi$$

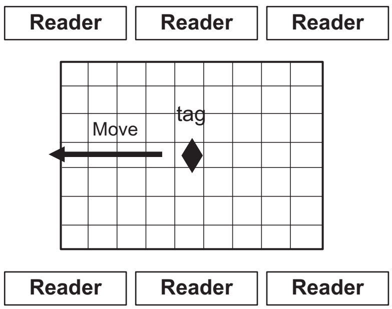

FIG. 10

Principle of the Tagoram system where the boxes with solid lines are RFID readers and those with the dashed lines are virtual readers.

where λ is the wave length, d is the distance between the tag and reader, $\theta_t + \theta_r + \theta_{tag}$ is called the diversity term that captures the signal's phase rotations caused by the reader's transmitter and receiver circuits and the tag's reflection characteristic.

To eliminate the impact of the diversity term, Tagoram makes use of an augmented differential hologram where the phase values measured on each reader is replaced by the phase difference between readers. In this way, the phase offsets generated by the tag and readers can be avoided because the offsets are the same in every measurement. The average localization error of Tagoram is 7 mm, i.e., the most accurate result in existing RFID localization systems.

4.3 PinIT

PinIt is a multipath profile-based localization system that achieves accurate localization in a NLOS environment (Wang and Katabi, 2013). It is by far the most accurate RFID localization system in NLOS environments. As shown in Fig. 3, the PinIt uses reference tags to assist in the localization of a target tag. Based on multipath profiles of target and reference tags, PinIt locates the target tag by finding its k closest reference tags.

In the PinIt system, a reader moves along a line to emulate an antenna array. By continuously querying the (target and reference) tags, multipath profiles composed of signal strengths in all possible directions of tags are constructed on the reader. The similarity of the multipath profiles between different tags represents the physical closeness between them. Since the absolute multipath profile of a tag is mixed with phase changes caused by signal reflections, the dynamic time warping (DTW) technique is used to compare the similarity of two profiles. Instead of comparing absolute values of two profiles, DTW first finds the best alignment between them and then measures the shift. Only the reference tags with small multipath profile shifts from the target tag are considered in the localization algorithm.

To efficiently find the position of a target tag located within a large amount of reference tags, PinIt uses a hierarchical approach to avoid querying a large amount of reference tags. As shown in Fig. 11, PinIt first queries the reference tags that are within a large (1 m) range and identifies a coarse-grained region where the target tag may be located. Then, PinIt queries tags in this region and gradually reduces the region until the requested resolution (e.g., 15 cm) is reached. Based on the experiments conducted in a library, PinIt is able to provide accurate localization with a mean error of 11.2 cm.

5 POTENTIAL RESEARCH ISSUES

Through the literature review, we note that the accuracy issue of RFID localization has been well addressed. The newest the RFID localization system (i.e., Tagoram) can achieve high localization accuracy with error less than 7 mm. The next step is to apply existing or newly developed RFID localization systems into real-world applications. The following trade-off issues need to be considered when a RFID localization system is deployed in practice.

5.1 ACCURACY VS. DEPLOYMENT

An ideal RFID localization system should be easily implemented and deployed with high accuracy. Although some RFID localization schemes (e.g., PinIt) provide high accuracy, large amounts of

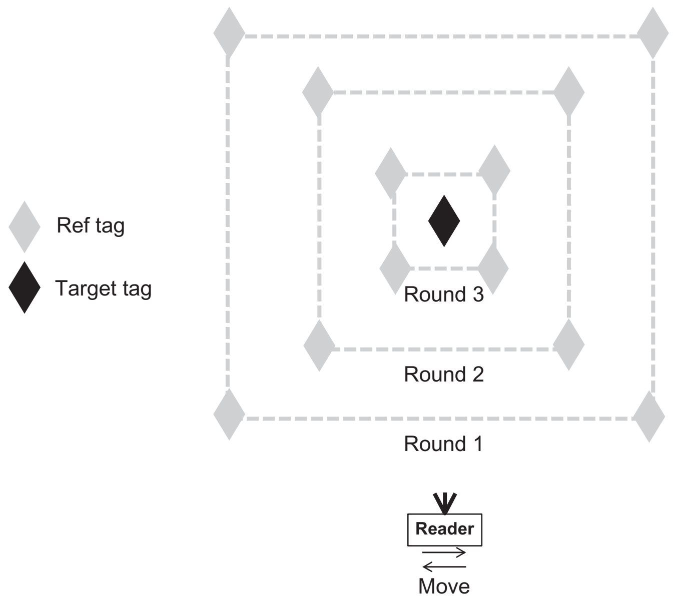

FIG. 11

Illustration of the hierarchical localization method in the PinIt system.

reference tags are needed. The higher the accuracy, the more reference tags would be needed. Even though passive RFID tags are cheap and small, it is either inconvenient or impractical to deploy tons of reference tags with known locations before conducting the localization task. In addition, reference tags could be easily blocked by metal materials, e.g., aluminum foil used in food and pharmaceutical packaging. Reference tags can also be torn off or destroyed by persons with benign or malicious purpose. Therefore, how to achieve high localization accuracy with a limited number of reference tags remains a problem.

5.2 ACCURACY VS. COMPLEXITY

Although phase- and multipath profile-based RFID localization approaches could achieve very accurate localization results without the help of reference tags, they typically require more computational, hardware, and/or software resources on a reader to process RF signals and perform mathematical calculations. For time-critical applications or recourse-limited devices, these methods seem to be inefficient and impractical. Therefore, how to achieve high accurate localization with reasonable and affordable resources should be a potential research issue deserved to be followed up.

5.3 ACCURACY VS. PORTABILITY

Due to the rapid development of the Internet of things (IoTs), an explosion of various IoT applications can be expected in the near future. That is to say, diverse system requirements are inevitable in RFID localization systems. On the other hand, it is impossible to design a one-size-fits-all localization system that addresses all the requirements from various applications. Therefore, an ideal RFID localization system should be adjustable according to the requirements posed by different applications. In other words, how to make a RFID localization system portable to various applications is another open yet challenging issue.

6 CONCLUSION

In this chapter, we investigate existing RFID localization technologies. We give a detailed introduction on the principles of various RFID localization approaches and follow case studies on three classic approaches. We also identify the advantages and drawbacks of each approach. In the end, we provide a discussion on the trade-off issues in a RFID localization system, which may lead to future research activities in the RFID localization domain.

REFERENCES

Almaaitah, A., Ali, K., Hassanein, H.S., Ibnkahla, M., 2010. 3D passive tag localization schemes for indoor RFID applications. In: 2010 IEEE International Conference on Communications (ICC). IEEE, Cape Town, South Africa, pp. 1–5.

Azzouzi, S., Cremer, M., Dettmar, U., Kronberger, R., Knie, T., 2011. New measurement results for the localization of UHF RFID transponders using an angle of arrival (AoA) approach. In: 2011 IEEE International Conference on RFID (RFID). IEEE, Orlando, FL, pp. 91–97.

Bekkali, A., Sanson, H., Matsumoto, M., 2007. RFID indoor positioning based on probabilistic RFID map and kalman filtering. In: Third IEEE International Conference on Wireless and Mobile Computing, Networking and Communications, 2007 (WiMOB 2007). IEEE, White Plains, NY, p. 21.

Finkenzeller, K., Waddington, R., 1999. RFID Handbook: Radio-Frequency Identification Fundamentals and Applications. Wiley, New York, NY.

Han, S., Lim, H., Lee, J., 2007. An efficient localization scheme for a differential-driving mobile robot based on RFID system. IEEE Trans. Ind. Electron. 54 (6), 3362–3369.

Hightower, J., Want, R., Borriello, G., 2000. SpotON: An indoor 3D location sensing technology based on RF signal strength. UW CSE 00-02-02. University of Washington, Department of Computer Science and Engineering. Seattle, WA, p. 1.

Hofmann-Wellenhof, B., Lichtenegger, H., Collins, J., 2012. Global Positioning System: Theory and Practice. Springer Science & Business Media.

Kulyukin, V., Gharpure, C., Nicholson, J., Pavithran, S., 2004. RFID in robot-assisted indoor navigation for the visually impaired. In: Proceedings. 2004 IEEE/RSJ International Conference on Intelligent Robots and Systems, 2004 (IROS 2004). vol. 2. IEEE, Sendai, Japan, pp. 1979–1984.

Kuruoglu, G.S., Erol, M., Oktug, S., 2009. Localization in wireless sensor networks with range measurement errors. In: Fifth Advanced International Conference on Telecommunications, 2009. AICT '09, pp. 261–266.

Lee, E.A., 2008, May. Cyber physical systems: Design challenges. In: Object Oriented Real-Time Distributed Computing (ISORC), 2008 11th IEEE International Symposium on. IEEE, Orlando, FL, pp. 363–369.

Li, X., Zhang, Y., Amin, M.G., 2009, April. Multifrequency-based range estimation of RFID tags. In: RFID, 2009 IEEE International Conference on. IEEE, Orlando, FL, pp. 147–154.

Liu, V., Parks, A., Talla, V., Gollakota, S., Wetherall, D., Smith, J.R., 2013. Ambient backscatter: wireless communication out of thin air. In: Proceedings of the ACM SIGCOMM 2013 Conference on SIGCOMM. ACM, Hongkong, China, pp. 39–50.

Lymberopoulos, D., Liu, J., Yang, X., Choudhury, R.R., Sen, S., Handziski, V., 2015. Microsoft indoor localization competition: experiences and lessons learned. GetMobile: Mobile Comp. and Comm. 18 (4), 24–31.

Moore, D., Leonard, J., Rus, D., Teller, S., 2004. Robust distributed network localization with noisy range measurements. In: Proceedings of the 2nd International Conference on Embedded Networked Sensor Systems. SenSys'04. ACM, New York, NY, pp. 50–61.

Nazari Shirehjini, A., Yassine, A., Shirmohammadi, S., 2012. An RFID -based position and orientation measurement system for mobile objects in intelligent environments. IEEE Trans. Instrum. Meas. 61 (6), 1664–1675.

Ni, L.M., Liu, Y., Lau, Y.C., Patil, A.P., 2004. LANDMARC: indoor location sensing using active RFID. Wirel. Netw. 10 (6), 701–710.

Niculescu, D., Nath, B., 2003a, April. Ad hoc positioning system (APS) using AOA. In: INFOCOM 2003. Twenty-Second Annual Joint Conference of the IEEE Computer and Communications. vol. 3. IEEE Societies, San Francisco, CA, pp. 1734–1743.

Niculescu, D., Nath, B., 2003b. DV based positioning in ad hoc networks. Telecommun. Syst. 22 (1–4), 267–280.

Nikitin, P.V., Martinez, R., Ramamurthy, S., Leland, H., Spiess, G., Rao, K.V.S., 2010. Phase based spatial identification of UHF RFID tags. In: 2010 IEEE International Conference on RFID, pp. 102–109.

Park, S., Lee, H., 2013. Self-recognition of vehicle position using RFID passive RFID tags. IEEE Trans. Ind. Electron. 60 (1), 226–234.

Parr, A., Miesen, R., Vossiek, M., 2013. Inverse SAR approach for localization of moving RFID tags. In: 2013 IEEE International Conference on RFID (RFID). IEEE, Penang, Malaysia, pp. 104–109.

Peng, C., Shen, G., Zhang, Y., Li, Y., Tan, K., 2007. Beepbeep: a high accuracy acoustic ranging system using cots mobile devices. In: Proceedings of the 5th International Conference on Embedded Networked Sensor Systems. SenSys '07. ACM, New York, NY, pp. 1–14.

Tsukiyama, T., 2003, June. Navigation system for mobile robots using RFID tags. In: Proceedings of the International Conference on Advanced Robotics (ICAR). Taipei, Taiwan.

Wang, J., Katabi, D., 2013. Dude, where's my card?: RFID positioning that works with multipath and non-line of sight. In: Proceedings of the ACM SIGCOMM 2013 Conference on SIGCOMM. ACM, Hongkong, pp. 51–62.

Wang, J., Adib, F., Knepper, R., Katabi, D., Rus, D., 2013. RF-Compass: robot object manipulation using RFIDs. In: Proceedings of the 19th Annual International Conference on Mobile Computing & Networking. ACM, Miami, FL, pp. 3–14.

Xiong, J., Jamieson, K., 2013. Arraytrack: a fine-grained indoor location system. In: Presented as Part of the 10th USENIX Symposium on Networked Systems Design and Implementation (NSDI 13). USENIX, Lombard, IL, pp. 71–84.

Yanakiev, B., Eggers, P., Pedersen, G.F., Larsen, T., 2007, September. Assessment of the physical interface of UHF passive tags for localization. In: Proc. 1st Int EURASIP RFID Workshop. Vienna, Austria, pp. 1–4.

Yang, L., Chen, Y., Li, X.-Y., Xiao, C., Li, M., Liu, Y., 2014. Tagoram: real-time tracking of mobile RFID tags to high precision using cots devices. In: Proceedings of the 20th Annual International Conference on Mobile Computing and Networking. MobiCom '14. ACM, New York, NY, pp. 237–248.

Zhao, J., Xi, W., He, Y., Liu, Y., Li, X.-Y., Mo, L., Yang, Z., 2013. Localization of wireless sensor networks in the wild: Pursuit of ranging quality. IEEE/ACM Trans. Netw. 21 (1), 311–323.

Zhong, Z., He, T., 2009. Achieving range-free localization beyond connectivity. In: Proceedings of the 7th ACM Conference on Embedded Networked Sensor Systems. SenSys '09. ACM, New York, NY, pp. 281–294.