Master's Thesis

Indoor Localization based on Time-of-Flight Fingerprinting

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Abstract

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The emerging of a positioning/localization system allows user to track their position in real-time by using a knowledge of radio frequency signal (RF). Global Positioning System (GPS) is the most famous outdoor localization system with leveraging RF signal from satellites. Even though it has been widely used in many applications, it is not be able to localize in indoor environment such as building because the signal from satellite cannot penetrate inside and if it does, the signal power is not strong enough to maintain the connection. Many researchers have found

a way to solve this issue by deliberately makes use of off-the-shelf wireless infrastructures such as Wi-Fi, and named these applications as Indoor Positioning System (IPS).

IPS has been currently researched in a way that it should provide higher accuracy, centimeter to a few meter-scale, than outdoor system and more reliable. Ranging-based localization technique that is mainly used in GPS, turns out to be inapplicable in IPS because this technique relies on signal propagation time to estimate user's location which is hardly to accurately measure in indoor environment due to strong multipath and hardware limitation of wireless devices, which is not optimized for specific purpose. Therefore, the feasible method goes to RSS-based fingerprinting where location is estimated by matching Received Signal Strength (RSS) profile with a database that contains the known locations with its profiles. However RSS profile is not robust and time-varying, causing large error in some scenario.

This work presented a new way of fingerprinting–based localization by using Time-of-Flight (ToF) as a reference information instead of RSS. Theoretically speaking, ToF is better than RSS in term of reliability and accuracy because they are less time-varying and more robust than RSS. Moreover, measuring ToF does not require synchronization between access point and user device, thus it provides this system less complexity. Although, it is not a famous measurement when ToF is used in ranging-based localization where hardware limitation reduces accuracy significantly to 10 meters error, our approach has shown that it provides precisely

localization when combining with fingerprinting technique.

We have experimented various estimation method in order to find a better solution than basic fingerprinting algorithm where accuracy is limited by a gap between fingerprinting. We found that by using a knowledge of neighbor fingerprinting, it can achieve sub-optimal resolution than the basic algorithm. We evaluated the performance, and the result has shown that our work outperformed previous works.

Keywords: Indoor localization system, Time-of-Flight, Fingerprinting technique, Wireless communication.

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Chapter 1 Introduction

1.1 Background

Positioning system has been developed to the point that we can rely on it and some said it has literally become part of our life. Relying on Radio Frequency Signal (RF) sent from sources; satellites, cellular base stations, today Global Positioning System (GPS) delivers user's global location via smart devices. However, the position's accuracy is significantly degraded in urban area and indoor environment due to multipath effect and shadowing [30, 31]. Consequently, real-time applications such as navigation system provide services inefficiently. In addition, people in urban area tend to spend their time mostly in buildings where GPS is not able to perform localization because signal from satellite cannot penetrate inside and if it does, the signal power is not strong enough to maintain the connection. Many researchers have found a way to solve this issue by deliberately make use of off-the-shelf indoor wireless infrastructures such as Wi-Fi [2, 5-9, 16-17, 20-22], Radio Frequency Identifications (RFIDs) [12,15,18], and Wireless Sensor Networks (WSNs) [10, 11, 13]. These applications is called Indoor Positioning System (IPS). While ten of meters scale is acceptable for outdoor positioning system, IPS is required to enable fined-grained resolution (a few meter or sub-meter scale) and have to deal with an unpredictable error that experienced only in indoor environment. This is, for example, because location error just a few meter in the building can make you lost the way in navigation system. Moreover, many researches have shown that by achieving very high accuracy, it is possible to turn Sci-Fi futuristic technologies on TV into real applications just only by leveraging IPS concept; RF-based Gesture recognition [26], detection or tracking people through the wall [24, 28], hearing what other people are saying in another room [29], or even virtual touchscreen [18].

Several Indoor localization techniques have been presented where the knowledge of measurable information; such as received signal strength (RSS) [14-22], propagation time [1-13], direction of incoming signal [15-18], and even Inertial Measurement Unit (IMU) sensors in smartphone [19-20], are used to precisely pinpoint the location. Although those information and the behavior of Radio wave are theoretically predictable and achievable, fine-grained indoor positioning system whose accuracy should be within a few meters or even centimeter resolution, still has many challenges to address. These problems come from Radio wave physical phenomena during propagation. Path loss and multipath caused by signal reflected on obstacles, people walking, and shadowing, generate an error. Therefore, accuracy also decreases by interference from other wireless applications [30, 31]. In addition, the scarcity of RF sources causes a large error, especially in the area where distance between user and sources is large because longer distance signal travels, higher noise it becomes.

RSS-Fingerprinting indoor positioning technique [14, 15] is numerously developed and some of them have already been commercialized because it is less complexity and does not require additional infrastructure. This concept is to collect a fingerprinting as RSS profile at known locations as reference toss localize user's mobile devices. However, this technique requires an offline phase to collect a RSS measurement at fingerprinting (reference node) beforehand which is a time-consuming process. Also the high noise's sensitivity and time-varying of RSS increases error tremendously. Despite of its downsides, the localization's accuracy, theoretically, is promising and depends on a size of gap between consecutive fingerprinting since location will be fit into the most-likely profile's location. Ranging technique [1-13] uses a propagation time as the measurement to perform localization by translating signal's traveling time to distance between user's mobile device and access points, then lateration is used to estimate location. This technique, although, provides an accurate and reliable location even better than the first technique, it is infeasible to achieve fined-grained positioning with off-the-shelf RF infrastructure whose hardware can collect propagation time which only provides 10-100 meters resolution and it also requires synchronization between mobile device and access points. Moreover, error is larger significantly when the distance between access point and mobile devices is increasing, and 3 access points are the minimum requirement for yielding location.

This project proposes a new techniques for localization system using Time-of-Flight (ToF) or signal's Round Trip Time (RTT) as a reference profile which is not commonly used in IPS due to hardware limitation, on top of fingerprinting indoor positioning technique. By doing this, the distance between access points and mobile devices, and number of available access point issues, are literally reduced because localization will now rely on fingerprinting location which is user-controlled variable. Hence, the merit of ToF allows system to measure without synchronization requirement. More importantly, the hardware issue can be possibly solved by borrowing a concept of statistical process [1, 2, 6, 9] to estimate sub-optimal propagation time measurement. Because we do not use the knowledge of ToF to directly estimate localization as ranging-based does, the error causes by statistical process can be ignored. Instead, this system follows a fingerprinting approach by matching ToF between fingerprinting and mobile device’s profile.

This idea was both simulated in MATLAB and implemented in Universal Software Radio Peripheral 2(USRP2) with GNURADIO, an open-source software development. In simulation sections, 3 access points, placed at the edges of 10 square-meter virtual area, are used for evaluating this technique's performance where fingerprinting points are placed uniquely 1 meter apart. In the experiment, we evaluated our system performance with RSS-fingerprinting technique and ranging-based technique. Moreover, we implemented the technique that use neighbor fingerprinting profile to enhance the accuracy. The result shown that our system achieves higher accuracy than other approaches and our technique delivers a sub-optimal resolution of basic fingerprinting technique. The implementation was experimented with the same setting as simulation on a 4 square-meter of our lab area, and it fortunately has provided a similar result with simulation.

1.2 Contribution

This project contributions are summarized as follows:

1. ToF is applied into fingerprinting-based technique to gain more robust localization than RSS measurement and this system does not require

synchronization between access points and mobile devices during collecting ToF measurement

2. Adaptive lateration technique is developed by leveraging neighbor fingerprinting to achieve sub-optimal resolution of basic fingerprinting technique (matching method). This method compares a different between ToF of neighbor and most-likely one to estimate location by imitating trilateration concept.
3. This technique is simulated and implemented and delivered outperformed in term of accuracy compering with existing approach.

1.3 Thesis organization

The rest of this thesis is organized as follows. Chapter 2 summarizes a related work, followed by an overview of the fingerprinting-based indoor localization with Time-of-Flight system in chapter 3. The system design is presented at chapter 4, begins with motivation and design requirement before moves into designing detail. Chapter 5 experiments and evaluates the performance in both simulation and implementation, and conclude this thesis in chapter 6.

Chapter 2 Related work

This paper is related to past works in a fingerprinting-based and a ranging-based indoor positioning systems.

2.1 Fingerprinting approach

Prior works have shown that a fingerprinting approach implemented in Wi-Fi system is able to accurately pinpoint user's location. RADAR [13] achieves 2-3 meters resolution with 3 neighbor access points assisted. This work was pioneered of using fingerprinting technique with RSS measured from 3 known-location access points. Then the estimated location is determined by the most-likely mobile device's RSS and RSS-fingerprinting information. The system performed over the 980 square-meter of floor area.

PintIt [15], RFID-based positioning system, collected multipath profile (RSS and Angle-of-Arrival information) of reference tags as a fingerprinting. The desired tag's location is determined by matching multipath profile with those from reference tags. This work borrowed Dynamic Time Wrapping (DTW) from speech recognition to use in matching process. It archived 10 of centimeters resolution. This work has already solved a large error of using Angle-of-Arrival in Non-Line-of-Sight (NLOS) scenario by exploiting a fingerprinting concept. The requirement of array-antenna to capture a direction of incoming signal, is also eliminated after PinIt implemented Synthetic Aperture Radar (SAR) where one movable antenna emulate an antenna array.

This project was inspired by PinIt in a way that it utilized a fingerprinting concept to tackle a limitation of another technique. Instead of improving AoA issue, this work propose Time-of-Flight fingerprinting to reduce error caused by signal strength which is more vulnerable.

2.2 Ranging approach

[1, 2] presented Ranging technique that obtains ToF in nanoseconds resolution without using a high speed Analog-to-Digital Convertors. This technique is called statistical processing. Exploiting the concept that noise randomly delays travelling time, ToF characteristics can be illustrated as Gaussians distribution when measuring a set of received packets' Round-Trip-Time (RTT), thus statistically computed sub-optimal ToF from the measuring. Higher precision of ToF are purposely used to estimate an accurate distance that later use for estimation a mobile device's location. This work achieved with less than 10-meters error. Other works attempted to increase the accuracy by proposing a new method for capturing time measurement at higher resolution; [3] uses Phase and frequency estimation, [8] leverages round-trip-phase of OFDM pulse, [6, 9] installed external high-speed ADCs to measure high resolution timestamp, and [19] SAIL relies on a benefit of 40-MHz bandwidth of 802.11n standard assisted by off-the-shelf smartphone sensor to archive centimeter resolution of localization.

By avoiding the hardware issue, [10, 11] change a communication frequency to acoustic sound whose speed (speed of sound) is slower than RF (speed of light). In exchange, it requires an additional acoustic sound transmitter attached with access points, and also effective area is greatly reduced due to noisy in this acoustic band. Cricket [13] proposes a make use of ultra wideband devices whose bandwidth is larger than Wi-Fi and sufficient for capturing nanosecond signal timestamp. Again. This work cannot use with existing RF infrastructure, and also require user to have an ultra-wide band receiver. Instead of directly measuring propagation time, [20, 21] presents another way to measure a distance by leveraging Channel State Information (CSI), a Wi-Fi Physical layer's information. CSI provides RSS in a function of time delay which has been exploited to indirectly estimate the distance.

This project conceptually is to utilize a fingerprinting-based indoor localization by using time propagation instead of RSS. ToF is used to eliminate synchronization requirement, and we implemented a statistical process to achieve sub-optimal resolution. Unlike previous work that requires a high accurate time measurement to perform localization, we applied ToF into fingerprinting concept which does not require high precision to convey a user's location.

Chapter 3 Indoor positioning system overview

Technological advance in electronic and computer along with an maturation of mobile computing have significantly impacted on positioning system by leveraging Radio Frequency signal generated from RF sources; satellite, cellular tower, and Wi-Fi. The succession of space-based satellite navigation system, Global Positioning System (GPS), which provides precisely location with an assistant from RF signal sent by GPS satellite, has completely eliminated the need for location information that we require for exploration and navigation [31]. Consequently, a need of positioning system has being moved from outdoor to indoor environment where GPS is not be able to operate. This big issue has opened a new way for many researchers to develop a robust and reliable Indoor Positioning System (IPS) by using an off-the-shelf RF infrastructure in a building such as Wi-Fi, micro-cellular base stations, Wireless Sensor Networks, and Radio Frequency Identification systems. However, these existing infrastructures are not purposely developed for positioning purpose, and also various objects inside a building along with a rich of Non-Line of Sight (NLOS) areas create high location error. These challenges make IPS more difficult in term of development than GPS.

3.1 Localization techniques

There are many localization techniques presented in academic societies, some is already commercialized, which are applicable with different RF Infrastructure systems. Wi-Fi-based and RFID-based indoor localization are the most popular systems because of an availability of personal mobile computing devices today that can work with. Since indoor is a diverse environment, there is no best technique or system that dominates others. In fact, there are many IPS-related applications that are optimized by different localization technique. Hence, In the following section, we will look into those 6 basic techniques.

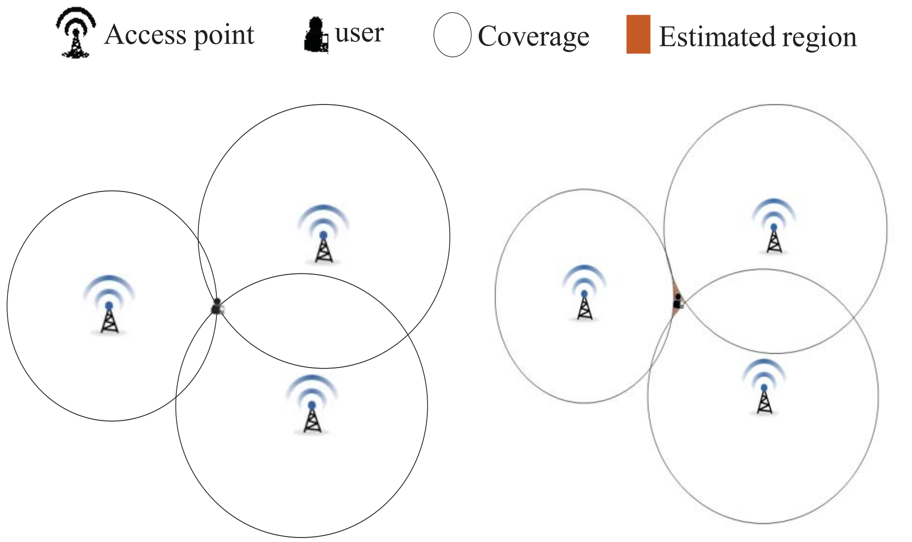
3.1.1 Proximity detection

This technique estimates the position of devices or object based on its adjacency to sources. Using a knowledge of RF source's coverage, devices which

Figure 3.1 Proximity Detection based Localization technique

perceives signal implies that its location should be nearly that transmitter. More accurately, signal strength that devices received can be used as an indicator to explicitly estimate coarse-grained location. Cellular system is suitable for this method due to its base-stations which are fundamentally distributed in everywhere for providing mobile phone communication. Hence once experiences the presence of a signal, localization system only approximates an area that user is located but cannot pinpoint exactly location.

3.1.2 Lateration



(a) Estimated location w/o error (b) Estimated location w/ error

Figure 3.2 Ranging-based Localization technique

Lateration technique uses a range (distance) measurement from multiple sources to calculate user's location. Commonly, Distance measurement is translated from propagation time of signal, multiplied by RF speed (speed of light). This is a technique that has been used in GPS-based outdoor positioning system. Some lateration techniques alternatively use both propagation time and received signal strength (RSS) by extracting from Channel State information (CSI) of Wi-Fi Physical Layer and estimates the location by path loss equation [20]. Figure 3.2 illustrates how distance is used for localization. In order to accurately localize with propagation time, it requires at least 3 RF sources to create a circular area whose center is a RF source, and radius is a calculated distance. In theory, the intersection of 3 circles will be inferred as an estimated location, (Figure 3.2a). In practical, however, a noise from measuring propagation time may cause an imperfect intersection such that it generates a region in a middle of sources whose user's location is contained in it(Figure 3.2b).

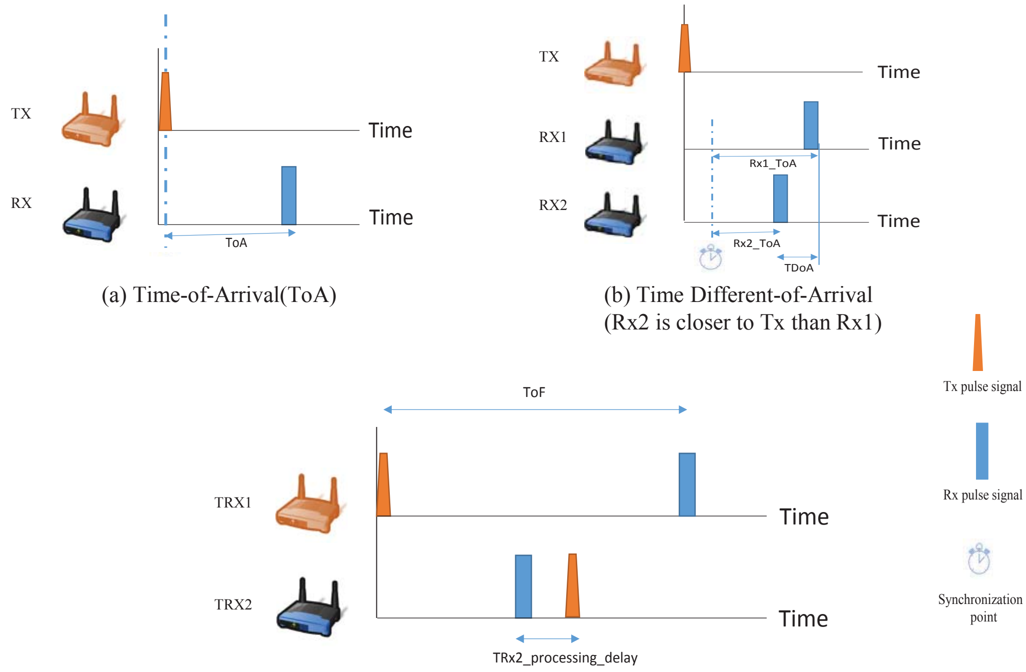
3.1.2.1 Time measurement

There are many propagation time parameters that can be leveraged for this localization technique such as received time, transmitted time, and round trip time. They are chosen to use in ranging-based depending on its applications. The commonly ranging technique that exploiting propagation time are addressed in the following.

- **Time of Arrival (ToA)** uses a knowledge of time of received signal in a one-way travel time from sender to receiver. It requires strictly synchronization in order to calculate propagation time by subtracting Time-of-Departure (ToD) with ToA.

- **Time of Flight (ToF)** or Round Trip Time delay, similar with ToA, conveys a propagation time delay from 2-way travel time of signal between access point and user device. Since ToF can measure at a same node, there is no requirement for synchronization.

- **Time Difference of Arrival (TDoA)** uses a time difference of 1-way or 2-way propagation time between two receivers (or 2 antennas with known gap in between) to indirectly estimate user’s location by multi-lateration. This technique also requires the synchronization between multiple receivers.



(a) Time-of-Arrival(ToA)

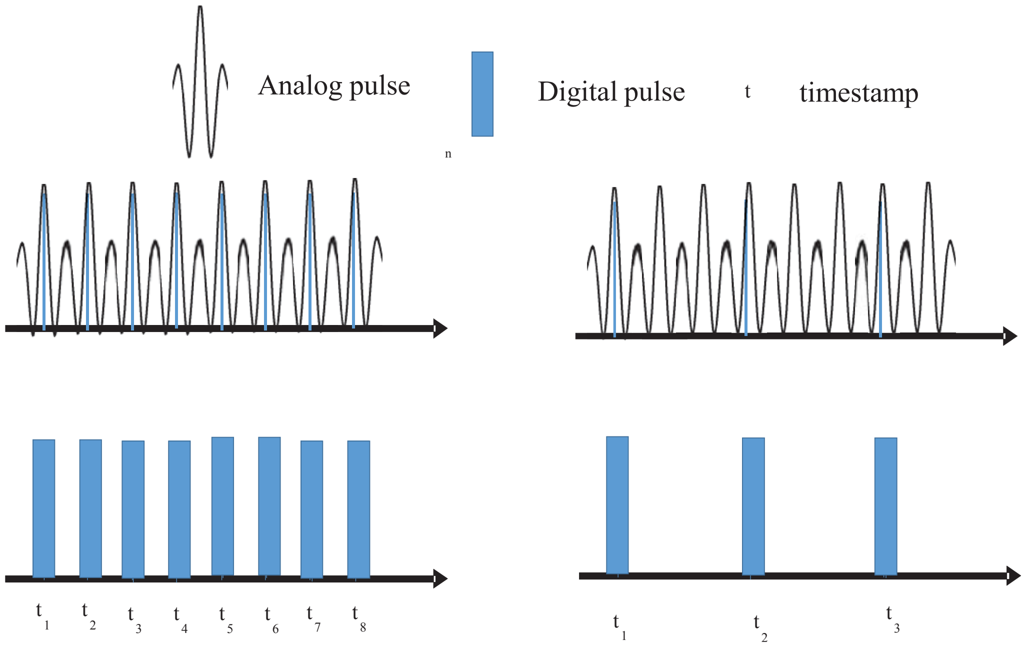
(b) Time Different-of-Arrival (Rx2 is closer to Tx than Rx1)

(c) Time-of-Flight

Figure 3.3 Time measurements that use in Ranging-based localization

3.1.2.2 Resolution of the time calculation

The resolution of time calculation or timestamp of a propagation time is depended on hardware. More specifically, it requires high speed analog-to-digital converters (ADCs) that operates at multi-Giga sample per second to achieve sub-nanosecond resolution which is able to calculate the approximate distance in a few meter. Such ADCs are power-hungry devices and very expensive. Commercial RF-transceiver such as Wi-Fi access point, however, has 20 Mega sample/s ADCs. This level of precision is insufficient for indoor localization.



(a) High-speed ADC handle capturing signal pulse

(b)Low-speed ADC cannot handle capturing signal pulse

Figure 3.4 Resolution of ADC sampler performance affects capturing timestamp

To improve the timestamp resolution over hardware constraint. [1-2] proposed a statistical process to achieve sub-resolution. It leverages noise to indirectly estimate propagation time with the concept that noise randomly delay signal's travelling time and then resulting in Gaussians distribution characteristic. The sub-resolution is statistically computed at a center of Gaussian where propagation time is conceptually noiseless. [8] also proposed how to gain sub-resolution by using an asynchronous analog approach to eliminate the limitation of the ADC. This requires an analog comparator to implement the threshold RSSI technique which alternatively converts to digital sample.

3.1.3 Angulation

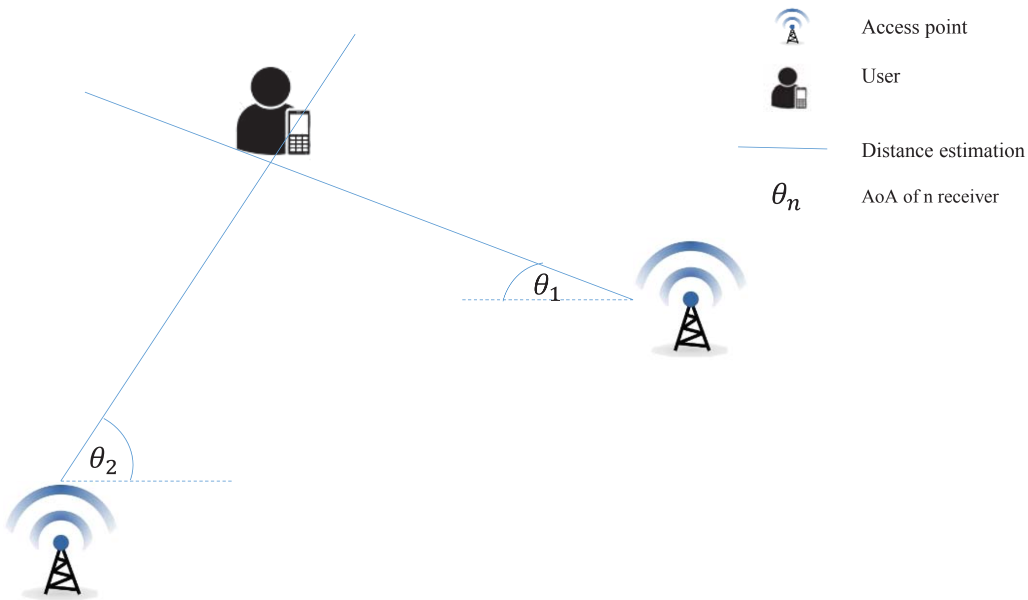


Figure 3.5 Angulation-based indoor localization

This technique measures an Angle of Arrival (AoA) of an incoming signal from 2 access points where location is determined at an intersection (Figure 3.4). To increase the accuracy, AoA may be combined with RSS or propagation time for distance estimation. Angle information can be possibly collected by leveraging directional antennas with MIMO technique. This technique assumes that location of access points and the distance between them are known. Apparently, this technique has a large error when there is no Line-of-Sight (LOS) presented in environment because received angle , in this case, becomes the angle of reflected-off other objects.

3.1.4 Fingerprinting

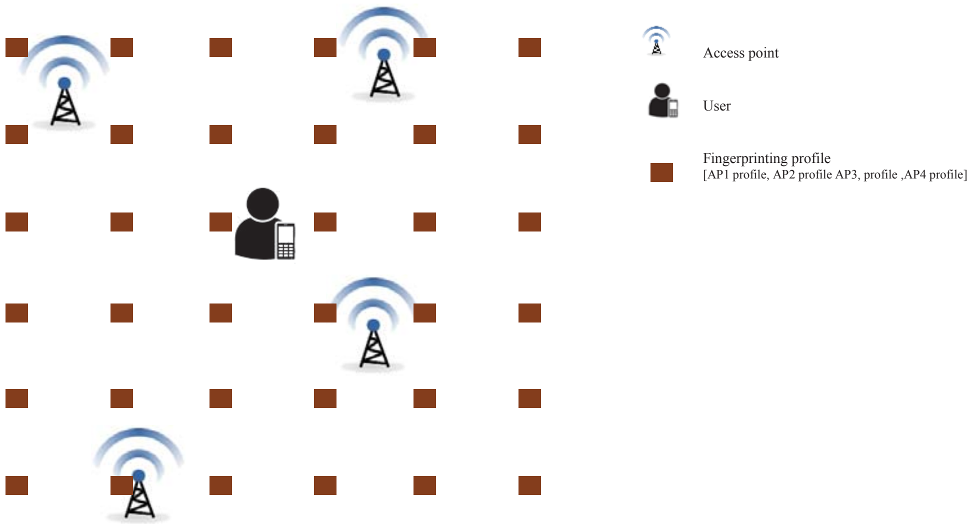


Figure 3.6 Fingerprinting-based indoor localization

Fingerprinting approach determines user's location with a fingerprinting profile in database during offline phase. The profile is a measurable RF information such as RSS, Incoming angle, Time of Arrival, and so on, which has been recorded at a known locations beforehand. During an online phase, user collects the profile and compares it with the database. Location will be determined by matched with the most-likely fingerprinting profile. The advantage of this technique is that nature of the propagation environment is not used [31], and less complex, because it is already included in the profile. On the other hand, the fingerprinting (time-invariant) is not frequently updated, thus the error rapidly increases when the environment change. To prevent this issue, profile should be collected over time or uses time-invariant parameter.

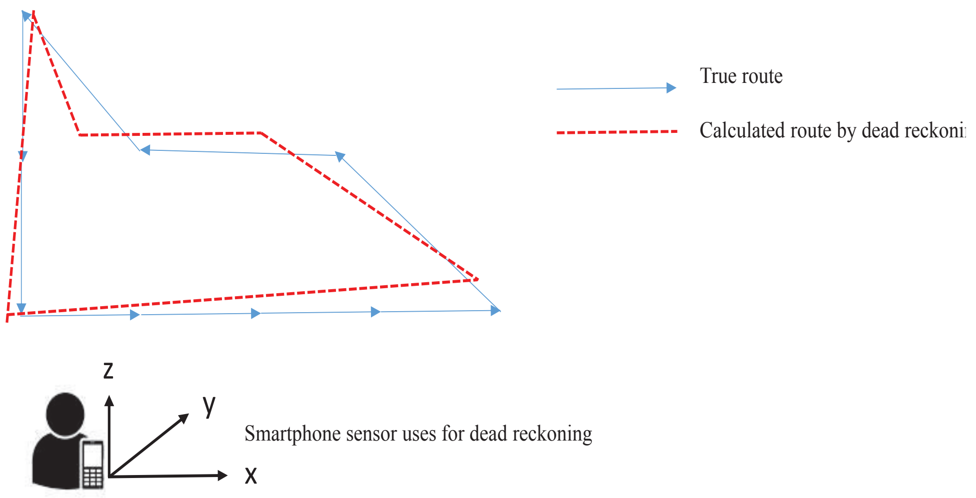


Figure 3.7 Dead reckoning-based indoor localization

The fingerprinting resolution depends on a distance between adjacent fingerprinting points (gap). However, if you reduce the distance to gain higher resolution, the fingerprinting uniqueness would be indistinguishable with resulting in high error.

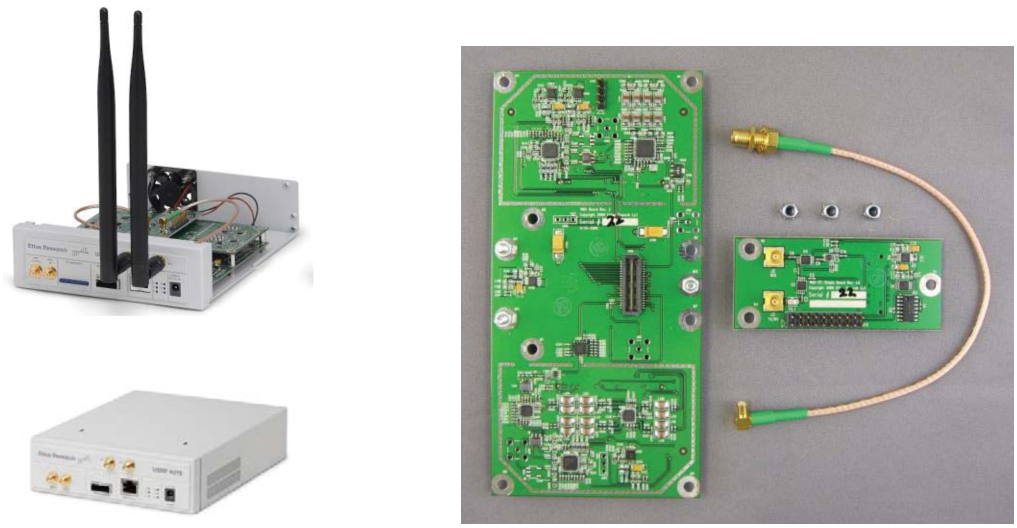
3.1.5 Dead reckoning

Dead reckoning relies on a user movement's history collected via sensors (accelerometer, gyroscope) to predict location. This technique becomes famous due to technological advance of Inertial Measurement Unit (IMU) in smartphone. The main limitation is its susceptibility to drift [31] with causes an error that gradually increases in every computation. In practical, this technique is always assisted with other localization technique for enhancing performance. Despite of limitation, Dead reckoning is sufficiently able localize without the system (standalone positioning system).

3.2 The Universal Software Radio Peripheral

Universal Software Radio Peripheral (USRP) is a type of software-defined-radio developed and distributed by Ettus research in National Instruments [33]. It is very famous and widely used by researchers and students due to its inexpensiveness compare with others, and providing an open source hardware. USRP builds on an Altera Cyclone FPGA board allowing them to do basic signal processing in baseband. It needs RF front-end module, called daughterboard, for analog operation. At time of writing, Ettus has RF daughterboard to support from DC to 5 GHz band in both half-duplex and full-duplex operation.

USRP is controlled by open source software, UHD, based on C++ and python language, and it is compatible with Linux, Window, and apple X operating system. It connected to host via USB 2.0 and Gigabit Ethernet cable (USRP2).



(a) USRP

(b) USRP's daughterboard (RF front-end) with cable

Figure 3.8 USRP N210 with RF-frontend

3.3 GNU Radio

GNU Radio is a free and open-source software development toolkit for implementing low-cost software-define-radio, and it can be used without hardware for simulation. Hence, it becomes the most famous software tools for USRP users. GNU Radio is licensed under the GNU General Public License (GPL) version 3.

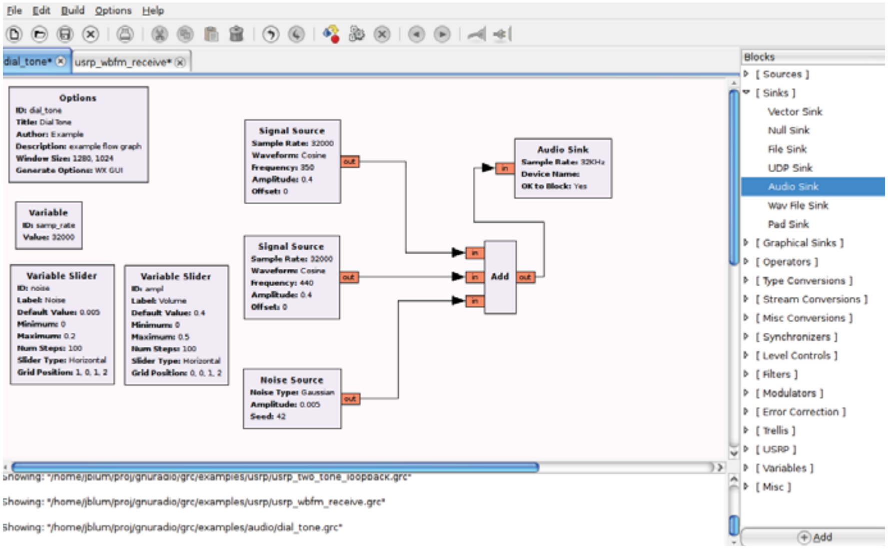


Figure 3.9 GNU Radio Companions (GRC) Signal flow graph

GNU Radio performs all the signal processing frameworks so called 'flow graphs' where signal processing blocks, written in C++ language, are connected together forming a desired system. Each block has their own function and executes independently. GNU Radio already provides various fundamental blocks for simulation/implementation wireless communication project. Moreover, if user cannot find a suitable block for his work, GNU Radio also provides Block-creating toolkit allowing user to quickly create their own block. While each blocks are using C++ language, Flow graphs are typically written in Python language which makes it more user-friendly. In addition, GNU Radio has a graphic user interface (GUI) tool called

GNU Radio Companion (GRC). It is benefit for the beginner users to easily understand GNU Radio structure, and so for expert users to quickly develop their research. Unfortunately, a few useful documents are available comparing with example codes developed by other users, therefore beginner users are recommended to learn from the example codes instead of documents. Both documents and codes are searchable from GNU Radio official website.

In addition, GNU Radio is an open source software whose code still remain in developing process. Consequently, many bug are being discovered and fixed causing frequently upgrading a new version whose code is, sometime, not compatible with the oldest one because code libraries and its locations are changed. Users should carefully check a GNU Radio version of example code before learning it.

Chapter 4 System design

In this chapter, I will introduce the motivation and goal to work on this research. Followed by design requirement, this section explains project's plan and tasks that this work should be performed step-by-step for achieving the project's objective. I start illustrating this work at a high level in the overview section. Then the detail of system design is presented arranging in two phases; Collecting fingerprinting profile, and Localization.

4.1 Motivation and goal

Typical Indoor localization system is used to determine user's current location by exploiting RF signal of existing RF infrastructure. In many systems, it needs to know access points' location of existing system using them as reference nodes. In practical scenario, these location does not publicize, and it belongs to the owner of buildings and they may not appreciate to share it out due to security issue. This challenge can be solved if buildings provides their own localization system; however, it is inconvenient for users who have to download applications of each building, the diversity issue. Regarding this problem, I was firstly motivated by fingerprinting-based technique where knowing access point location is not necessary, and also its simplicity allows everyone to develop their own system without any cost if you only have a portable device such as smartphone or tablet. Hence, there is no doubt why this technique has widely implemented in indoor localization system, unlike outdoor localization that prefers ranging-based technique. The second motivation comes from a problem in fingerprinting-based technique itself. In indoor localization, Received Signal Strength (RSS) is a popular measurement for making a fingerprinting profile despite the fact that RSS is high sensitive to noise and multipath causing a rapidly fluctuation which is contrast with the ideal of fingerprint profile that it should be time-invariant in order to provide reliable and robust reference for localization. After researching from many references, I have realized that propagation time, even though it is effected by noise and multipath, is less time-variant than RSS. Hence it should be a better choice for fingerprinting profile. However, the reason why propagation time is not preferable comes from the way to capture it. Theoretically speaking, measuring propagation time is not a difficult task because you simply ticks a device's clock to capture time when signal is being sent, and subtracts it with a time when signal is being received. However, when it comes to real world, the problem lies on the device clock of access point such that it infeasible to sample high precision. In particular, Analog-to-Digital converter of off-the-shelf access point, Wi-Fi, can possibly handle 20 MHz clock cycle which means approximately 15 meters-resolution, and yet is not enough to achieve fined-grained accuracy. In addition, high-speed clock causes more noise [28]. Back to my 2nd motivation, I was impressed by the idea of statistical process that allows system to achieve sub-resolution. Even though, it has shown a high error due to statistically approximated measurement [2], making it to be a fingerprinting profile omits this down side because profile does not consider the precision but only its uniqueness and sub-resolution makes it even more.

This research goal is to propose a fingerprinting-based indoor localization system using Time-of-Flight measurement as a fingerprinting profile. This system will provide more accurate than using RSS profile due to the reason that was explained before, and even more robust than Ranging-based localization in NLOS scenario. The experiment firstly simulated in MATLAB, followed by demonstration in software-defined-radio, USRP2, with GNU Radio software. The implementation will be conducted inside lab area by using an existing example codes with modifying physical layer in both transmitter and receiver such that USRP2 will capture ToF at RF front-end.

Regarding the project motivation and goal, the main objective and specific objectives were created, and presented as following:

- Understanding how and why Indoor Positioning system was introduced and has been continuously developed
- Understanding the Indoor Positioning technique in engineering level and be able to apply this knowledge to develop and create the system (fingerprinting-based indoor localization with ToF measurement)
- Be able to use USRP2 and GNU Radio for programing arbitrary RF applications, especially in localization application.

4.2 Design requirements

To completely cover this work's objectives that were addressed, these following tasks should be performed accordingly,

4.2.1 Researching previous works

Before starting the system design, understanding from related works should be addressed first, in order to understand how to improve system and what tools are used the best for experiment. Hence, research topics were aimed to fingerprinting-based and ranging-based localization system articles (see detail in chapter 2 and 3).

4.2.2 Create a virtual environment for localization simulation

To correctly create a simulation environment, Gaussian distribution is assumed to be an ambient noise (equation 1), as express in following.

$$Noise = Normal\_dist(\mu, \gamma) \tag{1}$$

where, μ,γ are noise mean and standard deviation. Parameters of these equations are determined according to [20, 31-32]. Making a Non Line-of-Sight (NLoS) scenario in virtual area is more complicated, thus the area is basically a perfect Line-of-Sight (LoS) which means that there is no obstacles virtually created. Simulating without NLoS scenario including in simulation can affect an output to be unrealistic, thus NLoS is implicitly addressed by adjusting noise parameter in equation 1 and 3.

4.2.3 Achieve time and RSS measurement during simulation

Because this is a simulation, distance which is used in calculating propagation time and RSS are known beforehand. Hence, the time measurement is simply measured by mixing an actual propagation time value calculated by equation 2, with ambient noise equation 1-3 whose parameters are converted to time domain regarding [2,19]. RSS measurement, on the other hand, uses Path loss to determine an ideal value (equation 3) and then mixed with noise. At this point, these time and RSS will be used for simulation of user position.

$$d = ct \tag{2}$$

$$P_R = P_0 - 10\alpha \log d \tag{3}$$

where d is a distance apart from RF source, c is a speed of light, and t is propagation time in equation 5. P_R *and* P_0 are received signal power at distance d and 1 meter respectively, α is a path loss characteristic depends on the propagation characteristic.

4.2.4 Implement algorithm for determining the user's location

In this research, the localization algorithm is coded in MATLAB for both simulation and implementation. It means that user's position will not be determined in real-time, but after measurements is completely collected. As a result, this localization system is a prototype for testing the performance of fingerprinting-based indoor localization with Time-of-Flight measurement.

4.2.5 Modify code to capture time and RSS at USRP2 front-end

To capture RSS along with arrival time, GNU Radio provides API to do it. However, it does not timestamp arrival time at front-end, but after processing every incoming raw sample (iq components) to readable signal. Thus, it needs a modification at physical layer source code of USRPs such that system autonomously writes a timestamp when every raw sample arrives. By doing that, system accidently collects noise, thus more modification in order to eliminate noise from raw signal is needed. However, we shifted this process outs of physical layer because it may cause unexpected error with a lot of modification at lower level. Generally speaking, raw sample and its timestamp are collected at physical layer and then bypasses to upper layer for eliminating noise purpose before using it as an input for computing user's position.

4.2.6 Establish wireless communication between 2 transceivers

To test the localization system, what it needs is nothing but a simple communication where any packets are transmitted and received, while collecting ToF at RF front-end. Hence, a 2-way communication example code, called tunnel, is chosen with some modification such that number of sending packets can be controlled. The tunnel, when it is established, creates a virtual mac layer allowing user to manage packet flowing freely. With this configuration, Time and RSS will be captured at RF front-end in both sender and receiver of each transceiver.

4.2.7 Collect and store fingerprinting profile

The previous sections have mentioned how to collect RSS and propagation time measurement roughly, thus the detail will be discussed in this section. In USRP, raw sample incoming and outgoing signal are in iq-component form. They are collected with timestamp by the modified code in physical layer which was mentioned in previous section. By processing iq component, signal is extracted in a form of symbol or bit with averaged timestamp. Propagation time measurement is basically the subtraction of the first arrival and departure time which are stored in a server as a fingerprinting profile, and so does to user's profile when performing localization algorithm. As a result, server should possibly store all of fingerprinting profiles and can be easily query during a positioning process.

4.3 System overview

The fingerprinting-based indoor localization with Time-of-Flight measurement is a less-complexity and low-cost system in which the user device communicate with neighbor access points, then send ToF measurement to a server to perform the localization algorithm. Eventually, server feedbacks the estimation of current location to a user. Figure 4.1 illustrates the designed system consisting of 2 processes: Fingerprinting profile collection, and localization process. The first process (Figure 4.1a) maps a ToF measurement at known location, called fingerprinting profile, by asking dedicated user to walk around the area and performs this process. Once database is completely filled up, Second process (Figure 4.1b) can be performed. In

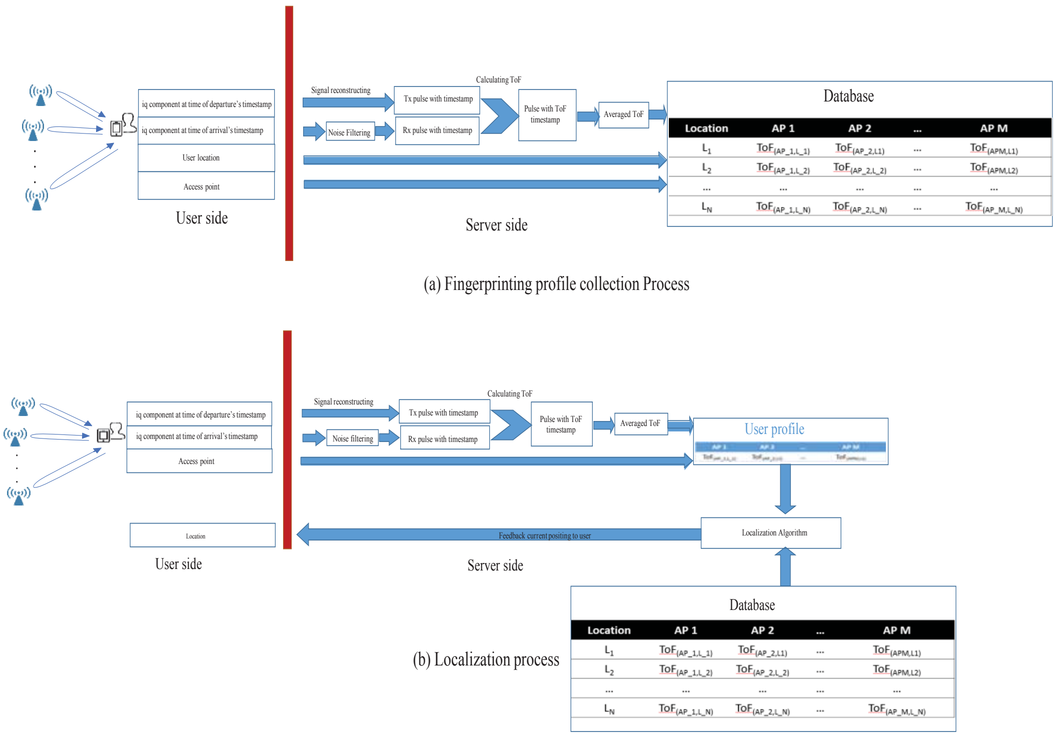


Figure 4.1 Overview of Fingerprinting-based localization with ToF measurement

this process, user who has no information about his location, collects ToF from APs. These measurements are preprocessed, and perform the statistical process to increase precision of ToF (this task is also done during the fingerprinting process) at server before transferring into localization algorithm which determines the current location by considering input ToF (user's profile) and fingerprinting profile in the database. At the high level, system compares profile between user and each fingerprinting, and yields user location with the most-likely one. This is a common fingerprinting method; however, accuracy can be improved by using this following purpose technique. This technique exploits nearby fingerprinting profiles of the most-likely one and uses them as anchor points. Then we will use lateration concept which borrowed from ranging-based indoor localization technique, to pinpoint sub-optimal location by considering a different between user profile and virtual anchor points (detail in section 4.5).

4.4 Time-of-Flight Measurement

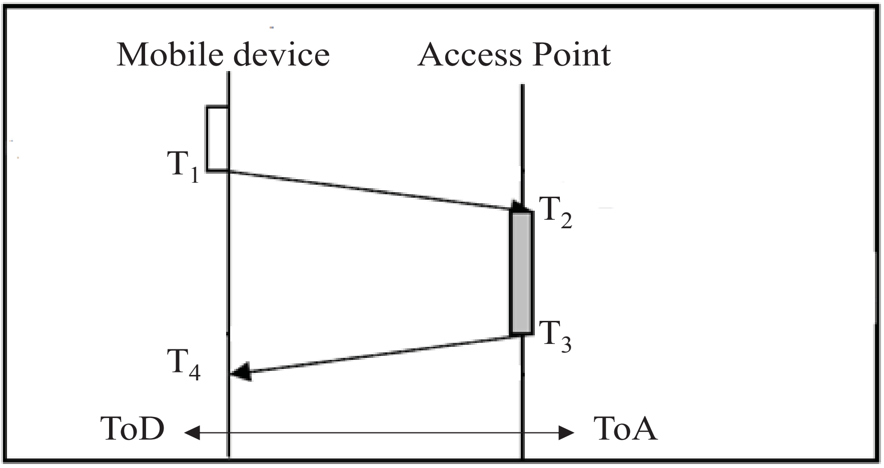


Figure 4.2 Two-way communication for measuring ToF

As it is mentioned in chapter 4 regarding concept of measuring Time-of-Flight, ToF is a 2-way propagation time or round-trip-time of packet. With this behavior, synchronization does not require between access point and user device because receiving and sending time are measured at a same node. In practical, however, there are some issues to consider of measuring ToF. Considering figure 4.2, when the device sends a signal to access point at a first-half of communication, access point creates a delay due to processing time before replies back the signal to device.

As a result, measuring ToF at user device includes access point's processing time. Therefore, the arrival and departure time at access point must be measured and reported to server in order to eliminate the processing time out of ToF by these following equation,

$$Processing\_time_{AP} = (ToA - ToD)_{AP} \quad (4)$$

$$ToF = (ToA - ToD)_{Device} - Processing\_time_{AP} \quad (5)$$

where ToA and ToD are time-of-departure and Time-of-Arrival.

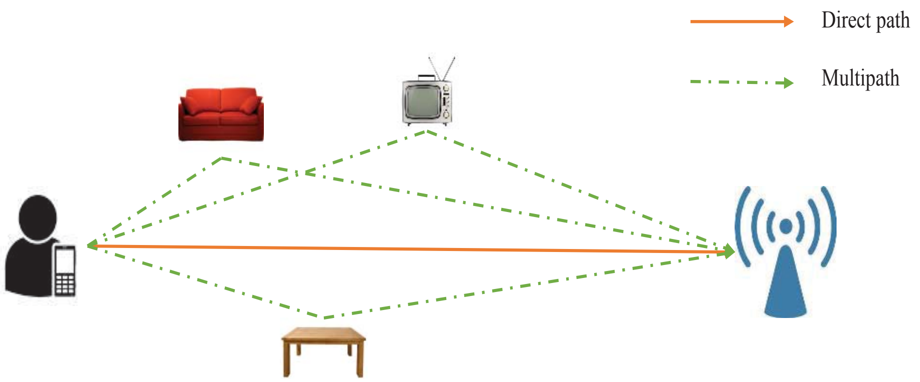


Figure 4.3 Multipath in indoor localization causes delay in propagation time

Multipath effect is another issue to be addressed. This is a phenomena where radio signal generates two or more paths toward the receiver due to it is reflected with environmental objects, figure 4.3. Consequently, it results in the delay of each propagation time in which it cannot tell which ToF is a correct one. In the LOS scenario, we can intuitively guess the less delay is a direct path; however, thing seems to be complicated in NLOS scenario. Thank to fingerprinting technique, this multipath effect is mitigated because fingerprinting profile itself experiences the same scenario as user does. Moreover, this system uses the statistical process (see detail in 4.4.1) which averages a set of ToFs, thus the propagation time seems to be more reliable and robust.

4.4.1 Statistical Process

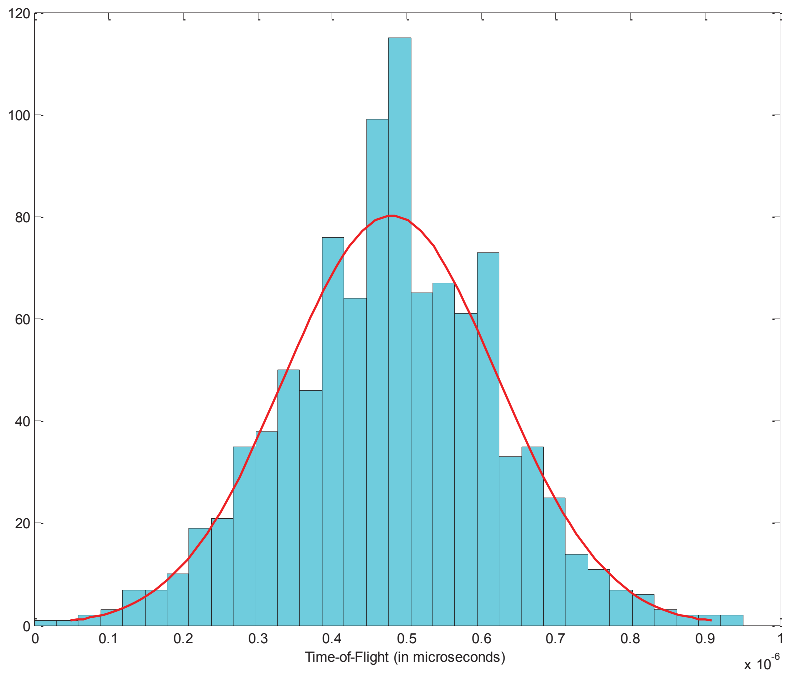


Figure 4.4 1000 ToF measurements in microsecond resolution are characterized as Gaussian distribution

This technique to use a knowledge of statistic and the presence of ambient noise to achieve sub-optimal resolution is called in [2] as a Gaussian noise approach. However, due to the concept, I would rather call it as a statistical process. This process measures the ToF of a set of packets as input, and due to an effect of noise, resulting in a ToF with short delay that, in theory, can be illustrated as a discrete Gaussian distribution, figure 4.4. As it is mentioned in previous section regarding hardware limitation, tradition ToF from off-the-shelf RF system is not accurate (microsecond resolution). Statistical process constructs a continuous Gaussian distribution from the discrete and assumes that the peak of the continuous is most-likely to be the ToF true value which can be achieved by averaging. As a result, the equation 5 which uses to calculate ToF should modify to be as

To simplify this equation, the access point's processing time can be assumed as a constant, thus ToA and ToD of access point on equation 4 is not necessary. Finally, the high precision is statistically estimated. Even though it is still an error happened which is mentioned in [9] where ToF is used in ranging-based technique, fingerprinting-based technique mitigates this error dramatically because fingerprinting profile requires only ToF uniqueness more than precision and vice versa the Ranging does.

4.4.2 Fingerprinting profile

In fingerprinting-based indoor localization (see detail in chapter 2), creating fingerprinting profile is the most critical step that plays an important role as a reference point to find a user's position. It can be said as a virtual node in the system's effective area in which dedicated user is asked to walk around the area and measured the RF information (propagation time, RSS, Angle-of-Arrival) at a known location which is given from a communication between user's device and access point. In particular, the system's database pairs fingerprinting profile with a specific location which later will be used during localization algorithm.

Designing the profile, 2 things needs to be concerned; what measurement a profile should be, and how far the distance between fingerprinting is. The first one is already decided to be ToF measurement where the reason is explained in previous section. The second can be designed manually and independently by each user with some constraints in the following.

- **The shorter the distance between fingerprinting profiles**, its uniqueness decreases, thus increases an error in localization. In addition, number of profile to make is larger which means more time spending for measuring.
- In contrast, **increasing the distance**, will reduce a resolution of localization. In another word, the minimum error gets higher; however, time to collecting profile reduces due to less number of them.
- **Number of access points that associate with the localization system** will have an effect to a profile uniqueness. Since the density of access points in building is uncontrollable unless they are intentionally installed for localization purpose. Therefore, less number of access point will make the flexibility for the system; on the other hand, it will, again, decrease the fingerprinting uniqueness.

To optimize these constraints, we should firstly look on to the localization requirements such as its effective area, resolution, and type of RF signal, etc.

4.4.3 User's profile

User's profile is collected with a same way as fingerprinting profile without knowing its location. In fact, it is the information that localization system uses to estimate user's location by comparing with fingerprinting profile, and informs back to user. The constraint is a processing time for creating user's profile. Because system

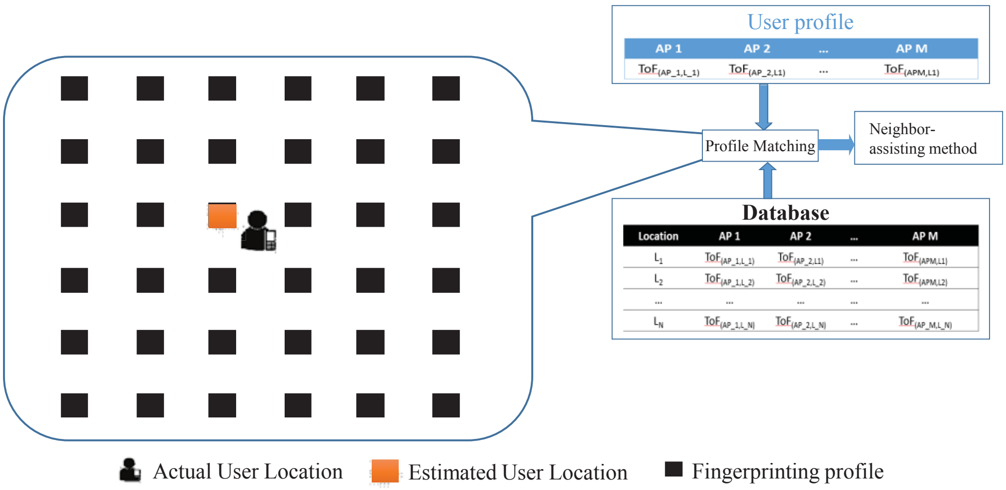


Figure 4.5 Localization Algorithm (Profile Matching)

uses the user's profile as an input, thus it affects a large delay at estimating position (system output). As a result, it cannot provide current position in real-time. However, this issue does not include in this work.

4.5 Localization algorithm

Localization algorithm performs the second process (Localization process), figure 4.1, after user's profile has completely created. It basically estimates a location based on fingerprinting profile that stored in database. The algorithm can be categorized in 2 steps, figure 4.5. Profile matching which is a fundamental method for fingerprinting-based system, matches user's location on to the most-likely fingerprinting profile. While, the second step improves a performance by leveraging neighbor profiles of the chosen fingerprinting profile of step one to yield sub-optimal location.

4.5.1 Profile matching

In this step, system is matching user's profile with each fingerprinting by subtraction. The fingerprinting that gives the minimum distance (subtraction result) is interpreted as the nearest point to the user, therefore its location will be implied as a user's current position. Since these 2 profiles consist of measurement from multiple access points, the subtraction metric (subtraction) cannot handle it sufficiently. Hence, the metric that possibly considers multiple inputs, is required. Euclidean distance metric from [14] that minimizes the distance by considering all of measurements at once is introduced to this process. It can be mathematically illustrated as this equation.

$$Euclidian\ Distance = \sum_{i=1}^{N} \sqrt{(ToF_{user} - ToF_{fingerprinting})^2_{AP_i}} \qquad (6)$$

where N is a number of profiles that minimize in each AP.

In general, the profile matching algorithm executes the subtraction (or Euclidian) metric to define the shortest distance amount them where user current location approximately put on to, figure 4.5. Note that Euclidian metric is chosen because this works follows [14] but other metrics may be used instead. However, benchmarking metric does not consider in this work.

4.5.2 Neighbor-assisting method

This step purposes the idea of how to achieve sub-optimal fingerprinting resolution which is limited by a gap between fingerprinting profile's location. It can be done by exploiting neighbor profiles of the output location from step 1, or coarse-grained location. First of all, it chooses the shortest distance neighbor of the coarse-grain location as see in figure 4.6. Then the chosen neighbor will be used to create the Ratio point. Finally the fine-grained location, the output of this process, is approximated at this point.

The process of calculation the Ratio point begun with an assumption that user's actual location in which translated to the form of user profile, should also affect multiple fingerprinting profiles nearby. Therefore, considering only the shortest distance is not sufficient to estimate location, thus extending to neighbor profiles is required. To realize this concept, we consider the assumption that the actual location is in between the coarse-grained location from matching profile process, and the neighbor profile's shortest distance because these are 2 profiles that user's location should possibly be. As a result, the equation to estimate the Ratio point that by

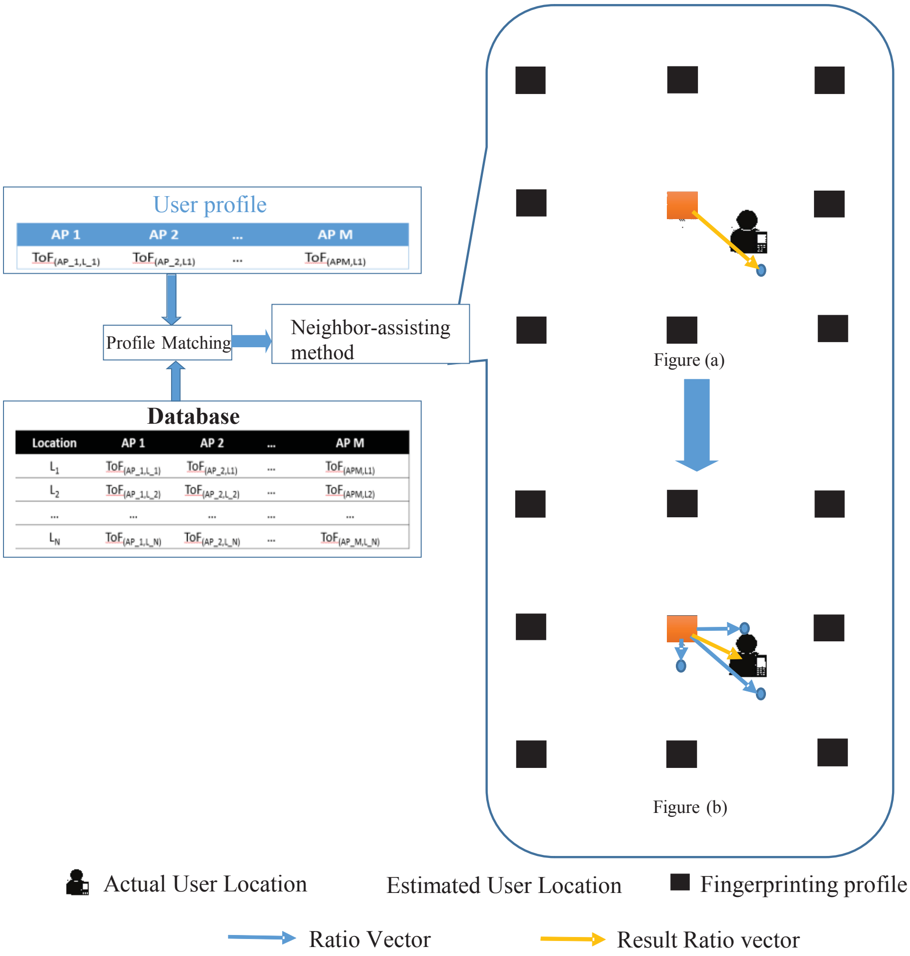


Figure 4.6 Localization Algorithm (Neighbor-assisting method)

considering distance of those 2 points are formed up, and expressed as the following equation

$$\frac{X}{L-X} = NB_1 ratio \tag{7}$$

where X is the Ratio point at a head of vector between chosen neighbor profile (NB_1) and coarse-grained location with length between them (L), and NB_1ratio is a ratio of NB_1's distance and the coarse-grained location.

This process can be extended its performance by using multiple neighbor profiles (X_N) to create N Radio points as figure 4.6b. Considering location of neighbor profiles around coarse-grained location, it is found that the 3 shortest distance neighbor profiles are sufficient because user's location, in this perspective, stays the nearest with this number. Since each Ratio point is in different axis regarding their position with coarse-grained location, the Result ratio points (X_R) should be computed with vector operation as equation below.

$$X_R = \sqrt{(X_1)^2 + (X_2)^2 + (X_3)^2} \tag{8}$$

$$\emptyset_R = \tan^{-1} \frac{X_{R_Y component}}{X_{R_X component}} \tag{9}$$

where $\emptyset_R$ is direction of Result ratio vector (X_R) points at.

In summary, Localization algorithm of the fingerprinting-based indoor localization with Time-of-Flight estimates coarse-grained position by following a fundamental technique of fingerprinting, Profile matching. Then it exploits the distance between neighbor profiles around coarse-grained location to create a small intersection area in which fine-grained position is approximately inside.

Chapter 5 Evaluation

The system that was introduced in previous chapter, had been experimented and evaluated in this chapter on both simulation and implementation. This work was evaluated its performance with 2 basic approaches: RSS-based fingerprinting approach and Ranging-based approach with ToF measurement in term of localization accuracy. Moreover, the effect of gap between fingerprinting profile and the effect of number if neighbor profile that used during localization algorithm, were considered.

5.1 Simulation

5.1.1 Experimental setup

In this experiment, the environment is virtually created for simulation purpose in MATLAB. In this environment, 121 square-meter (11 x 11 meters) floor map was built and 3 access points placed at the floor's edge as illustrated in figure 5.1. The system started to collect fingerprinting profile on each access point with 1 meter away gap as default. 1000 ToFs are measured during profile collecting process with added Gaussian noise in all 3 access points. Fingerprinting profiles can be seen graphically

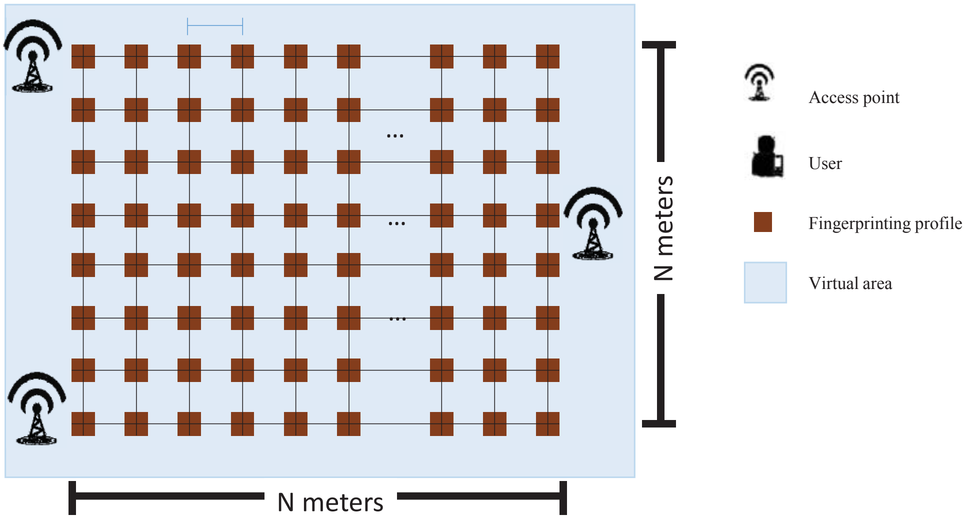
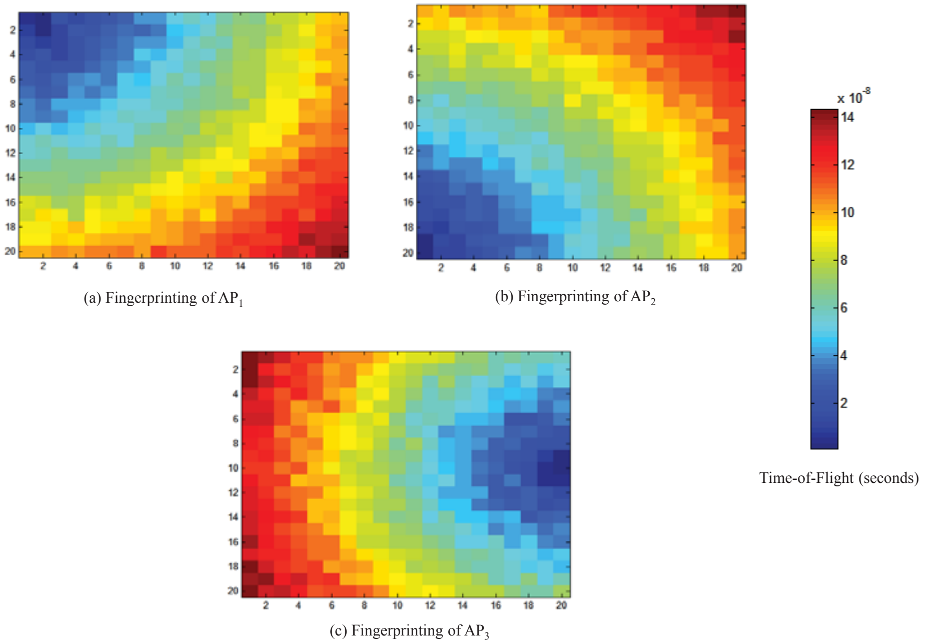


Figure 5.1 Experimental environment setup for simulation

in figure 5.2 where colors represented the measured ToF such that bluish-color profile is closer to access point than reddish one. This experiment assumed that access points and user's device are able to measure propagation time at a hundred-nanosecond resolution which means device's hardware has 10-MHz clock speed satisfying common WiFi-enabled device. To evaluate localization performance, the system generated 100 user's location randomly as an input and compared its error with an estimated location (system output) by following localization algorithm that was mentioned in chapter 4. In addition, number of neighbor profiles that used to enhance its performance was set to one.

In comparing scheme, RSS-based fingerprinting were performed with the same process but measuring RSS. It was measured by applying Path loss equation with



(a) Fingerprinting of AP_1

(b) Fingerprinting of AP_2

(c) Fingerprinting of AP_3

Figure 5.2 Graphical fingerprinting profiles with Time-of-Flight in each APs

added Gaussian noise. Ranging-based approach uses the same set of ToF measurements, but applied with trilateration technique for pinpoint user's location.

5.1.2 Effect of gap between fingerprinting profile

This experiment is to investigate the impact of gap between fingerprinting profile to the localization accuracy. Thus we literally increased the gap from 1 to 10 meters and measured the system accuracy in both with and without neighbor profile-assisting technique. Note that comparing approaches does not include in this investigation because we considers the effect only in our work only. Since the gap range that are varied during experiment, the virtual environment should be larger than

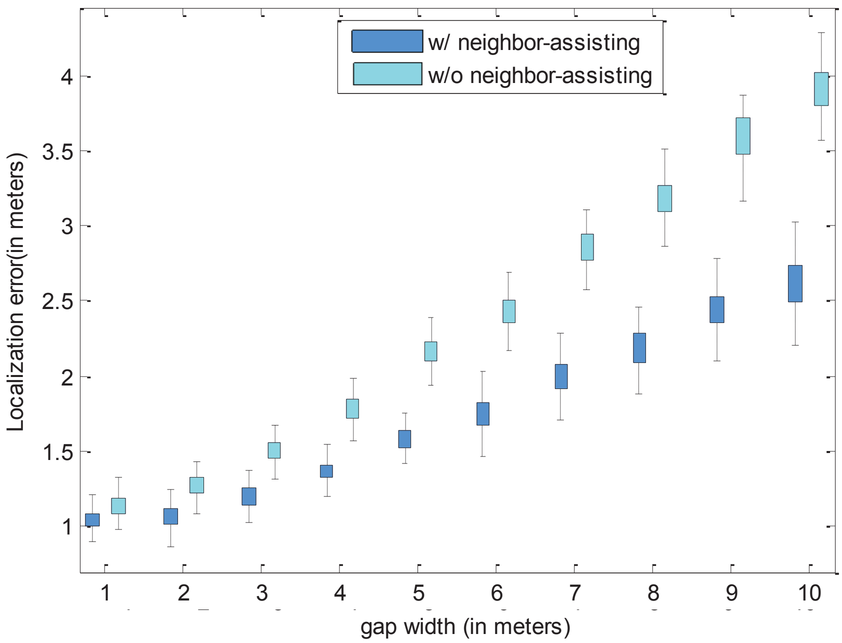


Figure 5.3 Localization error VS gap width

the default (20 square-meters). Therefore, the entire experiment in this section increased to 100 square-meters.

Figure 5.3 plots the localization error (y-axis) as a function of the profile gap (x-axis). The figure shows the median of the estimation error for our work in both with and without neighbor profile-assisting technique. Again, the system collects 1000 experiments in every size-gap cases.

The figure shows that the median localization accuracy increases when gap width becomes larger. In particular, accuracy of basic fingerprinting case (w/o neighbor-assisting) changes 1 to 2.5 meters for gap width 1 to 10 meters away, and 1.2 to 3.8 meters for with neighbor profile-assisting. As expected, because its coverage becomes broader when fingerprinting profile stays further away, therefore reducing localization resolution. Moreover, the higher accuracy in neighbor-assisting case has proven that localization performance can be improved by considering nearby fingerprinting profile.

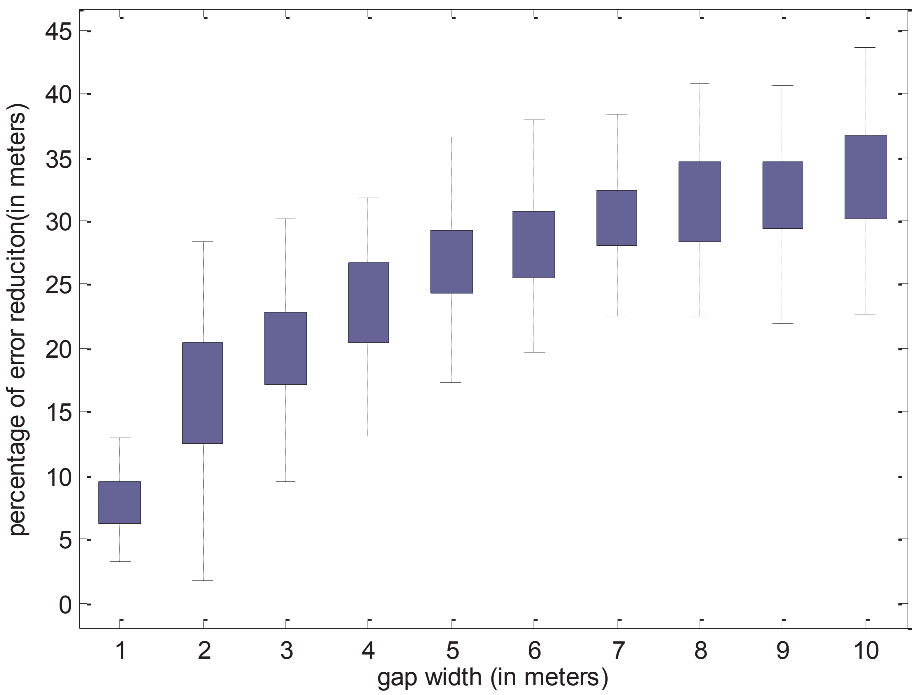


Figure 5.4 Neighbor-assisting technique improves the performance at different gap width

Figure 5.4 has illustrated the localization performance when neighbor-assisting technique is implemented in a function of gap width. It is stated clearly that error is reduced greater when gap width become larger; decreasing 8 to 37 percent for 1 to 10 meters gap width. This fact can be explained that exploiting neighbor profile implicitly extends the resolution or, in analogy, this process makes more virtual profile. Therefore, in larger gap width scenario (lower resolution), the effect of neighbor profile manifests efficiently which represented in higher reduction percentage.

5.1.3 Effect of number of neighbor profiles

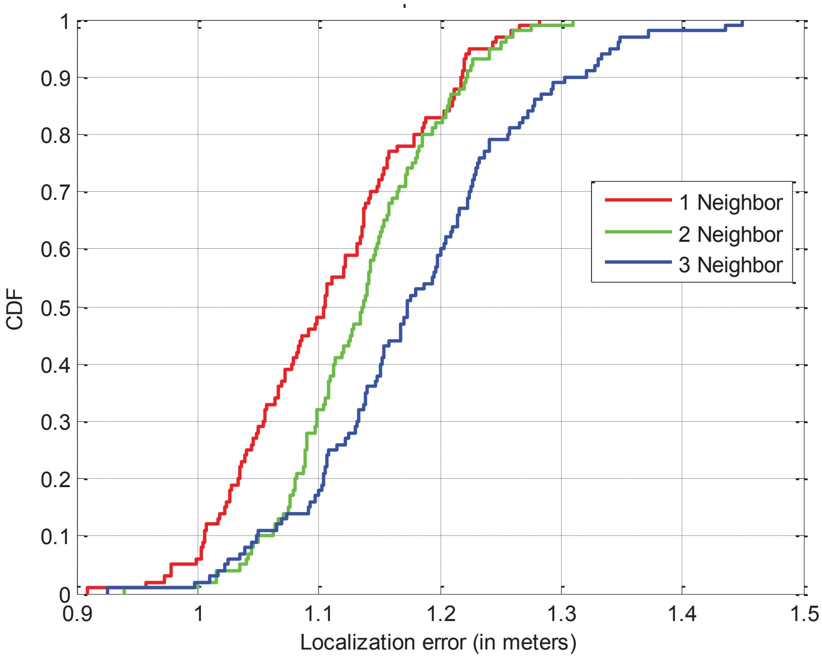


Figure 5.5 Effect of number of neighbor profiles

This experiment shows the effect of number of neighbor profiles corresponds to localization accuracy. As it was explained in chapter 4, we stated that by increasing number of neighbor profile should tremendously reduce the error because they might indirectly points to the actual location. Unfortunately, the result shows in the opposite way such that using only 1 shortest distance neighbor profile reveals system to nearest actual position; 1.08 meters error at median, while others have 1.13 and 1.18 meters. We explained this situation that because the noise variation has strongly influence at these neighbors, thus multiple neighbor profiles also accidently accumulate noise causing higher noise as depicted in the figure.

5.1.4 Localization accuracy

The experiment in this section evaluates our work performance, ToF-based fingerprinting indoor localization system, by comparing with 2 basic approaches; RSS-based fingerprinting, and Ranging-based system. Figure 5.6 shows these approaches' accuracy in term of error at median and 90th percentiles. Our work achieves the best accuracy than comparative approaches. In particular, our work slightly won RSS-based fingerprinting (around 10 centimeter) but remarkably outperforms Ranging-based with 1.5 and 4.3 meters at median and 90th percentile respectively.

Since our work and RSS-fingerprinting gain similar accuracy, this point may not convince this work as a better localization system. This issue can be explained in the following way. The experiment was simulated by assuming LoS and static environment which makes propagation time and RSS measurement to be less affected by noise and multipath. In the real environment, however, RSS performs poorly as it changes their signal strength easily due to others RF interference and even weather condition. This fact is also mentioned in many previous works [10-11, 13, 23-24, 30-

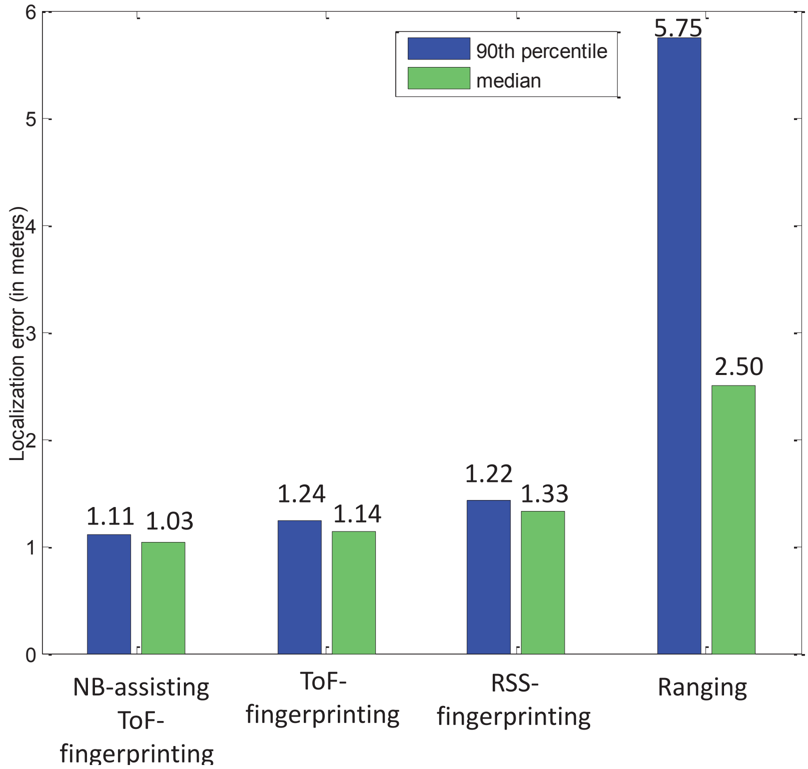


Figure 5.6 Localization Accuracy in simulation

31]. In contrast, propagation time which is affected less noises, is able to sustain the performance as in simulation (see more detail in implementation section).

Regarding the Ranging-based performance, it is straightforward that their accuracy shows the worst since propagation time is not accurate enough to provide the exact distance between access point and user's device, thus error is significantly huge. As oppose in our work that only needs the propagation time's uniqueness at certain locations to make the distinguishable fingerprinting profile, therefore localization accuracy increases rapidly even with inaccurate propagation time measurement.

According to our work, ToF-based fingerprinting with assisting from neighbor profile performs better than basic fingerprinting technique. The effect of this phenomena is explained in section 5.1.2

5.2 Implementation

5.2.1 Experimental setup

In this experimental task, we implemented our algorithm into 4 USRPs; 3 access points and 1 user device. They has been programmed to operate at 2.4 GHz with 10 MHz bandwidth as a transceiver and all connected with different Network Interface Controller (NIC) of the same PC host. The communication begins transmitting from user device to 3 access points whom act as an anchor node, then conveys the same signal back to user device. With this setting, we are able to measure propagation time by simply timestamp at both the user device and access points, see detail in chapter 4. Note that this work bases on 2D-localization, therefore all USRP are lifted at the same height, 0.8 meter above ground, during the experiment. We conducted the experiment at our lab's lobby area, and used the entire free-space that can expand to 16 square-meters (4x4 meters).

During collecting fingerprinting profile process, we manually moved USRP at every 1 meter and initiated the communication to collect 1000-ToF measurements by sending 1000-wideband pulse signals. Once profile is completely collected, we started to evaluate the performance by comparing with the same comparison scheme as simulation section. We randomly chose the 20 locations and simply collected ToF, then performs the localization algorithm which the same setup as collecting fingerprinting process. Regarding the comparison schemes, we used the same ToF

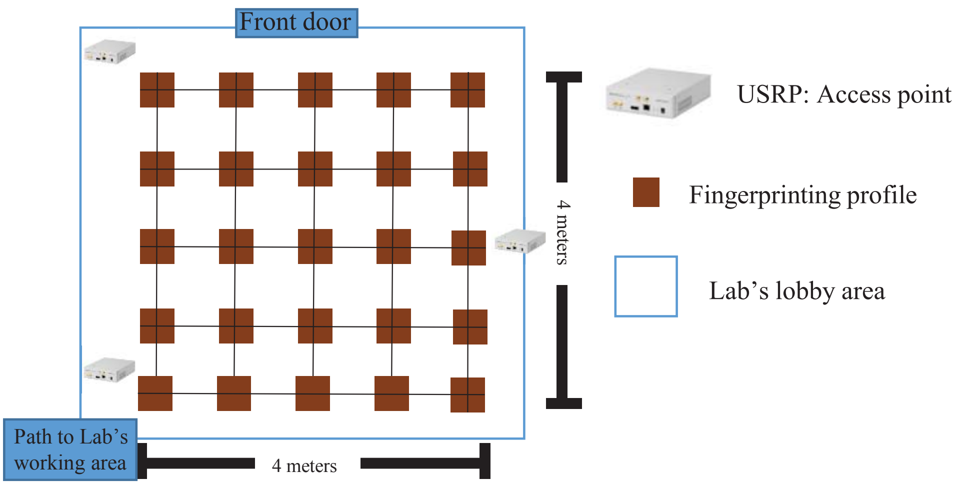


Figure 5.7 Experimental environment setup for implementation

measurement for Ranging-based, while RSS-fingerprinting used the signal strength that also collected with ToF.

5.1.2 Localization accuracy

The evaluation has been conducted in this section. As the same procedure with simulation section, Figure 5.8 shows these approaches' accuracy in term of error at median and 90^{th} percentiles. Our work achieves the best accuracy than other approaches. In particular, our work remarkably outperforms both RSS-based fingerprinting and Ranging-based with 0.3 and 1.8 meters at median and 1.3 and 2.7 meters 90^{th} percentile respectively.

The different of result lies on the RSS-fingerprinting approach such that it was slightly lower than our approach in simulation but vice versa in implementation. As expected, RSSs which have measured during experiment degraded significantly from ambient WiFi signal, people movement nearby, etc., however they does not strongly influence propagation time, thus it is less affected to ToF.

Regarding the Ranging-based performance, it is obvious that their accuracy shows the worst in both simulation and implementation due to the fact about inaccurate collecting propagation time. Moreover, the multipath effect that was not considered as a parameter in simulation, strongly manifested in real environment causing larger the localization error. Our work, on the other hand, avoids this issue with fingerprinting profile whose information inside already knows the effect of multipath. As consequence, ToF that collected at user device, also experienced the same multipath as fingerprinting, then result in less error.

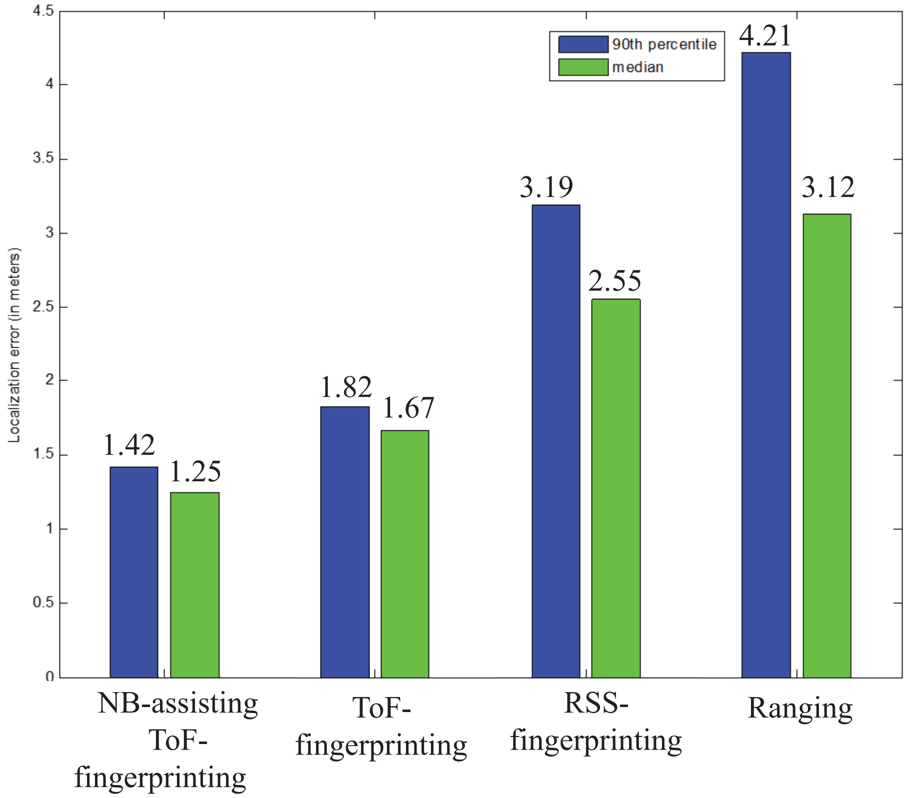


Figure 5.8 Localization Accuracy in simulation

Chapter 6 Conclusion

The thesis presented a new indoor localization system that uses Time-of-Flight measurement implemented in fingerprinting-based localization technique. This works, firstly issued (1) the difficulty of using time propagation measurement in indoor localization that cannot measure time in nanosecond-scale resolution due to hardware limitation, and (2) the unreliable phenomena of RSS that causes high error in RSS-based fingerprinting indoor localization system. By solving these challenges, this work borrowed the statistical process to achieve a high resolution time measurement, and has been implemented in fingerprinting approach instead of RSS as in previous work to avoid the error causes by unpredictable RSS phenomena. In addition, we introduce a new fingerprinting method that can boost up an accuracy from traditional fingerprinting concept. This method exploits neighbor fingerprinting profiles around the estimated location from basic fingerprinting algorithm, and re-estimated fine-grained location by considering a ratio between neighbor profile and the estimated location.

We evaluated this work's performance with 2 comparison schemes; RSS-based fingerprinting and Ranging-based technique. In simulation section with MATLAB, our work outperformed the comparison schemes in term of accuracy. Moreover, our proposing fingerprinting method achieved higher accuracy than the basic algorithm. Its effect showed clearly when fingerprinting profile's gap width becomes vast. In Implementation section, our work has implemented in USRP and tested inside lab.

Fortunately, this work has achieved a better localization accuracy than comparison scheme.

However, this work does not mention how to collect fingerprinting profile more efficiency which is the disadvantage of fingerprinting-based technique. Instead, we manually collected them location-by-location which is a very time-consuming process. Also, this work is not a real-time system as practical localization system should be. These issues should be carefully considered in the future work.

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요 약

Positioning/localization 시스템의 등장은 RF 시그널을 이용하여 사용자들에게 자신의 위치를 실시간으로 추적할 수 있게 해주었다. Global Positioning System (GPS)는 인공위성으로부터 오는 RF 시그널을 이용하여 outdoor localization 을 가능하게 해주는 대표적인 기술이다. GPS 는 다양한 어플리케이션에서 이용되고 있지만, 인공위성의 RF 신호가 건축물을 관통하여 높은 파워를 유지하기 힘들기 때문에 실내 환경에서 사용하기 어려운 단점이 존재한다. 이를 해결하기 위해 많은 연구진들은 시중에 판매중인 Wi-Fi 를 사용하여 Indoor Positioning System (IPS)이라는 이름으로 다양한 어플리케이션을 제안하고 있다.

IPS 는 indoor 한 환경에서 활용되기 때문에 outdoor 시스템보다 정확하고 신뢰성 있어야 하며, centimeter 나 meter 규모의 오류를 허용하는 높은 정확도를 필요로 한다. GPS 에서 주로 사용되는 거리기반 localization 기술은 IPS 에서 사용하기 어렵다. 실내 환경은 multipath 와 무선 모듈의 하드웨어적 제한으로 인해, 거리기반 localization 기술에서 주로 사용하는 전파시간 예측이 힘들기 때문이다. 그러므로 현재는 Received Signal Strength (RSS)의 값을 통해 위치 정보를 database 에 저장해둔 fingerprint 를 이용하여 위치 측위를 하는 RSS-based fingerprinting 방식이 제안되고 있다. 하지만, RSS 신호는 견고하지 않고 시간에 따라 변화가 일어나기 쉽기 때문에 높은 측위 오류를 발생시킬 수 있다.

본 저자는 RSS 신호를 사용하지 않고, Time-of-Flight (ToF) 정보를 활용하여 fingerprinting-based localization 을 하는 새로운 방안을 제안하였다. ToF 는 견고하고 시간에 따라 변화가 크지 않기 때문에 RSS 에 비하여 신뢰성과 정확성이 높다. 또한, ToF 의 측정은 Access Point 와 사용자 기기간의 동기화가 필요하지 않기 때문에 시스템의 오버헤드를 줄일 수 있다. ToF 를 이용한 거리 기반 위치 측위 기술은 하드웨어의 제한으로 인해 10 미터 이상의 오류가 생길 수 있어 잘 활용되지 않지만, 본 논문에서는 fingerprinting 기술과 ToF 를 접목하여 정확한 위치 측위가 가능함을 보였다.

정확도가 fingerprint 간의 간격으로 제한되는 기존의 fingerprinting 기반 방식을 해결하기 위해 우리는 다양한 방식의 실험을 진행하였다. 실제로 이웃 fingerprint 의 정보를 이용하여 기존 방안의 제한점을 해결할 차선책을 제안하였다. 제안하는 방안은 실제 실험을 통하여 기존의 방안보다 높은 성능을 가짐을 보였다.

주요어: 실내 측위 시스템, Time-of-Flight, Fingerprinting 기술, 무선통신

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