Indoor Location Based Systems

by

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Contents

1 Introduction

Indoor positioning systems have grown rapidly in the recent years, and various techniques and systems have been invented to estimate the position of an indoor device. While the Global Positioning System (GPS) is a term familiar to most of the population, GPS is very limited for indoor localization. Satellite signals are weak, and are interrupted by objects, or multiple waves may arrive at the device, causing a multipath effect. It is difficult to identify the correct wave from a number of interfering waves, which causes the accuracy of the location estimation to decrease.

The location of an indoor device can be used to provide different services such as user applications or emergency services [3]. For example, the user application can employ the estimated locations to provide location specific advertisements or recover a lost device. Emergency systems can access the location of the rescuers to allow safer navigation through dangerous areas and to locate a fellow member quickly.

2 Geometric Positioning Models

There are various ways to estimate the location of the target relative to a known reference point. The Time of Arrival (TOA), Time Difference of Arrival (TDOA), and Angle of Arrival (AOA) are positioning models which use signal waves emitted from source nodes to target nodes for localization. With the arrival time of the signal, TOA calculates the distance between the nodes, TDOA calculates the distance by taking the difference of two arrival times, and AOA determines the direction of the target.

2.1 Time of Arrival (TOA)

If the signal wave transmitted from the source node to the target node has the time of arrival τ, then the distance between the source node and the target node is $d = c\tau$, where c is the speed of light. The direction of the target node is unknown, so the target node must be positioned on the circle with radius d (see Figure 2.1). The nodes are synchronized to share the same clock, then the received signal is:

$$r(t) = \alpha s(t - \tau) + n(t) \tag{2.1}$$

where α is the channel coefficient and $n(t)$ is the white Gaussian noise with

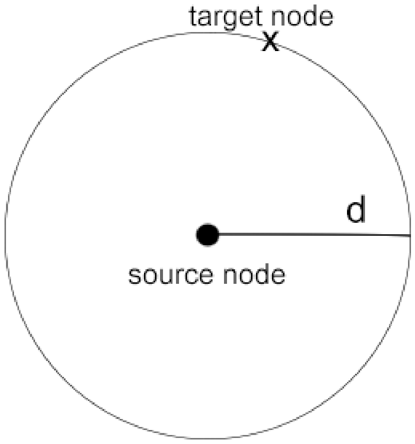


Figure 2.1: Possible target nodes on the circle of radius d from the source node.

zero mean and a spectral density of $\mathcal{N}_0/2$ watts per hertz for $\mathcal{N}$ = normal distribution. To find τ from $r(t)$, the maximum correlation between $s(t-\hat{\tau})$ and $r(t)$ is searched, in which $\hat{\tau}$ is the estimated TOA. The accuracy of calculating the TOA depends on the bandwidth of the signal, where large bandwidth systems such as Ultra-Wideband can have very accurate results with errors within a few centimeters.

2.2 Time Difference of Arrival (TDOA)

The TDOA is calculated by taking the difference of two arrival times. The source nodes involved must be synchronized on a matching clock to have the same time offset, which is critical to the accuracy of this method [22]. The first method to measure the TDOA is to use the same approach used in measuring the TOA. The TDOA value multiplied by speed of light ($d = c\tau$) produces the possible locations of the target node in the shape of a hyperbola (see Figure 2.2). The TOA at two source nodes are measured, called τ_1 and τ_2, then $\tau_{TDOA} = \tau_1 - \tau_2$.

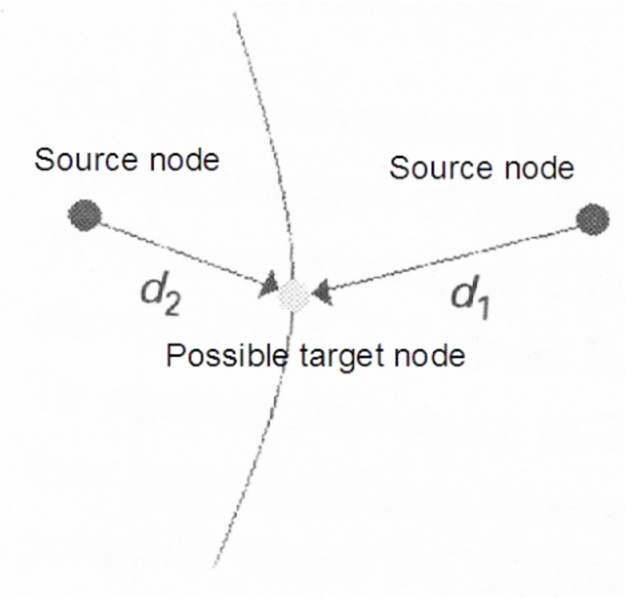


Figure 2.2: Possible target nodes with TDOA (from [19]).

The other method uses the cross-correlation between the two received signals. The cross-correlation reaches the maximum when the signal is shifted to the correct offset. Then the cross-correlation equation is:

$$\phi_{1,2}(\tau) = \frac{1}{T}\int_0^T r_1(t)r_2(t+\tau)dt \tag{2.2}$$

where $r_1(t)$ and $r_2(t)$ are received signals at each source node and T is the observation interval. Finally, the estimated TDOA, $\hat{\tau}_{TDOA}$ is:

$$\hat{\tau}_{TDOA} = \arg\max_{\tau} |\phi_{1,2}(\tau)| \tag{2.3}$$

where

$$\arg\max_{x} f(x) := \{x|\forall y : f(y) \leq f(x)\} \tag{2.4}$$

This method works significantly better for white noise and single path channels than multi-path channel or coloured noise.

2.3 Angle of Arrival (AOA)

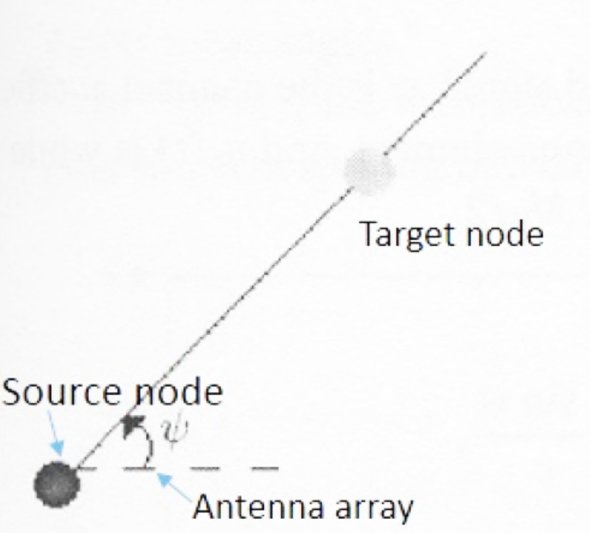


Figure 2.3: Angle ψ produced from the target node and the antenna of the source node (from [21]).

The two previous models can measure the distance between the target and the source nodes, but cannot determine the direction of the target node. If the angle between an array of antennas at the source node and the target node is ψ (see Figure 2.3), then the delay between the arrival of the signals, τ, to the antennas is given by:

$$\tau = \frac{lsin(\psi)}{c} \tag{2.5}$$

where l is the distance between the antennas and c is the speed of light.

The received signal to each antenna N_a is in the following form:

$$r_i(t) = \alpha s(t - \tau_i) + n_i(t) \tag{2.6}$$

which has the same format as Eq.(2.1), except with τ_i as the delay and $n_i(t)$ as the white Gaussian noise for the ith antenna. The delay at the ith antenna is expressed as:

$$\begin{aligned} \tau_i &\approx \frac{d}{c} + \frac{l_i sin(\psi)}{c} \\ l_i &= l(\frac{N_a + 1}{2} - i) \end{aligned} \tag{2.7}$$

where d is the distance from the target node to the center of the array of antennas.

2.4 Position Estimation

The signal parameters produce uncertainty regions in the shape of a circle (TOA), a line (AOA), or a hyperbola (TDOA).The intersection of these regions determines the position of the target node. For the TOA regions, there must be at least three source nodes with calculated distances, as shown in Figure 2.4. If the position of each source node is (x_i, y_i), then the position of the target node, (x, y), is

$$\begin{aligned} x &= \frac{(y_2 - y_1)\gamma_1 + (y_2 - y_3)\gamma_2}{2[(x_2 - x_3)(y_2 - y_1) + (x_1 - x_2)(y_2 - y_3)]} \\ y &= \frac{(x_2 - x_1)\gamma_1 + (x_2 - x_3)\gamma_2}{2[(x_2 - x_1)(y_2 - y_3) + (x_2 - x_3)(y_1 - y_2)]} \end{aligned} \tag{2.8}$$

where

$$\begin{aligned} \gamma_1 &= x_2^2 - x_3^2 + y_2^2 - y_3^2 + d_3^2 - d_2^2 \\ \gamma_2 &= x_1^2 - x_2^2 + y_1^2 - y_2^2 + d_2^2 - d_1^2 \end{aligned} \tag{2.9}$$

To calculate the TDOA of the system, two source nodes are required instead of one. Therefore, to obtain two regions from the TDOA, three source nodes are required (see Figure 2.5). Each hyperbolic region has the following equation:

$$\begin{aligned} d_{i1} &= d_i - d_1 \\ &= \sqrt{(x - x_i)^2 - (y - y_i)^2} - \sqrt{(x - x_1)^2 + (y - y_1)^2}, \text{for i = 2, 3} \end{aligned} \tag{2.10}$$

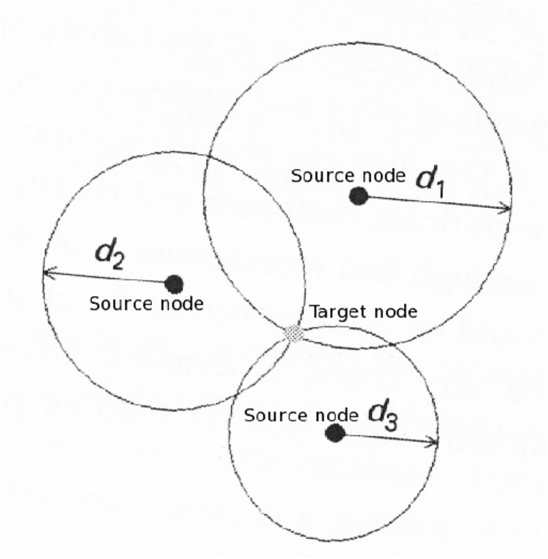


Figure 2.4: Three uncertainty regions intersecting at a single point (from [19]).

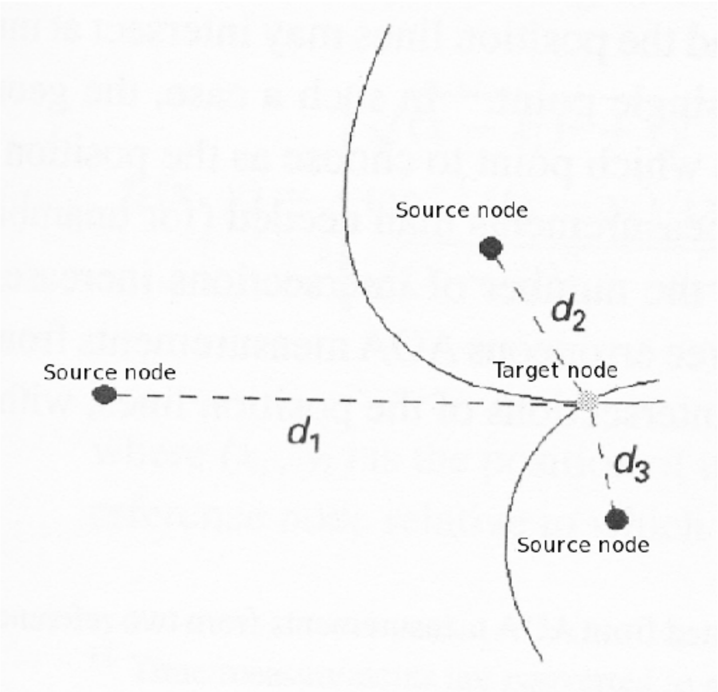


Figure 2.5: Position of the target node determined by three source nodes (from [19]).

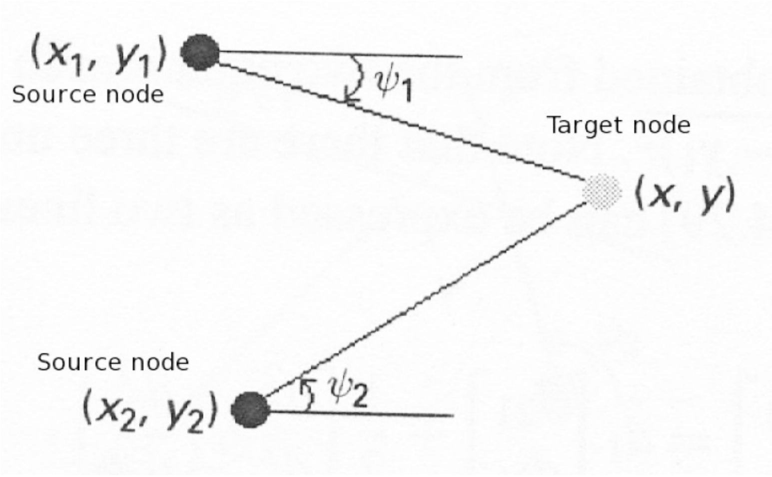


Figure 2.6: Two source nodes with angles ψ_1 and ψ_2 determining the target node (from [19]).

where

$$d_1 = \sqrt{(x - x_1)^2 - (y - y_1)^2} \tag{2.11}$$

The region created from the AOA approach is in form of a line, where at least two source nodes are required to determine the target node (see Figure 2.6).

If each line has the equation

$$tan\psi = \frac{y - y_i}{x - x_i}, i = 1, 2 \tag{2.12}$$

then the x and y values of the target node can be discovered as follows (from [19])

$$\begin{aligned} x &= \frac{x_2 \tan \psi_2 - x_1 \tan \psi_1 + y_1 - y_2}{\tan \psi_2 - \tan \psi_1} \\ y &= \frac{(x_2 - x_1) \tan \psi_2 \tan \psi_1 + y_1 \tan \psi_2 - y_2 \tan \psi_1}{\tan \psi_2 - \tan \psi_1} \end{aligned} \tag{2.13}$$

Combined approaches can measure the coordinate of the target node by different uncertainty regions. In a case of TOA/AOA approach (see Figure 2.7), only one source node is required to estimate the TOA and the AOA to the target node. The position of the target node is as follows:

$$\begin{aligned} x &= x_1 + dcos\psi \\ y &= y_1 + dsin\psi \end{aligned} \tag{2.14}$$

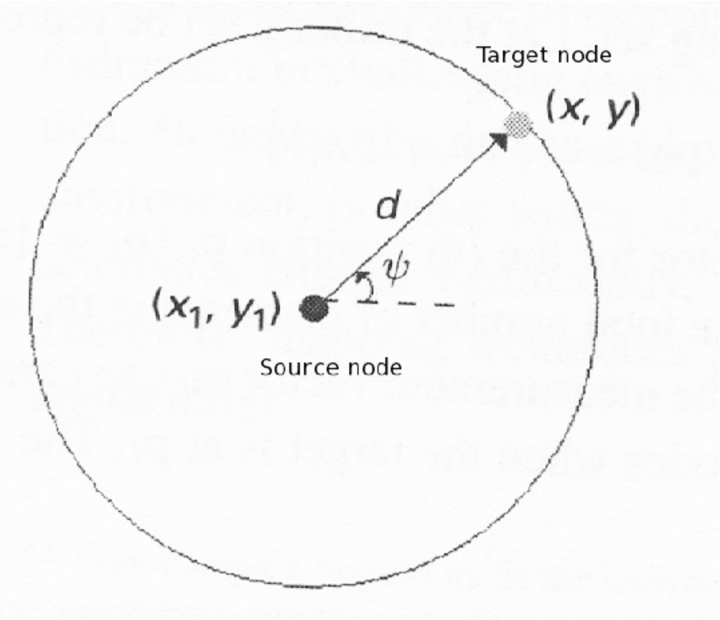


Figure 2.7: TOA/AOA approach to locating the target node (from [19]).

where ψ is the angle of arrival, and d is the time of arrival.

3 Approaches for Location

There are multiple solutions to indoor localization, all of which use unique systems and methods to locate the device. Each solution is advantageous under certain conditions, but fails in another. An example would be the Active Image Triangulation method, this method proposes an accurate way to utilize existing reference points to locate the device. The method produces an accurate position estimate of the device but requires the positions of the reference points to be known prior to usage. Many services need to be usable immediately without preparation, thus this method will not be suitable for those services. Meanwhile, if the reference points are known, its accurate estimation can be used in places such as shopping malls to provide better service.

3.1 Combined Wi-Fi and Cell Tower Signals

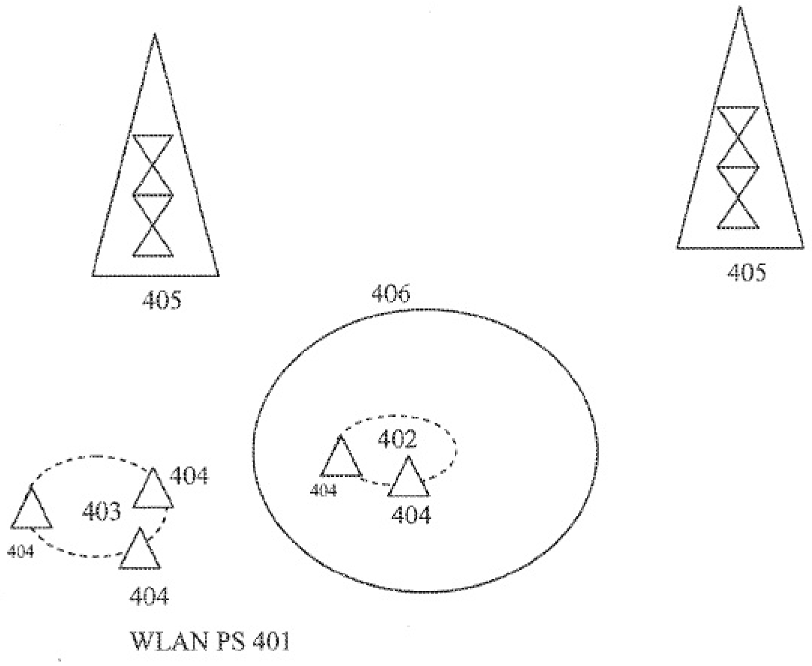


Figure 2.1: Example scenario involving two WLAN clusters 402, 403, and one CPS location estimate 406. WLAN cluster 402 is consistent with CPS location estimate 406 (from [1]).

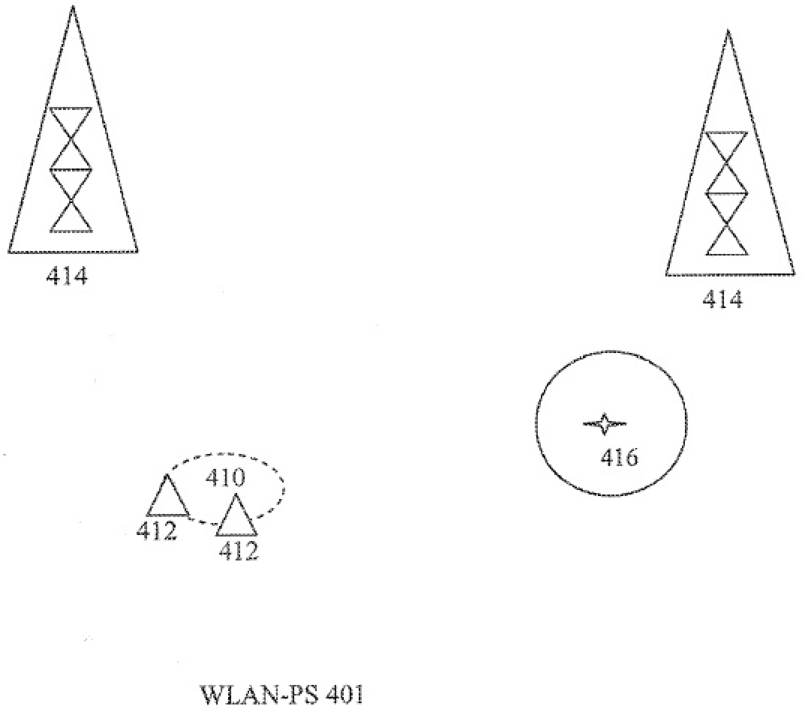


Figure 2.2: Example scenario involving one WLAN cluster 410 and one CPS location estimate 416. They are inconsistent with each other (from [1]).

This method integrates wireless local area network (WLAN)-based positioning system (WLAN PS) with cellular-based positioning system (CPS) [1]. The objective of this hybrid system is to improve the accuracy of the location estimate by inputting the results of one positioning system to another. This can be done in one of many ways, one method selects or rejects the WLAN location estimates based on the coverage area of the CPS. In Figure 2.1, two WLAN clusters 402, 403, and a CPS location estimate 406 are formed. While the WLAN cluster 402 is within the coverage area 406, WLAN cluster 403 is outside the range. It can be seen that WLAN cluster 402 is a more probable location estimate than WLAN cluster 403 since two different positioning systems cover the identical area. Using this methodology, estimates outside the expected error range can be assumed to be incorrect and rejected.

The distance between estimated positions can also indicate an error in the database. In Figure 2.2, the two areas 410 and 416 do not overlap, and if the distance between the two areas is very large, say tens of kilometers, it is

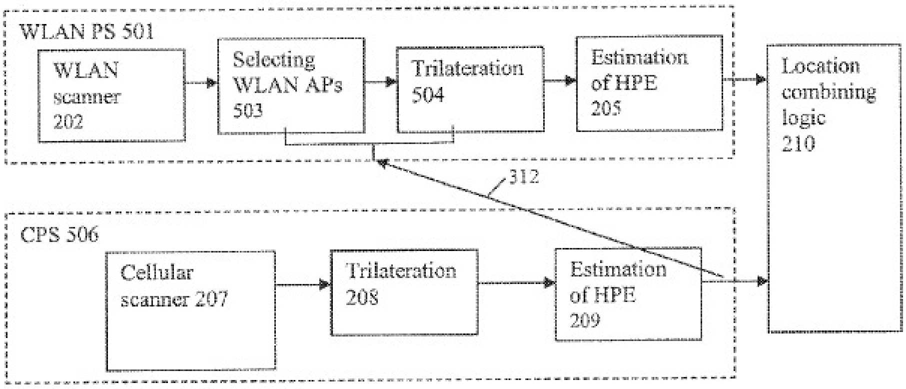


Figure 2.3: Diagram of integrated solution of CPS and WLAN PS (from [1]).

an indication that either one, or both estimates are incorrect. This implies the reference table is incorrect, and requires an update. The update can prevent possible errors occurring in the future, enhancing the accuracy and the reliability of the positioning systems.

The positioning systems can communicate with each other in various ways. The selected CPS locations may be passed as input to the WLAN PS to refine the final results. The system shown in Figure 2.3 shows the link which sends the input 312 from CPS to WLAN PS. The WLAN PS receives the input, and uses it to refine the results and produce a more probable position estimate.

2.2 Acoustic Direction Finding

The proposed acoustic direction finding method [8] uses acoustic signals produced from acoustic sources, like speakers, to locate the mobile device, specifically a phone. Huang et al [8] shake-and-walk acoustic direction-finding and indoor localization method called Swadloon measures the phase and frequency shift of the Doppler effect on the signals produced by acoustic sources, which are in the inaudible range of 17 to 19 kHz. These measurements represent the relative displacement and the velocity, respectively from the phone to the source. Swadloon is then able to obtain the direction of the sound source from the inertial sensors in the phone.

A Doppler effect is caused on the acoustic waves when the phone is shaken. If the acoustic source emits the sinusoidal signals at frequency f_a, v_a is the traveling speed of the signal, v is the velocity of the receiver, and v_s is the velocity of the source, then the observed frequency f_r is:

$$f_r = \frac{v_a + v}{v_a + v_s} f_a \tag{2.1}$$

In [8], the source node is assumed to be motionless, or its velocity negligible compared to v and v_a (i.e. $v >> v_s$ and $v_a >> v_s$). Then, the frequency shift f is:

$$\begin{aligned} f &= f_r - fa \\ &= \frac{v - v_s}{v_a + v_s} f_a \\ &\approx \frac{v}{v_a} f_a \end{aligned} \tag{2.2}$$

The last equation is derived with the assumption that v_s is 0, or very small compared to v and v_a.

The received signal $r(t)$ is in the following form:

$$r(t) = A(t)cos(2\pi f_a t + \phi(t)) + \sigma(t) \tag{2.3}$$

in which $A(t)$ is the amplitude, $\phi(t)$ is the phase shift affected by the Doppler effect, $\sigma(t)$ is the noise, and t is time. Assuming $\phi(t)$ is a continuous function, f_r and f at time t are:

$$\begin{aligned} f_r(t) &= \frac{1}{2\pi} \frac{d(2\pi f_a t + \phi(t))}{dt} \\ &= f_a + \frac{1}{2\pi} \frac{d\phi(t)}{dt} \end{aligned} \tag{2.4}$$

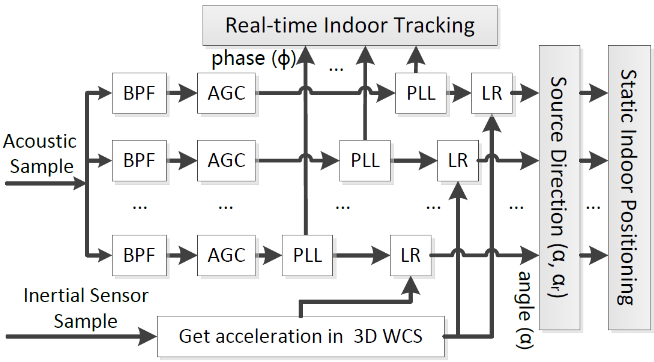


Figure 2.4: Implementation of Swadloon (from [8]).

$$f(t) = \frac{1}{2\pi}\frac{d(\phi(t))}{dt} \tag{2.5}$$

From Eqs.(2.2) and (2.5), velocity and displacement relative to the source are derived as follows:

$$\begin{aligned} v(t) &= \frac{v_a}{2\pi f_a}\frac{d\phi(t)}{dt} \\ s(t) = \frac{v_a}{2\pi f_a}\phi(t) &- \frac{v_a}{2\pi f_a}\phi(0) \end{aligned} \tag{2.6}$$

The implementation of Swadloon shown in Figure 2.4 breaks down each function into separate components. Band Pass Filer (BPF) allows only certain waves with specific frequency to pass through, reducing the noise $\sigma(t)$ in the acoustic waves. The next component, Automatic Gain Control (AGC), replaces the amplitude $A(t)$ to a constant, so the Phase Locked Loop (PLL) can successfully estimate the phase $\phi(t)$. If $\sigma(t)$ and $A(T)$ are eliminated by BPF and AGC, respectively, then Eq.(2.3) is refined as $r_c(t) \approx cos(2\pi f_a t + \phi(t))$.

To calculate $\phi(t)$, an adaptive estimation $\theta(t)$ such that $\phi(t) \approx \theta(t)$ is created to converge to $\phi(t)$ after enough iterations. In addition, a function $J_{PLL}(\theta)$ that converges to its maximum at the same time is defined to produce the following equations:

$$\theta' = \theta + \frac{dJ_{PLL}}{d\theta} \tag{2.7}$$

with $J_{PLL}(\theta)$ as follows:

$$\begin{aligned} max(J_{PLL}(\theta)) &= J_{PLL}(\phi) \\ J_{PLL}(\theta) &= LPF\{r_c(t)cos(2\pi f_a t + \theta(t))\} \\ &\approx \frac{1}{2}LPF\{cos(\phi(t) - \theta(t))\} \end{aligned} \tag{2.8}$$

where the Low Pass Filter (LPF) excludes the high frequency components. Furthermore, to change the continuous function in Eq.(2.7) to a discrete function, the following equations are used:

$$\begin{aligned}\frac{dJ_{PLL}}{d\theta} &\approx LPF\{\frac{d[r_c[k]cos(2\pi f_a kT_s+\theta)}{d\theta}\}\Big|_{\theta=\theta[k]} \\ &= -LPF\{r_c[k]sin(2\pi f_a kT_s+\theta[k])\}\end{aligned} \tag{2.9}$$

where T_s is the sampling period of the received signal, and k is the step count, so that $t = kT_s$. Finally, $\theta(t)$ can be estimated as follows:

$$\theta[k+1] = \theta[k] - \mu LPF\{r_c[k]sin(2\pi f_a kT_s + \theta[k])\} \tag{2.10}$$

The values for $\theta[k] = \theta(kT_s)$ and μ should be small and positive, so $\phi[k] \approx \theta[k]$ after enough iterations. For any following experiments conducted by [8], because $r_c[k]sin(2\pi f_a kT_s + \theta[k]) \approx \frac{1}{2}sin(4\pi f_a kT_s + 2\theta[k]) \leq \frac{1}{2}$, the value of μ is set to 0.03.

The direction of the acoustic source relative to the phone is calculated by Linear Regression (LR). The direction vector $\overrightarrow{\lambda} = (\lambda_x, \lambda_y, \lambda_z)$ and velocity vector $\overrightarrow{v} = (v_x, v_y, v_z)$ form the equality $\overrightarrow{v} \cdot \overrightarrow{\lambda} = \frac{v_a}{f_a}f$ (from Eq.(2.2)). The equation can be expanded as the following:

$$\lambda_x v_x[k] + \lambda_y v_y[k] + \lambda_z v_z[k] = \frac{v_a}{f_a} \cdot f[k], \forall k \tag{2.11}$$

The 2D direction α can be calculated from the 3D direction $\overrightarrow{\lambda}$ in the following form:

$$\alpha = \begin{cases} arcsin\frac{\lambda_y}{\sqrt{\lambda_x^2+\lambda_y^2}} & \lambda_x \geq 0 \\ \pi + arcsin\frac{\lambda_y}{\sqrt{\lambda_x^2+\lambda_y^2}} & \lambda_x < 0 \end{cases} \tag{2.12}$$

For 2D direction the phone is assumed to be at the same height as the acoustic source, or moving in the horizontal plane, setting $\lambda_z = 0$, and $\lambda_z v_z[k] \approx 0$. Then $\lambda_z v_z[k]$ is eliminated from Eq.(2.11), giving the following reduced equation:

$$\lambda_x v_x[k] + \lambda_y v_y[k] = \frac{v_a}{f_a} \cdot f[k] \tag{2.13}$$

Next, suppose $\hat{a}_x[i]$, $a_x[i]$, $\sigma_x[i]$ is the real acceleration, the calculated acceleration, the error of the acceleration, respectively, then $\hat{a}_x[i] = a_x[i] + \sigma_x[i]$.

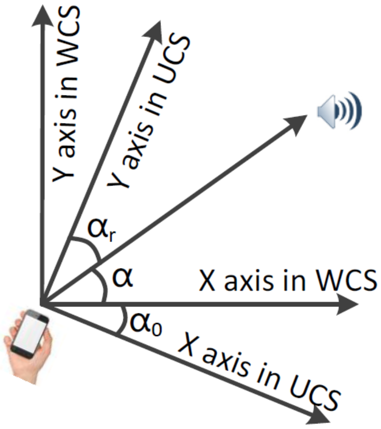


Figure 2.5: World Coordinate System (WCS) and User Coordinate System (UCS) (from [8]).

And v_x is derived as

$$v_x[k] = v_x[0] + \sum_{i=0}^{k-1} T[i]a_x[i] + \sum_{i=0}^{k-1} T[i]\sigma_x[i]$$

where $T[i]$ is the time interval between $a_x[i]$ and $a_x[i+1]$.

Assume σ_x is equal to a constant e_x, and let $t[k] = \sum_{i=0}^{k-1} T[i]$ to substitute $\sum_{i=0}^{k-1} T[i]\sigma[i]$ with $e_x t[k]$. Then, with Eqs.(2.14)(2.13)(2.12), an equation with 4 unknowns $(\lambda_x, \lambda_y, \lambda_0, \lambda_1)$ is shown as the following:

$$\begin{pmatrix} w_x[0] & w_y[0] & 1 & t[0] \\ w_x[1] & w_y[0] & 1 & t[1] \\ \dots & \dots & \dots & \dots \\ w_x[n] & w_y[n] & 1 & t[n] \end{pmatrix} \begin{pmatrix} \lambda_x \\ \lambda_y \\ \lambda_0 \\ \lambda_1 \end{pmatrix} = \frac{v_a}{f_a} \cdot \begin{pmatrix} f[0] \\ f[1] \\ \dots \\ f[n] \end{pmatrix}$$

where $w_x[k] = \sum_{i=0}^{k-1} T[i]a_x[i], w_y[k] = \sum_{i=1}^{k-1} T[i]a_y[i], \lambda_0 = \lambda_x v_x[0] + \lambda_y v_y[0]$ and $\lambda_1 = \lambda_x e_x + \lambda_y e_y$.

The vectors obtained from the equations are in World Coordinate System (WCS). Since the compass is not accurate, the X-axis of the phone may not point to east, which may cause errors in calculating the direction α. Therefore, Huang et al [8] proposes the use of User Coordinate System (UCS) that can be transformed from WCS by applying the rotation matrix. If the

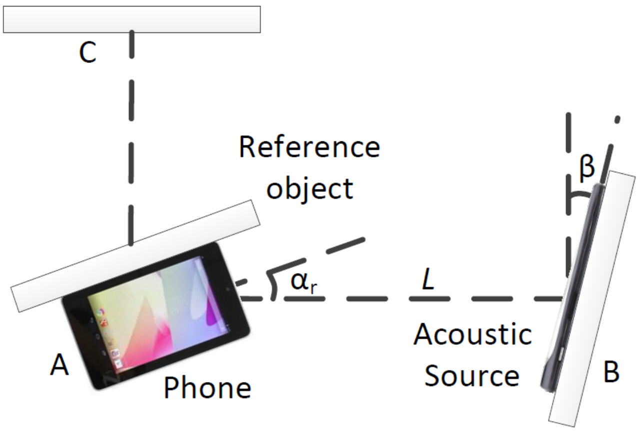


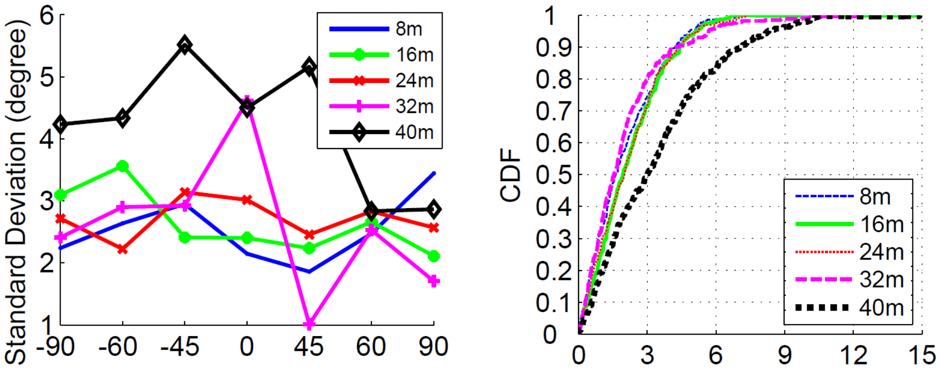
Figure 2.6: Experiment setup of Swadloon (from [8]).

direction of the acoustic source using UCS is denoted as α_r, and the opening angle from the X-axis in UCS transformed to WCS is α_0 (see Figure 2.5), then α_r is calculated by the following equation:

$$\alpha_r = \frac{\pi}{2} - \alpha - \alpha_0 \tag{2.14}$$

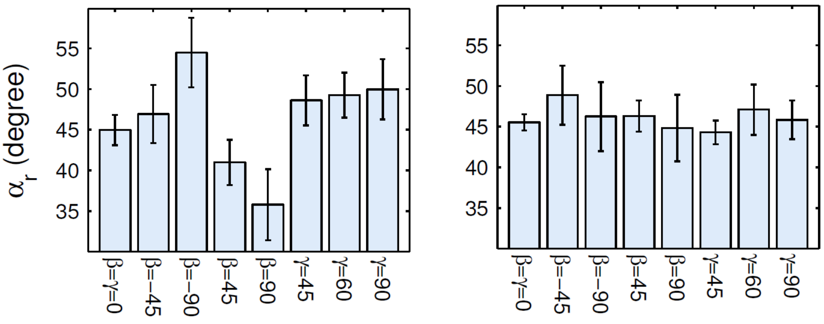
The experimental design of Swadloon is shown in Figure 2.6, where the orientation angle of the phone is α_r, the distance between the phone and the acoustic source is L, and the angle of the acoustic source at the horizontal plane is β. The elevation angle of the acoustic source, γ, is not shown. To evaluate the accuracy of Swadloon, $L, \alpha_r, \beta, \gamma$ are varied and α_r is measured 50 times for each variation.

To evaluate the effect of L and α_r, other variables β and γ are set to 0, and the result when L and α_r are altered is plotted in Figure 2.7. The mean error and standard deviation when $L \leq 32m$ is 2.10°, and 2.66°, while the angular errors are within 2.06°, 4.43°, 5.81° at 50%, 90%, 95%, respectively. Meanwhile, the effect of β and γ, shown in Figure 2.8, shows different results. The mean value at $L = 8$m fluctuates more than $L = 32$m, primarily because the acoustic source used in the experiment was not omnidirectional and the signal waves were stronger when L was smaller. It is also noted the elevation angle γ had no effect on the direction finding. To test the effect of non-line-of-sight to α_r, an obstacle was placed between the phone and the acoustic source. The errors produced from the position of the obstacle were measured in Figure 2.9. The error increases as the obstacle is closer to the



(a) Angle (degrees)　(b) Angular error (degrees)

Figure 2.7: The angular errors when $\beta = 0$ and $\gamma = 0$ (from [8]).



(a) β and γ when $L = 8$m　(b) β and γ when $L = 32$m

Figure 2.8: Mean and standard deviation of α_r (degrees) affected by β and γ (degrees) (from [8]).

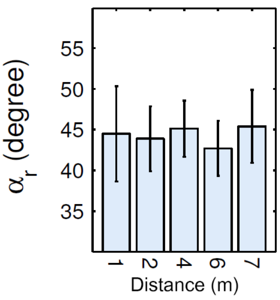
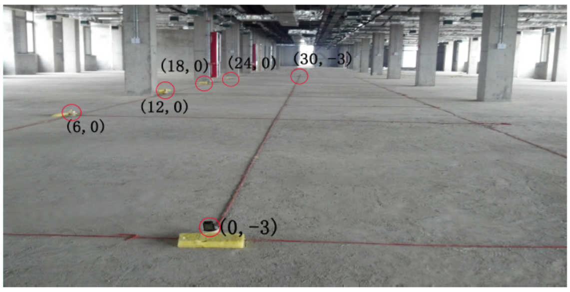
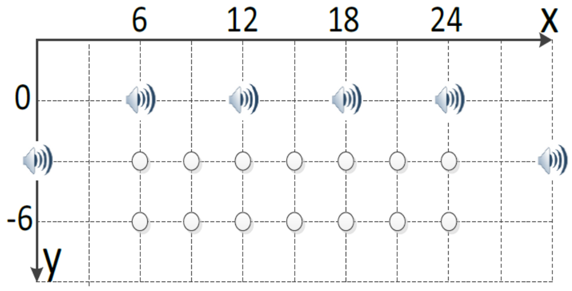


Figure 2.9: Mean and standard deviation of α_r (degrees) affected by non-line-of-sight (from [8])



(a) Test environment



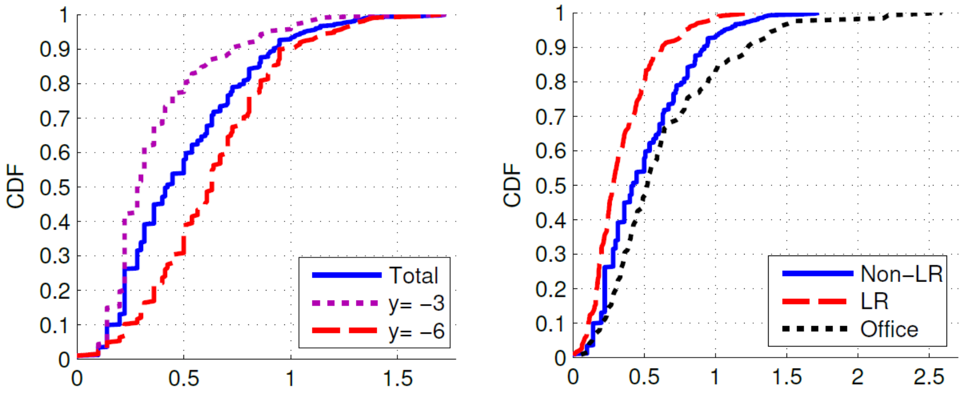
(b) Layout of the test environment

Figure 2.10: The test environment involving 6 anchor nodes (from [8]).

acoustic source or the receiver.

The test environment, an empty room with multiple acoustic waves (see Figure 2.10), was tested with 6 sinusoidal signals at frequencies between 17000Hz to 19500Hz. The variables α_r, β, γ are set to 0 and the results are plotted in Figure 2.11. The noisy office environment is used in both (a) and (b), producing worse results than the empty room. The mean error for line-of-sight environment is $0.5m$, while the non-line-of-sight environment produced errors between 1 to $2m$.

Real-time localization is possible, which is based on α and ϕ from the previous equations. The system first calculates the initial position of the user by the Doppler effect, and the system updates its position by calculating the relative displacement to the acoustic sources. Suppose in Figure 2.12, the location of the phone at time t is (x, y), then the new location $(\tilde{x}, \tilde{y})$ at time $\tilde{t}$ can be calculated by the relative distances $s(t)$ and $\tilde{s}(t)$. The distance from (x, y) to the acoustic source (x_i, y_i) is $L_i = \sqrt{(x - x_i)^2 + (y - y_i)^2 + h_i^2}$, where h_i is the relative height between the phone and the acoustic source. By Eq.(2.6)



(a) Position error (m)

(b) Position error (m)

Figure 2.11: Position error of the experiment (from [8]).

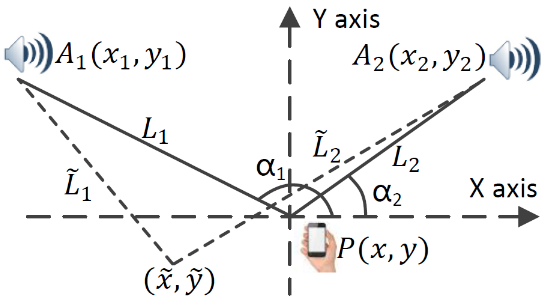


Figure 2.12: Locating the phone with trilateration (from [8]).

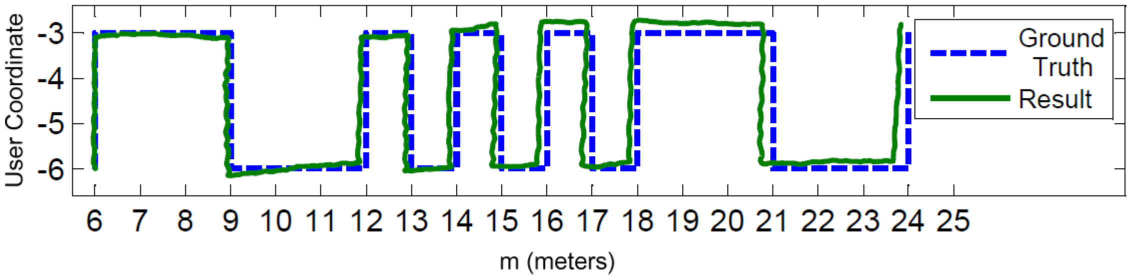


Figure 2.13: Real-time localization results (from [8]).

and Eq.(2.10), the relative distance at $\tilde{t}$ is as follows:

$$L_i(\tilde{t}) = L_i - \frac{v_a}{2\pi f_a}(\phi_i(\tilde{t})) - \phi_i) \tag{2.15}$$

Then, the system searches for a location $(\tilde{x}, \tilde{y})$ near (x, y) that minimizes $\sum_i M_i$ where $M_i = |L_i(\tilde{t}) - \sqrt{(\tilde{x} - x_i)^2 + (\tilde{y} - y_i)^2 + h_i^2}|$. The real-time localization experiment conducted showed very accurate results, as shown in Figure 2.13, where errors are within 0.4m.

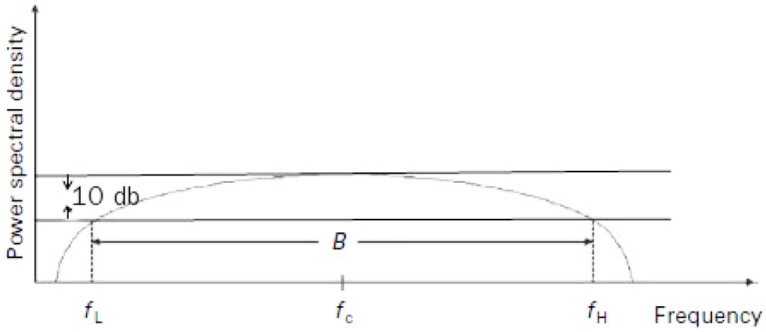


Figure 2.14: f_L, f_c, f_H of an UWB system (from [19])

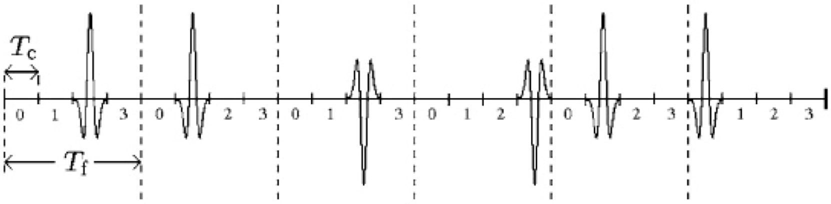


Figure 2.15: IR stream with binary data "101" (from [19]).

2.3 Ultra-Wideband

A system with absolute bandwidth greater than 500 MHz and f_c greater than 2.5 GHz, or a system with f_c lower than 2.5 GHz and B_{frac} larger than 0.2 is defined as the Ultra-Wideband (UWB) system [19][11]. The frequency at which the system has the maximum power density is defined as f_c, then f_H and f_L are the locations where the power spectral density is 10 db below f_c (see Figure 2.14). If the bandwidth of the system is B, then the following equations are produced:

$$\begin{aligned} B &= f_H - f_L \\ f_c &= \frac{f_H + f_L}{2} \end{aligned} \tag{2.16}$$

and

$$\begin{aligned} B_{frac} &= \frac{B}{f_c} \\ &= \frac{2(f_H - f_L)}{f_H + f_L} \end{aligned} \tag{2.17}$$

The large bandwidth allows high speed communication and to pass through obstacles easily by occupying low carrier frequencies. However, the inverse

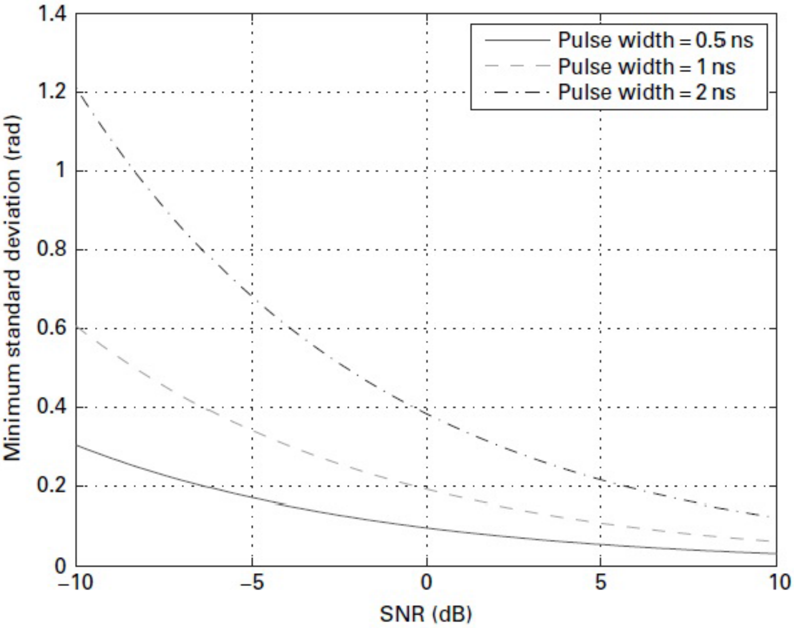


Figure 2.16: Cramer-Rao lower bound (CRLB) for AOA versus SNR with different bandwidth (from [19]).

relationship of time and frequency forces the life-time of the signal to be very short. There also is an inverse relationship between bandwidth and power consumption, and a direct relationship between capacity and bandwidth as follows:

$$C = Blog_2(1 + \frac{S}{N}) \tag{2.18}$$

where C is the capacity in bits per second, S is the average received signal power over B. Impulse Radio (IR) uses low duty UWB signals to transmit data, where each symbol represents one or more signals. The example case shown in Figure 2.15 has two consecutive IR signals representing one symbol. The position or the polarity of the signals describes the symbol, and the IR signal occupies one chip-interval (T_c) within a frame (T_f).

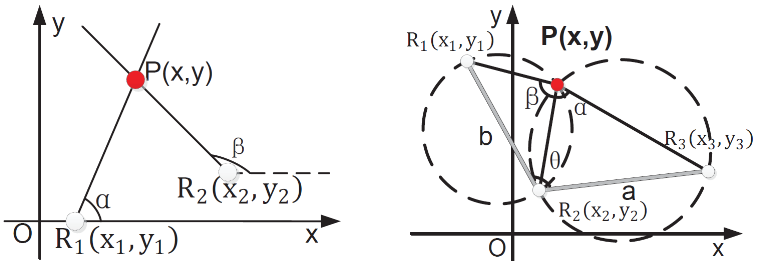
UWB system may use the basic positioning models (Section 2) and due to its large bandwidth, its accuracy is very high compared to other systems. Figure 2.16 shows the increasing bandwidth (decreasing pulse-width) has increasing accuracy. The larger the bandwidth, the lower the positioning error.
The high accuracy of the UWB system makes it suitable for indoor positioning. One of the systems, DecaWave [13], claims the accuracy of the device is $10cm$ for indoors. A large error may locate the user in another room, and

this can be critical in emergency cases where the user must be located immediately for attention. However, for some indoor services, the error range does not have to be within centimeters to be considered accurate. Nanotron [21] has estimated accuracy in line-of-sight environment is 1 to $3m$. Suppose Nanotron was used for device recovery, the error range of 1 to $3m$ is within human view, making it possible for the device to be recovered fairly easily.

The range of localization varies for each device, where Nanotron [21] has a range of $50m$ while DecaWave has a range of $290m$. An indoor environment, say a shopping mall, is a large area that is wider than 50 or $290m$. Multiple transmitters are required to cover the entire area, each of them dispatched at appropriate positions to locate the user device.

2.4 Active Image Triangulation

Signal waves are easily influenced by obstacles, affecting the measurements calculated from the waves. One solution implements a different technique to localize indoor devices, specifically mobile phones, to avoid changes in signal strength. This solution [20] utilizes environmental features, such as logos or posters, to locate the mobile device. There are two steps to this method, the user must first take snapshots of three nearby physical features and send the images to the server. The server then matches the image to its coordinates to calculate the user position.



(a) Device position P, Reference points R_1 and R_2, absolute angles α and β.

(b) Relative angles α and β formed with P and the three reference points.

Figure 2.17: Angles formed with reference points and the user (from [20]).

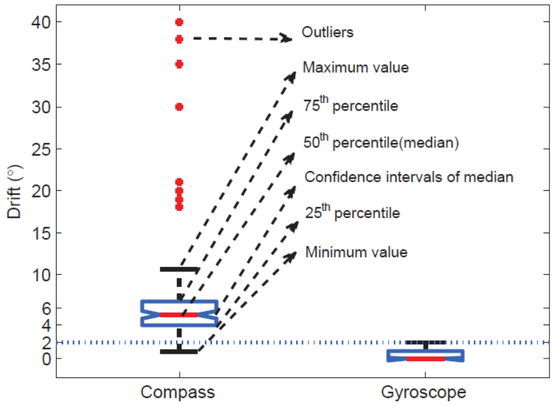


Figure 2.18: Compass and gyroscope readings when the device moves in a straight line (from [20]).

The mobile device forms absolute angles (Figure 2.17(a)) and relative angles (Figure 2.17(b)) with the reference points. Many modern mobile phones can measure the absolute angle with respect to the geographic north with a built-in compass and its rotation angle with a gyroscope. Multiple tests have been performed to examine the accuracy of the compass and the gyroscope, and it has been concluded that the compass measurements are often inconsistent. The test measured the compass and the gyroscope readings as the mobile device moved in a straight line. Figure 2.18 illustrates the compass and gyroscope drifts, and it is observable that the compass readings fluctuated while the absolute angle of the mobile device should have been constant. Therefore, the indoor device localization is based on relative angle for this method.

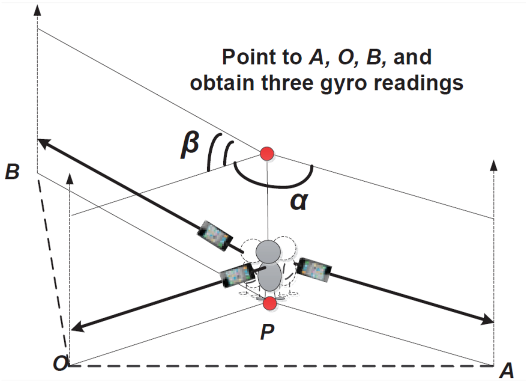


Figure 2.19: User choosing the reference points (from [20]).

A sample scenario shown in Figure 2.19 involves three reference points A, O, and B with relative angles $\alpha = \angle APO$, $\beta = \angle OPB$, and $\theta = \angle BOA$ (see Figure 2.17(b)). If the coordinates of A, B, and O are known and the angles are given, the position P is computed with the following equations:

$$\begin{aligned} x &= x_0 \frac{x_3 - x_2}{a} - y_0 \frac{y_3 - y_2}{a} + x_2 \\ y &= x_0 \frac{y_3 - y_2}{a} + y_0 \frac{x_3 - x_2}{a} + y_2 \end{aligned} \tag{2.19}$$

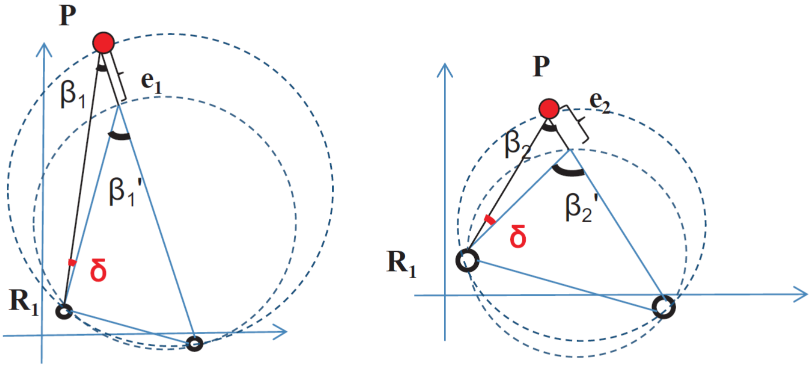
where

$$a = \sqrt{(x_3 - x_2)^2 + (y_3 - y_2)^2}$$
$$b = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2}$$

$$x_0 = \frac{ab[sin(\beta+\theta)cot(\alpha) + cos(\beta+\theta)][asin(\beta)cot(\alpha) + bcos(\beta+\theta)]}{[bsin(\beta+\theta) - asin(\beta)]^2 + [bcos(\beta+\theta) + asin(\beta)cot(\alpha)]}$$

$$y_0 = \frac{ab[sin(\beta+\theta)cot(\alpha) + cos(\beta+\theta)][bsin(\beta+\theta) - asin(\beta)]}{[bsin(\beta+\theta) - asin(\beta)]^2 + [bcos(\beta+\theta) + asin(\beta)cot(\alpha)]^2}$$

$$\theta = arccos[\frac{(x_3 - x_2)(x_1 - x_2) + (y_3 - y_2)(x_3 - x_2)}{ab}] \tag{2.20}$$

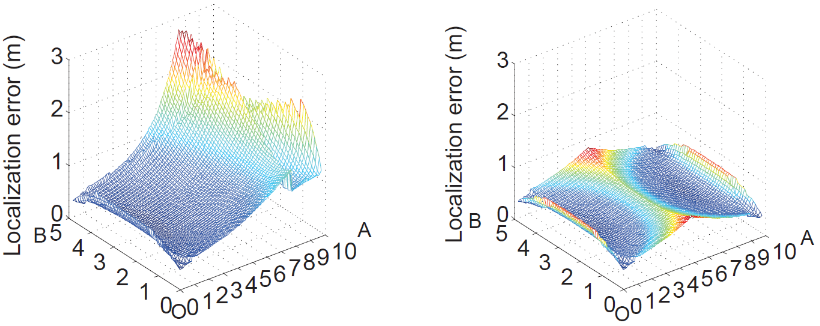


(a) Smaller angle β_1 (b) Larger angle β_2

Figure 2.20: Localization error e_1 and e_2 caused by angle drift δ (from [20]).

Since the environmental features function as reference points, their position greatly affects the accuracy of the position estimation. The magnitude of the angle impacts the distance between reference points, which is proportional to the localization error. The localization error, e_1 or e_2, in Figure 2.20 occurs from the angle drift δ. The length of R_1P is longer in (a) than (b) as $\beta_1 < \beta_2$, thus the angle drift δ creates a larger radius that ultimately causes a larger localization error in 2.20(a). Since distant reference points are likely to produce small angles, closer references points should be chosen.

To test this theory, localization error for fixed and closest reference points



(a) Localization error when the reference points are always fixed.

(b) Localization error when the closest reference points are chosen.

Figure 2.21: Localization error with reference points A, O, and B (from [20]).

were examined. The average localization error with fixed reference points in Figure 2.21(a) demonstrates an increasing localization error as the distance between the device and a reference point increases. Meanwhile, the average localization error when closest reference points are chosen is stable regardless of distance (see Figure 2.21(b)). This implies choosing the closest reference points in calculating the user position produces the best results.

The exact location of each reference point must be known for the positioning system to function properly. If a large number of coordinates are known and fixed in place, the server is able to calculate the device's location without constant updates. This is a great advantage as less human effort is required to maintain the information in the server. The coordinates of each feature may be measured by hand, but this requires a significant amount of work and is vulnerable to errors. A method to lower the required human effort is to set a starting object A as the origin with coordinates $(0, 0)$, and to locate another reference point at distance a as point $B(a,0)$ (Step-1 in Figure 2.22). The third point $C(x,\ y)$ can then be calculated by simple geometric sequences. The angles $\angle CAB$ (or α) and $\angle CBA$ (or β) can be measured from the device's gyroscope, giving the coordinates of C as:

$$\begin{aligned} x &= \frac{atan(\beta)}{tan(\alpha)+tan(\beta)} \\ y &= \frac{atan(\alpha)tan(\beta)}{tan(\alpha)+tan(\beta)} \end{aligned} \tag{2.21}$$

This process still requires a certain level of human effort to locate the initial

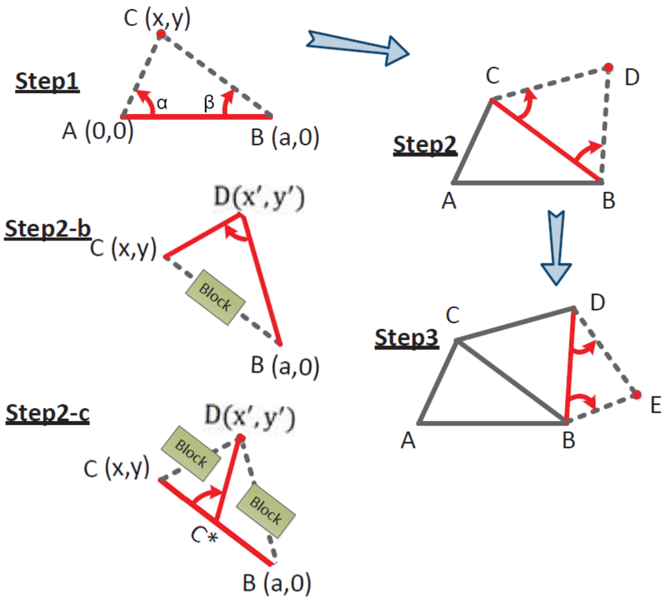


Figure 2.22: Coordinate estimation for each reference point (from [20]).

reference points, but with two initial reference points, any unknown reference point that can be aimed at with the device can be located with this procedure. If the object is blocked by obstacles, then the angle cannot be measured and other procedures must be taken. The obstacle may block the line-of-sight between the reference points B and C (Step 2-b in Figure 2.22), or between the reference point and the unknown point D (Step 2-c in Figure 2.22). In case of blocked reference point (Step 2-b in Figure 2.22), because there is no direct line-of-sight between C and B, $\gamma(\angle DCB)$ and $\delta(\angle DBC)$ cannot be measured by the gyroscope. To locate the unknown point D, the $\angle BDC$, $\overline{BC}$, and one of $\overline{CD}$ or $\overline{BD}$ can be used in the law of sines to locate D.

If the line-of-sight to D is blocked from both B and C (Step 2-c in Figure 2.22), another position C^* on $\overline{CB}$ that is able to measure $\angle CC^*D$ is used. When $\overline{CC^*}$, $\overline{C^*D}$ and $\angle DC^*C$ are known, the position of D relative to C can be calculated using:

$$\begin{gathered}\overline{CD} = \sqrt{(\overline{CC^*})^2 + (\overline{C^*D})^2 - 2(\overline{CC^*})(\overline{C^*D})cos(\angle CC^*D)} \\ \angle DCC^* = \arcsin[\frac{sin(\angle CC^*D)\overline{C^*D}}{\overline{CD}}]\end{gathered} \tag{2.22}$$

Now Eq.(2.21) can be used to locate *D(x,y)*, by substituting γ and δ for α and β, respectively.

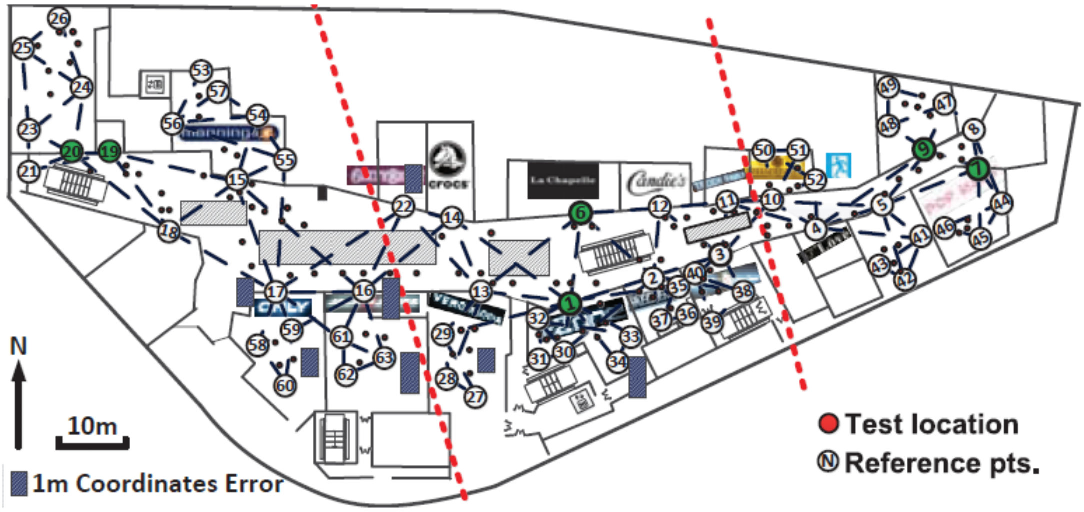


Figure 2.23: The floor map of the test environment: a mall with 63 reference points and 108 test locations (from [20]).

This method is useful in environments where physical features are present in large numbers; one of the suggested environments was a shopping mall, where multiple stores were present and set in place. The testing done by Tian et al [20] used 63 and 53 reference points for a mall (see Figure 2.23) and a station (see Figure 2.24), respectively. Each angle or distance took approximately 2 to 3 minutes, summing up to a total of 2 to 2.6 man-hours to locate every reference point in the environment as a part of the pre-processing phase.

Once the pre-processing phase is complete, the user application can function on user devices to calculate the position. The prototype captures the chosen reference point and measures the gyroscope readings. The measurements and the photo are sent to the server, and two more reference points are captured. The server matches the images from the user to the images on the server, which can take around 0.5 seconds. The transmission of the photos to the server is estimated to take less than a second, and since the initial captures of three reference points takes only a few seconds to complete, the localization process only takes a few seconds.

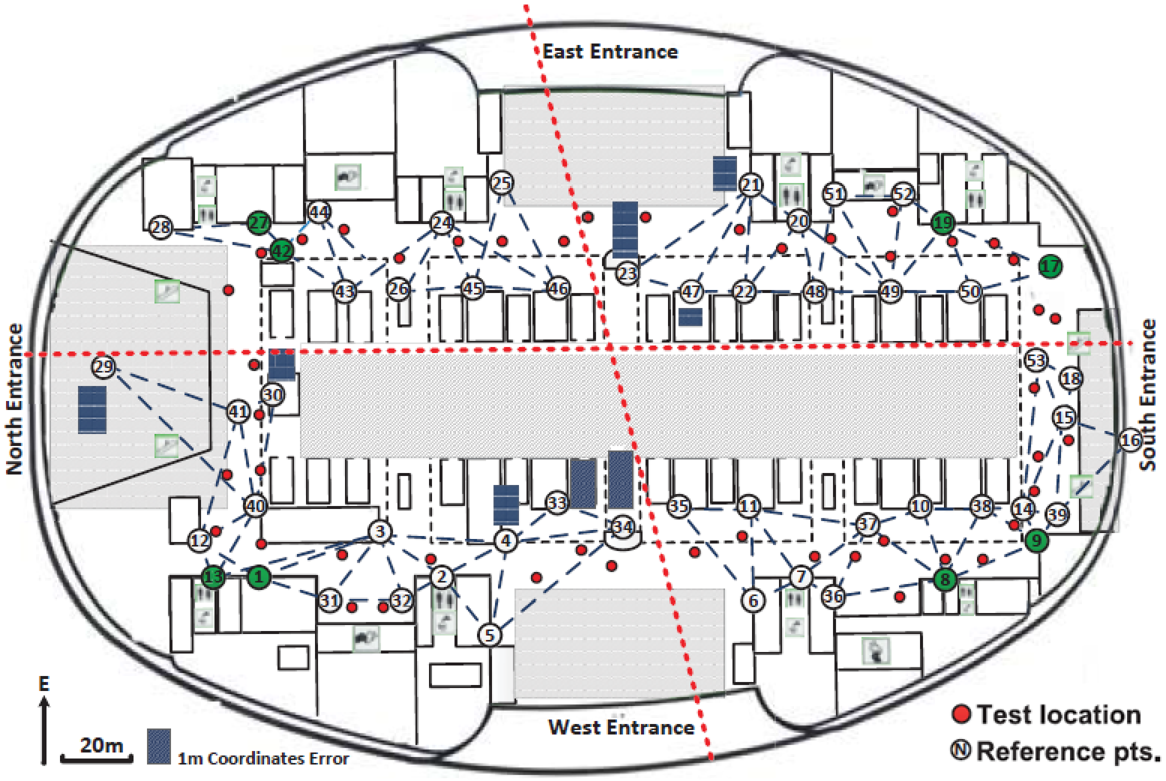


Figure 2.24: The floor map of the test environment: a train station with 53 reference points and 46 test locations (from [20]).

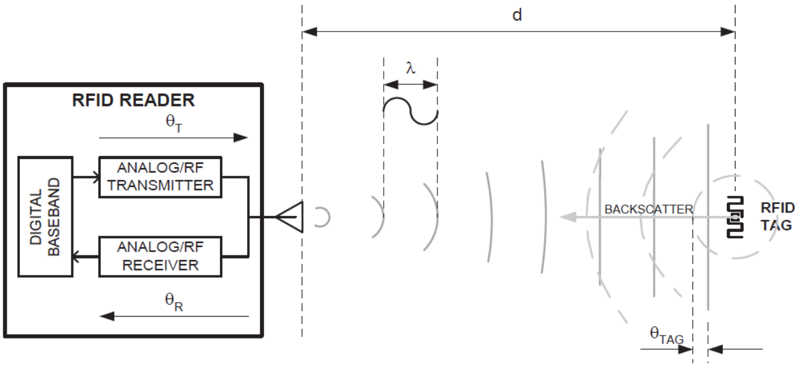


Figure 2.25: Backscatter radio link between the reader and the tag (from [12]).

2.5 Anchor Free Backscatter Positioning

A Radio Frequency Identification (RFID) system consists of a reader and multiple tags. Tags without batteries communicate with the reader by backscatter radio link, where the tag modifies the signal to transmit a message back to the reader (see Figure 2.25). The backscatter positioning technique proposed in [12], BackPos, uses the distance difference, Δd, from the target to the antennas and the phase difference, $\Delta\theta$, to locate the target tag.

If the antennas are spaced within a half of wavelength ($< \lambda/2$), then a hyperbola can be drawn with Δd. The points on the hyperbola are the possible positions of the target, then the intersection of multiple hyperbolas is the target position.

The distance traveled by the signal wave is $2d$, and if the tag's reflection characteristics, reader's transmit circuits, and the reader's receiver circuits are termed θ_{TAG}, θ_T, θ_R respectively, then the total phase rotation is expressed as:

$$\theta + 2k\pi = 2\pi\frac{2d}{\lambda} + \theta_T + \theta_R + \theta_{TAG} \tag{2.23}$$

where θ is an output parameter, and k is an integer, unknown in practice, that guarantees θ to fall between $[0,2\pi)$. The values of θ_R and θ_T can be found from the reader, but θ_{TAG} cannot be measured ahead as there are too many tags in existence. Therefore, for Eq.(2.23), the initial rotation of the tag (θ_{TAG}) is unknown and thus the distance d cannot be found either.

To solve the equation, assume there are two antennas $A_1(x_1, y_1)$ and $A_2(x_2, y_2)$ communicating with the target tag $T(x, y)$. Then the distance $|TA_1| = d_1$ and $|TA_2| = d_2$. If the phases θ_1 and θ_2 are measured by the two antennas, then Eq.(2.23) can be applied to each antenna as follows:

$$\theta_1 + 2k_1\pi = 2\pi\frac{2d_1}{\lambda} + \theta_{T_1} + \theta_{R_1} + \theta_{TAG} \tag{2.24}$$

$$\theta_2 + 2k_2\pi = 2\pi\frac{2d_2}{\lambda} + \theta_{T_2} + \theta_{R_2} + \theta_{TAG} \tag{2.25}$$

subtracting the above equations produces

$$\triangle\theta_{2,1} + 2(k_2 - k_1)\pi = \frac{4\pi}{\lambda}\triangle d_{2,1} + p \tag{2.26}$$

where $\triangle\theta_{2,1} = \theta_2 - \theta_1, \triangle d_{2,1} = d_2 - d_1$, and $p = (\theta_{T_2} - \theta_{T_1}) + (\theta_{R_2} - \theta_{R_1})$. Removing subscripts and isolating $\triangle d$, the equation becomes

$$\triangle d = \frac{\lambda}{4\pi}(\triangle\theta + 2k\pi) \tag{2.27}$$

where $\triangle\theta = \triangle\theta_{2,1} - p$ and k is an integer ensuring $\triangle\theta$ is within (-2π, 2π). The unknown value θ_{TAG} is eliminated from Eq.(2.27), enabling $\triangle d$ to be calculated from $\triangle\theta$. The target tag (x, y) is located by $\triangle d$ by constructing a hyperbola from the two antennas as follows:

$$\triangle d = |\sqrt{(x - x_1)^2 + (y - y_1)^2} - \sqrt{(x - x_2)^2 + (y - y_2)^2}|$$

Further,

$$\frac{x^2}{a^2} - \frac{y^2}{b^2} = 1 \text{ where } \begin{cases} a = \triangle d \\ b = \sqrt{c^2 - a^2} \\ c = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2}/2 \end{cases}$$

if the coordinate system meets the center of the antennas at the origin and the two focuses are located in the x-axis. The target position is confined on the hyperbola, where multiple hyperbolas can locate the target tag at their intersection.

Figure 2.26 shows two antennas A_1 and A_2 locating the target node T. If the distance between the antennas is d_{ant}, then it is possible to construct

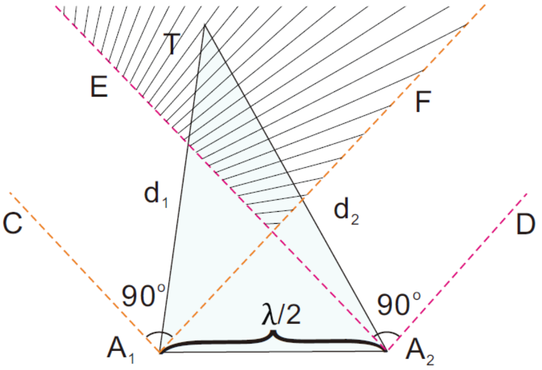


Figure 2.26: Two antennas locating the target tag (from [12]).

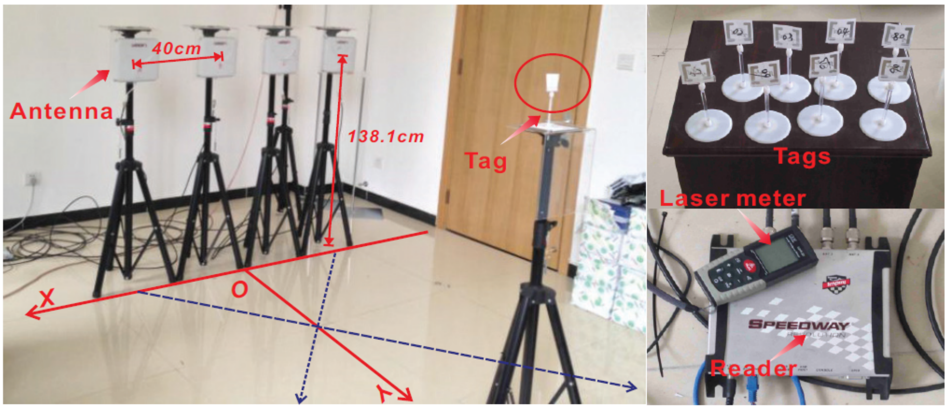


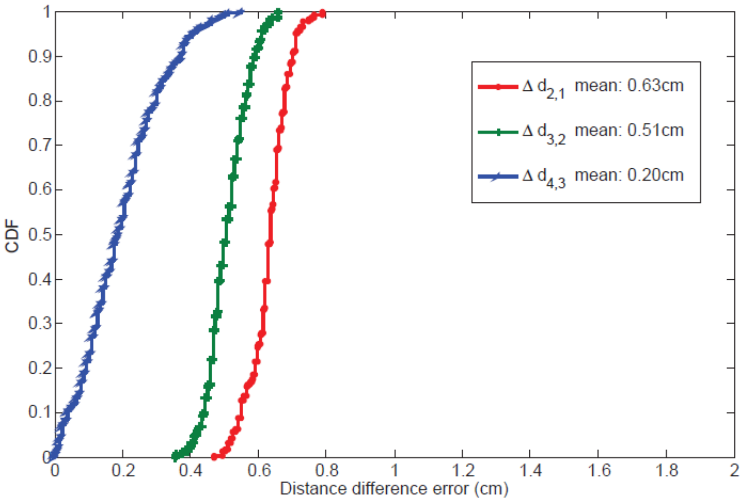
Figure 2.27: Experiment setup (from [12]).

a hyperbola C such that $|TA_1 - TA_2| = \lambda/2$ with the target tag T on the curve. The equation of the hyperbola is given by

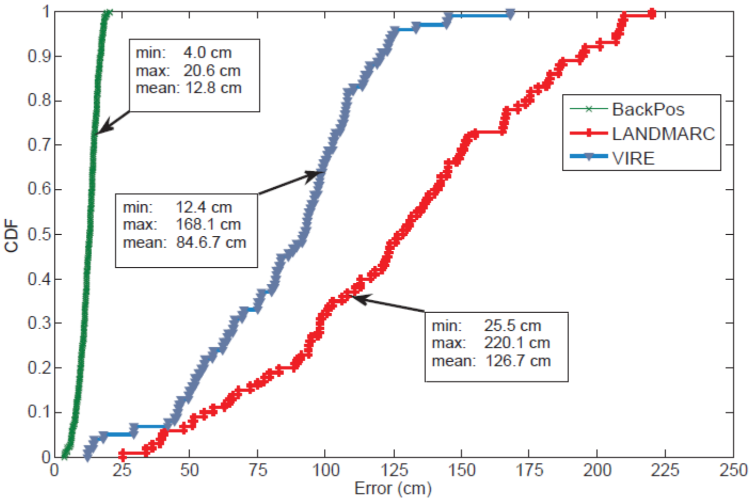
$$\frac{x^2}{a^2} - \frac{y^2}{b^2} = 1 \text{ where } \begin{cases} a = \lambda/2 \\ b = \sqrt{c^2 - a^2} \\ c = d_{ant}/2 \end{cases}$$

The space between the two branches of C is the feasible region, the shaded area in Figure 2.26.

The experiment in [12] implements a prototype of BackPos with four directional antennas (see Figure 2.27). The reader works in frequency of $920.5MHz$ to $924.5MHz$, and wavelength from $32.43cm$ to $32.57cm$. The θ_T and θ_R



(a) Ranging error



(b) Positioning error

Figure 2.28: Results from the experiment (from [12]).

are obtained from the from the reader's specifications. The test environment is an office room sized 500 X 800 cm^2 with antennas and target tags placed at $138.1cm$ height. The four antennas A_1(59.7, -1), A_2(12.7, -4), A_3(-23.8, -4), A_4(-61.8, -4) are positioned in a straight line, and the target tag T is positioned at (-43.2, 283.4). Letting $\triangle d_{2,1} = ||TA_2| - |TA_1||$, $\triangle d_{3,2} = ||TA_3| - |TA_2||$, and so forth, the experiment is repeated 100 times, and the ranging errors are plotted in Figure 2.28(a). The CDF of positioning error of BackPos and two baseline schemes LANDMARC and VIRE are plotted in Figure 2.28(b). The positioning error of BackPos is very small, in order of centimeters. In practice, maximum error of a few centimeters do not affect the position as much, which makes the solution effective for indoor positioning.

3 Services

Just as outdoor services take advantage of their location estimates, indoor services can benefit the user with location estimates. Most, if not all, localizing methods have a certain degree of error in their estimation. Depending on the service, this error may be acceptable within hundreds of meters or within only a few meters. For indoor localization, an error of several meters can locate the user in another room or a floor. Therefore, many positioning systems are keen on locating the user with the smallest localization error possible. Accurate location estimation is useful for all services, but these methods are generally more expensive, require equipment, and must install anchor nodes. It is very unlikely that a regular household can afford such methods, therefore each solution is suitable for a service of its own.

For certain services, the exact location of the user may not be required, and a clear indication of close proximity may be enough for the service. The proximity based positioning can be used to reduce cost while still providing enough information to use the services. Depending on the service, cost may be prioritized over accuracy, then proximity based solutions should be chosen. Meanwhile, if accuracy is crucial, like emergency services, then accurate systems must be chosen regardless of cost.

3.1 Advertising

Suppose the user is inside a store, and a sensor node recognizes the user is inside store. Since the sensor can detect the user is near, or inside the store, advertisements for the store can be displayed, like on the user's smartphone for example [6]. This design can surely be enhanced by estimating the exact position of the user and supplying the user with appropriate advertisement depending on where the user is. For example, if the user is standing in front of the dairy section of a supermarket, then more specific advertisements can be provided to the user. This can be mimicked with proximity, by analyzing the sensor's detection of the user. If each section or shelf is equipped with a sensor, then each sensor will detect the user's presence within its range. Whether the user is exactly 1 meter or 2 meters away from the shelf does not change the fact the user is in the area. Knowing that the user is near a certain section is enough to decide which advertisements to provide to the user.

3.2 Tracking

Many tracking services can be done without knowing the exact location, depending on the object being tracked. If the object is large and easily noticeable, than its position within a certain range or nearness to a sensor node is enough to locate it. But if the object is small, then proximity may not be enough to find the object.

3.2.1 Inventory

While proximity based solution works perfectly, a direct location estimation work better in most cases. This solution is appropriate for inventory tracking if the object to be tracked is easily noticeable, such as a tractor, it can be spotted easily by knowing just a rough estimation of proximity to the reference points. Meanwhile, a small object, for example a tiny chip, would be very difficult to find by proximity only. As an example scenario, suppose the target object is shelved at a storage room which holds thousands of products. Even if the proximity based solution can determine the region where the target is, because there are far too many objects within the area, it still requires a large amount of effort and time to find the target. Therefore, depending on the work environment and the features of the object, one solution is more appropriate than the other.

Using proximity based solutions can be cost effective in maintaining the warehouse, but may make it difficult to locate small objects when the product density is high. If the object is critical, then even if the object is large, it should use location based tracking. If the object is not important, then a proximity based solution will be suitable. It may seem large and visible objects do not need tracking services to locate them, but suppose the warehouse is kilometers long and there are thousands of items within the warehouse. It will be very difficult to locate the target object, even if it is large and visible from afar.

3.2.2 Devices

For inventory tracking, the industrial setting generally allows more expenses to be used for tracking. However, for regular mobile devices people use, the cost is very limited and it is very unlikely the users will pay additional fees for location based services. Therefore, the services to be used by regular users should not charge additional cost, meaning there should not be additional equipment involved to keep the cost same. It should also be noted mobile devices for regular users have a much shorter battery life compared to one working in professional workplaces or industry. The locational services are supplementary to existing services, so positioning equipment that drains a lot of energy from the device should be avoided.

3.2.3 Animals

Indoor environment mostly involves walls and obstacles interfering with direct line-of-sight. For an outdoor environment which has similar properties, like a forest full of trees, indoor solutions should be used as the condition is very similar to indoor localization. Take wild animals for example, these animals are in need of human help and their health conditions must be checked regularly. Where their habitat is covered with trees and bushes, an outdoor solution will not work properly with branches blocking their line-of-sight. The device equipped on the animal should not interfere with its movements. It should be small and light weighted for the animal to carry without difficulty. As the locational data is only used by the server and not the user(animal), the device does not need to receive or process any data. A solution like the RFID tags where the tag has no intelligence and battery would work for tracking animals.

3.3 People Location

One of the major services available for users is tracking. The location information can be used by the service for various reasons, it may be to find a lost equipment, to track a child who leaves by herself, or to track a patient who has health concerns.

3.3.1 Children

Children are very curious, exploring different places on their own. If they leave on their own at places they are familiar with, they are likely to reunite with their guardians since they are familiar with the area. But if they are lost at an unfamiliar, large or multistory building, they may panic or move from the spot, making it difficult to find them. Indoor location services in this situation will let the guardians know where the child is located at, or the child may use it on his own to locate himself, and to navigate the building to find the meeting place or the services center.

In recent years, many children, including both teenagers and younger, carry smartphones. As mentioned in Section 3.2.2, most smartphones have Wi-Fi feature installed, allowing indoor localization without additional equipment [14]. If the child is very young, or cannot carry a cellphone, for example at a kindergarten, the device should be small, and sturdy. Young children are very likely to lose the tracking device, whether on purpose or from forgetfulness. They may also damage the device from playing. The stronger the device is, the better it would be for children, but the cost of the device must be low, because it is easily lost and many guardians cannot afford expensive equipment [18].

3.3.2 Patients and Elderly

Location estimation for a patient or an elderly who requires health attention is very useful [16]. If a patient has fallen ill, and requires immediate help, indoor localization will decrease the search time by a large amount, allowing quick rescue. It is also the same for an elderly who may try to leave the facility. The person's position should be checked regularly for unexpected movements, and to alarm the watchers if the patient is outside the facility without notice. If the person did leave, then an outdoor localization solution is needed to locate the person. The device itself should be intact with the patient very closely, like a necklace, to reduce chances of it becoming loose [5]. Many patients will not intentionally tamper the device or remove it, but some may try to do so, like a patient who does not wish to be tracked or has forgotten the device is for tracking. Because of this possibility, the device should not be something out of the ordinary and be attached to a normally used equipment, a small necklace for example.

Facilities should be able to afford equipment required for indoor localization for safety measures. The direct position estimation will be useful in cases of emergency, because an error of just a few meters can change the room the patient is located at. If the facility only needs to track the patients or elderly inside the building to prevent their leave and emergency situations are very unlikely to occur, then proximity is enough to confirm the users are within the area.

3.3.3 Detention Facilities

The localization solution can help control dangerous situation and to even prevent such events. If the prisoners show any unnatural gatherings, like gathering frequently at places that have low surveillance, it may be an indication they are planning something, whether it is to jailbreak or to harm another member. Being prepared and preventing a possible outbreak can be very useful in keeping order within the facility.

The solution for indoor localization in detention facilities should be based on the appropriate equipment. Even if the system provides the most accurate position estimates with the lowest cost, if the equipment can be easily damaged or tampered, it is not suitable for this environment. The device is always in danger of being damaged, lost, detached, or tampered. Because the officers will watch the movements updated on the server, if the system shows no unusual behaviours, the officers are unlikely to suspect them. In reality, the device may have been detached, damaged, or tampered to provide false information. This will make the situation more dangerous, so while accuracy is useful, the equipment used in the localization method should be checked for this service.

The anchor nodes should be placed at locations out of reach. Altering the anchor node will affect the measurements obtained from it, making it very easy to falsify one's location. They may be installed on the ceiling to avoid direct contact, within walls to avoid notice, or be disguised as other objects to reduce suspicion. The user device must also be designed with extreme care, otherwise altering the user device may allow the user to modify measurements, thus cloaking his real location.

3.4 Indoor Route Navigation

The indoor navigation service can be used for people in route finding. The user location may be updated real-time to provide navigation inside a building, or a robot may use this navigation service to reach a destination. This service requires real-time localization to provide the most effective navigation, but many methods have difficulty in doing this. The problem may be that it involves user interaction, like the Active Image Triangulation method, or the update rate may be too slow for user movement. If the user has already passed the area when the method returns the location estimate, then the navigation service would not function properly.

The navigation service can utilize the map of the environment to reduce error. For example if the user location is estimated to be at places where the user cannot be, like in between walls, then it is very clear there is an error. The navigation service includes a map of the area, so using this technique to reduce error may be useful. The map data may be stored on the server, where the user location and map are sent from the server to the user device. In another example, the user may install the map on the device, where the device may only receive user location from the server. Or, the device may have both the map and the localization method installed on its system, where the navigation service involves no servers. In the final case, this would be like using Swadloon with the navigational data installed on the user's phone. The smartphone calculates the location by using its inertial sensors, producing its own locational data. There is no server required, so it may be beneficial for Swadloon to install the map data to remove any servers.

3.5 Public Safety

Public safety can utilize indoor localization to enhance the services provided to the citizens. Most services related to public safety prefer an accurate estimation of the user position instead of proximity. This is because many services require immediate action and an area compared to a single coordinate is rather large, increasing the search time and errors in their strategy.

3.5.1 Law Enforcement

Suppose the police is working undercover to infiltrate a crime scene. The member can continuously update his position by reporting his movement to the control center, but this will make him suspicious and the reports may not match his exact movements, causing errors in localization. If his position was located by indoor localization systems, the chances of him being noticed is low and provides more accurate results. The device will have to be very small, well hidden, and it must be executable without installing additional sensors. It should also be energy efficient, as the user may need to work for days without any time to recharge the device.

There may be an attack, hostages held captive and the teams must effectively infiltrate the building and rescue the hostages. The floor plan may not be acquired in time, and even with the floor plan it will be difficult to pinpoint the team member's position accurately. The building may have renovated, or certain parts may be blocked, and knowing the person's exact location with errors within a few centimeters is better than a rough estimate of where he is positioned at. Their timing may be off if only a rough estimation is given, and a few second delay may put the mission to failure, leading to casualties [18].

3.5.2 Emergency

In case of emergency, like fires, the indoor location services can be used to track the rescue personnel [10] and to draft a quick overview of the current environment. In an emergency situation, the building is very likely to change its structures due to walls or floors collapsing, meaning the members cannot follow a floor plan to navigate the building [4]. When the teams are deployed, the location of each team member indicates which floors have been searched, and which routes are safe. The following team members benefit from this information to reduce search time, take safer routes, search other places, and locate a lost or immobile member.

The users work under severe conditions such as high temperature or thick smoke, and must endure damage caused by hazardous environment. Because the rescuers' lives are endangered in these situations, even a small error in localization can be dangerous. The devices used in indoor positioning must withstand the damages and must not lose accuracy regardless of the condition. Furthermore, emergency cases occur without notice, so methods using pre-installed anchor nodes will not work effectively in emergencies. Real-time localization solutions without needing anchor nodes or other equipment is more useful in emergency cases.

4 Standards

Three standards related to location based services were researched. While none of these standards seem to be in wide use at this time, it was interesting to see what the developers believed were the functionalities required for a location based service, and what they have predicted to be useful for future developments.

4.1 OGC Location Services

The Open GIS Consortium (OGC) Tracking Service Interface Standard defines the bare minimum functionalities for geospatial tracking. The described services in the OGC Location Service Standards (OLS 1.2) are [9]: Directory, Gateway, Geocoding, Reverse Geocoding, Route, Navigation, and Presentation Services. The Directory Service allows the application to access the online directory to search for a location. If the user requests a nearby restaurant or provides a specific address, the application can access the online directory to search for the requested location.

The Gateway Service retrieves the location of the mobile device from the network. An application needing the most updated location may request an updated position of the device or ask for a previous location for another purpose. The Geocoding Service converts a readable address, such as street name or postal code, to a geographical coordinate location. The Reverse Geocoding Service does the opposite, turning a position into an address. Google has their own Geocoding API that is widely used, but the Google Geocoding does not appear to follow the OGC Geocoding standard and is not discussed further in this paper.

The Route Service determines a route from one position to another. The start point may be received from the Gateway Service, and the destination may be described with an address, phone number, or a position determined from the Directory Service. The user also should be able to choose the route, like fastest or shortest distance, and the transportation method. The Navigation Service is an enhanced version of the Route Service and can provide extra information, such as detour routes, directions, or to pass through specified waypoints. The request message of each service consists of different elements. For example, a Directory Service may accept the address, a maximum or minimum distance, range, which database to use, or identification of the destination.

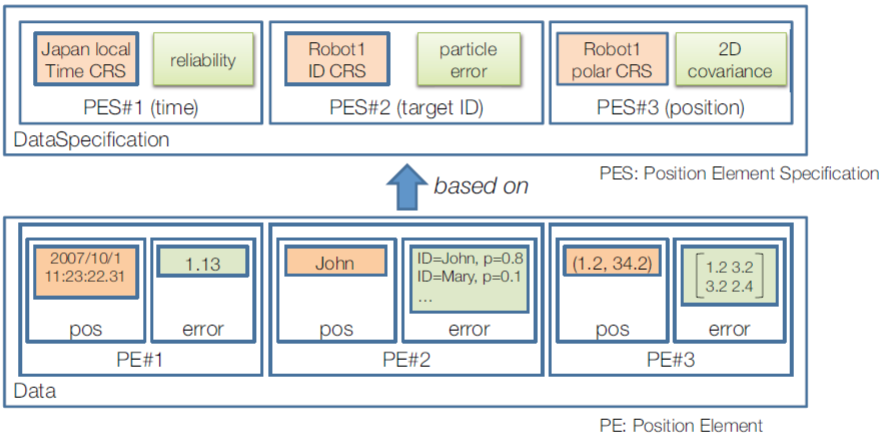


Figure 4.1: Sample data specification for robotic localization service (from [15]).

4.2 Robotic Localization Services

The localization of a robot is similar to localizing any tags or devices as described in Section 3, but if the robot must perform advanced functions like navigating or grabbing, then more parameters are involved. To manipulate the object, the robot must know where the target is located, navigate towards the target while avoiding obstacles, and know the orientation of its arm to reach out. The environment in which this procedure takes place may contain idle or mobile robots, and they may communicate with each other to assist in completing the task.

Each robot or sensor may have its own coordinate reference system (CRS) to locate nearby objects. When the robot moves, the CRS also shifts in space. The coordinate datum used by the robot location service can be a parameter that changes over time. The framework proposed in [15] uses a relative CRS where the relation to the fixed world can be unknown.

Each robot or sensing device creates its own ID system, assigning IDs to localized objects. Similar to how sensors use different CRSs to position localized objects, each sensor uses a local ID system to identify the objects. The localization service framework treats the ID information as positions and with errors (see Figure 4.1). The data structure used in the framework includes multiple measurements, such as position, velocity, or ID, and requires a complex data structure to contain these parameters. The sample robotic localization service data specification is shown in Figure 4.1, which has the position and the error information together.

Robotic localization service module supports at least one of the common data formats such as spherical coordinates for position or Euler angles for orientation [15]. By having this bare minimum requirement in each module, even if the actual data types are different between modules they can still communicate with this simple data format.

The major functionalities required by the robot service modules are localization based on sensors, integrating multiple results, and transforming the results into different CRSs. How the module completes these functionalities are not important, but each module's ability must be known. The ability of the module defines how the functionality is performed and configured, and it describes the parameters involved. This ability description helps in environments where multiple robots are deployed and it is essential to know each module's capabilities.

The steps in robotic localization service [15] are:

1. Obtain ability description (optional)
2. Set up parameters (optional)
3. Establish Connection
4. Set initial data (optional)
5. Perform data passing
6. Perform adjustment (optional)
7. Disconnect

4.3 Mobile Location Service Requirements

Open Mobile Alliance (OMA) proposed a set of location specifications for a mobile location service. When an application requests the location of the target with high accuracy, the server may respond with an increasing precision.

The steps in Mobile Location Service [2] are:

1. An application requests the location to the Mobile Location Service (MLS) Enabler, the source that returns location data.
2. The MLS Enabler selects an available positioning method to calculate the target location.
3. The selected method is performed to obtain locational data.
4. The obtained locational data is transformed into a valid format which can be read by the application.
5. The MLS Enabler responds with the transformed locational data and the associated precision.
6. The MLS Enabler continues to calculate the location with an increasing precision. During this procedure, it may send interim results to the application.
7. The final, most accurate result is returned.

The OGC Location Service Standards contained details about each service requirement. For example, the standard focused on how the location service may be used, including services such as Geocoding or Directory Services which are not necessarily related to localization itself. However, the OMA standard focused specifically on the mobile location service, where the application only requests its location to the MLS Enabler, and no considerations to Geocoding or Directory Service were given. All three of these standards do not seem to be in wide use, as can be seen from their last update dates which are 2008 for OGC, 2010 for the Robotic, and 2011 for the OMA standard. These documents were the most recent documents available, meaning it has been years since their last update.

5 Summary

Indoor location services may be supplementary options to enhance an existing service, like advertising services, or it may be a crucial feature, like localization in emergency cases. Many solutions exist and new methods are in research to produce better location estimates. For indoor localization, an error of several meters can locate the user in a different room or a floor, making the location based services ineffective. Certain services depend heavily on the accuracy of the position estimation, for example emergency services, and errors can be life threatening.

A detailed table for localization methods is shown in Tables 1 and 2, with its range, mean error, user interaction, rate of update, existence of a server, and whether it requires pre-installed anchor nodes as columns. The mean error for most indoor localization methods are very low, UWB systems have a minimum mean error of $0.1m$, and the maximum mean error of $3m$ is still accurate. The BackPos method has a low mean error of $0.128m$, but when compared to an UWB system, its range is extremely small ($<1m$). For UWB systems, the target device may be aware of its own location, which is useful, for example, when a robot needs its location for navigation. For services that do not require this function, like tracking people on the server, self-awareness of location can be removed to use less computation power, and less cost, which can lead to a wider range of users. The indoor localization method may be chosen depending on the services provided from it, which is discussed in Table 3.

The second summary table, Table 3, shows each service with its acceptable range, hardware dependency, and server requirement. Services may or may accommodate additional hardware for the users. For example, someone using an advertising service may not wish to purchase additional hardware. For navigation, tracking, and people location services, additional equipment may be used to produce accurate results, or existing equipment may be used. Someone using a navigation service could use her smartphone for localization, or she may use an UWB module for enhanced localization. The server requirement is similar; the server may or may not be used, depending on the service provider. For advertising and emergency services, the server is mandatory to keep the advertisement lists or to track the location of all rescuers on the mission. The other three services may use a server to track the location of targets, for example an inventory, or a people tracking service may create a map with localized targets. On the contrary, the targets may use a local server on the device, or no server, which can reduce the communication

Table 1: Summary table for localization methods, part 1.

System name	Pre-install anchor nodes	Mean error (m)	Range (m)	User interaction
Hybrid (H)	No	~ 10	many km	None
Swadloon (S)	Yes	0.50	32	Minimal
UWB (U)	Yes	0.1 to 3	50 to 300	None
Image (I)	Yes	2 to 6	10 to 30	Significant
BackPos (B)	No	0.128	<1	None

Table 2: Summary table for localization methods, part 2.

System name	Device aware of its own location	Rate of position update	Server required
Hybrid (H)	Yes	Slow	Yes
Swadloon (S)	Yes	NA	No
UWB (U)	Yes or no	100 to 200 Hz	No
Image (I)	Yes	Slow	Yes
BackPos (B)	No	NA	No

delays between the target and the server.

Table 3: Summary table for indoor location services.

Name	Acceptable error range (m)	Additional hardware acceptable for users?	Server required	Acceptable methods
Advertising	1 to 5	No	Yes	H, S, I
Navigation	0.5 to 3	Yes or no	Yes or no	H, S
Tracking	5 to 10	Yes or no	Yes or no	H, U, B
People Location	1 to 5	Yes or no	Yes or no	H, S, U, I, B
Public Safety	0.5 to 1	Yes	Yes	U, B

6 Future Work

There are many indoor localization solutions available with high accuracies, but a large portion of these solutions have only been tested in empty rooms, or line-of-sight environments. An indoor environment involves many obstacles interfering the signal waves transmitted through space, altering its strength or blocking the wave. Since the location parameters are not in their natural forms, they will cause error in localization. While certain services are not influenced greatly by localization errors, for other services a small error of a few meters can be critical, and must be researched further [17].

A solution by Tian et al [20] tries to solve a non-line-of-sight problem by finding another location where there is line-of-sight. While this solution is easy to visualize, in practice it may be difficult to detect a non-line-of-sight environment and to find a suitable replacement location. The replacement location may be at an extreme angle which causes larger errors, or such location may not exist and the system must tolerate weakened signals to locate the target. In such cases, it may produce better results if the system chooses the location estimate with the highest accuracy from a set of results produced from deflected or weakened signal waves. While the first step to solving the non-line-of-sight problems would be to detect a non-line-of-sight between the target and the source, this first step may be difficult to overcome, or useless in certain cases. This problem occurs frequently in indoor localization, but a solution to overcoming this problem is still under investigation.

From the Table **??**, the UWB system has a very low mean error while its range is fairly large compared to other methods. UWB systems work effectively for indoor environments, and the sensors and tags are relatively small. If the UWB system is integrated with another system, localizing the tag would be equal to localizing the target system. For example, if the UWB sensor module was integrated with a smartphone, then the smartphone can be localized by using UWB positioning methods. Finding a method for integrating an inexpensive UWB module to a smartphone can allow regular smartphone users to utilize indoor location based services with a simple plug-in device.

Real-time positioning systems may be used for navigation services, and they can also be used to automatically update the user position for advertising services. An indoor location based service could use the real-time positioning system to provide fast services to the users, but problems can occur with the server if the server response is more than one or two seconds. The server and the positioning system must be integrated efficiently to provide timely services to the users.

By remembering which direction the user has come from, at which points the user had stopped, or at what speed the user is moving at, it may be possible to estimate the user's future movements. For example, as the user enters a particular store section, the advertisements for that section may be shown. Since data request and response have delays, this is not very likely to happen exactly on time if future prediction is not used. When the user enters a section, the user location is obtained by the indoor localization method, which is sent to an application for the advertising service. The application returns with the appropriate list, but this may take a few seconds depending on user hardware, the indoor localization method, data communication delays, and server traffic. The user may have already left the area by the time the application displays the advertisement. It is very difficult to predict human movements as they are bound to change routes at unexpected locations, but it should still be possible to predict user movement with a fairly high accuracy.

Many of these indoor services may be applied to robots, instead of humans. The robots can be used in factories for dangerous tasks, or be used as rescue robots in emergency situations [7]. The robotic services standard [15] proposed some functionalities these robots should contain, such as easy communication links between them. This standard uses direct communication between robots, but another method proposed by Hu et al [7] uses cloud computing to allow robots at further distances to communicate with the cloud. The main idea of cloud robotics is to have the information stored on the cloud for all robots to access, while the robots only keep the hardware such as sensors, actuators, or basic processing power. The robots may communicate with the cloud if they are within range of a cloud access point, and they can also communicate with each other if they are within range. The robots closer to the cloud access point can retrieve the tasks and database, and pass the information to other robots which have no direct access to the cloud access point. This allows the robots to use the same data over the whole system, and use less storage. For this cloud service, if this is implemented with indoor location based services such as emergency services, it would be very useful as their storage space can be very small, and the robots can focus only on indoor localization while the cloud stores the data. The idea for cloud robotics is very useful, but challenges such as worst case communication delay, trade-off for energy use by robots for cloud communication, and security concerns remain to be solved.

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