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Review on Ultra Wide Band Indoor Localization

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ABSTRACT

Ultra-Wide Band (UWB) is an important means of indoor positioning. Carrying out the research of UWB is of great significance to the development of indoor positioning technology. This article gives a review of the application of UWB in indoor positioning. The motivation and development status of UWB are introduced. UWB localization algorithms such as received signal strength indication, time of arrival, time difference of arrival are analyzed one by one. In this paper, the derivations of the algorithm are summarized. Several technical difficulties of UWB technology development and future development of UWB are presented. This paper provides researchers with a clear insight into the UWB indoor positioning system so that they can further develop other advanced techniques.

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1. INTRODUCTION

1.1. Motivation

The development of the Internet of things and wireless communication technology makes people more and more concerned with the indoor positioning. There are several potential applications such as navigation within a complicated building, industrial automation, and guaranteeing the safety of tunnel construction personnel to mention a few. Nevertheless, it is difficult for the traditional global positioning system (GPS), which is applied widely in the outdoor environment, to provide satisfied indoor localization information due to attenuated signals and complexity of interior construction. Thus, other technologies like Bluetooth, Wireless Fidelity (WiFi), Radio Frequency Identification (RFID), and Ultra-Wide Band (UWB) were established to achieve the goal of accurate positioning in buildings. Among all of them, UWB localization system, which sends ultrashort pulses (typically <1 ns) periodically to transmit data based on a wide spectrum (even >500 MHz wide) (Liu *et al.,* 2007), appears to have various advantages: strong anti-interference ability due to wideband and superior penetration compared with Bluetooth; centimeter-accuracy provided (Erić *et al.,* 2013) compared with WiFi whose average precision is about 3~4 meters along with unacceptable large errors (e.g., 6~8 m) sometimes occurring (Liu *et al.,* 2014); relatively wider regional scope and lower power consumption compared with limited RFID. In addition, the implementation of UWB system structure is relatively simple since it applies nanosecond non-sinusoidal narrow pulse instead of a traditional carrier wave. Strong multipath resolution is also advantageous, reducing the interference caused by reflections and improving communication quality, due to the ultra-wideband. Based on its outstanding performance, UWB is considered as the most promising positioning system at present. Therefore, it is meaningful to do explorations on its precision.

1.2. Development Status of UWB

At present, although many countries have put a lot of effort into the research of UWB, there is still no mature product for the public in the market. Before the 21st century, UWB technology was mainly used in the military field, involving military communication and positioning (Abdulghafor *et al.,* 2019). However, because UWB has been used in the military field for a long time made UWB lacks development in the civilian market (Davide *et al.,* 2009). Until the 21st century, the rapid development of science and technology, people's living standards have been greatly improved and began to pursue more high-quality wireless services (Khan *et al.,* 2019). UWB began to slowly open to the public, and government officials gradually opened up the extensive research of UWB technology.

UWB technology is a new wireless technology which is different from traditional communication technology, it does not need to use the carrier wave in traditional communication system, but transmits and receives very narrow pulses in the level of nanosecond or less. Due to its advantages of strong penetration, low power consumption, good anti-interference effect, high security, low system complexity, and accurate positioning accuracy, UWB is widely used in indoor positioning (Peng *et al.,* 2019). Meanwhile, in December 2008, China's Ministry of Industry and Information Technology issued the "UWB Technology Frequency Usage Regulation". Specifies the bandwidth of the UWB device and the EIRP value (Vivek *et al.,* 2017).

UWB itself has the characteristics of extremely narrow pulse and extremely wide frequency band, its bandwidth is equivalent to 1,000 TV channels or 30,000 FM radio channels (Stan and John, 2003). In addition, the state has very strict limits on its equivalent isotropically radiated power (EIRP), therefore, the power density of UWB equipment within the unit bandwidth is very low, and its power density is even lower than the general noise level (Shou *et al.,* 2011). Thus, the UWB device has such a low power density that it has very little interference with other devices and is highly compatible. **Table 1** shows EIRP limits for UWB equipment in China.

Table 1. EIRP limits for UWB equipment in China

Frequency range (GHz)	Limit (dBm/MHz)	Detection methods
1.6	-90	RMS
1.6~3.6	-85	RMS
3.6~6.0	-70	RMS
6.0~9.0	-41	RMS

Currently, the leading countries in UWB technology research are mainly the United States, Japan, and the European Union. The two leading companies in the U.S. are MOTOROLA and Intel, but they implement their UWB technology in different ways. Intel uses the multi-band approach, while MOTOROLA uses the single-band approach (Huan-Bang *et al.,* 2020). The Xtreme Spectrum is MOTOROLA's second-generation chip with speeds up to 114 Mbps and power consumption up to 200 mw, and A small number of prototypes of this chip are already in circulation (Kazemi, 2018). At the same time, Intel showed off its first UWB chip using 90 nm technology at a recent forum, It is also the first demonstration of a 480 Mbps wireless UWB technology with a range of more than 10 M. Since then, Singapore researchers have been able to increase the transmission rate of UWB technology to 500 Mbps, which is the world's fastest UWB technology (Trivedi *et al.,* 2019).

The remainder of this article is organized as follows. The next section introduces several mainstream algorithms applied in UWB technology and briefly presents the history, development of these algorithms. Section 3 and section 4, the derivation of the algorithm and future development of UWB are described respectively. Section 5 provides some future development areas of UWB and many of the technical difficulties of UWB will also be demonstrated in this section. Finally, section 6 concludes the article with a critical perspective.

2. LOCALIZATION ALGORITHMS

To realize the UWB localization system, firstly the wireless positioning technology is needed to estimate the distance between anchors and the tag, then the equation set representing tag location will be solved with the positioning algorithm. Additionally, filtering will be applied to eliminate the noises and get higher positioning accuracy. Several common filtering, along with positioning technologies and algorithm are introduced as follow.

2.1. Distance Measurement Technology

2.1.1. Received Signal Strength Indication (RSSI)

In the application of RSSI technology, the distance between tag and anchors can be calculated using energy loss during signal propagation. But the signal is easily affected by multipath effect, multiple access interference and background noise, etc. (Huang, 2020). which represents that energy loss during signal propagation cannot be measured accurately. Cao *et al.* developed an indoor localization algorithm based on RSSI, combining both Convolutional Natural Networks (CNN) and fingerprint library. Simulation results show positioning accuracy within 1 m is approximately 65%, and 85% for 1.5 m precision (Cao *et al.,* 2020). Also, in order to improve the positioning accuracy of traditional wireless signal path loss, a new method optimized by genetic algorithm (GA) was proposed: experimental results represent that accuracy of the proposed model is 48 % better than previous one, without requiring dependence on environmental parameters (Yu *et al.,* 2020).

2.1.2. Time of Arrival (ToA)

ToA theory is able to figure the distance between anchors and tag out by measuring the arrival time of the received signal. Then circles can be drawn using the base stations as center and distance as radius, whose intersection area represents the location of the mobile tag. As **Figure 1** shown, this method requires at least three base stations to calculate the tag location. Though ToA has relatively high accuracy, it requires accurate time synchronization between nodes.

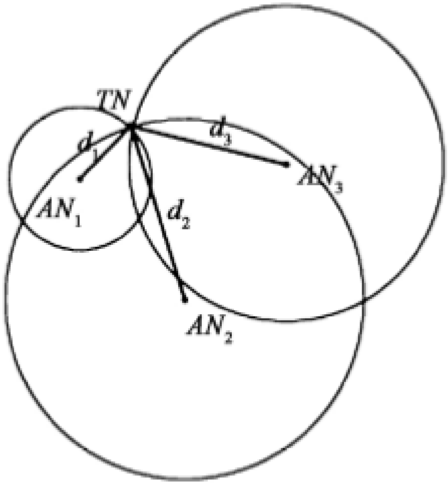

Figure 1. Two-dimensional ToA Positioning System with three fixed anchors (Liu *et al.,* 2007).

Lei *et al.* developed a high precision ToA estimation algorithm for low-frequency groundwave propagation with Loran C data as correction, both simulation and real results demonstrate its feasibility (Lei *et al.,* 2020). In order to reduce the positioning error caused by clock drift of the UWB system, the SDSTWR algorithm is proposed. Meanwhile, the steady-state error is attenuated by the addition of Receiver Autonomous Integrity Monitoring (RAIM) algorithm. Experimental data shows the positioning accuracy improved from 30 cm to about 18 cm (Yu *et al.,* 2019).

2.1.3. Time Difference of Arrival (TDoA)

To measure the distance between fixed anchors and tag, TDoA measurement is implemented.

a. The Tag sends a signal to four surrounding anchors;

b. Estimating 6 times difference of arrival of each two-anchor pair;

c. Converting time difference into the distance;

d. Plotting hyperbola for each pair

Du *et al.* proposed a method to reduce energy waste along with increasing anchors number: it combines Cramer-Rao Lower Bounds of target position space rule and K-means algorithm. Simulation results show a higher positioning accuracy for the proposed TDoA system (Du *et al.,* 2020). Also, based on TDoA, Wang developed a system using a set of calibration sources as an estimator to reduce the attenuate influence of non-synchronization (Wang *et al.,* 2019).

2.1.4. Angle of Arrival (AoA)

AoA theory achieves the distance between anchors and tag by measuring the arrival angle of the received signal. Antenna arrays are widely used to determine the angle α_i (i = 1,2 for a two-dimensional case, as **Figure 2** represents). Angles of arrival α_1, α_2, and given distance L_{12} between these two fixed anchors will act as inputs to solve location (x,y) of the mobile anchor using trigonometry.

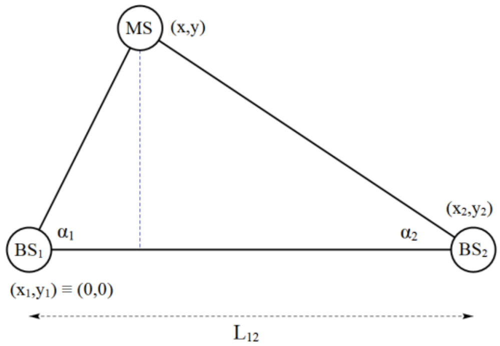

Figure 2. AoA Positioning with two fixed stations (Stan and John, 2003).

Then rays can be drawn from each fixed anchor with a specific value of the angle. As **Figure 2** shown, only two rays can lead to an intersection point, which is the theoretical localization of tag. Therefore, this method requires only two base stations for positioning.

The corresponding solution from (Ngoc *et al.,* 2013) is shown as follows:

$$\begin{bmatrix} x \\ y \end{bmatrix} = \begin{bmatrix} \frac{\cos\alpha_1 \sin\alpha_2}{\sin(\alpha_1+\alpha_2)} L_{12} \\ \frac{\sin\alpha_1 \sin\alpha_2}{\sin(\alpha_1+\alpha_2)} L_{12} \end{bmatrix} \quad (1)$$

Collecting and rearranging equations about L_{1n} will obtain H x = b. where,

$$H = \begin{bmatrix} 1 & 0 \\ 0 & 1 \\ 1 & 0 \\ 0 & 1 \\ \vdots & \vdots \\ 1 & 0 \\ 0 & 1 \end{bmatrix}, x = \begin{bmatrix} x \\ y \end{bmatrix}, b = \begin{bmatrix} \frac{\cos\alpha_1 \sin\alpha_2}{\sin(\alpha_1+\alpha_2)} L_{12} \\ \frac{\sin\alpha_1 \sin\alpha_2}{\sin(\alpha_1+\alpha_2)} L_{12} \\ \vdots \\ \frac{\cos\alpha_1 \sin\alpha_n}{\sin(\alpha_1+\alpha_n)} L_{1n} \\ \frac{\cos\alpha_1 \sin\alpha_n}{\sin(\alpha_1+\alpha_n)} L_{1n} \end{bmatrix} \quad (2)$$

Then, the LS solution is given by,

$$x_{LS} = \left(H^T H\right)^{-1} H^T b \quad (3)$$

For higher precision of an AoA localization three-dimensional system, Bartosz *et al.* constructed an analytical method linking UWB with Real-Time Locating System (RTLSs) (Bartosz *et al.,* 2017).

2.1.5. TDoA/ AoA

Due to the limitation of single wireless positioning technology, the research community also investigates the integration of multiple technologies.

TDoA based AoA is one of the most common ones since it enables researchers to reduce the number of anchors and improve the accuracy of indoor positioning. Additionally, TDoA focuses on the time difference of arrival from tag to a pair of fixed anchors, there is no requirement for anchors synchronization. Therefore, it is widely selected for the positioning system due to its accuracy and convenience.

Many types of researches have been done based on hybrid technique TDoA / AoA. As what is represented by **Figure 3**, for a two-dimensional positioning system, AoA theory will be applied after basic measurements from TDoA, using Eq. (4) for the position of the target.

$$d = \sqrt{\left(\frac{d_1^2 - d_2^2}{4l}\right)^2 + \left(d_1^2 - \left(\frac{d_1^2 - d_2^2}{4l} + l\right)^2\right)} \quad (4)$$

Additionally, Zhang *et al.* investigated a three-dimensional localization algorithm based on RSSI-ToA, using RSSI ranging in the near and ToA in the far end. Simulation results show that this stated algorithm has higher positioning accuracy and lower energy consumption (Zhang *et al.,* 2019).

Also, the combination of TDoA with the AoA is proposed in Yang's research (Yang, 2019). AoA is added to deal with the unreasonable case with more than one intersection of hyperbola derived from TDoA, and its validity is checked by simulations.

2.2. Positioning Algorithm

With each two-anchor pairs, locations of tag can be represented as the well-established ternary equation system of hyperbolas obtained from TDoA. However, it is exceptionally troublesome to directly solve the hyperbolic equations to get the intersection as a specific position. Therefore, they are required to be linearized by further algorithms such as Fang algorithm, Chan algorithm, and Taylor series method.

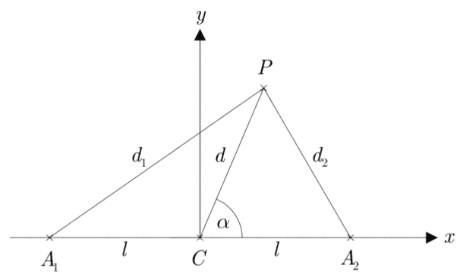

Figure 3. Two-dimensional Combined TDoA/AoA Positioning with two fixed stations (Du and Chen, 2020).

Fang algorithm is a convenient non-recursive method with few calculations to linearize the hyperbolas, but it can't fully take advantage of abundant information provided by more than three anchors to achieve higher accuracy (Fang, 1990). Chan algorithm is also a non-recursive hyperbolic equation solution with an analytic expression solution (Cheng *et al.,* 2019). High positioning accuracy and comparably small calculations are achieved when measurement error obeys the ideal Gaussian distribution in line of sight environment. Additionally, the accuracy of the algorithm can be improved by increasing the number of anchors rather than be limited to three anchors. Taylor series method can achieve high precision and robustness by performing Taylor extensions on hyperbolas to carry out complex recursive calculations. However, the effectiveness and complexity of this method are highly influenced by the accuracy of the initial tag position (Li *et al.,* 2018).

Compared with Fang algorithm, Chan proves to be advantageous since it can be applied in the situation with more than three anchors. When it comes to Taylor, Chan turns out to be easier to carry out without the requirements of initial position and complex recursive procedures. In order to provide a basic and typical concept for researchers, later Chan algorithm for four anchors is specifically introduced.

2.2.1. Kalman Filtering

Kalman Filtering is implemented to positioning algorithm for noise eliminating and interference reduction. It consists of two processes: prediction and correction. For prediction, it will estimate a prediction for the current state from data of the previous state. Then the observed value of the current state will be compared with the predicted value. A new estimation at that point, which is more accurate, can be obtained. Besides, Kalman filtering has limitations since it is only appliable to a linear system. For a nonlinear dynamic system, extended-Kalman filtering is developed, and it is often applied in the target tracking system.

Currently, there are many researches based on Kalman filtering. Wang *et al.* developed a localization algorithm combing traditional TDoA and filtering for higher UWB positioning accuracy: Kalman filtering and median average filtering algorithm are added to attenuate the accuracy decrease with mobile tag (Wang, 2017).

3. ALGORITHM DERIVATION

Compared with Fang and Taylor algorithm, Chan algorithm turns out to be more effective and simpler, as it is mentioned before, to obtain the precise positions of the tag. Thus, it is specifically derived to provide researchers with a basic and clear understanding of the localization procedures.

Set T(x,y) as tag position, X_i(xi,yi) as known position, where i∈[1,n], assuming n known points available. Then the distance between T and each X_i is:

$$r_i = \sqrt{(x_i - x)^2 + (y_i - y)^2} \quad (5)$$

Apply X_i as the reference, the difference between the distance from T to X_i (i≠1) and from T to X_1 is:

$$r_{i,1} = ct_{t,1} = r_i - r_1, i = 1, 2, \cdots n \quad (6)$$

where, c is the speed of electric wave; and $t_{t,1}$time difference of wave traveled from T to X_i and from T to X_1.

According to Eq. (5) and Eq. (6),

$$\begin{aligned} r_{i,1} &= r_i - r_1 = r_i \\ &= \sqrt{(x_i - x)^2 + (y_i - y)^2} - \\ &\quad \sqrt{(x_1 - x)^2 + (y_1 - y)^2} \end{aligned} \quad (7)$$

With derived equation from Eq. (5), we have:

$$r_i^2 = (x_i - x)^2 + (y_i - y)^2 = K_i - 2x_i x - 2y_i y + x^2 + y^2 \quad (8)$$

where, $K_i = x_i^2 + y_i^2$,

Therefore, Eq. (7) can be rewritten as follows:

$$r_i^2 = (x_i - x)^2 + (y_i - y)^2 = K_i - 2x_i x - 2y_i y + x^2 + y^2 \quad (9)$$

Then, plug Eq. (8) back into Eq. (9), which is the linearization step to eliminate squared terms of the unknown point positions.

$$\begin{aligned} & r_i^2 = (r_{i,1} + r_1)^2 \Leftrightarrow \\ & K_i - 2x_i x - 2y_i y + x^2 + y^2 \\ & \quad = r_{i,1}{}^2 + 2r_1 r_{i,1} + r_1^2 \Leftrightarrow \\ & K_i - 2x_i x - 2y_i y + x^2 + y^2 \\ & \quad = r_{i,1}{}^2 + 2r_1 r_{i,1} + (x_1 - x)^2 + (y_1 - y)^2 \Leftrightarrow \\ & K_i - 2x_i x - 2y_i y \\ & \quad = r_{i,1}{}^2 + 2r_1 r_{i,1} + x_1^2 - 2x_1 x + y_1^2 - 2y_1 y \Leftrightarrow \\ & r_{i,1}{}^2 + 2r_1 r_{i,1} \\ & \quad = K_i - x_1^2 - y_1^2 - 2(x_i - x_1)x - 2(y_i - y_1)y \Leftrightarrow \\ & r_{i,1}{}^2 + 2r_1 r_{i,1} \\ & \quad = K_i - K_1 - 2x_{i,1}x - 2y_{i,1}y \end{aligned} \quad (10)$$

where, $x_{i,1} = x_i - x_1, y_{i,1} = y_i - y_1$

Then, a linear equation set is obtained through Eq. (10):

$$r_1 r_{i,1} + x_{i,1}x + y_{i,1}y = \frac{1}{2}\left(K_i - K_1 - r_{i,1}{}^2\right) \quad (11)$$

Set $z_a = \begin{bmatrix} x \\ y \\ r_1 \end{bmatrix}$ as independent variables, rewrite the linear system as,

$$G_a z_a = h \quad (12)$$

With $G_a = \begin{bmatrix} x_{2,1} & y_{2,1} & r_{2,1} \\ x_{3,1} & y_{3,1} & r_{3,1} \\ \vdots & \vdots & \vdots \\ x_{n,1} & y_{n,1} & r_{n,1} \end{bmatrix}$,

$$h = \frac{1}{2}\begin{bmatrix} K_2 - K_1 - r_{2,1}{}^2 \\ K_3 - K_1 - r_{3,1}{}^2 \\ \vdots \\ K_n - K_1 - r_{n,1}{}^2 \end{bmatrix}.$$

In order to improve localization precision, the measurement error needs to be reduced.

Assume the error vector,

$$e = h - G_a Z_a^0 \quad (13)$$

approximately obeys Gaussian Distribution. And the covariance matrix can be defined as,

$$\psi = E\left(ee^T\right) = c^2 BQB \quad (14)$$

Where, $B = diag\{r_2^0, r_3^0, \cdots, r_n^0,\}$ and Q is the vector covariance matrix of noise (also obey the Gaussian Distribution).

Therefore, the least-squares solution of Eq. (13) is successfully converted to a normal equation solving:

$$G_a{}^T G_a z_a = G_a{}^T h \quad (15)$$

With the assumption that all elements in z_a are mutually independent, the error of each group of data will be determined separately. Then it can be solved with a weighted least square method using Eq. (15):

$$\left(G_a{}^T \psi G_a\right) z_a = G_a{}^T \psi h \quad (16)$$

Currently, z_a can be easily obtained by:

$$z_a = \left(G_a{}^T \psi^{-1} G_a\right)^{-1} G_a{}^T \psi^{-1} h \quad (17)$$

The actual distances between T and X_i can be calculated with matrix B, but the complex relationship requires a large amount of calculation and it is unclear. To find the wanted data, we use Q instead of ϕ when the T is comparably far from X_i.

$$z_a \approx z_a = \left(G_a{}^T \psi^{-1} G_a\right)^{-1} G_a{}^T \psi^{-1} h \quad (18)$$

To find the value of z_a with satisfying precision, several estimation steps will be repeated. First, plug the initial solution of Eq. (18) back into matrix B, and use the new matrix B to evaluate z_a through Eq. (16). The second evaluation z_{a1} will be realized with an equation system constructed with z_a, applying measurement error:

$$\begin{cases} z_{a,1} = x^0 + e_1 \\ z_{a,2} = y^0 + e_2 \\ z_{a,3} = y^0 + e_3 \end{cases} \quad (19)$$

where, $z_{a,i}$ represents the i-th component, i∈[1,3]. e_1, e_2, e_3 are the correspondingly estimated error.

Then, the second evaluation can be realized:

$$z_a = \left(G_a{}^T \psi^{-1} G_a\right)^{-1} G_a{}^T \psi^{-1} h_W \quad (20)$$

here, $z_{a1} = \begin{pmatrix} (x - x_i)^2 \\ (y - y_i)^2 \end{pmatrix}$, $G_{a1} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \\ 1 & 0 \end{bmatrix}$,

$$h_1 = \begin{bmatrix} (z_{a,1} - x_1)^2 \\ (z_{a,2} - y_1)^2 \\ z_{a,3}{}^2 \end{bmatrix},$$

$\psi = 4B_1 \operatorname{cov}(z_a) B_1$,

$B_1 = diag\left\{x^0 - x_1, y^0 - y, r_1^0\right\}$,

$\operatorname{cov}(z_a) = \left(G_a{}^{0T} \psi^{-1} G_a{}^0\right)^{-1}$

Finally, the actual position of the tag can be obtained:

$$(x, y)^T = \pm\sqrt{z_{a1}} + (x_1, y_1)^T \quad (21)$$

In order to address the shortcomings of some individual technology, many researchers implement filters to fuse UWB and IMU (Liu *et al.,* 2017) (Yao *et al.,* 2017) to improve precision. The main process is to adjust the parameter in the filtering based on the performance of two data resources so that the corrected position can be presented. Since this paper proposes to show a basic introduction for researchers, the fusion process is not shown.

4. FUTURE DEVELOPMENT OF UWB

With the progress of The Times, UWB positioning technology will gradually spread to every corner of life. Its usage scenarios will be greatly extended. For example, use UWB in the underground garage of a large shopping mall or railway station. In China, such underground garages are often very complex, with many levels and divided into many different areas. It is no exaggeration to say that underground garages are like labyrinths. And because the garage is underground and is an enclosed indoor environment, it is difficult for traditional GPS to give people accurate positioning. This makes it difficult for people to find their parking space. With UWB, people and their own cars can be accurately positioned at this time. A special APP can also be developed to assist the process of certain parking spaces so that people can quickly find parking spaces. Meanwhile, the algorithm of UWB can be combined with the convolutional neural network in deep learning in the future, so as to achieve higher accuracy. The convolutional neural network can learn the deep and abstract characteristics of the data from a large number of sample data and can be applied to the study of indoor positioning to achieve the effect of independent optimization of the route (Baojun *et al.,* 2020). At the same time, because the transmission distance of the UWB signal in the room is limited, and its signal will have a large error when circumnavigating obstacles, it is not competent for the NLOS scene or indoor scene with the blind area. Meanwhile, PDR is a good NLOS positioning method, which can obtain motion information such as acceleration and direction through multi-axis inertial sensors and calculate pedestrian position cumulatively. In the future, researchers can fuse UWB algorithm with PDR algorithm to solve the problem that UWB cannot be applied in NLOS scenarios, and the motion data such as heading Angle obtained from IMU can also improve the jitter caused by the inherent error of UWB system (Jianming *et al.,* 2020).

At the same time, the development of UWB also has many challenges. For example, UWB MIMO technology. The bandwidth of UWB technology makes it have super data transmission capability. But to achieve the theoretical transmission power must produce a lot of radiation power. However, the combination of UWB and MIMO technology provides a new solution to the power problem. UWB can also be combined with cognitive radio. In this way, cognitive UWB (CUWB) can be built. CUWB can intelligently manage the spectrum and adjust the waveform according to the cognitive radio's perception results, so as to improve the efficiency. In this way, the original bottleneck of UWB can be broken and various shortcomings of UWB can be solved without increasing interference to existing equipment.

So, UWB research is a long way off, and we still have a lot more difficulties to overcome. However, UWB research has a bright future, and it will certainly benefit society. So, we have to persevere to overcome different problems. Promote UWB to every part of society.

5. CONCLUSION

The need for location-based services has aroused great concern currently. This review paper discusses the UWB and its application in indoor localization. The reason why UWB is considered as a promising positioning method is explained from its origin and development state. It also introduces and compares different distance measurement technologies as well as positioning algorithms applied to implement the indoor positioning system. Besides, some technical difficulties and future development of the UWB indoor localization system are listed to provide researchers with a clear insight on the realization of it.

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