Determining Your Location Using Wi-Fi

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1 Introduction

For this project, I researched various ways to implement a Wi-Fi positioning system, a method that utilizes wireless Wi-Fi access points to determine a device's location. In this paper, we will examine various positioning methodologies as well as investigate the plausibility of implementing such a system on Westminster College campus without any additional hardware installation.

2 Previous Work

One of the primary advantages of Wi-Fi positioning comes from being able to be used in locations where satellite positioning systems like GPS are unreliable. In most outdoor settings, GPS can provide the best results, but for indoor settings or even dense urban areas, GPS becomes unreliable. As such, one of the primary uses for Wi-Fi positioning today is to determine device locations for businesses in these types of settings. A mall, for example, could implement a Wi-Fi positioning system to know where shoppers are at in real time by tracking the locations of devices connected to their network. Another use would be to integrate the system with a map of the mall to allow shoppers to easily find where they are located and navigate from store to store. Two of many companies that specialize in implementing systems such as these include Inpixon and Skyhook.

While each company may have general methods of implementation, the specific ways these systems operate can vary greatly depending on what works best in a given environment. Wi-Fi positioning, for example, is only one positioning technique they have at their disposal. Inpixon uses a wide range of other technologies to determine location as well, including "radio-frequency (RF) technologies like UWB (ultrawide band), BLE (bluetooth low energy) and Chirp (compressed high-intensity radiated pulse), as well as wireless devices, such as tracking tags and smartphones," while Skyhook also utilizes GPS and cellular signals [1]. Factors such as environment topology, company budget, and current infrastructure can play a large part in these decisions.

Another leading company in indoor navigation is Mapsted. While they do not use Wi-Fi positioning, their work in the field of indoor positioning is worth mentioning. Mapsted's technique is particularly unique as they are able to determine a mobile device's location accurate to 1-3 meters without beacons, Wi-Fi, or any additional external hardware. Rather, their algorithm "uses magnetic or wireless disturbances in the environment to learn and determine location, essentially converting that 'noise' into useful information." As such, they claim this technology works with any "off-the-shelf smartphone" [3].

One of the greatest advantages to using Wi-Fi positioning over other systems, however, is that it is particularly designed to be used with existing Wi-Fi infrastructure, something most businesses already have! Additionally, accuracy is directly related to the density of access points in a given area, so this infrastructure can be easily built upon by adding more access points in key areas to improve accuracy. As such, Wi-Fi positioning is often used today for its ability to provide accurate location data while remaining highly affordable and convenient. Furthermore, these are the reasons I chose to implement Wi-Fi positioning at Westminster over other techniques as they are better aligned with the scope of this project.

3 Background

To understand what is going on in these systems, let's provide some background. For the purposes of this paper, I will distinguish between two types of positioning systems, Wi-Fi-based and non-Wi-Fi based. As the names suggest, Wi-Fi-based systems utilize Wi-Fi hotspots, or wireless access points, to determine device location, whereas non-Wi-Fi based systems use other technologies and hardware aside from Wi-Fi to determine location. As mentioned above, these other technologies can include RF, cellular, or GPS. As we will be focusing on a Wi-Fi based method for this project, we will not go into detail about how these other technologies are used. As such, let's move onto how these Wi-Fi-based systems work.

There are two primary methods that are used to implement Wi-Fi positioning systems. The first method utilizes a technique called Wi-Fi trilateration. Wi-Fi trilateration is a technique that utilizes a measurement inversely proportional to distance called RSSI (Received Signal Strength Indicator) to determine the location of the target device relative to given access points. Note that an access point, or AP, is simply a hardware device that allows Wi-Fi devices to connect to a wired network. Assuming the target device is connected to this network, we can find the signal strength between the two devices. This method requires known locations of at least three fixed access points. Then, since RSSI is inversely proportional to distance, these locations can then be used along with the RSSI data to estimate the distance between the device and each access point. Using these distances, the algorithm can then use trilateration to approximate the device's relative position. This method is otherwise called multilateration when more than three access points are used.

The second method, on the other hand, utilizes a similar technique called Wi-Fi triangulation. The major difference in this method is that while Wi-Fi trilateration determines location based on known distances (from collecting signal strength data), Wi-Fi triangulation determines location based on the angle from which the signal is received by an antennae of the access points, a measurement known as angles of arrival (AoAs) (see Figure 1 to the right). While this method has been known to yield higher levels of accuracy than its counterpart, the ability to measure AoAs is unfortunately not a feature a typical access point has available. Rather, implementation of a Wi-Fi triangulation system requires additional hardware called MIMO antenna systems in order to make these measurements, hardware which was not available in Westminster College's existing network infrastructure.

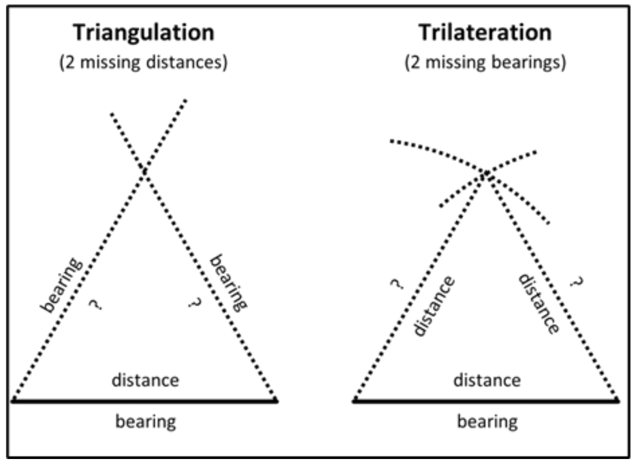


Figure 1 *A demonstration of the differences between triangulation and trilateration[4]. Note that bearings are angles.*

A technology that is readily available in Westminster's infrastructure, however, are access points. In fact, every major building across campus is densly populated with them on every floor. As such, Wi-Fi trilateration is the positioning method I used when investigating a Wi-Fi positioning system on campus due to its convenience and affordability uniquely suited for this project.

Additionally, we are able to acquire distance approximations using the Free Space Path Loss (FSPL) formula. This formula provides us with an RSSI to distance conversion that attempts to account for the signal strength drop off between two network devices through free space (usually air) [5]. This formula is derived by the Friis transmission equation [6], stating "that in a radio system consisting of a transmitting antenna transmitting radio waves to a receiving antenna, the ratio of radio wave power received P_r to the power transmitted P_t is:

$$\frac{P_r}{P_t} = D_t D_r \left(\frac{\lambda}{4\pi d}\right)^2$$

where

- D_t is the directivity of the transmitting antenna
- D_r is the directivity of the receiving antenna
- λ is the signal wavelength
- d is the distance between antennas" [5]

Assuming $D_t = D_r = 1$, the FSPL formula is then derived from this equation by noting that free-space path loss is the ratio of power received to power transmitted:

$$\text{FSPL} = \left(\frac{4\pi d}{\lambda}\right)^2$$

Furthermore, since the frequency of a radio wave f is equal to the speed of light c divided by the wavelength, we can also write the formula as follows.

$$\text{FSPL} = \left(\frac{4\pi df}{c}\right)^2$$

Since RSSI is measured in units of decibels (dB), we must express the FSPL formula in terms of dB. We do this with the following calculation.

$$\begin{aligned}
\text{FSPL(dB)} &= 10\log_{10}\left(\left(\frac{4\pi df}{c}\right)^2\right) \\
&= 20\log_{10}\left(\frac{4\pi df}{c}\right) \\
&= 20\log_{10}(d) + 20\log_{10}(f) + 20\log_{10}\left(\frac{4\pi}{c}\right)
\end{aligned}$$

To get d in terms of meters and f in terms of megahertz, we set $c = 4\pi 10^{1.3775}$.

$$\text{FSPL(dB)} = 20\log_{10}(d) + 20\log_{10}(f) - 27.55$$

This constant can be found for whatever units are necessary, such as 32.44 for d, f in kilometers and megahertz, 92.45 for d, f in gigahertz and kilometers, etc. Finally, we can use the Fade Margin equation [7] to represent this formula solely in terms of RSSI, and a given frequency value:

$$d(\text{km}) = 10^{\left(\frac{27.55 - 20\log_{10}(f) + RSSI}{20}\right)}$$

4 Implementation

As previously mentioned, the implementation of these positioning systems can vary greatly from system to system. As such, my implementation may be vastly different from other systems because it is uniquely designed to work with Westminster College's existing network infrastructure and physical environment. In Figure 2 below, we can see a map of Westminster College campus from a birds eye view. For my implementation, the goal was to be able to pinpoint exactly where my device is located on this map relative to known access point locations. Ideally, this would be able to work outdoors as well as indoors, but the primary objective was to focus on indoor accuracy, especially considering outdoor AP systems were not yet installed on campus at the time of this project.

Figure 2 *Map of Westminster College campus from Google Maps.*

To accomplish this goal, I developed a computer application using the Python programming language to implement this system with Wi-Fi trilateration. This implementation can be broken down into three primary steps: collect necessary data from Wi-Fi access points around campus, use this Wi-Fi data to calculate a relative distance between the user device and each AP, and finally approximate user device location using Wi-Fi trilateration. Now let's go into each of these steps in more detail.

4.1 Step One: Collect Data

As mentioned, in order to perform Wi-Fi trilateration, there is some necessary information we need to collect from each AP, namely their exact locations, signal strength, and mac addresses. To determine each AP's location, I recorded its latitude and longitude global coordinates using Apple Maps GPS in an on-site survey.

I began by surveying two of the main buildings on campus and used these buildings for testing. In Figure 3 to the right, we can observe these access points on our map in red. Note that while this set of APs was sufficient for testing, it is only a small portion of how many there are in each building. Thus, more APs could easily be surveyed to increase the program's reach as well as accuracy later on. While performing the survey, I also associated each location with the mac address corresponding to that access point, where a mac address is a unique identifier that is assigned to every device connected to a network. Doing so allows us to uniquely distinguish one AP and its corresponding location from another. This mac address information was provided thanks to the Westminster ITS Network Operations team.

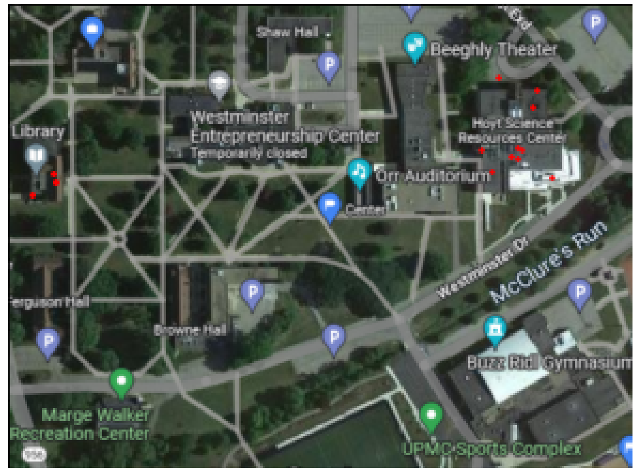
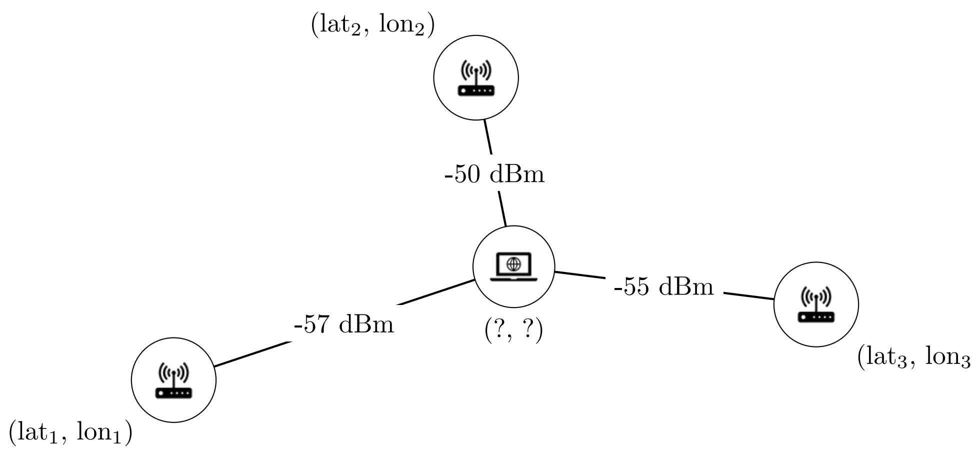


Figure 3 *Map of Westminster College campus containing the locations of access points, labeled with red dots, surveyed during the testing phase.*

Next, we must also scan the access points themselves for certain network data, such as RSSI and mac address data. Note that while we have already hard coded in each AP's mac address data with their locations, we must now dynamically scan for mac address data in order to match each scanned AP with a previously recorded location. To collect this information, I used a tool called an API (Application Programming Interface), a type of software interface that provides a service to other software. For my purposes, I specifically utilized the Windows WLAN API as it allowed me to get a dynamic network list of all the access points within signal range of my device. Within this list, I was then able to query for various information I needed from each access point, including the signal strength (RSSI) and mac address data as mentioned. Additionally, I also recorded each AP's SSID, or network name, so that I could filter for specific networks only. Westminster's network is comprised of two network SSIDs broadcasted from each access point: WC-Secure and WC-Public. WC-Secure is available for faculty, staff, and students and requires Westminster credentials, while WC-Public is available for visitors and is publicly available to anyone. As WC-Secure provides a much better and more reliable network connection, I decided to filter out all other networks that were not labeled as WC-Secure using their SSID names. Now that we have collected the necessary data, we can proceed with the rest of the program.

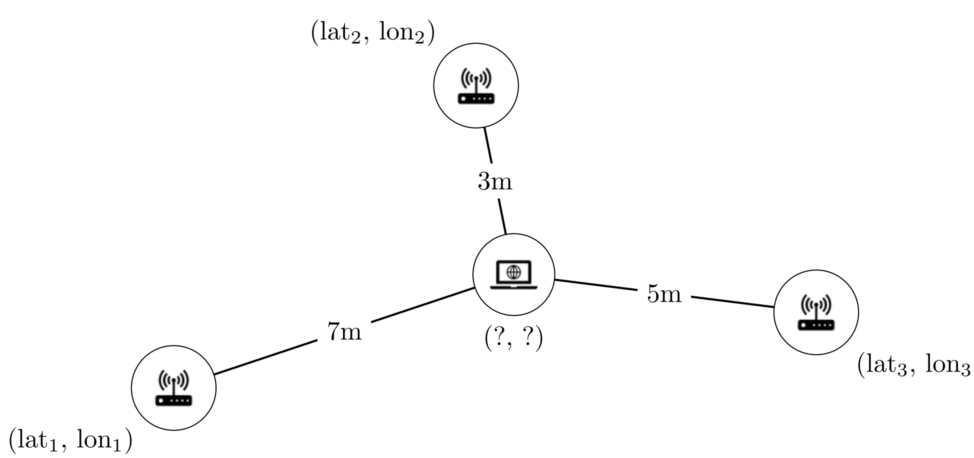
For a visual representation of what we have so far, observe Example 1a below.



Example 1a *Graph representing an example network system containing 3 access points with known global locations and RSSI values with respect to a user device of unknown location.*

4.2 Step Two: Calculate Distance

The first measurement we need to calculate is distance, which we can now approximate using the previously collected RSSI data with the FSPL formula. As we have already derived this formula to calculate metric distance in terms of RSSI and frequency, all we need to do a plug in our data. For the purposes of this project, I hard coded in a frequency of 2412 MHz as the standard frequency for all the access points on campus. Note that this formula only gives us a general approximation of distance, not an exact value. Due to obstacles and other objects obstructing free space, this estimate has varying levels of accuracy across different environments. Let's go ahead and update our example from before to reflect this new distance data in Example 1b below.



Example 1b *System from Example 1a, now updated to reflect the RSSI to metric distance conversion using the FSPL formula.*

Before moving on to step three, however, there is one problem we must resolve. Currently, we are measuring distance in the metric system and the locations of the APs in the geographic coordinate system. Consequently, if we were to plot these on a coordinate plane right now, the distances would not make sense with our locations. As such, in order for Wi-Fi trilateration to work, we must make sure everything is in the same system of measurement! To resolve this issue, I converted everything into the metric system with the following approximations:

$$\text{Latitude : 1 degree} = 110.574 \text{ km}$$
$$\text{Longitude : 1 degree} = 111.320 \cos\text{ (latitude) km}$$

Furthermore, these conversions allowed me to represent my map of Westminster College as a coordinate plane in terms of meters by finding the change in distance between the top left and bottom right corners:

$$x_{\max} = 110574 * |x_{\text{top left corner}} - x_{\text{bottom right corner}}|$$
$$y_{\max} = 111320 \cos\left(41.117\frac{pi}{180}\right) |y_{\text{top left corner}} - y_{\text{bottom right corner}}|$$

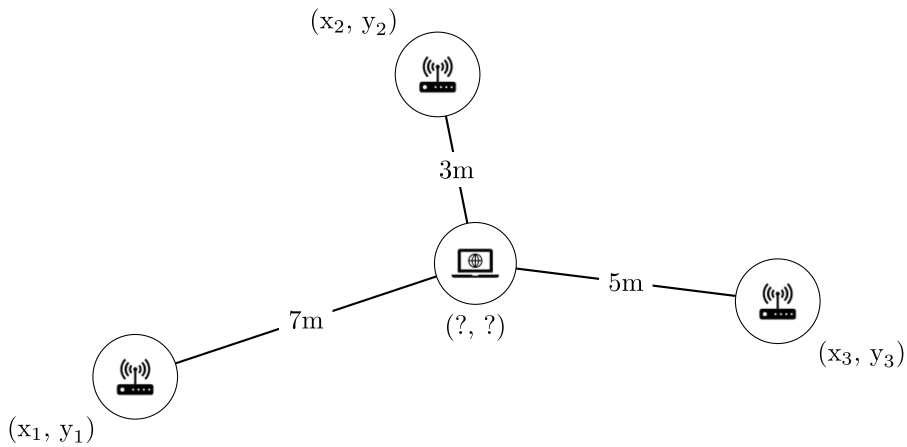
Note that I use $41.117\frac{\pi}{180}$ for my latitude value because it is about halfway up my map and provided a good estimate for the conversion. I also multiplied each term by 1000 since I wanted meters, not kilometers. In Figure 4 below, we can see the resulting coordinate plane running about 330 meters by 450 meters in dimension.

Figure 4 *Map of Westminster College campus as a coordinate plane in terms of meters.*

We can then easily map any latitude longitude coordinate point on our map to a location in this coordinate plane in terms of meters using these same conversions:

$$x_{\text{max}} = 110574 * |lon - x_{\text{bottom right corner}}|$$
$$y_{\text{max}} = 111320 \cos\left(41.117\frac{\pi}{180}\right) |lat - y_{\text{bottom right corner}}|$$

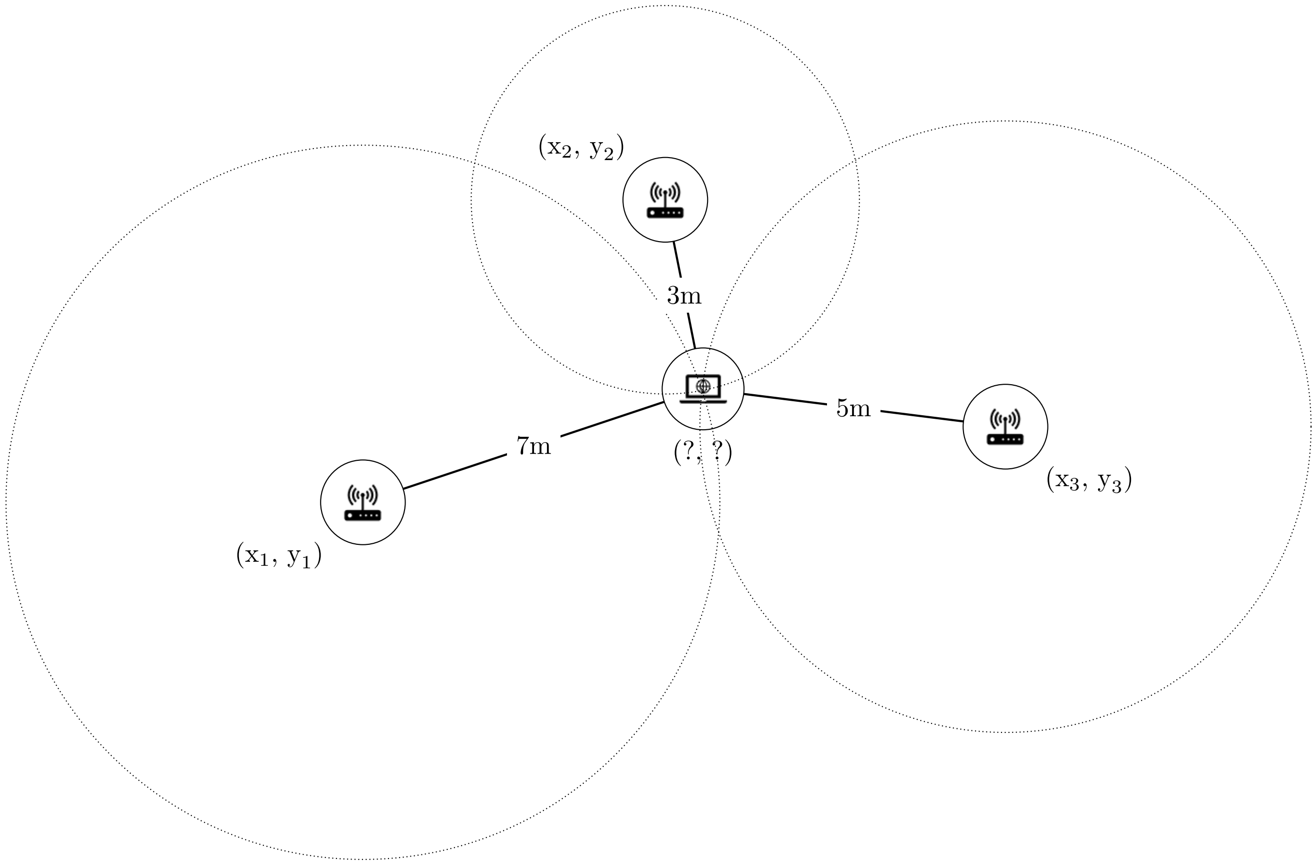
where *lat* and *lon* represent the (latitude, longitude) pair we want to convert. Once again, let's update our example system accordingly:



Example 1c *System from Example 1b, now updated to reflect the conversion of locations from the geographic coordinate system to the metric system.*

4.3 Step Three: Determine Location

Now that we have collected all the necessary information and all of our measurements are in the same system of measurement, we are ready to find our location using Wi-Fi trilateration! To do so, Wi-Fi trilateration produces three circles, one around each of the access points, each with a radius equal to the distance between the user device and the given access point. Then, as long as we have precise location data and accurate distance measurements, the intersection of these three circles will be the location of the user device. Note that with one circle, the location of our device could be anywhere on that circle. With two intersecting circles, our device could be located in one of two intersecting points, but with three circles, there is only one location where all circles intersection. As such, we need at least three circles to perform this process. To demonstrate, let's continue our example below.

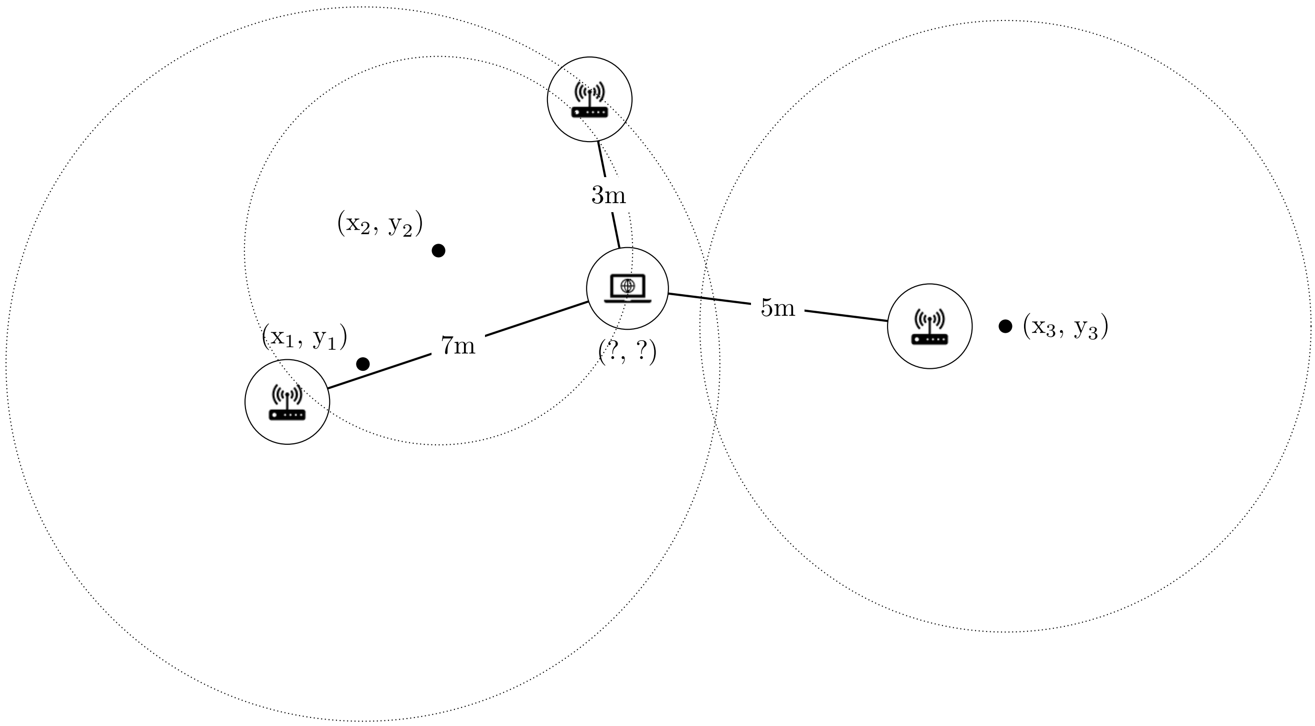


Example 1d *A visual demonstration of how Wi-Fi trilateration determines location based on a three circle intersection.*

5 Results

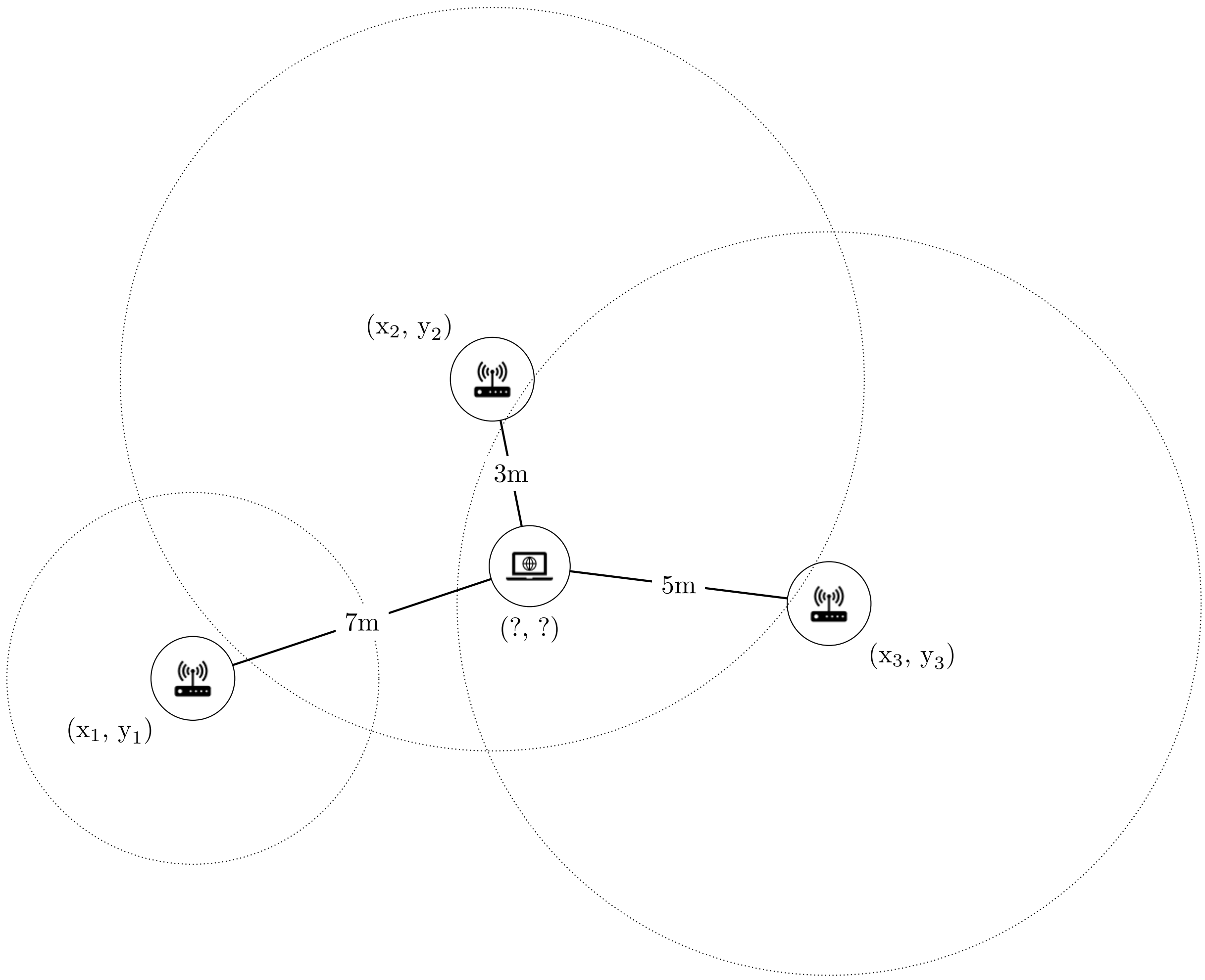
Now that we have seen how my approach should work theoretically, let's look at some results from actually implementing this system on campus. To test my program, I threw this positioning algorithm in a loop so that my signal strength data, distance measurements, and resulting device location would update dynamically as I walked around. While testing, I ran into a problem, however.

Despite having enough access points nearby to perform Wi-Fi trilateration, I would not always get a three circle intersection. Going back through the data I had collected in step one, I realized my method of recording AP locations was a likely contributor. One of the primary reasons Wi-Fi positioning is so good is because our usual positioning method, GPS, is not reliable indoors. As every AP I surveyed was located indoors and GPS was the technology I used to record these locations, this location data was inherently inaccurate to some degree. In performing the survey, I was able to get roughly the correct locations, but in testing we can see that these locations were far from accurate enough. To remedy this problem, I tried hand picking the access point locations from Google Maps. While these did yield more accurate location values, however, this is clearly not a viable solution due to inherent inaccuracies on account of human error. Without being on-site, there is no sure way of knowing I have recorded the correct location. As such, the centers of the circles produced by Wi-Fi trilateration would be wrong, preventing a three circle intersection. Rather, I might get something like in Example 2a below:



Example 2a *A visual representation of Wi-Fi trilateration being used with inaccurate location values. Rather than achieving a three circle intersection, we only end up with a two circle intersection, with one circle contained within the other. Note that the black dots represent the inaccurate location values where the actual locations are denoted by the AP icons.*

As I continued testing, I discovered another likely contributing factor was simply that the FSPL formula was also not outputting accurate enough distance approximations. As I mentioned earlier, this formula is bound to give us varying levels of accuracies depending on the environment and how many obstacles are obstructing line of sight. As such, even assuming the locations were correct, the formula may output me being much further or closer than I actually am, such as in Example 2b. To further investigate this idea, I tested my program in an area on campus where I could simultaneously maintain unobstructed line of sight with three access points, each within about 20 meters of my device. Despite being able to test my program in this ideal environment, however, my program could not find an intersection due to at least two circles having no intersection. This result is likely due to the FSPL formula producing circles that are too small to intersect with the others and/or the inaccuracies in AP locations setting the circles too far apart. As there are no obstructions, I presume it is more due to the underlying inaccuracies in location data, although both may be a factor.



Example 2b *A visual representation of Wi-Fi trilateration being used with inaccurate distance approximations from the FSPL formula. Rather than achieving a three circle intersection, we end up with two two circle intersections instead.*

6 Future Work

In the future, there are many ways we could improve upon the project. To resolve the two primary inaccuracy issues I came across in the testing phase, we could purchase a dedicated GPS tracker as well as utilize a technique called fingerprinting. A dedicated GPS tracker, although somewhat costly, would allow us to consistently and reliably record access point locations with much higher accuracy indoors than GPS was providing. Fingerprinting, on the other hand, is a machine learning method that collects signal strength and distance data over time to build a more accurate representation of what the signal strength and distance actually is, rather than relying on one scan. While this would take more time to implement, it would make up for it in accuracy. Assuming then that we could get a three circle intersection, we could also use a technique called the Least Squares Method to increase the overall accuracy of the program. To do so, we could instead scan for a set of four APs, then run our Wi-Fi trilateration algorithm on subsets of three APs, resulting in four potential locations, one from each subset. Then, this is where the Least Squares Method becomes useful as it allows us to minimize the error associated with each location value. In other words, this is in a way allowing us to minimize the distance between all points to give us a more accurate answer. As such, this is definitely a method that could be looked into for future work on this project.

Additionally, I will mention again that this is only one of many different ways to implement a Wi-Fi positioning system. Although likely more costly and complicated, there are many non-RSSI based methods that often lead to better guarantees of accuracy. As such, these methods are also worth looking into for future work given the time and resources.

7 Conclusion

Thus far, we have showcased how Wi-Fi positioning technologies are being used today, provided background as to how these technologies work, walked through my approach to implementing such a system on Westminster College campus, and analyzed the results. Based on the results, we can conclude that while there are many possible ways to implement Wi-Fi positioning systems, our approach was not sufficient to have success with the resources available for this project. While perhaps a different approach would yield better success given the same resources, we do conjecture that our approach has high likelihood for success given the modifications and additions suggested above.

References

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