

# **Chapter 15**

## **Principles and Techniques of RFID Positioning**

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### **15.1 INTRODUCTION**

Radio frequency identification (RFID) systems, which basically consist of readers and tags, were originally developed for the identification of tagged objects, as the name RFID implies. Recently, precise positioning and tracking of RFID tags or readers has received considerable attention from both academia and industry. For example, finding the position of RFID tags is an important task in various real-time locating systems (RTLS) to locate and track products, assets, and personnel with attached RFID tags in an area covered by the RFID readers (e.g., (BY03, SPF04, NLL04, TFD06, TS06, ZAK07, AAM07, OAC08, Con08, Amir09)). In other applications, it is desirable for a reader to identify its own position with the assistance of reference tags (e.g., (CJJ04, HBF04, XG06, KPN06, ZLH07, SVZ07, WWT07, DB08, SMI08)). Numerous RFID localization products have been developed for various applications. RFID positioning techniques and applications have been surveyed in (Mil06, BMG07, BS08, ZS08, SK08).

It is pointed out that, depending on applications, the required positioning accuracy may differ. For some applications, such as parcel tracking in a warehouse, one-meter accuracy is acceptable and considered sufficient (IHQ04), whereas an accuracy of several centimeters is desired to unambiguously identify tagged parcels placed on a conveyer belt (ZAK07). Therefore, it is important to select the appropriate positioning technique that meets the varying positioning accuracy and cost requirements.

This chapter provides a comprehensive introduction of the principles and techniques of RFID positioning. The majority of RFID positioning systems are based on the fusion of multiple pieces of relevant information. Examples of such information include range, direction-of-arrival (DOA), and the propagation characteristics which are obtained from signal strength, time, and/or phase measurements at a single or multiple antenna positions.

One of the commonly used approaches to locate an RFID tag is trilateration. This approach determines the tag position by incorporating the range information of an RFID tag estimated at multiple reader antenna positions. Range information can be obtained, for example, through the received signal strength (RSS), round-trip time-of-flight (TOF), time-difference-of-arrival (TDOA), and/or phase-difference-of-arrival (PDOA) of the RFID signals. RSS is an easily measured quantity which provides range information based on the fact that a radio frequency (RF) signal emitted or backscattered from a tag attenuates with a law related to the distance which the RF signal travelled. Passive (including semi-passive) RFID systems can use round-trip TOF of a signal transmitted from an RFID reader and backscattered from the RFID tag for the estimation of the round-trip distance between the reader and the tag. In active RFID systems, the estimation of one-way TOF from the tag to the reader is often difficult because it requires precise synchronization between the reader and the tag. A rather practical solution, referred to as TDOA, is to compute the difference of the time-of-arrival (TOA) between multiple reader antennas which receive the same signal transmitted by the RFID tag. Range estimation using PDOA

utilizes the different phase delays exhibited by signals with different carrier frequencies when propagating over the same distance between the reader and the tag.

Tag localization can also utilize the triangulation technique based on the DOA information observed at multiple reader antenna positions. Array processing techniques that exploit the phase information of signal arrivals observed at multiple collocated antennas can achieve high DOA estimation accuracy. When high positioning accuracy is not required, the use of directional antennas is a low-cost alternative approach to obtain DOA information. RFID tag positions can also be determined at a single reader position by combining range and DOA information. Other RFID tag locating techniques include proximity and radio map matching. The former locates a tag by finding the closest reader antenna, whereas the latter compares the RSS or other signal signatures of a tag with that of reference tags whose positions are known a priori.

It is worth noting that a very challenging problem in RFID positioning lies in the effect of complicated wave propagation due to the presence of various obstacles and reflectors in the environment. Walls, human bodies, furniture and supplies that contain metallic and liquid materials, such as partitions, cabinets, bookshelves, water containers, may cause obstruction and reflections of electromagnetic waves. When a signal transmitted/backscattered from an RFID tag arrives at an RFID reader over a multiplicity of paths, it extends the delay profile and results in fluctuation in the RSS as well as the received signal phase (Rap02, ZYL09). Similar effects can be observed for downlink propagation from a reader to a tag. Multipath propagation alters both signal strengths and phase. As such, RFID positioning techniques based on RSS and/or signal phase may become inaccurate. The localization performance of the TOF- and TDOA-based techniques may also be compromised due to multipath.

A number of approaches have been developed to improve the RFID positioning performance in a multipath environment. A class of such approaches is based on the comparison of the RSS, tag count/tag detection rate, and/or distribution probability of RSS corresponding to an unknown RFID tag with those

measured for multiple known reference tags located in its vicinity (NLL04, WPA07, SPZ07, HJG06). Because tags in the same area and close proximity are likely to be similarly affected by the propagation channel, multipath propagation effect can be mitigated through calibration using the information collected from the reference tags (S00). A well-known example of such approaches is LANDMARC (NLL04). Another approach is to use ultra-wideband (UWB) signals that allow high-resolution delay profile estimation and thereby achieve effective discrimination of multipath signals. As a result, the range information can be estimated based only on the TOF of the direct path (Oco04, MS, MW08). The use of frequency hopping signals can achieve frequency-domain diversity to combat multipath effects (AN06).

RFID based positioning and tracking techniques share similarities with those exploiting other technologies, such as acoustic, ultrasound, vision, infrared, laser, radar, GPS and WLAN (see, e.g., (HHP99, WHF92, BP00, PCB00)). In particular, positioning of active RFID systems has high similarity to WLAN based positioning techniques. The concept of a passive RFID system, on the other hand, is analogous to an active radar system for the estimation of tag range and DOA, whereas differences exist as well. An RFID system is usually required to operate in much reduced complexity compared to other systems. Contrasting with radar systems which are typically wideband, non-UWB RFID systems use much narrower frequency bandwidth. In addition, RFID systems have anti-collision capabilities and, as a result, only one tag needs to be considered at a time. While range-Doppler radars use the Doppler frequencies associated with moving targets to mitigate clutter, many RFID systems do not benefit from Doppler frequencies for clutter mitigation as they are typically stationary or move at a low-speed. Rather, backscattered signals from passive RFID tags are modulated and thus their spectra are shifted from that of the energizing carrier signal, enabling the suppression of strong carrier presence from the reader and clutter reflection.

Non-RFID positioning techniques can be incorporated into an RFID system to enhance its positioning capability, such as coverage extension and positioning accuracy improvement. For example,

incorporating GPS and other global navigation satellite system (GNSS) receivers into RFID tags can provide positions in wide outdoor areas. WLAN infrastructure can be used to construct RTLS in indoor environment (EKA08). Passive RFID and laser range scanner are jointly used to improve the localization accuracy of mobile robots and persons (HBF04). A laser-activated RFID-based indoor localization system was developed for mobile robots, where a number of laser-activated active tags are placed in the environment as landmarks (ZLH07). A real-time identification and localization system, named LotTrack, uses active RFID and ultrasound technologies to improve tracking visibility for logistics in a wafer fabrication cleanroom (TFD06).

The aim of this chapter is to provide a comprehensive introduction of the principles and techniques involved in RFID positioning. We first summarize key principles of information acquisition, and then introduce RFID positioning algorithms and techniques. As depicted in Fig. 15.1, an RFID positioning system typically involves two major functional blocks, i.e., location sensing and positioning processing. The location sensing block senses the tag location in terms of range and/or DOA using proper location metrics. This function block is discussed in Sections 2 and 3, respectively, for range and DOA estimation techniques. The objective of the positioning processing block is to find the location of an RFID tag or reader based on the information obtained from the location sensing block. The positioning processing algorithms, techniques, and applications are addressed in Section 4. In Section 5, possible measures for the improvement of positioning accuracy are discussed. The chapter is concluded in Section 6.

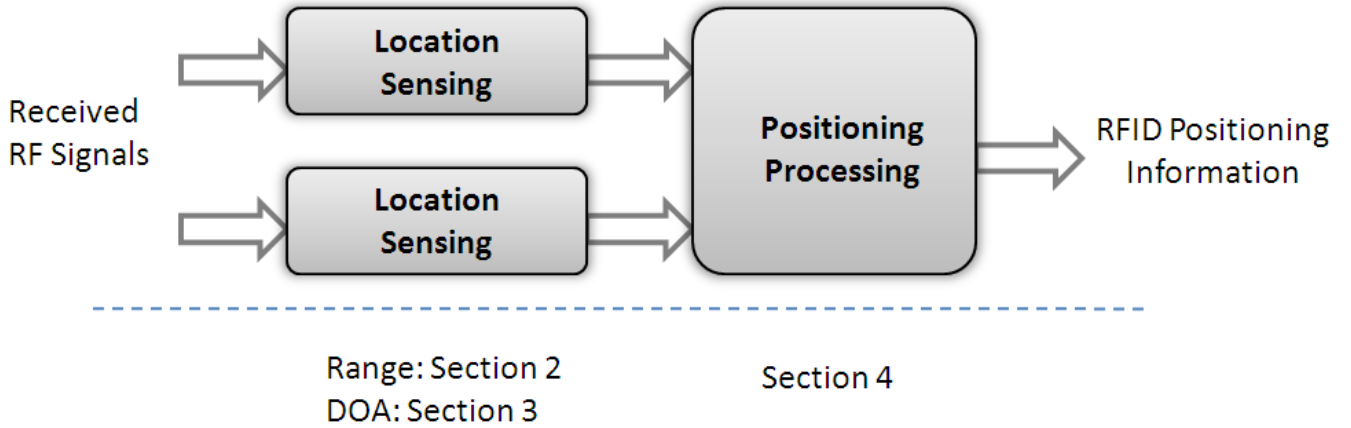


Fig. 15.1. Block diagram of an RFID positioning system.

## 15.2 TAG RANGE ESTIMATION TECHNIQUES

Many RFID positioning techniques are based on the range information of tags, evaluated from a single or multiple RFID reader antennas. The accuracy of range estimation, therefore, directly affects the performance of the positioning of RFID tags. In this section, range estimation techniques based on RSS, phase, and time measurements are presented.

### 15.2.1 RSS-based Techniques

For an active RFID system operating in a free space environment, the signal power received at the reader is expressed as (Dob08)

$$P_{RX,reader} = P_{TX,tag} G_{tag} G_{reader} \left( \frac{\lambda}{4\pi d} \right)^2, \quad (1)$$

where  $P_{TX,tag}$  is the transmit power at the active tag,  $G_{tag}$  and  $G_{reader}$  are the antenna gain of the tag and the reader, respectively,  $\lambda$  is the wavelength, and  $d$  is the range between the tag and reader.

For a passive RFID system, the signal is transmitted from the reader tag and backscattered at the tag. Thus, a round-trip path loss should be considered. The received signal power becomes

$$P_{RX,reader} = P_{TX,reader} \eta G_{tag}^2 G_{reader}^2 \left( \frac{\lambda}{4\pi d} \right)^4, \quad (2)$$

where  $P_{TX,reader}$  is the transmit power from the reader and  $\eta$  is the backscatter transmission efficiency of the passive tag. The typical value of  $\eta$  is 1/3 or -5 dB (Dob08), but this value may change as technology advances.

Equations (1) and (2) clearly show that the RF signal power decays with  $d$ . In the above two equations, which consider free-space propagation, the one-way power attenuation is proportional to  $d^2$ , whereas the round-trip power attenuation is proportional to  $d^4$ . The actual attenuation rate varies, however, depending on the environment where the RFID system is deployed. In this case, equation (2) is revised as

$$P_{RX,reader} = P_{TX,reader} \eta G_{tag}^2 G_{reader}^2 \left( \frac{\lambda}{4\pi d} \right)^{2n}, \quad (3)$$

which shows that the signal strength is inversely proportional to  $d^{2n}$ , where  $n$  is referred to as the path loss exponent. The typical value of  $n$  is between 1.6 and 1.8 for line-of-sight (LOS) indoor environments, and between 2 and 6 for outdoor propagation environments (Rap02). As a result, when the path loss exponent is known or can be estimated for a specific environment, range  $d$  can be estimated from RSS measurements. The ratio between the backscattered signal power a reader receives from a passive RFID tag and the power the reader transmits is illustrated in Fig. 15.2, where different values of path loss exponent  $n$  are considered. The following parameters are used:  $f = 915$  MHz,  $\eta = 1/3$ ,  $G_{tag}=1$  (or 0 dB), and  $G_{reader}=4$  (or 6 dB). In practice, tags are expected to have low directivity, whereas a reader antenna gain of about 6 dB is commonly used because FCC regulations require proportional reduction of the transmit power when the transmit antenna gain exceeds 6 dB.

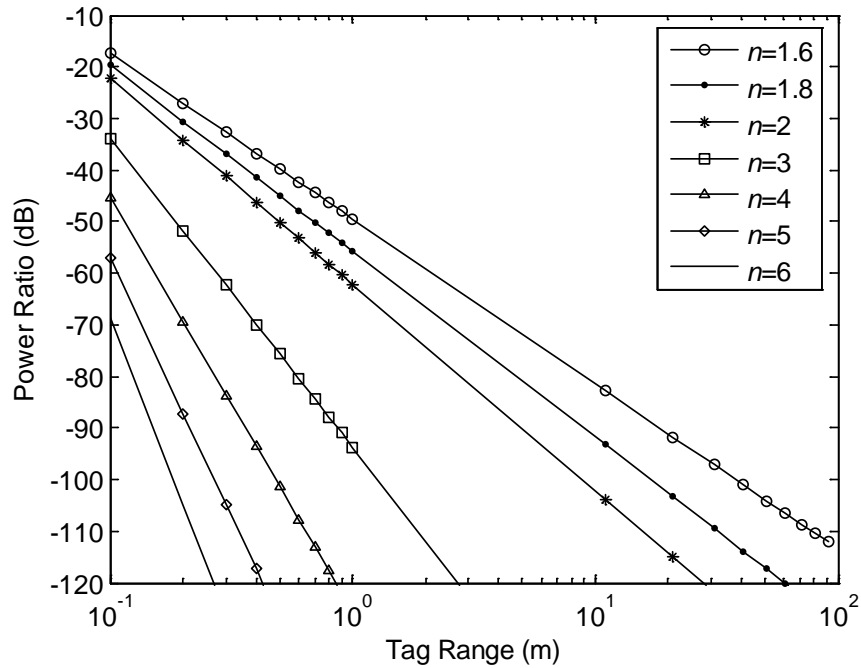


Fig. 15.2 Ratio between the received power and the transmitted power of a passive RFID reader for different path loss exponents ( $f=915$  MHz,  $\eta = 1/3$ ,  $G_{\text{tag}}=0$  dB, and  $G_{\text{reader}}=6$  dB).

The use of RSS for range estimation is simple and handy (Assad07, HAP06, HP05, HP07, DB08). Many RFID readers make the RSS information available. Moreover, the tag detection rate or tag count patterns also provide information related to the RSS and thus can be used to estimate the range (SPZ07, WPA07). That is, the number or rate of successful readings of a tag is associated with the RSS information. The tag detection rate and the tag count patterns can be fused with the RSS measurements to increase the localization reliability (SSS08). Multiple measurement results can be used to improve the reliability of RSS-based range estimations, particularly in a multipath environment. A convenient way is to use frequency hopping method in which a reader sends out bursts at specified intervals in a frequency hopping manner and measures response at the corresponding frequency each time (AN06). As such, multiple RSS values evaluated at these frequencies become available and the reliability of range



estimation is improved by selecting the highest, average, median values, or by using other combining approaches.

The range estimation performance from RSS is, however, not robust, particularly when the RFID system is operated in a complex propagation environment. Obstruction of LOS between the reader and the tag yields additional signal loss, often referred to as shadowing. The effect of shadowing is typically characterized by using the log-normal distribution with mean  $10\log_{10}(P_{RX,reader})$  and variance  $\sigma_{sh}^2$ . In addition, RSS is also sensitive to reflection and scattering from walls, furniture, and various conductive materials in the propagation environment. Such reflection and scattering yield the multipath fading phenomenon. The effect of multipath fading can be described using the Rayleigh distribution or the Ricean distribution. The latter assumes that a dominant direct path is present, whereas the former assumes no dominant path. Various models are available to describe and predict the RSS in different indoor and outdoor propagation environments (Rap02).

For unbiased parameter estimators, the Cramer-Rao lower bound (CRLB) is known to provide the minimum achievable mean square error (MSE) of a set of parameters, given the probability density function (pdf) of random variables involved in the problem (Poor94). For the range estimation  $\hat{d}$ , the CRLB of the range estimation error due to log-normal shadowing effect is given, in the form of root mean square error (RMSE), as (GTG05, Qi04)

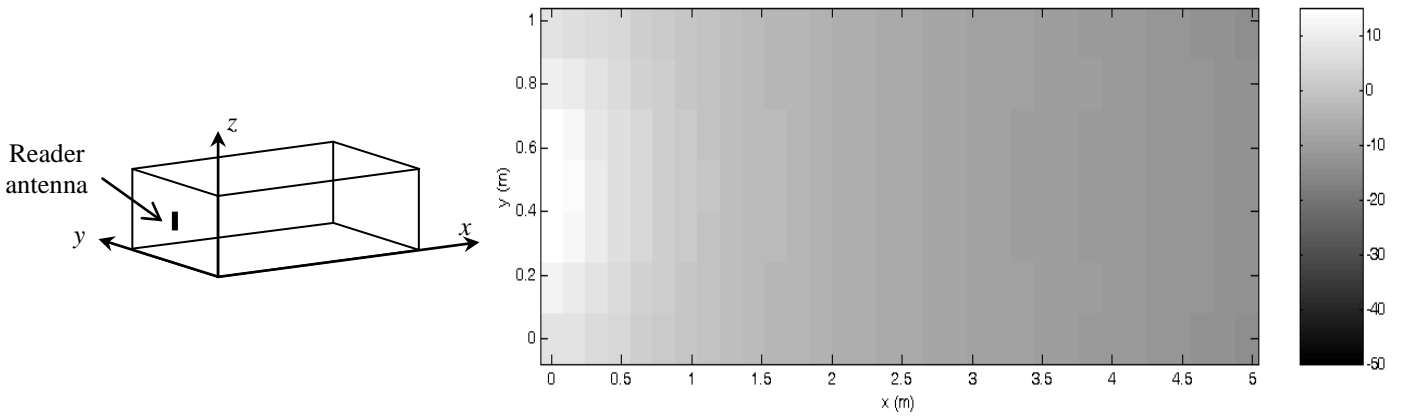
$$\text{RMSE}(\hat{d}) \geq \frac{\ln 10}{10} \frac{\sigma_{sh}}{n} d. \quad (4)$$

It shows that the error increases with the standard deviation  $\sigma_{sh}$  of the shadowing, and decreases with the path loss exponent. In addition, the accuracy of RSS-based range estimation degrades as the range increases.

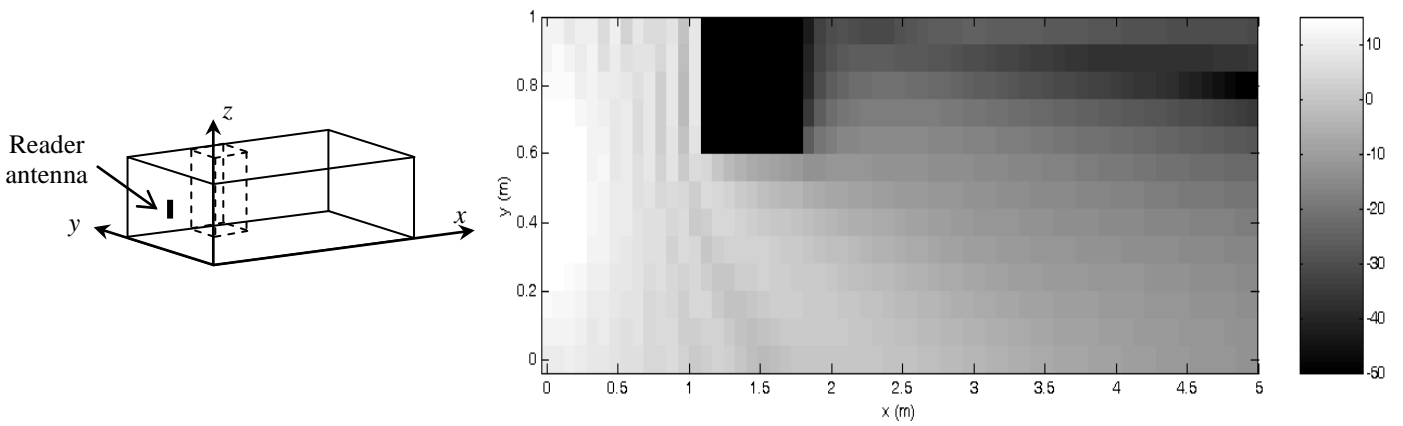
Figure 15.3 shows simulated RSS results to illustrate the significance of path obstruction and reflection for a downlink scenario (ZYL09). The reader transmits a 1W RF signal from its antenna located at  $x = 0$  m,  $y = 0.5$  m, and  $z = 0.5$  m. The signal power received by a tag at various locations is shown in different gray levels in dBm. In a free space, as depicted in Fig. 15.3(a), the received signal power is monotonically attenuated as the range increases. When a metallic cabinet, consisting of perfect conductor surfaces, is placed at the side of the link path, as depicted in Fig. 15.3(b), the RSS behind the cabinet is significantly reduced due to path obstruction. On the other hand, when the cabinet is in front of the transmitter, as depicted in Fig. 15.3(c), the received power oscillates with observation locations. In the latter two cases, the RSS no longer shows a unique, monotonic relationship with the range, making RSS-based range estimation difficult.

## 15.2.2 Phase-based Techniques

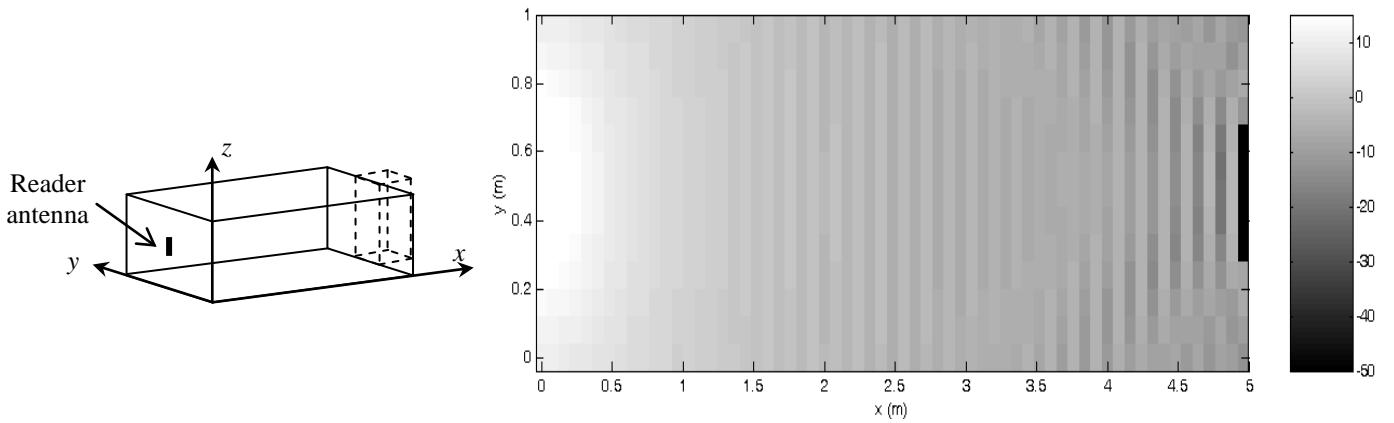
PDOA-based approaches allow coherent signal processing and, therefore, in theory, can improve range estimation performance of passive RFID tags compared to RSS-based techniques (KB06). During a time period designated for uplink data transmission, a reader transmits two continuous-wave (CW) signals which are then backscattered by a tag and received at the reader. The two CW signals propagate over the same distance, but their phase delays are proportional to their respective carrier frequencies. Therefore, a reader can estimate the tag range based on the phase difference observed at the two frequencies. Note that, the response time that an IC-based passive tag takes is irrelevant to the phase difference used in PDOA-based range estimation. PDOA-based approaches share the same concept as the dual-frequency radar techniques for range estimation (AAS06, ZAA08a).



(a) Free space



(b) Metallic cabinet at the side of link path



(c) Metallic cabinet in front of the reader

Fig. 15.3 Simulated RSS in free space and in the presence of a metallic cabinet.

Consider that an RFID reader transmits two CW signals at frequencies  $f_1$  and  $f_2$ . Without considering the modulation performed at the RFID tag and the receiver noise, the phase of the uplink signal at frequency  $f_i$  can be expressed as  $\phi_i = 4\pi f_i d / c$ , where  $i = 1, 2$ ,  $c = 3 \times 10^8$  m/s is the velocity of RF signal propagation, and  $d$  is the range between the reader and tag. Therefore, range  $d$  can be estimated from the phase difference observed at the return signal corresponding to the two frequencies. In reality, the phase observation is subject to wrapping, that is, the phase at each frequency is observable only within the range  $0 \leq \phi_i < 2\pi$ . As a result, the tag range is estimated as

$$\hat{d} = \frac{c\Delta\phi}{4\pi(f_2 - f_1)} + \frac{cm}{2(f_2 - f_1)}, \quad (5)$$

where  $0 \leq \Delta\phi = \phi_2 - \phi_1 < 2\pi$  is the wrapped phase difference observation and  $m$  is an unknown integer. The second term in the above expression denotes the range ambiguity due to phase wrapping. Note that, because backscattering modulation changes the signal phase at both carrier frequencies in the same way, equation (5) remains valid when the backscattering modulation is applied. The maximum unambiguous range is  $d_{\max} = c/[2|f_2 - f_1|]$ . For example, when  $\Delta f = |f_2 - f_1| = 10$  MHz,  $d_{\max}$  is 15 m. When  $\Delta f = 1$  MHz,  $d_{\max}$  becomes 150 m. Clearly, a large frequency separation, which is more resistant to noise (LZA09), yields a small value of  $d_{\max}$ .

The PDOA approaches can be extended to more than two frequencies to provide multiple frequency pairs. The ranges estimated from multiple frequency pairs can be averaged to yield a more robust range estimation against noise and other perturbations (KB06, KBD06). In this case, equal frequency separation is desirable to obtain range estimates with similar variance. Multiple frequencies can also be designed to have unequal separation for robust range estimation over an extended unambiguous tag range (LZA09). Instead of simultaneous transmission of multiple CW signals, they can also be transmitted in sequential, yielding a frequency hopping implementations (ZAA08b).

The advantage of PDOA approaches lies in its high accuracy in range estimation and its robustness to the variation of signal strength due to obstructions (DB08). On the other hand, the range estimation accuracy is sensitive to the phase distortion caused by multipath propagation. Averaging over multiple frequency pairs or/and multiple estimation results may improve the reliability in a multipath environment.

### 15.2.3 Time-based Techniques

Measurement of round-trip TOF in a passive RFID system can be used to estimate the tag range as

$$\hat{d} = c \cdot \frac{\text{TOF}}{2} = \frac{c \cdot (\text{TOP} - T_p)}{2}, \quad (6)$$

where TOP is the overall round-trip time delay which includes the round-trip propagation time, TOF, as well as the signal processing time consumed at the tag circuitry, denoted as  $T_p$ . The measurement of round-trip TOF or TOP only utilizes the clock at the reader and thus does not require clock synchronization between the reader and the tag.

For active RFID tags, on the other hand, for active RFID tags, measurement of one-way TOA requires that the reader and the tag have precisely synchronized clocks. In many active RFID systems, however, achieving precise synchronization between a reader and a tag is impractical. Rather, it is often feasible to synchronously process the data received at multiple readers or reader antennas, and thus the TDOA related to different tag-reader antenna paths can be estimated. The TDOA information obtained from a pair of reader antennas corresponding to the same signal transmitted from an active RFID tag yields hyperbola location trajectories with the foci positioned at the two reader antennas. Thus, by utilizing multiple reader antennas to form multiple antenna pairs, the tag position can be determined as the intersection of the respective hyperbolas.

For a conventional narrowband RFID system, immediate application of time-based techniques (e.g., TOA and TDOA) for the localization of RFID tags is often difficult because of the poor time

resolution limited by the frequency bandwidth. In addition, time-based techniques may experience additional challenges in the presence of multipath (SHA08, GSPL07, GSO06, MAK03, LW98, MVT94).

Nevertheless, time-based range estimation techniques could be promising when sufficient signal bandwidth is available, e.g., when the UWB techniques are used (AN06, MS). UWB is defined by FCC and ITU-R in terms of a transmission from an antenna for which the emitted signal bandwidth exceeds 500 MHz or 20% of the center frequency. FCC approved license-free use of low-power UWB radio transmission with an enormous bandwidth of 7.5 GHz at the frequency band 3.1–10.6 GHz (FCC02). Such a wide bandwidth provides an excellent means for wireless positioning due to its high time-domain resolution. Specifically, for a single-path additive white Gaussian noise (AWGN) channel, it was shown that the RMSE of the range estimate  $\hat{d}$  derived from the TOA estimation is lower bounded by (GTG05):

$$\text{RMSE}(\hat{d}) \geq \frac{c}{2\sqrt{2\pi}\sqrt{\text{SNR}BW}}, \quad (7)$$

where SNR is the signal-to-noise power ratio and BW is the effective signal bandwidth. Therefore, UWB RFID systems can achieve a high range resolution by utilizing a wide bandwidth, although the SNR is usually low. Note that, unlike RSS-based techniques, the RMSE of the range estimate obtained from time-based approaches is independent of  $d$ .

UWB signaling can be carrier-based or impulse-based. Both types of UWB RFID systems can provide good immunity against signal distortion and multipath effects. Carrier-based UWB RFID systems can achieve frequency diversity to alleviate the impact of multipath fading (GTG05). On the other hand, due to high time-domain resolution, impulse-based UWB RFID systems can resolve multipath components to eliminate the effect of reflection and scattering paths.

## **15.3 DOA ESTIMATION TECHNIQUES**

Some RFID tag positioning techniques are based on the DOA information of the RF signal, observed at multiple reader antenna positions. In these techniques, the positioning performance of RFID tags is affected by the accuracy of DOA estimation. DOA estimation is typically achieved using directional antennas, phased arrays and smart antennas. Utilization of directive beams also helps to enhance the read range and to reduce interference as well as multipath effects.

### **15.3.1 Directional Antenna**

A directive antenna can transmit energy to or receive energy from a small angular sector so as to improve the radiation (or reception) efficiency or to mitigate interference. In an RFID system, when a tag enters the area covered by a directional reader antenna, the reader can sense it and thus determine its rough DOA. The accuracy of the DOA depends on the antenna beamwidth. An antenna with a narrower beamwidth yields a higher DOA accuracy.

### **15.3.2 Phased Array**

A phased array is a group of antennas in which the relative phases of the respective signals feeding or weighted to the antennas are varied in such a way that an effective radiation/reception pattern of the array is reinforced in the desired direction, whereas low array sensitivity is exhibited in other directions. Some phased arrays steer, without physical movement, the beams to fixed directions (known as the switched beam technique), whereas some can electronically steer the beams to any directions. For example, the bidirectional electronically steerable phased array (BESPA) developed by RF Controls steers beams with a phase shift network and firmware control algorithm (RC09).

### **15.3.3 Smart Antenna**

Smart antennas, also known as adaptive array antennas or adaptive arrays, are antenna arrays with sophisticated signal processing capability. They can be designed to adaptively steer beams and nulls

toward arbitrary directions and to provide high-resolution DOA estimations. The number of antennas and the size of the array aperture are key parameters that determine the capability of an adaptive array.

An RF signal generates time delays when it propagates in the space. For a narrowband signal, such time delay can be equivalently considered as a phase delay across multiple antennas. Thus, the measurement of the phase difference between signals received at different array antennas can be used for DOA estimation. Commonly used DOA estimation techniques include maximum likelihood (ML), multiple signal classification (MUSIC), estimation of signal parameters via rotational invariance technique (ESPRIT), minimum variance distortionless response (MVDR), matrix pencil method or one of their derivatives (Hud81, VT02). For a narrowband tag signal arrived from DOA  $\theta$  observed at an RFID reader equipped with an  $N$ -element uniform-linear array (ULA) with inter-element spacing  $l$ , the RMSE of the estimated spatial frequency, defined as  $\omega = \frac{l}{\lambda} \sin(\theta)$ , is lower bounded by the CRLB (SN89)

$$\text{RMSE}(\hat{\omega}) \geq \sqrt{\frac{6}{KN^3 \text{SNR}}}, \quad (8)$$

where  $K$  is the number of available data snapshots. It shows that the accuracy of DOA estimate can be improved by increasing SNR, the number of snapshots, and the number of array antennas.

Note that most literature considers far-field DOA estimation problems where the unknown object is located at the far field of the antenna array. When the tag is closely placed around a reader, RFID tag positioning and tracking may involve rather complicated near-field DOA estimation problems, where the phase difference between different array antennas is a function of both DOA and the range (WAZ06). For a two-antenna array, however, it is shown that the phase difference is approximately a function of only the DOA, thus simplifying the DOA estimation problem. Another important issue to be taken into account in near-field DOA estimation is the effect of radiation filed pattern, particularly the phase, of the antennas. Because the tag may be viewed by different array antennas from different angles, the observed



phase difference should first be compensated by the phase difference in the antenna patterns before it is used for DOA estimation (WAZ06).

In the presence of multiple tags, simultaneous estimation of their DOAs, in principle, requires more antennas than the number of tags. However, in practice, multiple tags are often discriminated in the process of collision avoidance and, as a result, only a single tag should be considered at each time. With the use of multiple antennas, nevertheless, it is possible to design a reader to simultaneously resolve multiple tags without collision, yielding faster tag reading and DOA estimations.

## **15.4 RFID POSITIONING TECHNIQUES**

Using the estimated range and/or DOA information, a tag or reader can be localized using various techniques. In this section, we provide an overview of different RFID positioning techniques.

### **15.4.1 Trilateration/Multilateration**

#### **15.4.1.1 Principles and Algorithms**

The trilateration/multilateration method determines the position of a tag or reader using the range information estimated at several spatially separated reference points (reader antennas or reference tags). As previously mentioned, the range can be estimated using RSS-, phase-, or time-based techniques. Specifically, to unambiguously localize a tag in an  $n$ -dimensional space, range information from at least  $n+1$  reference points is required. However, in some cases,  $n$  reference points may suffice if the range ambiguity can be resolved by other means. For example, bilateration that uses only two reference points yields two intersections in a two-dimensional (2-D) plane (TFD06), and the tag position may be uniquely determined if the other intersection is out of the interested area.

Consider a tag positioning problem in a 2-D space as an example. Fig. 15.4 shows how the tag position can be estimated using the trilateration method, where the range of the unknown tag to reference

points (reader antennas)  $p_1(x_1, y_1)$ ,  $p_2(x_2, y_2)$ , and  $p_3(x_3, y_3)$  are estimated as  $d_1$ ,  $d_2$  and  $d_3$ , respectively. The location of the unknown tag, denoted as  $(x, y)$ , can be determined by solving the following three equations

$$(x - x_i)^2 + (y - y_i)^2 = d_i^2, \quad i = 1, 2, 3. \quad (9)$$

As a result, the coordinate of the unknown tag is obtained as

$$\begin{cases} x = -\frac{1}{2} \frac{(d_1^2 - y_1^2 - x_1^2)(y_2 - y_3) + (d_2^2 - y_2^2 - x_2^2)(y_3 - y_1) + (d_3^2 - y_3^2 - x_3^2)(y_1 - y_2)}{x_1(y_2 - y_3) + x_2(y_3 - y_1) + x_3(y_1 - y_2)} \\ y = -\frac{1}{2} \frac{(d_1^2 - y_1^2 - x_1^2)(x_2 - x_3) + (d_2^2 - y_2^2 - x_2^2)(x_3 - x_1) + (d_3^2 - y_3^2 - x_3^2)(x_1 - x_2)}{y_1(x_2 - x_3) + y_2(x_3 - x_1) + y_3(x_1 - x_2)} \end{cases} \quad (10)$$

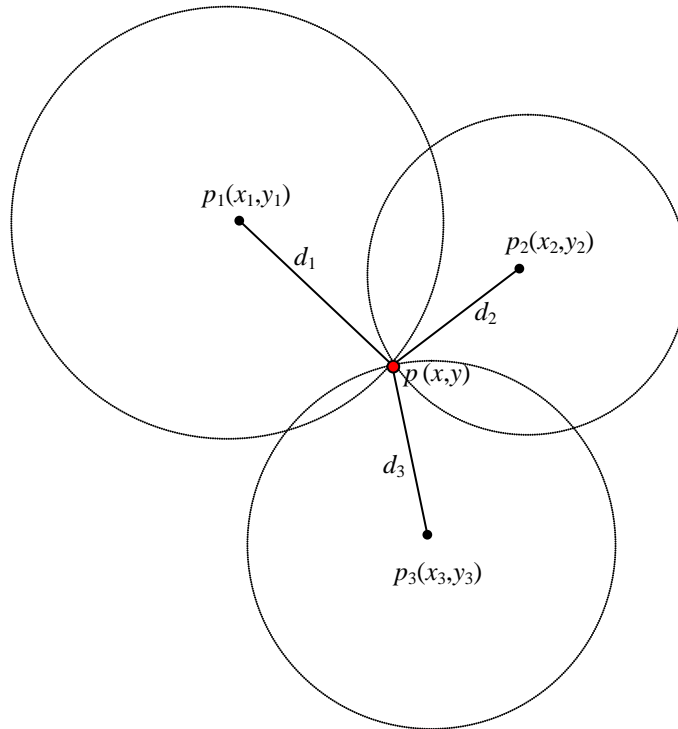


Figure 15.4 Tag positioning using trilateration. All circles are intersected at the tag position.

In reality, the range estimates would have measurement errors, thus yielding erroneous estimation of the tag position. One way to improve the positioning accuracy in this case is to use multilateration method as described below, where more than three reference points are utilized.

For  $M > 3$  reference points,  $M$  equations can be established similar to equation (9). In this case, it becomes an over-determined problem. For expressional convenience, we express them in a vector form as (STK05)

$$\mathbf{A} \begin{pmatrix} x \\ y \end{pmatrix} = \mathbf{b}, \quad (11)$$

where  $\mathbf{A} = \begin{pmatrix} x_1 - x_2 & y_1 - y_2 \\ \vdots & \vdots \\ x_{M-1} - x_M & y_{M-1} - y_M \end{pmatrix}$  is an  $(M-1) \times 2$  matrix, and  $\mathbf{b} = \frac{1}{2} \begin{pmatrix} d_2^2 - d_1^2 + x_1^2 - x_2^2 + y_1^2 - y_2^2 \\ \vdots \\ d_M^2 - d_{M-1}^2 + x_{M-1}^2 - x_M^2 + y_{M-1}^2 - y_M^2 \end{pmatrix}$  is an  $(M-1) \times 1$  vector. The least-square solution of equation

(11) is given by

$$\begin{pmatrix} x \\ y \end{pmatrix} = (\mathbf{A}^T \mathbf{A})^{-1} \mathbf{A}^T \mathbf{b}, \quad (12)$$

where  $(\cdot)^T$  denotes the transpose of a matrix or a vector.

#### 15.4.1.2 Applications

SpotON (HVB01, HWB00) uses RSS to localize long-range active RFID tags in a three-dimensional (3-D) space. Multiple receivers collect RSS measurements and use the trilateration/multilateration method to estimate the tag locations. The Local Position Measurement (LPM) method (SPF04) localizes outdoor active tags based on TDOA measurements using at least four

synchronized reader antennas with known positions. Positioning accuracy can be improved by increasing the number of reader antennas through the minimization of the weighted mean square error. A Patient Management and Tracking System (PMTS) using the RSS-based trilateration technique is developed in (KKK08). It is reported that the average accuracy is less than 1 m in an open-space test.

UWB-based RFID systems have been developed for RTLS (Oco04, MS). The Sapphire DART system developed by Multispectral Solutions achieves a 200 m read range with an accuracy of about 0.3 m even in a multipath environment (MS). Recently, development of passive and semi-passive UWB-based RFID techniques was also reported. For example, Martec developed a UWB-based carrierless RFID system, named Passpulse (MW08), for both passive and semi-passive operations.

Passive SAW (Surface Acoustic Wave) ID-tags use TOA measurements to localize a tag (BY03). SAW is an electromechanical device constructed of a piezoelectric crystal or ceramic to convert an RF signal to mechanical wave, which has a much smaller wavelength than that of the RF signal and thus is convenient to implement or measure the delay with a miniaturized size. Localization of a SAW tag is achieved by analyzing the round-trip TOF observed at three separated reader antennas through trilateration. Each tag has a fixed code described as its unique impulse response. Thus, a reader interrogates a tag by transmitting the time inverse of the tag-specific impulse response, and the tag then retransmits the correlated signal with a high peak to be easily detected at the reader. A 20-cm position accuracy was reported in (BY03) for a signal of carrier frequency 2.5 GHz and signal bandwidth of 40 MHz.

RSS-based trilateration/multilateration technology can also be used to locate the position of an RFID reader. Using multiple reference tags which are placed at known positions, a mobile reader can localize itself based on the RSS measurements corresponding to two or more tags (DB08).

## 15.4.2 Triangulation

### 15.4.2.1 Principles and Algorithms

Triangulation is a process to determine the location of a radio transmitter by measuring the DOA of the received signal from two or three known reference points. As we discussed in Section 3, DOA information can be obtained using directional antenna, phased array, or smart antennas.

Fig. 15.5 illustrates the basic principle of triangulation. In this example, the DOAs of the tag signal measured at two reference points  $p_1(x_1, y_1)$  and  $p_2(x_2, y_2)$  are respectively  $\alpha$  and  $\beta$  with respect to the line determined by the two reference points (observation antennas). The tag can be localized by intersecting the two rays. The coordinate of the tag is thus given by

$$\begin{cases} x = x_1 + D \cos(\alpha + \gamma) \\ y = y_1 + D \sin(\alpha + \gamma) \end{cases}, \quad (13)$$

where  $D = \frac{\sin(\beta)}{\sin(\alpha + \beta)} \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2}$  is the distance from the unknown tag to  $p_1$  and

$$\gamma = \tan^{-1} \left( \frac{y_1 - y_2}{x_1 - x_2} \right).$$

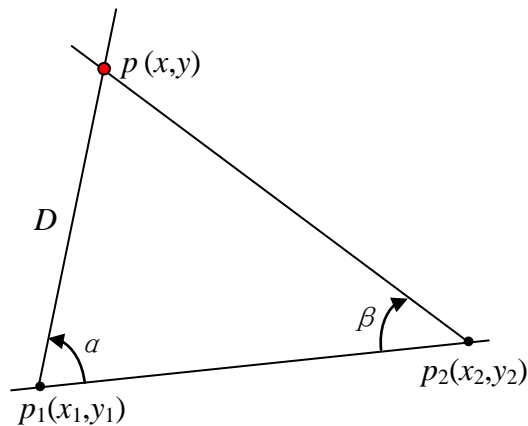


Figure 15.5 Tag positioning using triangulation. The tag location is obtained by intersecting the two lines.

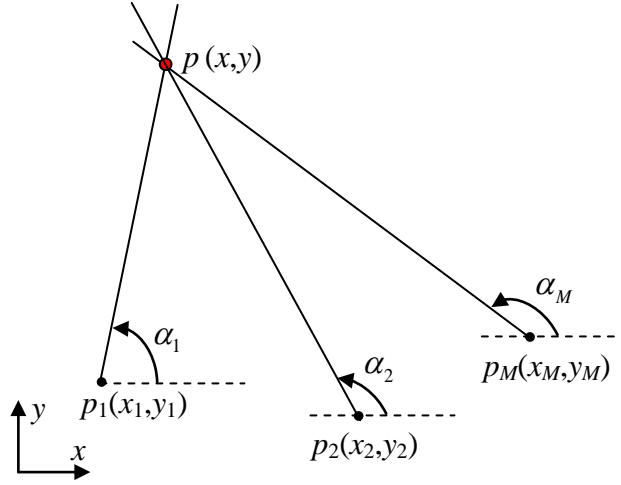


Figure 15.6 Tag positioning using triangulation with more than two reader antennas. The tag location is obtained by intersecting the multiple lines.

When there are  $M > 2$  reference points,  $p_i(x_i, y_i)$ ,  $i = 1, \dots, M$ , and the  $i$ th reference point has the measured DOA  $\alpha_i$  with respect to the  $x$ -axis, as shown in Fig. 15.6, the unknown tag location can be obtained by intersecting the multiple lines, each passing through an observation position with the slope determined by the respective DOA. Thus, the tag location is estimated by solving the following equations

$$k_i x - y = k_i x_i - y_i, \quad i = 1, \dots, M, \quad (14)$$

where  $k_i = \tan(\alpha_i)$  refers to the slope of the line passing through  $p_i(x_i, y_i)$ . Stacking equation (14) for the  $M$  observations yields the following over-determined problem

$$\mathbf{C} \begin{pmatrix} x \\ y \end{pmatrix} = \mathbf{d}, \quad (15)$$

where  $\mathbf{C} = \begin{pmatrix} k_1 & -1 \\ \vdots & \\ k_M & -1 \end{pmatrix}$  is an  $M \times 2$  matrix, and  $\mathbf{d} = \begin{pmatrix} k_1 x_1 - y_1 \\ \vdots \\ k_M x_M - y_M \end{pmatrix}$  is an  $M \times 1$  vector. Note that, for the case of  $|k_i| = \infty$ , i.e.,  $\alpha_i = 0.5\pi$  or  $1.5\pi$ , equation (14) becomes  $x = x_i$ , and the corresponding row of  $\mathbf{C}$  and  $\mathbf{d}$  should be  $[1, 0]$  and  $[x_i]$ , respectively.

Similar to (12), the least-square solution of equation (15) is given by

$$\begin{pmatrix} x \\ y \end{pmatrix} = (\mathbf{C}^T \mathbf{C})^{-1} \mathbf{C}^T \mathbf{d}. \quad (16)$$

The localization accuracy can be improved by incorporating more reference points.

#### 15.4.2.2 Applications

The FAST Tag Over-the-Conveyer RFID Tunnel System developed by Accu-Sort uses narrow-beam antennas to locate tags between closely spaced cartons (ASS05). In (ZAK07), DOA information obtained at two separate arrays is used to locate and track a moving tag on a conveyor belt. With the use of two sets of obliquely oriented two-element arrays, tags on the belt can be accurately localized through a triangulation operation. At the expense of higher signal processing complexity, it can be formulated as a near-field DOA estimation problem using a four-element array to yield more accurate positioning estimation (WAZ06). In (Amir09), the triangulation principle is used to locate indoor tags. Each reader uses two directional antennas to identify which side the tag is located. Although the angle estimation based on one reader does not have a high resolution, the use of multiple readers is expected to improve the estimation. In another example, three directional antennas are used to determine the rough area in which the tag is located (JST08).

### 15.4.3 Hybrid Direction/Range Methods

#### 15.4.3.1 Principles and Algorithms

When both the DOA and range information of a tag is available at a reference point (reader antennas), the location of the tag can be uniquely determined. The principle is illustrated in Fig. 15.6, where the DOA of the backscattering signal from the tag is  $\alpha$  with respect to the horizontal axis of the reference coordinate and the estimated range is  $d$ . The tag is localized by intersecting the incident ray and range curve and thus one can get its coordinate as

$$\begin{cases} x = x_1 + d \cos \alpha, \\ y = y_1 + d \sin \alpha. \end{cases} \quad (17)$$

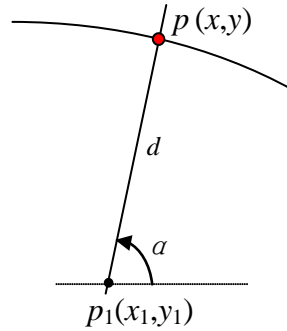


Figure 15.7 Tag positioning based on direction and range information. The tag is localized by intersecting the incident ray and the range curve.

When the range and direction information at multiple reference points  $p_i(x_i, y_i)$ ,  $i = 1, \dots, M$ , is available, the tag location can be estimated by solving the following equations

$$\begin{cases} x = x_i + d_i \cos \alpha_i, \\ y = y_i + d_i \sin \alpha_i, \end{cases} \quad i = 1, \dots, M, \quad (18)$$



where  $d_i$  is the range from the tag to the reference point  $p_i$ , and  $\alpha_i$  is the DOA of the tag measured at reference point  $p_i$ . Similar to (14), stacking the above equation for the  $M$  reference points renders the following over-determined problem

$$\mathbf{E} \begin{pmatrix} x \\ y \end{pmatrix} = \mathbf{f}, \quad (19)$$

where  $\mathbf{E} = \begin{pmatrix} 1 & 0 \\ 0 & 1 \\ 1 & 0 \\ 0 & 1 \\ \vdots & \vdots \\ 1 & 0 \\ 0 & 1 \end{pmatrix}$  is a  $2M \times 2$  matrix, and  $\mathbf{f} = \begin{pmatrix} x_1 + d_1 \cos \alpha_1 \\ y_1 + d_1 \sin \alpha_1 \\ x_2 + d_2 \cos \alpha_2 \\ y_2 + d_2 \sin \alpha_2 \\ \vdots \\ x_M + d_M \cos \alpha_M \\ y_M + d_M \sin \alpha_M \end{pmatrix}$  is a  $2M \times 1$  vector.

The least-square solution of equation (19) is given by

$$\begin{pmatrix} x \\ y \end{pmatrix} = (\mathbf{E}^T \mathbf{E})^{-1} \mathbf{E}^T \mathbf{f}, \quad (20)$$

which results in

$$\begin{cases} x = \frac{1}{M} \sum_{i=1}^M (x_i + d_i \cos \alpha_i) \\ y = \frac{1}{M} \sum_{i=1}^M (y_i + d_i \sin \alpha_i) \end{cases}. \quad (21)$$

The localization accuracy can be improved by incorporating more reference points.

### 15.4.3.2 Applications

Trolley Scan developed an RFID Radar system for identifying and locating passive RFID tags (TS06). For 2-D applications, a reader is equipped with three high-gain patch antennas. One of them is used to transmit energizing signal, whereas the other two receive backscattered tag signals to enable range

and DOA estimations. For 3-D applications, a third receive antenna is required. In a static situation where tags are relatively stationary, the radar achieves high range and DOA estimation accuracy by taking a long integration time. It is reported that the accuracy of range estimation is less than 0.5 m, and DOA accuracy is better than 1 degree, and the maximum coverage range of 100 m.

A scheme for real-time 2-D localization of a SAW tag using a single reader antenna was demonstrated in (AAM07). In this scheme, the range is estimated based on the TOF measurement, and the DOA is implicitly obtained using the angular rotation of the reader's antenna and performing an operation of complex pattern matching (maximum correlation) between the received tag signal response and the ideal signal response (pattern) saved in the reader. This scheme requires that the tag is normal to that of the LOS between the tag and the reader antenna, and that the tag's response pattern is known.

## 15.4.4 Radio Map Matching Methods

### 15.4.3.1 Principles

Radio map matching methods are also known as “scene analysis” approaches. They are composed of two distinctive steps. In the first step, the radio scene information or RF fingerprints in the environment are collected to form a radio map, described as

$$M = \{(\mathbf{m}_1, \mathbf{p}_1), (\mathbf{m}_2, \mathbf{p}_2), \dots, (\mathbf{m}_{N_R}, \mathbf{p}_{N_R})\}, \quad (22)$$

where  $\mathbf{m}_i$  denotes the measurement vector corresponding to the  $i$ th known position  $\mathbf{p}_i = [x_i, y_i, z_i]^T$ , and  $N_R$  is the total number of elements in the radio map. The elements of vector  $\mathbf{m}_i$  correspond to the RF fingerprint measurements at multiple reader antennas. The RSS and tag count can be used as the fingerprints (WPA07). In the second step, unknown tags are localized by matching the measured data corresponding to the unknown tags with an appropriate subset of fingerprints recorded in the radio map. Two major fingerprinting-based matching methods are the k-nearest-neighbor (kNN) and the probabilistic

methods. The kNN method (NLL04) uses the fingerprint (say, the RSS measurement) of an unknown tag, recorded as  $\mathbf{m}$ , to find its  $k$  closest matches  $(\mathbf{m}_{m_j}, \mathbf{p}_{m_j})$ ,  $j = 1, \dots, k$ , in the radio map according to

$$m_j = \arg \min_{i \in \{1, \dots, N_r\}, i \notin \{m_1, \dots, m_{j-1}\}} \|\mathbf{m} - \mathbf{m}_i\|. \quad (23)$$

The estimated location of the unknown tag,  $\hat{\mathbf{p}}$ , is then obtained as the weighted sum of the positions corresponding to the  $k$  nearest neighbors, that is

$$\hat{\mathbf{p}} = \sum_{j=1}^k w_j \mathbf{p}_{m_j}, \quad (24)$$

where  $w_j$  is the weighting factor for the  $j$ th nearest neighbor. There are several ways to determine the weighting factors. Specifically, when the uniform weighting scheme is used, that is, all  $w_j$ 's take the same value of  $1/k$ , it becomes the arithmetic average of the  $k$  nearest neighbors as

$$\hat{\mathbf{p}} = \frac{1}{k} \sum_{j=1}^k \mathbf{p}_{m_j}. \quad (25)$$

The probabilistic methods (RMT02, HBF04, SVZ07, BSM07, SSS08, OAC08, JST08), on the other hand, are to find the location of a tag from multiple possible locations to yield the highest posterior probability. In this case, vector  $\mathbf{m}_i$  describes the joint pdf of the measurement or measurement error, observed at multiple reader antennas, corresponding to the  $i$ th reference tag at  $\mathbf{p}_i = [x_i, y_i, z_i]^T$ . In this way, the probabilistic radio map models the distribution of the measurement in different geographical positions. By exploiting the Bayesian rule, location estimation errors can be mitigated for improved tag positioning. Let  $\mathbf{o} = [x_o, y_o, z_o]^T$  denote the observation of the position  $\mathbf{p} = [x, y, z]^T$ . For any given reference position  $\mathbf{p}$ , the probability distribution of the observation variable  $p(\mathbf{o}|\mathbf{p})$ , namely, the likelihood function, can be obtained through measurements at multiple readers. By using the Bayesian rule, the posterior probability of the position  $\mathbf{p}$  is

$$p(\mathbf{p} | \mathbf{o}) = \frac{p(\mathbf{o} | \mathbf{p})p(\mathbf{p})}{p(\mathbf{o})}, \quad (26)$$

where  $p(\mathbf{p})$  is the prior probability of being at position  $\mathbf{p}$  before knowing the value of the observation variable. When a uniform prior distribution is assumed, i.e., the distribution of unknown tag does not have any preference toward any particular position, the likelihood function completely determines the posterior distribution of the location. Further, the posterior distribution can be used to choose an optimal estimator of the unknown tag. For example, the position of the unknown tag can be estimated as

$$\hat{\mathbf{p}} = \sum_{i=1}^{N_i} p(\mathbf{p}_i | \mathbf{o}) \mathbf{p}_i \quad (27)$$

Consequently, the posterior probability is maximized and the squared localization error is minimized.

In practice, the RSS measurements often suffer from multipath propagation and shadowing. By taking these factors into account in the pre-stored radio map, their effects to the location estimation can be mitigated. In addition to the RSS, the spatial signatures can also be used into map matching. The primary advantage of map matching methods lies in the corporation of the environment effect, such as NLOS propagation and multipath. However, the radio map should be constructed based on dense reference tags to represent the current environment and should be periodically updated to reflect the environmental dynamics (YYN08).

#### 15.4.4.2 Applications

Radio map matching methods have been widely used for RFID positioning. LANDMARC (NLL04) is a well-known approach that uses several readers and a number of reference tags to locate indoor active RFID tags. The RSS of the reference tags are first recorded at each reader. When an unknown tag is present, its RSS is measured and the Euclidean distance relative to the RSS vector of each reference tag is calculated. The unknown tag is localized using the kNN method that takes a weighted sum of the coordinates of the  $k$  reference tags with the smallest Euclidean distance. Empirically, the

reference tag with shortest Euclidean distance takes the highest weight. The advantages of using reference tags are multi-fold. First, by using low-cost reference RFID tags, it maintains a low number of expensive RFID readers. Second, the effect of environment dynamics can be mitigated because the unknown tag and the reference tags are subject to similar propagation characteristics. The radio map of the reference tags can be dynamically updated to maintain the accuracy. Accurate positioning requires proper and dense distribution of reference tags and that the RSS of the reference tags is adequately updated.

Several variants of LANDMARC have been developed to improve the positioning accuracy and/or to reduce the system complexity. For example, the positioning error can be reduced through the removal of dissimilar reference tags (ZCO08, ZLN07). For the localization of stationary tags, the use of mobile readers for the measurement of the RSS of all tags from different locations is proposed (BSM07). Further, to reduce the effect of RSS fluctuation and measurement noise on the position estimation, Kalman filtering and probabilistic map matching can be utilized (BSM07).

In the Flexible Localization EXploits Rfid (FLEXOR) scheme, the area of interest is divided into a number of hexagonal cells (STL06). Reference tags are placed at the center as well as on the vertices of each cell. Two localization modes are provided: the region mode finds a cell tag nearest to the unknown tag, whereas the coordinate mode determines the coordinate of the unknown tag through the weighted average of the coordinates of three reference tags, one at the center and two on the vertices of the same cell. It is reported that this scheme reduces computation overhead and provides similar accuracy as LANDMARC. A smart Book-LOCating System (BLOCS) was developed to locate tagged books on bookshelves (SL07). The single book mode localizes a tagged book by minimizing the RSS-based Euclidean distance between bookshelf tags and the tagged book, whereas the book list mode routinely provides a list of the bookshelves and the misplaced books to help a librarian to localize all misplaced books.

When reference tags can be simultaneously detected by a set of readers, the difference between their actual and RSS-based estimated locations can be used as a correction factor to mitigate the position estimation error of the unknown tag (JLP06). The use of multi-power level transmission in a LANDMARC-based tag positioning system was proposed in (WWT07). To locate an unknown tag, the readers start with the lowest power level and gradually increase the transmit power until they receive the response from the unknown tag. Only the reference tags that are activated by the same power level as the unknown tag but not activated by a lower level are selected to estimate the range of the unknown tag. Such range estimation obtained from multiple readers are then used to trilaterate the position of the unknown tag.

As we discussed above, the use of a large number of reference tags can improve the localization accuracy of a LANDMARC system. The Virtual Reference Elimination (VIRE) scheme develops the concepts of virtual reference tags, instead of placing more physical reference tags, to improve the positioning accuracy without increasing the number of actual reference tags (ZLN07). In this scheme, the entire sensing area is divided into a number of small regions. Each region is centered by a physical reference tag and contains many virtual reference tags whose RSS values corresponding to each reader are determined through interpolation operations.

## **15.4.5 Proximity**

### **15.4.5.1 Concept**

An RFID reader has a limited read range and thus can only reach those tags that are located within a limited coverage area around the reader antennas. Therefore, observing whether a tag is within the reach of a reader antenna yields the proximity (or connectivity) information of the tag (SHC07). While high accuracy of tag positions in this case requires dense deployment of reader antennas with a small coverage area, this approach is easy to implement. The simplest implementation may be the distributed antenna

scheme, where a variety of antennas, regardless of being omnidirectional or directional, are distributed in an area of interest. Each antenna senses tags in its respective coverage area. When a tag is sensed by a reader antenna, the tag location is assumed to be the same as this antenna. When a tag is detected by more than one antennas, it is considered that the tag is close to the antenna with the strongest RSS. Alternatively, the tag position can be localized using a weighted average of coordinates of those antennas. As thus, the positioning accuracy is on the order of the size of the antenna coverage area or smaller. In this case, the position of the unknown tag is estimated as

$$\hat{\mathbf{p}} = \sum_{i=1}^{N_R} w_i \mathbf{p}_i, \quad (28)$$

where  $\mathbf{p}_i = [x_i, y_i, z_i]^T$  denotes the coordinate of the  $i$ th reader antenna,  $N_R$  is the number of reader antennas. The weighting factor  $w_i = 0$  if the  $i$ th antenna cannot sense the unknown tag.

#### 15.4.5.2 Applications

Mojix's STAR system consists of a single STAR receiver and multiple transmitters (known as eNodes) via wired connection (Oco08). A STAR receiver can manage up to 512 eNodes, which are daisy-chained with STAR receiver to cover a large geographical area or mounted in a facility in an orientation to enable the STAR receiver determining a tag's location in three dimensions. The eNodes transmit RF signals that interrogate and power up the tags, which then backscatter the signal to a receiver as far as 600 feet (200 m) away. The STAR system can localize a tag by determining which eNodes can activate the tag.

Robot search and rescue suffers from hostile conditions encountered after a disaster. A robot equipped with an inertial measurement unit can record its own trajectory. By further utilizing RFID readers in the robots and deploying RFID tags in the area, the robots can use the deployed tags as common references so as to minimize the trajectory error and better coordinate their exploration (KPN06). An embedded navigation system composed of GPS and active RFID is proposed to localize pedestrians (KSO06). With

the use of Kalman filtering, the GPS is used outdoors to adjust errors in position and direction, whereas the RFID is used for indoor localization. RFID readers are placed on fixed positions so that the pedestrian with an active tag can be localized by detecting the ID signal from the tag.

A 3-D localization scheme is proposed for locating passive or active RFID tags based only on the connectivity information associated with multiple readers (BP08a, BP08b). The estimated position of the unknown tag is obtained by simply averaging the corresponding positions of the virtual landmarks contained in the bounded space. Clearly, the accuracy depends closely on the density of the readers and on the size of virtual landmarks.

A localization system using geographical location for wireless sensor and RFID networks is demonstrated in (KKA08). In this scheme, an RFID reader first obtains its own location information from the messages broadcast by the nearby reference nodes. The reader then reads nearby tags and reports data upward until it arrives at the location server. Thus, the location system can monitor and track RFID tags based on the general purposed geographical location identifier for each region.

An RFID-based human-probe positioning system for urban sensing was proposed (SMI08). In this system, RFID tags are deployed as landmarks in urban area. When a person who carries an RFID reader moves into the area, the reader can be self-localized based on the proximity principle.

## **15.5 IMPROVING POSITIONING ACCURACY**

As we discussed in Section 1, an RFID positioning system, in general, consists of the location sensing and the positioning processing. The former obtains necessary information, such as range and DOA, using various resources transmitted and received at single or multiple antennas. Such information is then fed to the positioning processing block for data fusion to yield the location information of the RFID tag or reader of interest. Therefore, positioning accuracy of an RFID system can be improved from both location sensing and positioning processing perspectives.



The selection of appropriate sensing techniques, under the resource limitations and system constraints, is critical in achieving satisfactory range and DOA estimations. For example, RSS-based range estimation techniques are simple but its sensitivity reduces as the range increases, whereas time-based range estimation techniques require a large signal bandwidth, and the accuracy is not sensitive to the range. A high SNR is always beneficial to improve the positioning performance. In addition, improved location sensing can be achieved by collecting more and diversified information in terms of time, frequency, space, and polarization. It is desirable to have over-determined measurement data sets that are more than the minimum requirement.

- Time diversity: A simple way to combat noise is to accumulate over a longer time, provided that the reader and tag are stationary (HVB01, TS06).
- Frequency diversity: The use of a wider frequency bandwidth provides frequency diversity for enhanced robustness against noise as well as multipath fading. In particular, the use of UWB signals enables the achievement of significant frequency diversity or, equivalently, time resolution in discriminating reflection paths from the direct path (Oco04, MS, MW08). Using frequency diversity at the same antenna, however, is not effective to combat path obstructions.
- Spatial diversity: Multiple spatially separated readers or reader antennas can be exploited to improve the RFID positioning in the presence of path obstruction because the probability that the LOS to all the readers is obstructed is very low. Moderately separated antennas (one wavelength or larger inter-element spacing) are effective to combat multipath fading. The use of more collocated antennas in a smart antenna enables higher degree of processing capability to provide more accurate DOA estimation. The antennas at different locations can be physically placed, or can be synthesized by moving antennas in different positions (HL08).

- Polarization diversity: The use of antennas with different polarizations is another effective way to combat multipath fading. Compared to spatial diversity, polarization diversity does not have an inter-element spacing requirement because different polarizations experience different propagation characteristics even the antennas are closed spaced.

Better positioning processing can be achieved by fusing the collected data in an optimal or suboptimal way. For example,

- Utilizing as much information as collected at the location sensing block. Use all observation data to globally optimize a criterion, such as the mean square of positioning error or the likelihood function.
- Using positioning methods that exploit the probabilistic characteristics of the measurement data and the historical status (HBF04, SVZ07, SSS08). For example, Bayesian algorithm can be used to maximize the posterior probability of the positioning estimation. Kalman filter is a convenient approach to exploit the dynamics of an RFID tag or RFID, particularly when they are in motion (BSM07).
- Exploiting optimization algorithms to solve over-determined localization problems with noisy observations generally yields performance improvement. Using convex optimization techniques for target and node localization is an important area in radar and wireless network communities (CMS04, BLT06).
- Weighted averaging incorporating the reliability of the measurement data or processed results usually improves the positioning accuracy.

The collection of more location sensing data as well as advanced positioning processing require more investment in terms of hardware and/or signal processing capability. The decision is to best tradeoff between the affordable system complexity and the required system performance.

The presence of various obstacles and reflectors in the environment alters the propagation decay and delay profile and thereby imposes significant challenges to RFID positioning. By using diversified information in terms of time, frequency, space, and polarization, as summarized above, the RFID positioning performance in a multipath environment can be improved. When it is available and feasible, the use of signals with excessive signal bandwidth, such as UWB signals, allows separation and discrimination of multipath signals and thereby enables elimination of the multipath effects. The use of directional antennas can also reduce the significance of multipath effects for performance improvement.

## **15.6 CONCLUSION**

In this chapter, we have reviewed the principles, algorithms, and techniques of RFID positioning. In most RFID positioning problems, the location information of RFID tags is interested, but some applications involve the localization of RFID readers. An RFID positioning system, in general, consists of the location sensing component and the positioning processing component. The location sensing component provides necessary information, such as range and DOA, which is then fed to the positioning component for data fusion to yield the location information of the RFID tag or reader of interest. Different range and DOA estimation techniques have been introduced. RFID positioning principles and techniques based on trilateration, triangulation, hybrid direction/range, radio map matching, and proximity methods were presented. Potential approaches for improving positioning accuracy were also discussed.

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