Survey of Indoor Positioning Systems Based on Ultra-wideband (UWB) Technology

Guowei Shi and Ying Ming

Abstract Indoor positioning is a challenging research area, and various kinds of indoor positioning systems have been developed based on different technologies. Ultra-wideband (UWB) positioning technology is mainly used for high-accuracy indoor wireless positioning. This paper provides an overview of indoor positioning solution based on UWB technology. First, the conception, standardization, and advantages of UWB were introduced, and then four location measure techniques based on UWB technology are analyzed. Finally, the applications and future trends for the technology are provided.

Keywords Indoor positioning systems · Ultra-wideband · Measure technique

1 Introduction

In recent years, location-based services have a large amount of demands for various applications, such as navigation and tracking [1–3]. Location information becomes one of the key factors to analyze people's behavior. For outdoor location information, we can obtain it easily using GPS. The accuracy could achieve 10 m for commercial utilization. Currently, GPS has been the standard configuration of mobile devices. Same as outdoor location information, indoor location information is very useful for applications, like personalized service in banking, retail, healthcare, and workforce management. It is estimated that the indoor positioning market will achieve to $2.60 billion by 2018, forecasted by Markets and Markets.

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Q.-A. Zeng (ed.), *Wireless Communications, Networking and Applications*,
Lecture Notes in Electrical Engineering 348,
DOI 10.1007/978-81-322-2580-5_115

Compared with outdoor positioning, indoor location information is more difficult to obtain due to the complex indoor environment, which could cause the reflection and attenuation of signals, and also mix with various interference from walls, furnishes, and even human [4]. GPS for outdoor positioning has poor performance for indoor positioning because the line-of-sight (LOS) transmission between GPS devices and satellites will be attenuated in an indoor environment. Therefore, indoor positioning has more technical challenges than those of outdoor positioning. There are many techniques used in the indoor positioning [5–7]. Figure 1 shows the main methods used in indoor positioning. They can be classified based on the media used or the principle used. Based on the media used, the main indoor positioning techniques can be classified as several types, as illustrated in Table 1.

Techniques using Based on the principles used for positioning, the techniques can be classified as:

- Techniques using angle of arrival
- Techniques using time of arrival
- Techniques using signal strength
- Techniques using proximity

When evaluating a technique for indoor positioning, we should consider the accuracy, deployment complexity, cost, and easy portable. Taking WiFi as an

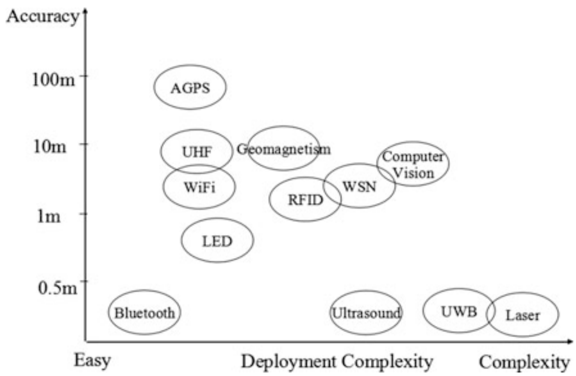


Fig. 1 Comparison of indoor positioning system

Table 1 Indoor positioning techniques based on media

Media	Techniques
Optical	Techniques using LED, infrared, laser
Ultrasound	Techniques using ultrasound
Wireless signal	WiFi, ultra-wide band (UWB), RFID, bluetooth, near field communication (NFC), wireless senor network (WSN), UHF
Magnetic	Techniques using magnetic
Video	Techniques using video

example, we can localize an object using the WiFi signal strength. In general cases, the accuracy of WiFi positioning can be 3–5 m in a typical indoor environment. Since most of mobile phones have WiFi function, this technique is portable and low cost. However, the deployment of WiFi-based positioning system is complex and time consuming. Using fingerprint method, we need to create the radio map before the whole system running. The engineering work is huge with the increasing of indoor size. That's why Apple's iBeacon solution (Bluetooth 4.0) is used in retail widely instead of WiFi. For UWB technology, it can achieve high accuracy up to 20 cm. Therefore, for applications request high accuracy, UWB is the good choice for indoor positioning. In this survey, we focus on UWB IPSs which can provide high-accuracy positioning.

1.1 The Definition of UWB

Federal communications commission (FCC) and ITU-R define UWB as a transmission from an antenna for which the emitted signal bandwidth exceeds the lesser of 500 MHz or 20 % of the center frequency. In 2002, the 3.1–10.6 and 22–29 GHz bands were opened to UWB by FCC, and the power spectral density emission for UWB transmitters was limited within −41.3 dBm/MHz [8].

1.2 The Standardization Efforts for UWB

Channel Model IEEE has standardized the channel models for UWB. For high throughput applications [9], IEEE defines the channel model for IEEE 802.15.3a; And for low data rate systems, IEEE defines the channel model for 802.15.4a [10]. In both of channels models, there are three components to describe the channel model. They are path loss, small-scale fading, and large-scale fading. There are some key differences between IEEE 802.15.3a and IEEE 802.15.4a channel models. First, IEEE 802.15.4a models the channel impulse response as a complex base-band process, while IEEE 802.15.3a uses a real model. Second, ray arrival times in 802.15.4a are mixed Poisson, while IEEE 802.14.3a is modeled as plain Poisson. Third, intra-cluster decay factor depends on cluster arrival time. Fourth, the distribution of small-scale amplitudes is assumed as Nakagami distribution in 802.15.4a, but in 802.15.3a it is a log normal [11].

Physical Layer (PHY) There are three UWB PHY Layer standards defined in IEEE 802.15.4a, IEEE 802.15.6, and IEEE 802.15.4f [12, 13]. IEEE 802.15.4a defines the direct sequence UWB PHY, which is very efficient and can support precision ranging, and is very robust even at low transmit powers. The UWB PHY in IEEE 802.15.4f targets to reduce the transmitter's complexity, simplify the modulations, without scrambling and dithering, and with simple pulse shaping and low pulse repetition frequency (PRF). For impulse-radio UWB, the UWB PHY is defined in IEEE 802.15.16. It includes IR-UWB and FM-UWB technologies. The impulse-radio UWB is mainly used for body area networks (BANs).

1.3 The Advantages of UWB IPSs

UWB IPSs have the following advantages [14]. First, unlike conventional radio systems operating on specific radio frequency, UWB IPS transmits a radio signal over ultra-wide band of frequencies. Second, UWB signals are transmitted for a much shorter duration with very low-power spectral density, so that consume less power than conventional systems. Third, since it has very low-power spectral density, UWB can be used in close proximity to other RF signals without causing or suffering from interference. Fourth, UWB short duration pulses are easy to filter in order to determine which signals are correct and which are reflection and diffraction. Fifth, the UWB signal can transmit easily inside indoor environment. Finally, UWB can achieve very high indoor location accuracy (i.e., 20 cm) with the precise time of arrival (TOA) measurement.

2 Measure Techniques of UWB IPSs

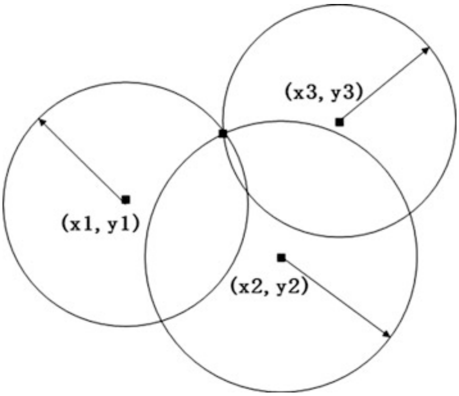
2.1 Measure Technique Based on Time of Arrival (TOA)

TOA is a widely used method to measure the distance between the mobile target and the measuring unit. It is based on the facts that the distance is proportional to the propagation time. For two-dimensions positioning, we need at least three reference points for TOA measurements, as shown in Fig. 2 [15]. For TOA-based systems, the distance could be calculated through measuring the signal propagation time. Using triangulation algorithm, we can derive the position of the mobile user. Direct TOA measurement needs two prerequisites. First, the IPS system should be synchronized for all transmitters and receivers. Second, we need to insert a time stamp at the transmitted packets for propagation time measurement. Errors in synchronization will cause incorrect localization. A direct calculation approach is to compute the intersection points of the circles of TOA using geometric method. The equation of a circle is given by

$$R_i = \sqrt{(x_i - x)^2 + (y_i - y)^2} = c(t_i - t), \tag{1}$$

where c is the speed of light, t_i is the signal arrival time in measuring unit i, (x_i, y_i) represents the coordinate of the beacon unit i, and (x, y) represent the coordinate of the mobile target. The location of mobile target can be calculated using Eq. (1).

Fig. 2 Measure technique based on TOA



For 2-D application, the parameter i can be selected as 1, 2, and 3. Some optimized algorithms used for position computing were proposed by article [16, 17].

2.2 Measure Technique Based on Time Difference of Arrival (TDOA)

Unlike the TOA method that uses the absolute propagation time, the TDOA selects the difference in time to derive the relative position of the mobile target. The difference in time refers to the time difference for arriving at multiple measuring units. It can solve the part of the problem caused by measurement error of TOA. Using measuring units, we can obtain some hyperbolas. The mobile target should be at the intersection of a hyperbola formed through TDOA measurements, as illustrated in Fig. 3. The equation of the hyperbola is given by

$$R_{i,j} = \sqrt{(x_i - x)^2 + (y_i - y)^2} - \sqrt{(x_j - x)^2 + (y_j - y)^2} = c(t_i - t_j), \quad (2)$$

where (x_i, y_i) and (x_j, y_j) represent the coordinate of measuring units i and j; (x, y) represents the coordinate of the mobile target; t_i and t_j represent the signal arrival time in measuring unit i and j; for 2-D application, i and $j = 1, 2, 3, 4$. The answer of Eq. (2) could be derived from nonlinear regression. In [18], the author proposed a linearized iterative algorithm to make it more easier. In [19], Depeng et al. used compressive sensing TDOA for positioning.

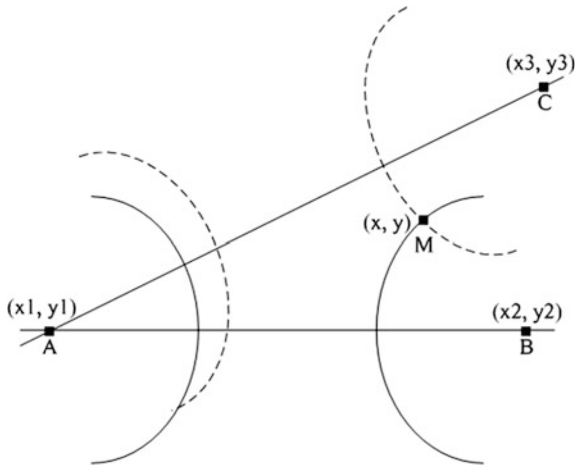


Fig. 3 Measure technique based on TDOA

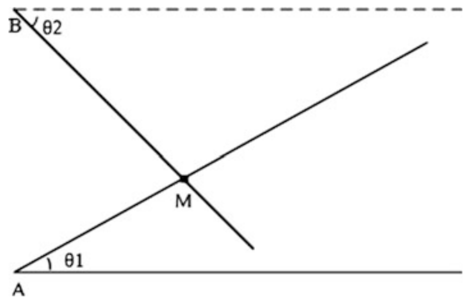


Fig. 4 Measure technique based on AOA

2.3 Measure Technique Based on Angel-of Arrival (AOA)

The AOA method is to use the special information of signals for positioning. According to the angel-of-arrival, we can draw the angle direction line between a measuring unit and the mobile target. The location of the mobile target is the intersection of those direction lines. For a mobile target, it needs two measuring units to form two angels for positioning. Figure 4 is an illustration for AOA. The equation of angel is given by

$$\tan(\theta_i) = \frac{x - x_i}{y - y_i}, i = 1, 2, \tag{3}$$

We can use antenna array or directional antenna to measure the AOA. One of the main advantages of AOA method is no synchronization requirements for the positioning system, which release the issue in TOA and TDOA. Compared with TOA and TDOA, AOA needs less number of measuring units. Thus it will make system deployment easier and faster with less cost. The disadvantage comes from the complexity of hardware used in AOA based system. And the performance degradation for mobile targets moving far away is another main shortcoming of AOA method [20–22].

2.4 Measure Technique Based on Received Signal Strengths (RSS)

The measurement techniques discussed above have a common drawback that they have worse performance for NLOS environment. However, for most of indoor environment, they have furniture, people, and building elements inside, which will cause signals inflection and diffraction. Signals can not propagate in LOS channel and will suffer from multipath effects. Thus the positioning accuracy will decrease. In recent years, positioning methods using signal strength becomes more attractive. Adopting some propagation models, we can calculate the distance between the mobile target and the measuring unit according to the signal strength received at the mobile target. However, the distance derivation largely depends on the propagation model selected. The in-accurate model will cause large error in positioning. In order to release the model-caused issue, scientists begin to use RSS information directly for positioning, such as fingerprint method [23]. For fingerprint method, we need to create a radio map of the indoor environment through RSS measurement. A radio map is a RSS distribution map with pre-defined density and measuring points. With this radio map and updated RSS information, we can derive the position of mobile target through varied machine learning algorithms. In general, it can achieve good performance both for LOS and NLOS channels.

3 Applications of UWB IPSs

3.1 Commercial Applications of UWB IPSs

Indoor positioning system can be used for many applications. Since UWB system can provide high-accurate positioning, it is more often used in applications needed high accuracy, such as military, health care, and asset tracking. Zebra enterprise solution (ZES) and Ubisense demonstrated UWB IPS for asset tracking [24, 25], which utilize TDOA or a combination of TDOA and AOA. A hybrid system named as Navis™, developed by ZES, integrates UWB, GPS, and WiFi for robust asset tracking. The solution could be used for airport process optimization, marine terminals, defense, and automotive assembly optimization, etc. [26]. The Ubisense also developed a system to track automobiles at different stages in assembly plant. It also provided an indoor and outdoor combination positioning solution for military usage, which integrated GPS and UWB technology seamlessly [27]. UWB IPS can also be used in autonomous cruise control, driver assistance and safety systems available in the Mercedes-S Class [28].

3.2 Research Applications of UWB IPSs

In UWB IPS research area, there are major achievements in certain topics, such as high-accuracy 3-D positioning for surgical navigation [29], low-power UWB CMOS for biosensors [30], and the development of the IEEE 802.15.4a standard for WSNs [31]. As depicted in article [29], real-time 3-D accuracy of 5–6 mm was obtained in a range of experiments including tracking a robotic arm, free-form motion, and movement along an optical rail. The WSNs can also be used in personal area networks (PANs) for sensing, communication, and positioning. Recently, the UWB imaging is used for breast cancer detection and through-wall imaging. With integration of UWB positioning and imaging, UWB can be used in a global coordinate system.

4 Conclusion and Future Trends

In this paper, we describe the conception of UWB, introduce the standardization efforts for UWB, and discuss advantages of UWB used for IPS. Then we analyze four location measure techniques based on UWB technology. Finally, we overview the applications of UWB-based IPSs in both commercial and research areas. From this survey, we can see that UWB IPS is promising technology for high-accuracy indoor positioning due to its special characteristics.

For UWB positioning, it will keep on improving the accuracy of positioning, such as 1-mm 3-D accuracy. Compared with other popular positioning technologies based on wireless signals, high accuracy is the key differentiation of UWB IPS. And the UWB IPS will integrate with other systems to make redundant positioning strategy. Since UWB IPS needs special transmitter and receiver, it limits the general applications of UWB on some degree. We can imagine that UWB IPS will coexist with other indoor positioning technologies with considering from different aspects.

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