Recent Advancements in Radio Frequency based Indoor Localization Techniques

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Abstract. Recent developments in location-based services have heightened the needs for decent accuracy localization system for different applications. The Global Positioning System (GPS) provides adequate accuracy in the outdoor environment but suffers from poor localization accuracy in the complex and dynamic indoor environment. Therefore, the number of indoor localization researches to apply in different applications with different technologies have increased in recent years. The purpose of this paper is to summarize recent advancements in Radio Frequency (RF) based indoor localization techniques and provide insights in the indoor localization field especially in the range based localization. The range based localization is then categorized into few common algorithms such as AOA, TOA, TDOA and RSS. The discussion between algorithms in term of their advantages, disadvantages and improvement strategies to improve their accuracy are also present in this paper.

1. Introduction

In recent years, there has been an increasing interest in indoor localization because most of the human activities happen in the indoor environment. According to a survey in [1], the human species had a fundamental characteristic of spending most of their time indoors. Therefore, it is necessary to have an accurate indoor positioning system in modern society. Although the Global Positioning System (GPS) provides adequate accuracy in most of the outdoor application, the performance of GPS drops significantly in indoor environment. From the office localization performed by an active badge to the Internet of Things (IoT) based indoor localization researches, different techniques and measurements are introduced and improved throughout the years [2]. The objective of this paper is to summarize recent...
advancement and compare the research works related to indoor localization to provide deep insights in the field.

2. Main challenge in indoor localization

In this section, we discuss some of the possible main challenges that significantly degrade indoor localization performance. However, different environments have different challenges other than the one discussed in this paper.

The indoor environment often has the characteristics of complex signal propagation which leads to reduced localization accuracy. The objects and obstacles available in the indoor environment such as wall, furniture and the presence of human that will lead to the signal scattering, reflection, absorption and other signal attenuation effects in the indoor environment. These phenomena are commonly referred to the multipath effect of signal transmission. Furthermore, each indoor environment is unique in term of its size, arrangement and objects present, rendering general models inaccurate. Therefore, an indoor localization system that provides high accuracy in specific testbed may not have the same performance in another environment.

Other than the multipath effect, the interference between signals is one of the challenges in indoor localization. Interference happens when two or more signal waves meet while traveling in the same medium. The interference phenomenon happen in RF devices that propagate radio signal waves in the same frequency region. Many devices for indoor localization fall under the categories of 2.4GHz Industrial, Scientific, Medical (ISM) band resulting interference among operating devices within the area. These devices include Wi-Fi, microwave oven and cordless phone that are allowed to operate in this frequency range [3].

To overcome the key challenge in indoor localization, researchers proposed different methods to achieve high accuracy solutions in the indoor localization system. Among different methods proposed, all of them can be broadly categorized into range free localization and range based localization. The range free localization methods often have limited performance in location determination accuracy. Meanwhile, the range based localization can overcome the limitation of accuracy performance in range free methods with additional hardware to support the algorithms.

In recent years, the implementation of Machine Learning (ML) into the range based indoor localization system to extend its performance in location determination. The ML range based indoor localization system could gain benefits from the tremendous amount of data supplied and provide minimum effort to tune the localization model. On the other hand, the probabilistic based localization provides significant advantages compared to traditional deterministic based localization. As the traditional deterministic method in localization may require more data to represent the indoor environment, this will increase the computational requirement for the location determination. The problem can be easily encountered by the probabilistic algorithm where probability distributions based on the environment can be formed with a lesser amount of data required compared to the deterministic algorithm.

3. Range based indoor localization

The RF range based indoor localization can be categorized based on different measurement used such as angle-based, time-based, and signal strength-based measurement. The angle-based algorithm utilizes the antenna arrays to measure the difference in angle of signal received to determine the location. Meanwhile, the general principle in time-based algorithm uses the time arrival of signal propagation from sender to receiver to determine the location of the sensor nodes. The signal-based algorithm avoids the angle and time but relies only on the strength of a signal propagation to estimate the distance between the anchor and sensor nodes.
3.1. Angle of Arrival (AOA)
In the Angle of Arrival (AOA) localization, the localization is performed by the antennas array on the receivers’ side to capture the direction of radio wave propagation. The basic rationale of AOA localization can be summarized as shown in Figure 1.

![Figure 1: Angle of Arrival localization measurement](image)

Assume that two antennas with a separation of distance d, the phase of the RF wave arrival in both the antenna can be measured as $\phi_1$ and $\phi_2$. The difference between the phase of RF signal arrival in the antennas array leads to a phase shift within the RF signal. In order to determine the AOA signal for location determination, the AOA can be calculated as shown in Eq. 1.

$$\theta = \arcsin \left( \frac{\Delta \phi \cdot \lambda}{2\pi d} \right)$$  \hspace{1cm} \text{Eq.1}

Where $\theta$ indicated the AOA signal, $\Delta \phi$ is the phase shift between two subsequent antennas ($\phi_1$ and $\phi_2$), d indicated the distance between two antennas, $\lambda$ is the wavelength of the RF signal.

In general, the AOA localization technique can be categorized into probabilistic approaches and signal and noise subspaces techniques. In signal and noise subspaces techniques, Multiple Signal Classification (MUSIC) algorithm is performed by Li et al. [4] that utilized the signal coherence to determine human location. The authors achieved an error of median 0.6m without any offline training required in three different locations with an area range between 18.9m$^2$ and 68.5m$^2$. Although the MUSIC technique has the advantage in the super resolution estimation, the performance degrades rapidly in correlated sources estimation [5].

On the other hand, probabilistic AOA localization approaches utilized algorithms such as Maximum Likelihood algorithm to assist the AOA technique. The performance of Maximum Likelihood in AOA localization outperforms other similar algorithms especially in correlated signal conditions environment. However, the high performance could come with a trade-off of high computational requirement due to the parameter searches involved compared to MUSIC algorithm that discussed previously [6].

The RF technologies used in indoor positioning system usually suffer from sensor and environment limitations such as Non Line of Sight (NLOS), multipath effects and sensor failure during the data collection. To overcome the problem especially in AOA localization techniques, researches toward the accurate AOA localization with unreliable sensor detection and multipath studies are performed in recent years [7,8]. In [7], the single anchor AOA localization system is evaluated in both 2.4GHz and 5GHz band for both LOS and NLOS environments. Based on the authors’ observation, the 5GHz band comprised larger localization errors due to greater attenuation in signals with higher frequencies. Meanwhile, authors in [8] discussed a method to identify unreliable sensors in AOA localization. The
authors utilized a similar assumption of the inverse proportional of square distance of signal strength to determine the sensor distance with the source. The outliers were determined by any points beyond the statistical measurement of the estimated position in the AOA techniques. By doing so, the method helps in reducing the error caused by the outliers and hence improve the AOA localization accuracy and execution time.

The high accuracy of AOA algorithm comes with a tradeoff of additional antennas array requirement. As a consequence, the additional hardware requirement may significantly increase the power and cost required to fulfill the technique required to perform accurate location prediction.

3.2. Time of Arrival (TOA)

Time of Arrival (TOA) exploits the speed and time of signal propagation to determine the distance between anchor nodes and unknown nodes. In general, the location of interest is determined by obtaining the signal propagation time and the speed which can be calculated as shown in Eq. 2.

$$d = c \times t$$  \hspace{1cm} \text{Eq. 2}

Where $d$ is the distance estimation, $c$ is the signal propagation velocity, $t$ is the time required for the signal travelled from transmitter to receiver. By combining between several transmitter distance estimation, the intersection between circles are determined as the source location. Although intersection between two circles may be adequate to determine the source location, a third circle is required to minimize the ambiguity in the source location determination in practice. The basic rationale of TOA localization as shown in Figure 2.

![Figure 2: Time of Arrival localization measurement](image)

Since the technique exploits the time of signal propagation, the time synchronization between the nodes is necessary for this technique. The TOA technique has demonstrated to produce significant accuracy in most simulation studies [9] and avoids the necessity to perform mapping in the technique. The authors in [9] proposed probabilistic method Bayesian expectation propagation in a 120m x 80m indoor go-cart track to reduce the impact of environmental variations. The results have shown that the proposed method probabilistic was able to trace the movement of the go-cart.

The effect of NLOS in a practical environment could degrade the performance of TOA based localization. Gao et al. [10] discussed the worst-case robust least square problem to mitigate the NLOS error especially in estimating the location and time in an environment with the prevalence of unavoidable NLOS errors and unknown transmission time for the TOA technique.
Authors [11] discussed multiple factors that can contribute in the performance of TOA localization in industrial environment including heights of sensor nodes, antenna orientation, outliers, ranging errors in distance measurement and external interference. The authors also showed an average accuracy of 2m in a 21m x 66m indoor environment. The paper shows that the usage of 20 mobile vacuum cleaning robots in the experiment would significantly increase the cost of the localization system.

Although high accuracies are observed in many TOA localization technique researches, the cost of a TOA localization system is not cheap especially due to the requirement of time synchronization between the anchor nodes and unknown nodes in a large distributed network.

3.3. Time Difference of Arrival (TDOA)
The basic rationale of Time Difference of Arrival (TDOA) localization algorithm works in a similar rationale as the TOA localization. However, the TDOA localization is determining the location by calculating the differences in signal arrival time received between receivers. To obtain the time synchronization between the anchor nodes and the unknown nodes, researchers introduced the least squares algorithm that utilized the TOA signals from anchors to determine the position of unknown node. For example, authors in [12] performed tag localization based on the TDOA localization technique that makes use Maximum Likelihood algorithm that has a least squares interpretation under Gaussian noise assumption to localize the tag.

On the other hand, least squares algorithm also seen in hybrid range based localization between TDOA and AOA technique in [13]. In the paper, authors proposed a first order Taylor expansions based weight least squares algorithm to reduce the bias in the traditional least squares algorithm in TDOA localization. By proposing of hybridization between TDOA and AOA technique, the algorithm avoids the ghost targets problem available in a solely TDOA localization. Based on the paper, the proposed weight least squares based on first order Taylor expansion perform better than traditional least square algorithm even the target is beyond the convex hull formed by the sensors.

In indoor environments, the TDOA localization technique usually suffer from the nonlinear relationship between derived equation and the environmental parameter to obtain the location of node [14]. This results in performance degradation in the TDOA technique and leads to large errors introduce between the true position and the estimated position for the technique.

3.4. Receive Signal Strength (RSS)
The most common technique used in recent years for indoor localization might be Received Signal Strength (RSS) [15–17]. The RSS is used in many positioning algorithms such as trilateration, fingerprinting and many signal propagation models. The main advantage of RSS is the accessibility in most signal based device and does not require any hardware other than the device to support the technique. The basic rationale of RSS localization is utilizing the transmission between transmitter and receiver signal strength to determine a target’s location.

The localization in signal propagation refers to location determination with signal behaviour within the environment. In general, Friis propagation is commonly used in signal propagation as the Friis propagation explains the relationship between RF signals and distance. Hence, the distances of the target from the receivers can be derived using the model. On the other hand, the fingerprinting method determines the location based on prebuilt database that show the uniqueness of the indoor environment. The fingerprinting method consists of two different phases. During the first phase of fingerprinting, the RSS value is collected at every reference position and saved as a database. The second phase of fingerprinting determines the unknown location RSS based on the least dissimilarity location prebuilt in the database.

The RSS based measurement suffers from complex signal propagation in indoor environment. Dynamic conditions of indoor environments where people and object move causes deviation from the prebuilt reference database. This results in a weak performance in RSS to determine location especially the presences of factors such as multipath effect, signal fading, signal interference and obstacles result in fluctuation in RSS signal propagation. The research in [18] indicated that certain WSN technologies
that performed localization with RSS are found more robust to environment changes. Authors compared different technologies such as Bluetooth Low Energy (BLE), WiFi, LoRaWAN and Zigbee for position estimation with RSS trilateration algorithm. Based on the results presented in the paper, WiFi RSS localization outperformed other wireless technologies with the lowest average error of 0.664m in two different environments: laboratory environment and meeting room environment. However, WiFi RSS localization is also found that has the highest power consumption compared to other wireless technologies mentioned.

To tackle the unreliable performance of RSS in noisy environment, recent research in [19] implemented AI solution to solve the intrinsic problem in RSS localization. Authors proposed Recurrent Neural Network (RNN) in RSS WiFi fingerprinting localization for indoor environment. Out of different algorithm in the RNN family, Long Short Term Memory (LSTM) had shown in the best result of 0.75m average error in a 21m x 16m testbed.

In conclusion, the RSS may show weak performance in complex indoor environment, but the simplicity and cost consideration of RSS could be one of the ideal usages for nodes position estimation in indoor localization for many practical situations.

4. Conclusion
An accurate localization system may be a challenge for most of the indoor environment for many possible applications. It is expected to continue its development as it brings convenience and impact to human’s life. In this paper, the recent researches and advancement of RF indoor localization are discussed in detail especially in the range based technique category. Among different range based techniques, the RSS based measurement is still one of the best technique to implement in indoor localization system as it avoids additional hardware requirement and time synchronization to support the indoor localization system. Although the RSS based measurement may suffer from a few factors that degrade the accuracy performance, solutions such as probability based system built based on RSS probability distributions to represent the environment. In the other hand, RSS based indoor localization that adapts machine learning algorithm to the measurements could improve the accuracy of the location determination with the data feature extraction capability to learn from the supplied data.

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