Triangulation: A Complex System of Radio Frequency ID Beacons

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Abstract

Indoor GPS or localization can be tackled through a means of establishing a network or grid of active iBeacon devices. If a signal grid can be created effectively and the positions of the beacons are pre-calibrated to specific locations, then we have a great shot at indoor GPS/localization research. We only need a medium to intercept the signal that the beacons will be broadcasting. Instead of inventing a receiver for these specific signals why not use existing technology via phones? These iBeacons will be utilizing iBeacon technology with apple hardware, or better known as iPhones. Our original project was inspired by an amazing young woman who attends a local high school here in Sonoma County[1]. We came up with the idea a year ago around this time from one of our group members spouses who knew her mother. You can read an article done on her by following the link at the bottom of this page, published by "USA Today".

Background

From Fall 2015 – Spring 2016 I was part of a group of engineers who came up with a great idea that started as a suggestion for our Senior Capstone project. We had many great ideas but none of them sounded too innovative to us. A mutual friend of one our team members knew of a young women who would begin her college career. However, that child is a special needs child and she is visually impaired, blind. We were tasked to try and come up with a device that might help her navigate her new surroundings without the help of a guide. This is where Sense-It was born. We successfully built a discrete network of devices that utilizes the latest Bluetooth 4.o technology designed specifically by apple for iOS devices called iBeacons. A standard definition of an iBeacon is basically a bluetooth enabled chip that utilizes the latest in "Bluetooth Low Energy" technology, currently available only in bluetooth 4.0. Apple sets the specification standards for these iBeacons that are providing a new way to give location based information, compatible only to iOS devices. However all bluetooth technology is governed by standards set forth by the Bluetooth Special Interest Group (*"Specification of The Bluetooth System",2001*). These devices

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[1] USA TODAY Link:
http://www.usatoday.com/story/news/nation-now/2016/12/08/high-school-yearbook-staff-surprises-blind-student-braille-yearbook/95135090/

are constantly advertising their position while actively powered up. The produced signal can be read with any iPhone equipped with our coded application. Once the signal is read via iPhone, then SIRI audibly voices proximity to the nearest point of interest. For example, suppose each iBeacon is associated with a room number. In our application we chose the room number and the iPhones SIRI will tell us how close we are. However, there is a problem with the way we read the signal. Each iBeacon's signal is read and associated with a set of commands in our application. Due to the way signals propagate we can pick up false readings because of reflection and attenuation. Here is where my research starts, I'm proposing a new method to pick up the signals. Triangulation is based on geometry and since our network of iBeacons will be placed in known locations we have reference points to use.

Beacon Operation

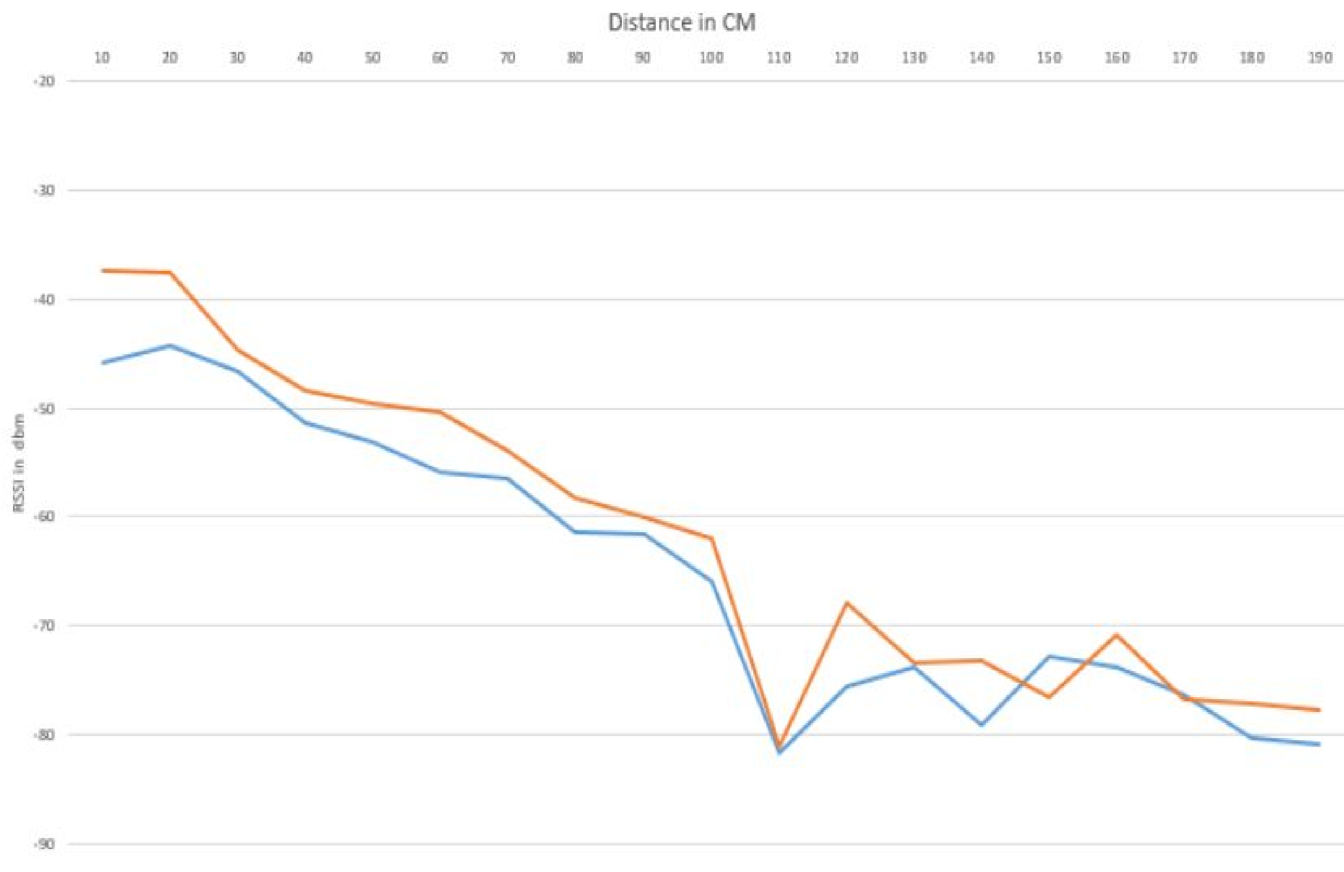


Figure 1. Non-linear 2D Graph: y-axis in dBm, x-axis in centimeters

Figure 1 shows a nonlinear correlation done on the average signal strength of two beacons compared to distance. The red and blue lines are from two different beacons that are utilizing the same technology as our iBeacons. The relevance of this graph is to show that the technology of these beacons regardless of different model types, will ultimately run into the same problem that our team's constructed beacons ran into. The way the waves propagate and reflect off of surfaces is basic physics. The problem being that since those reflected or absorbed waves ultimately measure in a false power signal rating used to categorize different proximity levels. This occurs because reflected waves vary in signal strength and have various time delays relative to the primary signal. The top graph Figure 1 shows exactly that the next signal reading cannot be predicted because of the various spike levels and non-straight line segments. Since our system reads exactly what that power level is at that instant, and has SIRI vocalize it, we see that this is not good enough to rely upon. Rather it is a means to make sure that the beacons that were built are proving the concept of indoor localization. Figure 1 graph came from an experiment done while taking measurements at different varying points in centimeters.

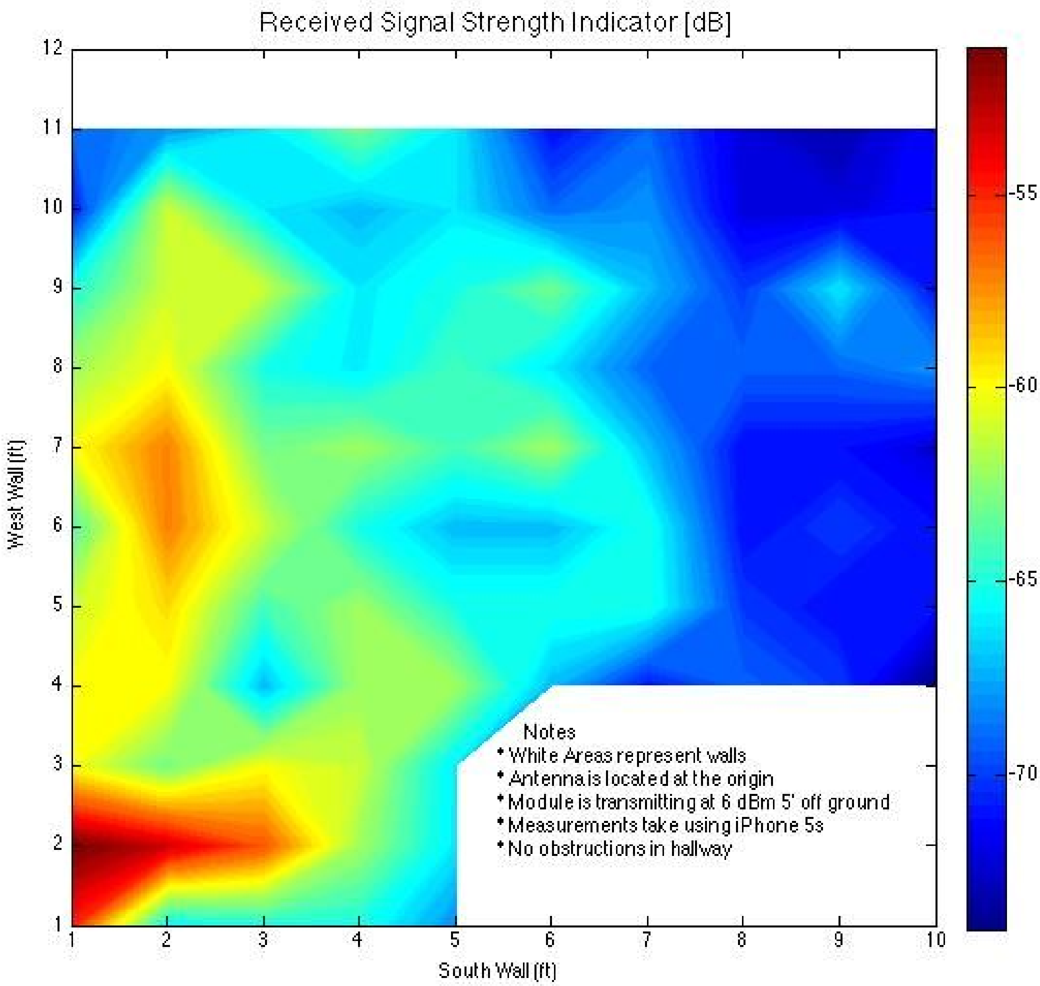


Figure 2. Signal Intensity versus location (11 feet x 10 feet area)

Figure 2 shows collected data with the beacons that we constructed and used the data in real time with a third party application on an iPhone. This data shows that further analysis can be done with our iBeacons improving the accuracy of vocalized location information using SIRI. Just like with the graph in Figure 1, this graph Figure 2 demonstrates the same concept or problem that is universal. The signal's waves attenuate over time if they are not reflected off of a surface. Figure 2 graph was generated using a computer program called "Matlab" and used to generate a 3-D image with the data points collected. We got our data from iBeacons by placing a beacon at fixed locations in an empty hallway with no obstructions. We read the data from the signal strength received on an iPhone without any movement of the phone. So the stationary readings recorded from the phone were taken 3 times per foot in each direction away from our iBeacon. We took the average of each received data point to generate the graph shown above.

The Original System

The way our team tackled the basic concept of indoor proximity localization is with interpreting signal strength power levels with different degrees of vocal cues. In other words if the signal strength being received shows as strong, more than likely the user is close to one of the iBeacons. Our code that we developed in our iOS application parametrized the scale at which these values showed best strength to weakest in dBm (*"Specification of The Bluetooth System",2001*). In detail, we associate power levels with an RSSI (received signal strength indicator) value. This value works well if it is being used strictly for signal strength indication. However, going back to the purpose of triangulation, getting rid of this system all together is the point of my research. These received values are simply unreliable. They fluctuate too much to form a great foundation for indoor localization. Figure 3 is a picture diagram of how the RSSI signal signal strength values are being interpreted. We coded up our iOS application directly to mimic what the chart in Figure 3 is illustrating with SIRI as a vocal notifier.

Signal Strength	TL;DR		Required for
-30 dBm	Amazing	Max achievable signal strength. The client can only be a few feet from the AP to achieve this. Not typical or desirable in the real world.	N/A
-67 dBm	Very Good	Minimum signal strength for applications that require very reliable, timely delivery of data packets.	VoIP/VoWiFi, streaming video
-70 dBm	Okay	Minimum signal strength for reliable packet delivery.	Email, web
-80 dBm	Not Good	Minimum signal strength for basic connectivity. Packet delivery may be unreliable.	N/A
-90 dBm	Unusable	Approaching or drowning in the noise floor. Any functionality is highly unlikely.	N/A

Figure 3. RSSI Scale (received signal strength indicator scale)

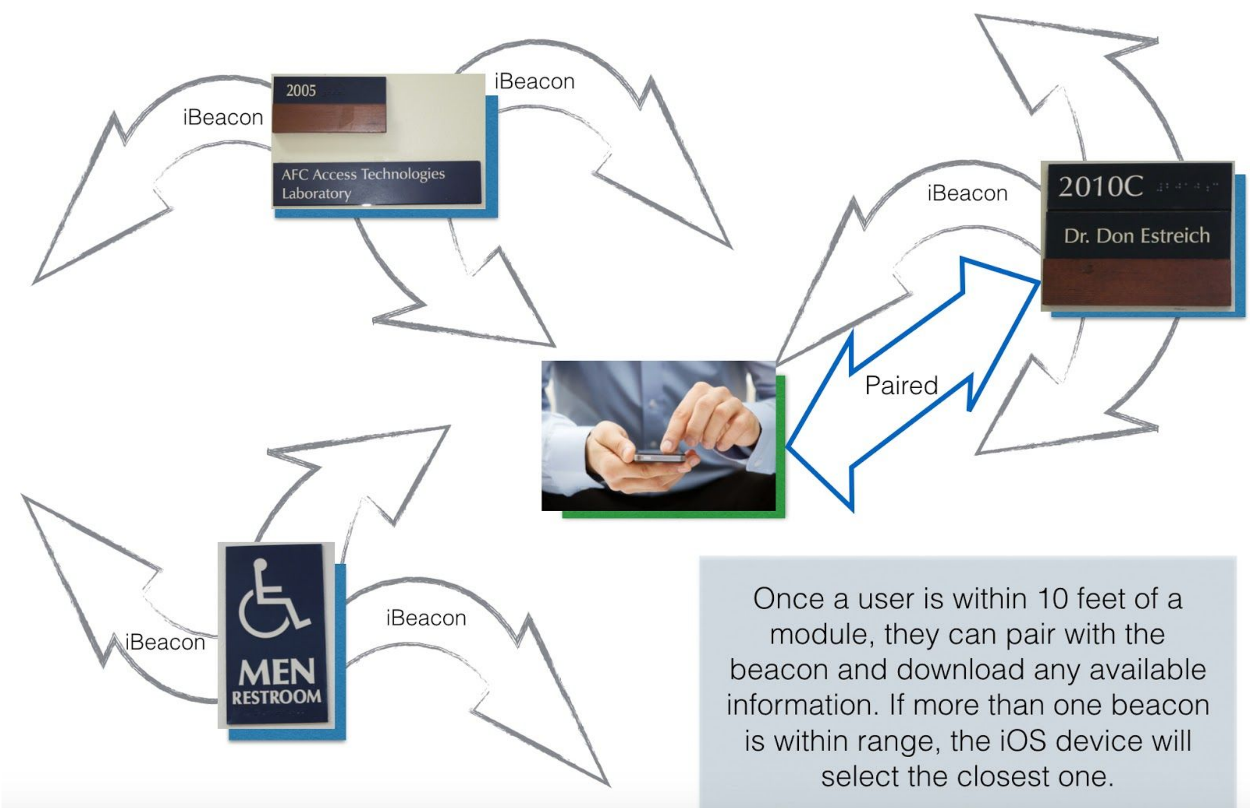


Figure 4. Original System Diagram

The following is a high level diagram of how the original system works. We demonstrated that our system works well within the walls and hallways of our institution. Providing a basis for further research to try to solve the issue of signal readings. Figure 5 shows an actual image of what one of our iBeacons looks like along with a circuit schematic. Our iBeacon PCB (printed circuit board) layout is comprised of two bluetooth modules utilizing the latest bluetooth 4.0 technology. One bluetooth module is setup to work as in regular bluetooth mode while the other we configured to advertise in iBeacon mode. These are basic settings that we had to access and configure using AT commands through a serial port interface. We used a 32-bit surface mount microcontroller unit to direct traffic for a handheld unit to any iBeacons themselves for communication purposes. Mainly it was intended for a future feature that would allow administrators and users to leave important messages behind for each other via bluetooth. We have the code running in a standalone scenario to the point where we can send and receive messages through a serial port terminal. However, the code itself was not integrated in our ios application due to time constraints.

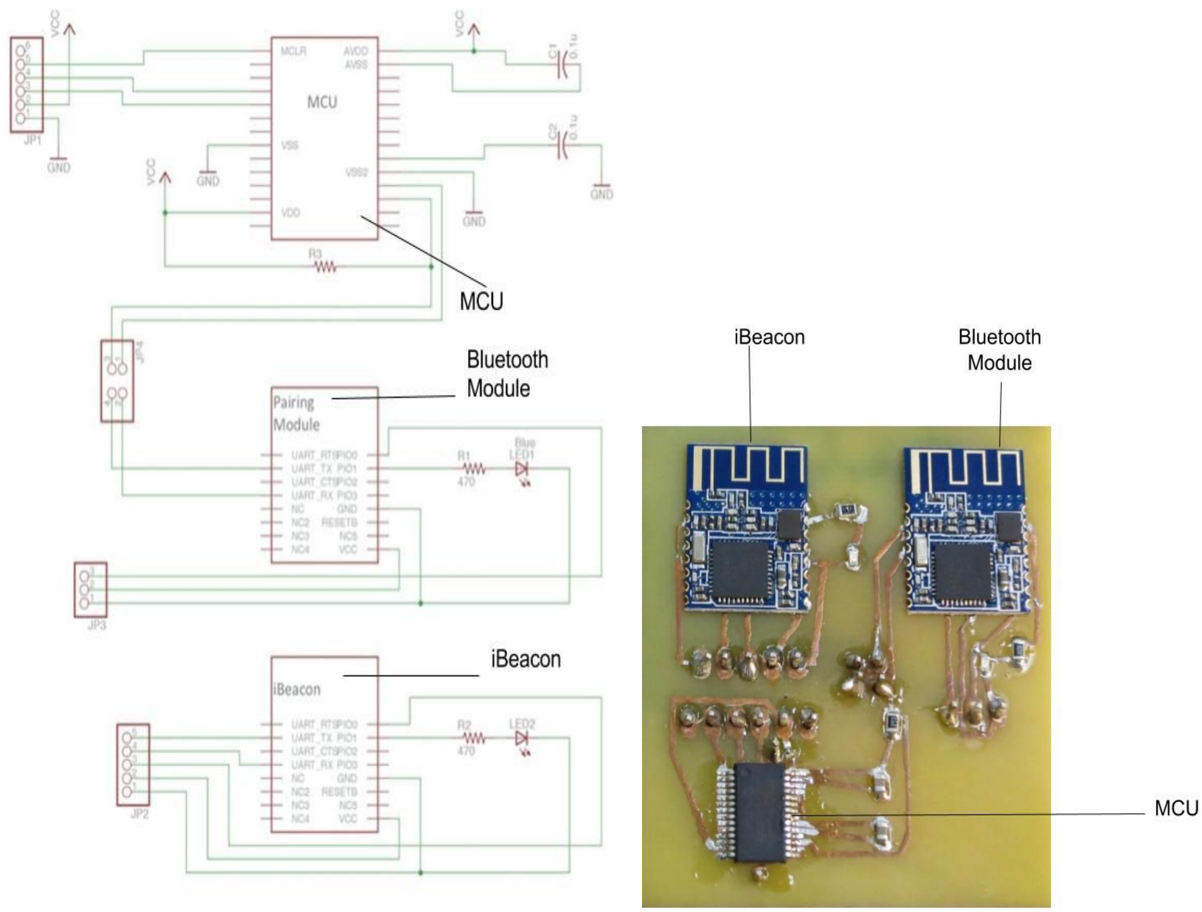
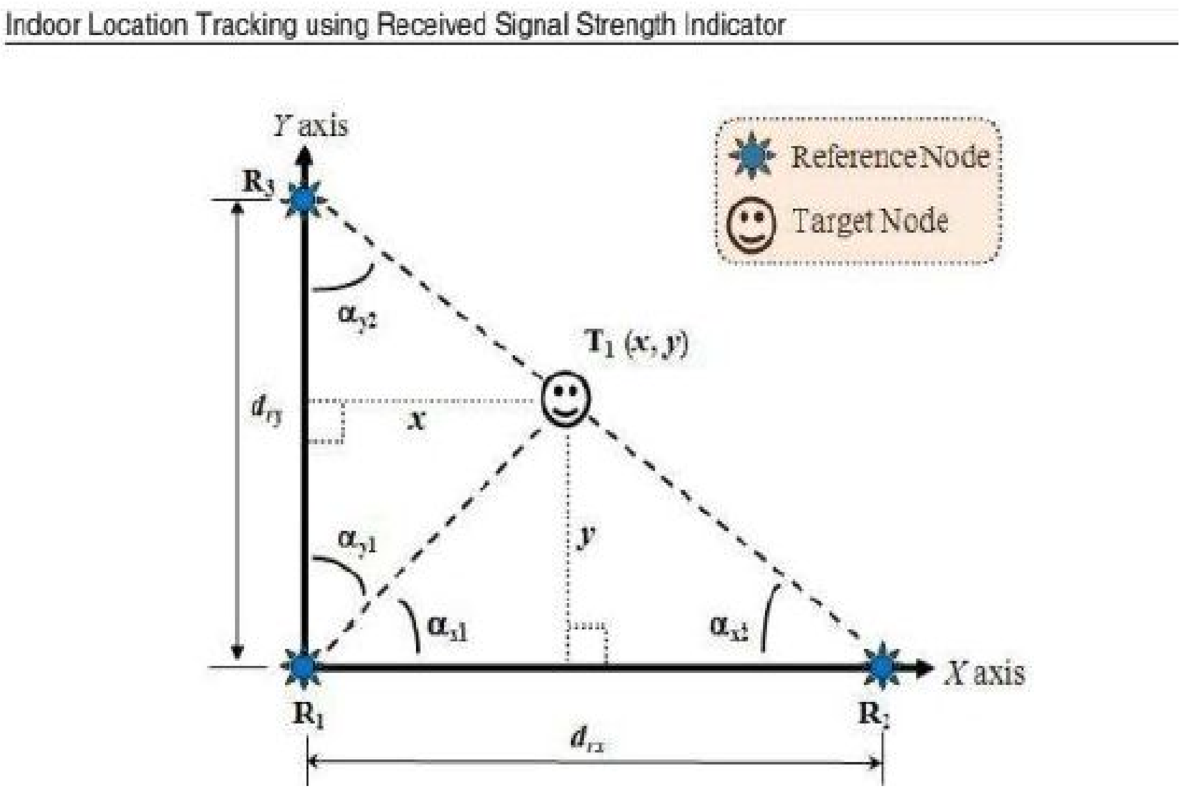


Figure 5. iBeacon Diagram Schematic

Description of The Research

Triangulation/Localization in it’s most basic form is utilizing geometry and triangles to determine location or distance. It is relevant to my research because I would like to optimize our network of iBeacons using this methodology. Already there is research being done on this exact topic. However, I'm doing research with variables that are preset to specific locations already known as well as signal strength, and frequency. I'm proposing that with already known variables we can use these facts to help determine location while the user's location is varying within our pre-calibrated grid. The signal strength can be calibrated to specific power levels to help minimize any unwanted guessing. The location of the iBeacons will be the nodes, or reference points needed to start the triangulation. The frequency at which the iBeacons operate at is around 2.4MHz (*"Specification of The Bluetooth System",2001*). Our iOS application can also store the values of the received signal strength indicator values easily in a vector. I can calibrate each node by turning it on and reading how long the first signal took to reach the iPhone. Storing three specific values for time of flight hops that each signal gave. The following is an illustration of what I am proposing:



$$x = \frac{d_{ry}\sin(\alpha_{y1})\sin(\alpha_{y2})}{\sin(\alpha_{y1} + \alpha_{y2})}$$

$$y = \frac{d_{rx}\sin(\alpha_{x1})\sin(\alpha_{x2})}{\sin(\alpha_{x1} + \alpha_{x2})}$$

Figure 6. Mathematical Theory and Model Behind the Triangulation(Chuan-Chin Pu, Chuan-Hsian Pu and Hoon-Jae Lee (2011)

Both the illustration and equation shown on Figure 6 are how the triangulation would work. Again in order for this to work we would need to know the dimensions of the room that would utilize the technology. This can be easily obtained through structure blueprints, once known we can begin the process of the triangulation and zeroing out each beacon to understand the time of the first received signal hop. The equation shown above is to obtain the x and y coordinates at any point in time while within or on the parameters of the respective triangle. I would be replacing the d_{rx} and d_{ry} (Pu, Pu, and Lee, 2011) components of the equation with the calculated value of the first signal hop. I will refer to the value as the "True Signal", meaning that it will represent the first signal acquired after averaging out many collected received signal points from each node individually. It is critical that I find the true signal because clearly, as shown in figure 6, the perimeter of the triangle are functions of d_{rx} and d_{ry}. The true signal will replace the d_{rx} and d_{ry} components associated with each node with the following:

$d_{rx} = True_{rx}$ and $d_{ry} = True_{ry}$

This will allow me to calculate the triangulation coordinates with all the other values already known.

Methodology

For the purpose of proving the basics of concept I am proposing setting up pre-calibrated reference points for which the sides of are already a pre-measured triangle. This is important because knowing the measurements of the nodes with respect to each other will help with comparing our signal results sent to the iPhone with respect to time. Here is an example of what I am trying to illustrate. There will be three of our iBeacons and they will be set up to form a triangle. We can preset the signal power output to reach up to at least fifteen feet. The signal being transmitted is in the form of a circle of at least radius fifteen. The following is an illustration what the diagram should look like.

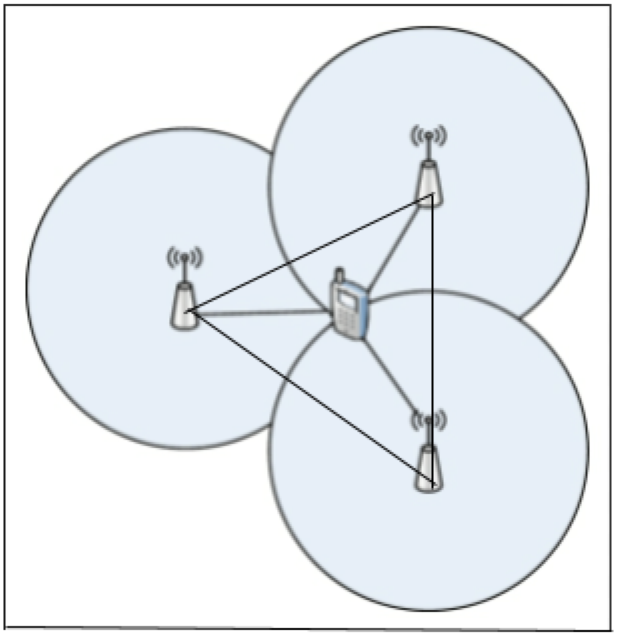


Figure 7. Triangulation Diagram

As stated above the sides that enclose the cell phone and the user, are all pre-calibrated and have known values related to each distance in feet. The process to start the triangulation is straightforward. With each of our iBeacons in place what first needs to happen is turn each iBeacon on one by one individually capturing the signal sent from one iBeacon to the iPhone. Essentially what is needed is the very first signal that the iBeacon transmits to be captured in the iPhone and record the time that the signal took to reach the phone get recorded. Do this multiple times for one iBeacon on a fixed receiving location and average out the time by the number of attempts. This will roughly be how long the signal took to transmit and get successfully received by the iPhone. Since the distances between the nodes are already known we can associate those distances with the respective sides of that node or triangle. The illustration in figure 8 at the bottom shows how the system would look overall in a real world customer setting.

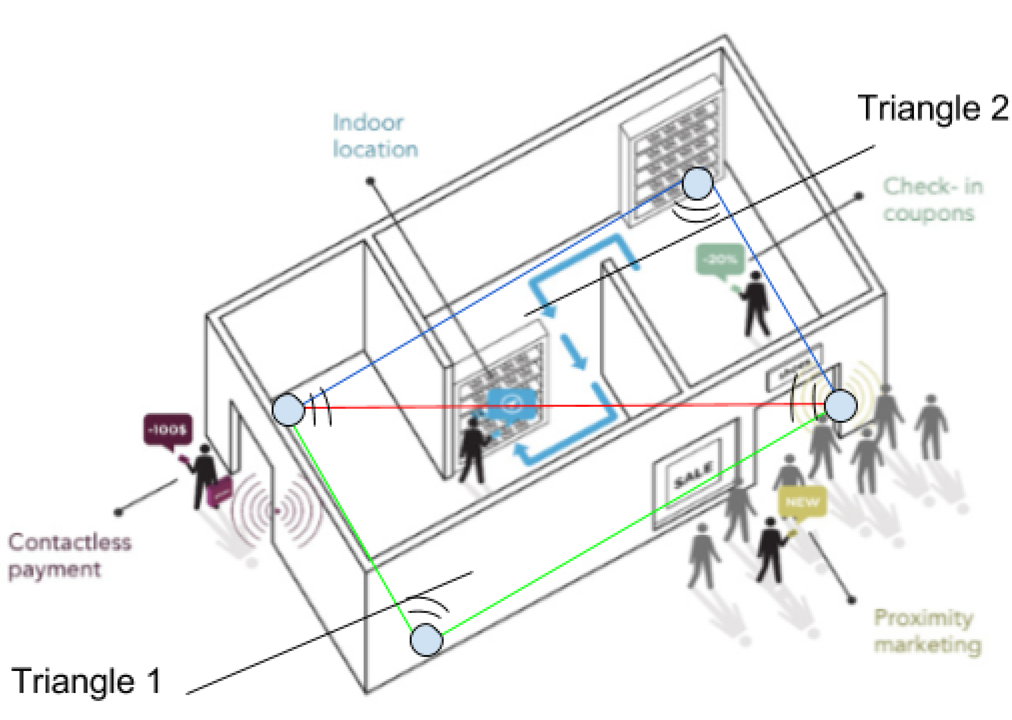


Figure 8. Real World Triangulation Diagram

Key points shown in Figure 8 are how the triangulation would function once every component of the system has been put in place. In order to successfully divide a room to use the triangulation method we would have to utilize two triangles to cover the span of the whole room. The benefits of perfecting the system open an array of possibilities for indoor localization as well as new business ventures. For example one could utilize this technology to conduct sales without the use of cashier's or eliminate long checkout lines. It could all be wireless payments that could be as easy as grab and go. Or even open up the possibility of having indoor robotic devices come to a user at the click of a button.

Results

The most important part of my research is that I have results to quantify my projections. All my data has been captured under ideal conditions. Meaning there are no obstructions within or around the perimeter of the triangle. What I did was set one iBeacon at a measured distance away of 10 feet. I wrote an algorithm on the iphone app to start counting as soon as we start looking for the incoming signal. Specifically, there is a counter that initiates as soon as I power the iBeacon. When the desired signal coming in is read then the counter stops. I averaged out the received time of the first incoming signal and used the counter value and treated it as a value in seconds. The average was between .9 and 1.5 seconds. However there is a lot of human error in those averages as well as error from the internal clock of the iphone itself. The human error comes from manually initiating the iBeacon to transmit at the same time as we start the counter to look for the first signal. Most definitely in future experiments I would like to try and zero in on the true value of the first received signal in milli-seconds. The next phase after I have captured this true value would be to develop a similar algorithm shown in figure 6, and utilize it within the iPhone's application to begin the triangulation.

Future Applications

Overall the data looks promising, at the moment there is not any type of indoor GPS technology readily available. Seeing as the "Internet of Things", where people are connected and can interact wirelessly, is fast approaching. It is expected to be showing up in 2020, this research falls directly under that category. I have been involved in this project for more than a year now and already companies such as Amazon have introduced "Amazon Go" just recently, which is utilizing wireless technology for people to shop with on the go. The future for developing such technology is already showing up. This could really turn into a business model once the system is concrete.

Conclusions

Ideally this would be something that I would love to work on for a longer period of time while dedicating all my attention to my research without work or school. I would also continue researching different methods to develop a solid system. More data is needed to make a definitive conclusion regarding the process itself. However it is very promising because there is a solid basis for the theory to make sense in the real world. As well as demonstrating that the first signal hop can be acquired and relating that to the dimensions of the respective triangle. It would be great to know the relationship that the first received signal has with respect to increased distances. Proving further a linear relationship with increased distance and the true first received signal. Therefore, proving a new system that is linear and can predict effectively location whereas the original system had a non-linear correlation, Figure 1.

Acknowledgements

Anthony Hargrove, Aaron Marquez and our intern Nick Alvarez, our original Sense-It team. I have had the pleasure of working with a great group of engineers who have invented a great product. To be able to develop such a system and acquire concrete qualitative data that has led to researching this topic is a testament to all the hard work that was done. This research paper would not exist if it were not for all your hard work. Even on those nights that we felt completely overwhelmed, thank you for sticking by. I would like to extend my thanks to the Sonoma State Engineering Department. I have learned all the tools necessary to create innovative devices because of the education that I have received. Dr. Mariana Garcia and Dr. Daniel Smith who are the awesome people who make the McNair's program here at Sonoma State possible, Thank You. Last but certainly not least I would like to give a huge thank you to Dr. Estreich for taking me under his tutelage for my first research paper. Dr. Estreich's years of industry experience and having written many papers himself have helped this process be a lot smoother. I have never met a man such as Dr. Estreich, with vast knowledge and expertise in various fields of engineering. I hope that in my professional career I can become a respectable engineer with great knowledge such as yourself. From the bottom of my heart, Thank You.

Appendices

Figure 1: “*Figure 1. Non-linear 2D Graph”*, Source: *Google Images*

Figure 2: “*Figure 2. Signal Intensity versus location (11 feet x 10 feet area)*”, Source: “*Sense-It”*
Website: “*http://hargrove7.wixsite.com/sense-it/product”*

Figure 3: “*Figure 3. RSSI Scale(received signal strength indicator scale)*”
Website: “*http://www.metageek.com/training/resources/understanding-rssi.html*”

Figure 4: “*Figure 4. Original System Diagram*”, Source: “*Sense-It”*
Website: “*http://hargrove7.wixsite.com/sense-it/product”*

Figure 5: “*Figure 5. iBeacon Diagram Schematic*”, Source: “*Sense-It”*
Website: “*http://hargrove7.wixsite.com/sense-it/product”*

Figure 6: “*Figure 6. Mathematical Theory and Model Behind the Triangulation*”
Website: “*http://www.intechopen.com/books/emerging-communications-for-wireless-s nsornetworks/indoor-location-tracking-using-received-signal-strength-indicator”*

Figure 7: “*Figure 7. Triangulation Diagram*”, Source: *Google Images*

Figure 8: “*Figure 8. Real World Triangulation Diagram*”, Source: *Google Images*

References

Bluetooth Special Interest Group. Specification of The Bluetooth System., (February 22 2001) https://www.inf.ethz.ch/personal/hvogt/proj/btmp3/Datasheets/Bluetooth_11_Specifications_Book.pdf

Pu,C.C,Pu,C.H, & Lee,H.S (2011) "Indoor Location Tracking Using Received Signal strength Indicator, Emerging Communications for Wireless Sensor Networks" ISBN: 978-953-307-082-7

The article can be found after Fall 2017 in the Sonoma State University McNair Scholars webpage, https://www.sonoma.edu/mcnair/journal/index.html