Algorithms of Indoor Localization on Range-based Wifi System

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Abstract

This report aims to give a brief introduciton of indoor localization algorithms based on Wifi system. It will mainly focus on the basic principles behind each kind of realization. All of these specific designs and implementations are introduced from those very classic and impressive papers. All of these ideas have been classified and summarized here. Besides, there are also some of my own understading and views on some of the algorithms.

1 Introduction

An indoor positioning system (IPS) is a system to locate objects or people inside a building using radio waves, magnetic fields, acoustic signals, or other sensory information collected by mobile devices. [1]

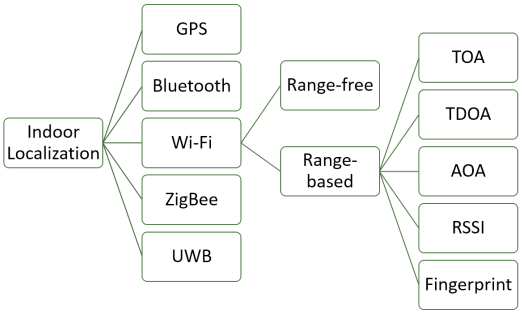

Figure 1: The structure of indoor localization algorithm

Wifi-based system or Wi-Fi positioning system (WPS) is used where GPS and GLONASS are inadequate due to various causes including multipath and signal blockage indoors. Wi-Fi positioning takes advantage of the rapid growth in the early 21st century of wireless access points in urban areas. [2]

Recent years have seen significant advances in indoor localization systems among which range-based algorithms are always the popular ones. Even though, they are just a very small part of all the systems. Figure 1 is a graph showing the structure of all these algorithms. However, in this report, we mainly discuss about the range-based ones.

Indoor localization using wireless infrastructure is a well-studied problem. There is a large body of research which, for conciseness, we classify into five types: TOA based, TDOA based, AOA based, RSSI based, and fingerprinting based techniques. And they will be discussed one by one in this report.

2 TOA based algorithm

TOA means **time of arrival**, sometimes being called time of flight. It is the time spent by the signal transfering from the transmitter to the receiver.

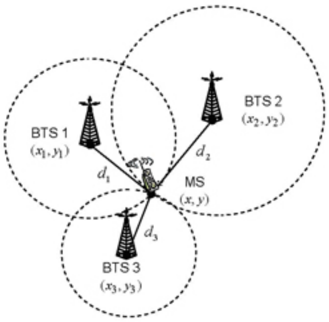

Figure 2: Time of arrival

From the picture above we can see that once we know TOA, refered as t, we know the distance between the transmitter and receiver, refered as d, their relationship goes like

$$d = t \times c$$

where c means the speed of light.

After knowing the distance, it can be inferred that the target is now on a circle, with radius d. Therefore, it's very easy for us to locate the target as long as we can get three such circles and then find the intersection. Mathmatical calculation goes like here.

First, we know the position of the three centers of the circles, $(x_1, y_1), (x_2, y_2), (x_3, y_3)$, and we have the following equations

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

Then, equations 1 minus equation 3 and equations 2 minus equation 3, we have

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

Finally, we get the result

$$\begin{bmatrix} x \\ y \end{bmatrix} = 2 \begin{bmatrix} x_1 - x_3 & y_1 - y_3 \\ x_2 - x_3 & y_2 - y_3 \end{bmatrix}^{-1} \begin{bmatrix} x_1^2 - x_3^2 + y_1^2 - y_3^2 + d_3^2 - d_1^2 \\ x_2^2 - x_3^2 + y_2^2 - y_3^2 + d_3^2 - d_2^2 \end{bmatrix}$$

The difficulty in this method lies in the measurement of TOA. Systems that use timestamps reported byWiFi cards can obtain time of flight at a granularity of several nanoseconds, resulting in ranging error of few meters, which is unbearable.

3 TDOA based algorithm

TDOA means **time difference of arrival**. Literally, other than measuring the absolute time of arrival, it measures the difference.

Recall what we have discussed in the TOA part, when we know TOA, we know the distance, and then the target is sure to be on a circle. Similarly, when we know TDOA, we know the difference of distance, and then the target is sure to be on a hyperbolic curve.

$$\begin{cases} d_1 = \sqrt{(x - x_1)^2 + (y - y_1)^2} \\ d_2 = \sqrt{(x - x_2)^2 + (y - y_2)^2} \\ d_3 = \sqrt{(x - x_3)^2 + (y - y_3)^2} \\ d_1 - d_3 = c(t_1 - t_3) \\ d_2 - d_3 = c(t_2 - t_3) \end{cases}$$

TDOA relies on having time synchronization between measurement units. For WiFi, time synchronization is already available within the network; infrastructure networks only have one wireless hop, which ensures good synchronization with little possibility of time skew. However, time synchronization across an ad hoc network can potentially take a short time to achieve; therefore, a time difference of one or two microseconds can be observed.

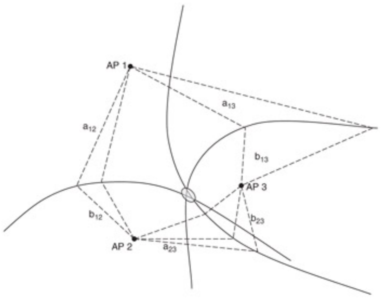

Figure 3: Time difference of arrival [3]

The calculation of the target position is exactly the same with what is in TOA case. But here, the really difficult problem is to get TDOA, jsut like in TOA we need to get the exact value of t.

Usually, two forms of time difference can be used for location estimation.

The first method is easy to come up with. Now that we have already know the eaxct time of TOA in TOA-based algorithm, of course we know the time difference if two TOAs. However, this kind of method is pointless because it has no difference with what we have done in TOA-based algorithms in essence.

The second method is more often to use in real implementations, and usually more accurate which I will introduce in the next part of this report.

4 AOA based algorithm

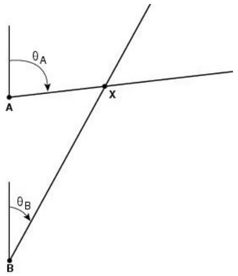

Figure 4: Locate the target by AOA

AOA means **angle of arrival**, it measures the angle of each antenna and the arriving signal.

For a wifi access point, it usually has more than one antenna. Therefore, there are different angles for each antenna and the arriving signal. If we know the arriving angle, we can make sure that the target is in one specific direction, and by getting at least two such angles and finding the intersection, we can locate the target. That's the basic idea of AOA-based algorithms.

By observing the graph below, naturally, we have a question. How to measure the angle?

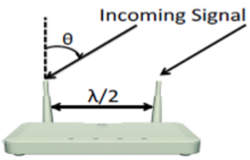

Figure 5: Measuring angle of arrival [4]

The key idea is to analyze the phase of the received signal, a quantity which changes linearly by 2π for every wavelength traversed by the signal. For the simplicity of explanation, consider a single path between the transmitter and the receiver. Just like what has been shown above.

Let us consider that the AP has only two antennas, placed at a distance of $\lambda/2$. Let θ be the angle at which the signal arrives at the two antennas. The signal travels an extra distance before reaching the second (left) antenna. This extra distance Δd can be approximated as:

$$\Delta d = \lambda/2sin(\theta)$$

We know that an extra distanceΔd will result into a phase difference$\Delta\phi$:

$$\Delta\phi = 2\pi\Delta d/\lambda$$

Thus, by observing the phase difference $\Delta\phi$ of the arriving signal, we can find the angle-of-arrival as:

$$\theta = arcsin(\Delta\phi/\pi)$$

So back to the original quesiton, when we have already known the AOAs of different antennas, we can locate the target simply by finding the intersection now. However, the accuracy of this method can be affacted by a lot of facters [14–16], one of which being multipath, and we will discuss that in the later part.

5 RSSI based algorithm

RSSI means **received signal strength indicator**, which is a measurement of the power present in a received radio signal. RSSI is usually invisible to a user of a receiving device. However, because signal strength can vary greatly and affect functionality in wireless networking, IEEE 802.11 devices often make the measurement available to users.

Therefore, the basic idea is, if we can find the relationship between RSSI and distance, next time by measuring RSSI we can get the distance. And there indeed exsits very strong relationship between them, like what shows in the following piture.

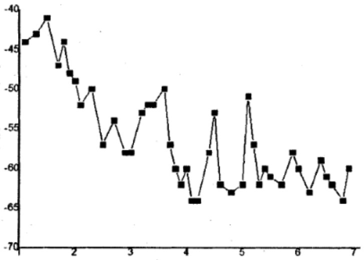

Figure 6: Outdoor mean RSSI measurements

Even though, we can see from the measured picture that, the relationship is not fixed. It's not a function or one-to-one mapping. Instead, given a value of RSSI, we may have several corresponding distance. Then, the problem comes. We are not sure which distance is the real one. Therefore, there could be too much deviation.

There are some methods to improve the accuracy of measurement, one of them being RSSI filtering. There are usually two ways of dealing with the original signal, mean-value model and Guassian model. They will not be discussed here but I give some related papers here [5–7].

6 Fingerprint based algorithm

Fingerprint means a vector of recorded parameters (can be RSSI or others), it is a natural way to solve the problem that we meet in RSSI-based algorthms. Its basic idea is that one RSSI value may be difficult to decide the distance, but many such RSSI values can improve the accuracy effectively.

In detail, we first measure the RSSIs of different positions in advance and have a recorded vector. Next time by measuring the RSSIs again and matching it with the recorded vector before, we can find the same position.

Even though, the accuracy of this method is still unbearable. Also, I choose some very impressive work here involved with this method [8–11], and after applying these skills, most of the implementations can reach an accuracy of decimeter level.

7 Typical problems about indoor localization

What have been discussed above are only the basic principles behind these indoor localization systems. Actually, some of these methods can be combined together to improve the accuracy, for example, by combining TOF and AOA we have Chronos [12], a system that enables a singleWiFi access point to localize clients to within tens of centimeters.

Generally, indoor localization systems usingWiFi infrastructure should ideally satisfy the following three requirements [13]: deployable, universal and accurate. However, there are a lot of common problems in this field which every kind of algorithm should give a solution. And here I make a summary of them, for the solutions to each problem, we can find the corresponding papers.

7.1 Multipath

So far, our discussion has assumed that a wireless signal propagates along a single direct path between its transmitter and receiver. However, indoor environments are rich in multipath, causing wireless signals to bounce off objects in the environment like walls and furniture.

Have a recall of what we do when discussing the AOA-based algorithm. We face the same problem, the signals on each of these paths may propagate over the air incurring different time delays as well as different attenuations. The ultimate received signal is therefore the sum of these multiple signal copies.

But a lot of methods have been found to solve this problem. For example, in Chronos system, they use the Non-uniform Discrete Fourier Transform to disentangle these different paths and recover their propagation delays.

7.2 Package detection delay

In practice however, there is a difference between the channel over the air and the channel measured by the receiver, Specifically, the measured channel at the receiver experiences a delay in addition to time-of-flight: the delay in detecting the presence of a packet.

This delay occurs because WiFi receivers detect the presence of a packet based on the energy of its first few time samples. The number of samples that the receiver needs to cross its energy detection threshold varies based on the power of the received signal, as well as noise.

While this variation may seem small, packet detection delays are often an order-of-magnitude larger than time-of-flight, particularly in indoor environments, where time-of-flight is just a few tens of nanoseconds. Hence, accounting for packet detection delay is crucial for accurate time-of-flight and distance measurements. [12]

7.3 Synchronization

Synchronization is a critical problem in indoor localization system. Just imagine, 1 nanosecond's error will result in a $1ns \times 3 * 10^8 m/s = 0.3m$ deviation. This kind of error is unbearable for a localization system.

Sometimes, synchronization is not only needed within one wifi access point between antennas, but also between many APs, in which case it is rather difficult to have an accurate result.

Moreover, synchronization is not only needed in TOA based algorithm, but almost all of the algorithms and this step may be needed more than once in a period of measurement. All of this makes synchronization a key problem in indoor localization algorithms.

7.4 Phase offsets

There are generally two kinds of Phase offsets needed to be removed.

PLL Phase Offset: Frequency hopping causes a random phase offset in the measured channel. This is because the phase-locked loop (PLL) responsible for generating the center frequency for the transmitter and the receiver starts at random initial phase. This phase offset, if left uncorrected, could render the phase information uncorrelated with the time-of-flight of the signal.

Carrier Frequency Offset: This offset occurs due to small differences in the carrier frequency of the transmitting and receiving radio. This leads to a time varying phase offset across each frequency band. Such differences accumulate quickly over time and need to be corrected for every WiFi packet.

There are also a lot of work been made about phase offsets, here is what Chronos has done to remove the offsets [12]

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