Improving trilateration for indoors localization using BLE beacons

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***Abstract*—While the Global Positioning System (GPS) tends to be not useful anymore in terms of precise localization once one gets into a building, Low Energy beacons might come in handy instead. Navigating free of signal reception problems throughout a building when one has never visited that place before is a challenge tackled with indoors localization. Using Bluetooth Low Energy[1] (BLE) beacons (either iBeacon or Eddystone formats) is the medium to accomplish that. Indeed, different purpose oriented applications can be designed, developed and shaped towards the needs of any person in the context of a certain building. This work presents a series of post-processing filters to enhance the outcome of the estimated position applying trilateration as the main and straightforward technique to locate someone within a building. A later evaluation tries to give enough evidence around the feasibility of this indoor localization technique. A mobile app should be everything a user would need to have within a building in order to navigate inside.**

I. Introduction

In everyone's daily routine, at some point, we might make use of GPS to locate ourselves, thus allowing us to pinpoint our favorite restaurant or an unknown place we have never been to. Without satellites it would be annoying to compute a precise location. Outwards, we can play with GPS or even Wi-Fi beacon signals as Google did back in 2010 (collecting SSID -Service Set Identifier-, network name, MAC addresses)[2]. Normally, in most of the cases, a poor user experience is felt using GPS inside a building. Moreover, indoors, when surrounded by (thick) walls or even within a room prone to have metallic surfaces or machines, GPS might not turn out to be the best solution.

The contribution outlined here relies on the use of the emerging BLE devices (beacons) coupled with a mobile app and its intrinsic features. Pretty much as it happens with satellite geopositioned systems, trilateration is similar in the sense that the location estimate is calculated given three known pivots (beacons' positions) and then computing distances to the user.

Trilateration allows us to calculate an estimate of the user's position without the requirement of knowing any trigonometric angles as it happens with triangulation. The distance between someone and BLE devices is enough to trigger a series of calculations that will compute user's location. A requirement that should be known in advance is the coordinates or location of the beacons. You can plot the scenario on a map or similar.

Using such ubiquitous channel as the smart phone is, eases the chance of deploying an indoors localization system within any building. It is crystal clear that one can take advantage of the intrinsic features of the pervasive handheld smart phone: the user more often than not brings the device with him/her, it is a personal, private and very well known device which he/she will feel comfortable with. Integrating any kind of indoors localization system (preferably with BLE devices) and bringing it to the user by means of just installing an app enhances the intelligence of the building empowering it with avant-garde use cases of any kind. The building would provide a smarter relationship with the inhabitants guiding them to the room or place he/she is looking for.

The paper will focus on the improvement of the results estimated out of the calculations done after applying trilateration. Surrounded by a set of beacons and in conjuction with a mobile app, a hypothetical scenario will permit locate the owner of the device. Although trilateration technique will be briefly explained, post-processing filters will definitely gain weight throughout the paper, outlining how can be integrated based on beacons.

II. Background and Rationale

From its inception back in 2013 when Apple introduced the concept at World Wide Developer Conference[3] (WWDC): iBeacon and its multiple scenarios plus use cases have evolved year after year. Soon after, in July 2015 another format called Eddystone was released, in this case by Google. The open beacon format Eddystone can be broadcasted in three different schemes or profiles: URL, UID and TLM. Whichever case, the signal received from beacon devices are one-way transmissions, thus, there is no chance of responding back to the beacon, which means that the "conversation" is unidirectional.

Aruba Networks[4] (a Hewlett Packard Enterprise company) is closely working in innovative scenarios with mobile and IoT.

[1] https://www.bluetooth.com/what-is-bluetooth-technology/how-it-works/low-energy

[2] https://googleblog.blogspot.com.es/2010/05/wifi-data-collection-update.html

[3] https://developer.apple.com/wwdc/

[4] http://www.arubanetworks.com/products/mobile-engagement/aruba-beacons/

Among the services of their portfolio they offer a location service using their own manufactured beacons with the potential of deploying a set of beacons in a certain venue or public place. Apart from the uses cases linked to indoor localization, little we know about the technology or the algorithm behind the localization feature.

Different applications arise when we are using beacons, one of them being the push notification use case where depending on which entity is acting as the mobile element, either the beacon or the user him/herself, the latter would receive a push notification. This happens when both parties are close to each other. A rapid glance on Internet[5] discloses several interesting applications, most of them, heavily linked to user's whereabouts. Here, we sum up some of them:

- **Retail:** a customer can receive coupons and offers depending on his/her assiduity.
- **Content delivery and advertising:** independently of the place or event, messages or advertisements can be delivered highlighting a given news, for instance, on museums [1], sporting venues etc.
- **Healthcare and hospitals:** identifying assets within a hospital or medical center might be interesting towards the inventory and to make sure no essential tool is out of place. A given patient at some point in time [2] could also be tracked. In the health industry there exists a trend towards more efficient care giving maximizing the comfort for the patient. In this sense, patient localization has triggered novel indoors localization at some medical centers in some cases [3].
- **Airports:** having your suitcase under control after leaving it on the endless belt would make some people relax. Beacons might be used for that purpose [4] carefully considering that the accuracy could be improved.

Supermarkets and shopping-malls may find intriguing from the business point of view, knowing customers whereabouts and their movements within the building or shop. To do so, some ideas revolve around a deployment making use of beacons and outputting a heat-map (Fig. 1) revealing the most visited or popular spots. Some people focus on a distinct use case, for instance, recycling. In Casado-Mansilla et al. [5] paper the underlying idea tries to raise awareness of sustainability issues in a certain community, being the beacons the tool whereby promote environmental behavior on users. BLE fingerprinting conveys really interesting field of study where an offline training is carried out (building a fingerprint database) immediately followed by an online estimate of a given object's position matching the closest fingerprint previously computed [6] [7] [8] [9].

The work in [10] collects statistics regarding the signal strength readings captured from beacons through an Android application, whereas in [11] proposes an extended iBeacon system for indoor route guidance advertising the user where the exit in a building is, similarly to what a car navigation system does. Actually, trilateration is not the only technique with which someone's position can be computed, law of cosines, as seen here [12], can be implemented mainly because the goal, in this case, was to reduce the amount of collisions and interference. Some other projects like [13], leverages BLE beacons in a different way by creating a service platform, location based service (LBS), associated with RESTful Web Services providing a suite of several options towards a client.

Fig. 1: Heat-map showing clients' flow.[6]

Received Signal Strength Indicator (RSSI) and the estimated distance have a relationship [14] that motivates most of location-based applications. In this paper we will give some insight into this relationship too. RSSI is the power level of the signal when reaches the receiver, but once again, the strength is dependent on different factors such as: real distance between the two parties, objects (people, wardrobes, walls) in-between and the broadcasting power of the device (which sometimes can be modified within the beacon itself). Some beacons return any of the well known *enum* three possible values: immediate, near, far (or similar terminology). However, a distance can be estimated computing some formulas that will be introduced later on in this paper. In regards with improving the accuracy of the estimated location position, [9] proposes novel correction phases related to received RSSI signal filtering noises and interference.

III. Algorithm for indoor localization

Trilateration is a technique used to figure out the coordinates (location) of a given person based on several already known spots and the corresponding distances to them (for instance, distance measurements that beacons broadcast). In the context of GPS and navigation systems, a position is calculated, with the intersection of three spheres. To remove uncertainties, four spheres will actually give a unique value that will be used to locate someone on the Earth. One of the two points that are computed from the intersection of three spheres can be eliminated due to being an irrelevant solution (situated in the outer space), thus, the rest one should be enough to locate someone. The case of GPS corresponds to a three-dimensional world, hence, it requires basic math calculations that involves angles. Bringing this idea to the case of indoor localization, a 2D scenario might serve the purpose because almost all use cases relies on a building as the main venue to place the beacons, plus, people will not be anywhere than on a plain floor. Trilateration does not involve calculating angles

[5]http://www.businessinsider.com/top-emerging-applications-for-beacons-2014-4

[6]Image source: Bluevision.com

(contrary to what anyone would do with triangulation), still it is applicable in a 2D or 3D scenarios.

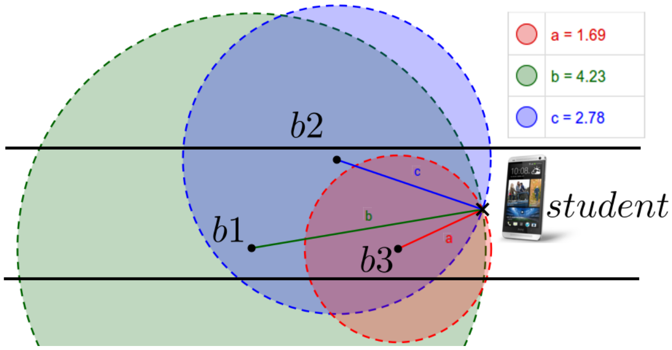


Fig. 2: Locating a student in an aisle[7]

Now, focusing on the two-dimensional scenario, the idea behind trilateration in such cases is to find the intersection of three circles knowing their respective radii values. The steps are straightforward in the sense that, if the required minimum values and conditions are respected, the outcome should come out without any major problem. Firstly, formulate the circles' equations (1) having to solve for *x*, *y* and *z*. It is mandatory to follow and respect three strict conditions:

- The centers of the circles are on the $z = 0$ plane.
- One of the centers must be at the origin of coordinates.
- Another different center must be on the X-axis.

Trilateration requires knowing beforehand the coordinates of the beacons, at the same time that complies with the restrictions aforementioned. These requisites do not usually meet the reality, more often than not, once the solution is found, the Cartesian coordinate system might have to be transformed to fit your own particular use case scenario. Fig. 2 is an example of applying and respecting the conditions of trilateration. *a*, *b* and *c* are the distance estimations from beacons, *b1*, *b2* and *b3* are beacons' coordinates and should also be known. The unknown is the student location.

The formulas behind localization technique described here are not particularly tricky. We need to find a point (x, y, z) that satisfies all three equations (1):

$$\begin{aligned} r_1^2 &= x^2 + y^2 + z^2 \\ r_2^2 &= (x-d)^2 + y^2 + z^2 \\ r_3^2 &= (x-i)^2 + (y-j)^2 + z^2 \end{aligned} \tag{1}$$

Subtracting second equation from first equation, the result in terms of variable *x* gives a formula to obtain the user's *X* coordinate. Substituting the obtained result into the first equation produces the equation of a circle, that is, the solution to the intersection of the first two spheres (circles in this case). Now, substituting $z^2 = r_1^2 - x^2 - y^2$ back into the original formula of the third sphere and solving for *y* gives an equation to obtain user's *Y* coordinate. Since $z = 0$, then we stop from further calculations. At this point, we know how to compute a given person's position and it can be coded in any programming language. The approach followed here is depicted in Fig. 3.

[7]The diagram was built with Geogebra -https://www.geogebra.org/-

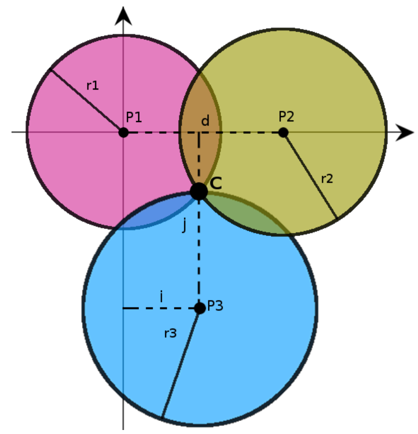
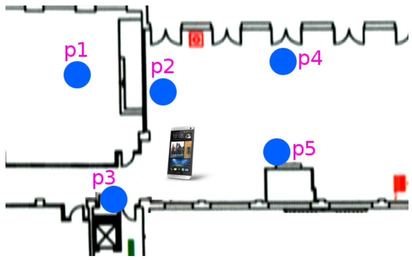


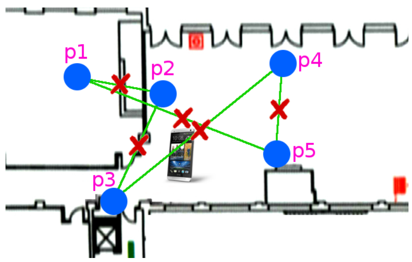
Fig. 3: The intersection of three circles turns out to be user's location

A. Enhancing trilateration: accuracy function

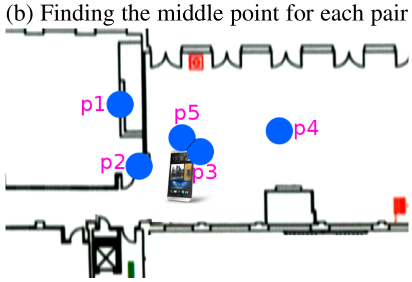
Surprisingly enough, the position estimate obtained from vanilla trilateration is not as accurate as one would desire. Owing to the fact that the RSSI values received from all beacons around are not stable enough (physical objects in the middle, low battery after a while, some other interference etc.) it might be better to come up with an accuracy function that filters computed *(X,Y)* coordinates and narrows down to a better position estimate. The accuracy function is intended to be executed after estimating user's *(X,Y)* coordinates since it tries to improve its accuracy based on a set of already computed user locations, thus, trilateration calculus is a black box for the accuracy function in the sense that the latter one just takes the several output values from the former one. Fig. 4 shows linked and sequential steps of the procedure carried out during each iteration of accuracy function. The illustration shows graphically what programatically is carried out. The blue dots depicted in Fig. 4a represent **a set of estimated locations** for the user. Notice that prior to depicting any estimated user position, an average of 5 measurements were taken to eventually come up with a single *(X,Y)* position coordinate (blue dot on the image). The number of measurements to take is arbitrary, but we believe five is fair enough. Being the broadcast rate 1 second and the update rate of the last known-three beacons half a second, shortly after starting scanning for beacons, we capture enough data in a short period of time. The smart phone in the middle represents the user real position, which we actually want to pinpoint. Next, the Euclidean distance is calculated for each pair of position starting from the initial ones, calculating now also the middle point between the two of them. Therefore, the red crosses (Fig. 4b) will become now the next iteration's dummy positions. This process can be repeated as many times as desired, it is eventually influenced by the environment conditions, the



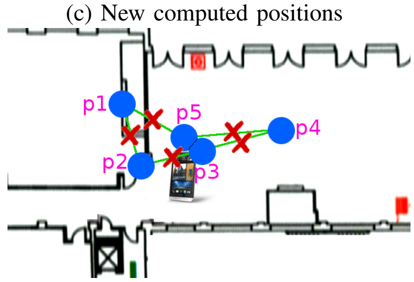
(a) A given set of estimated positions for user



(b) Finding the middle point for each pair



(c) New computed positions



(d) Finding again middle points for each pair

Fig. 4: Steps carried out to narrow down a better position in a hypothetical scenario

hardware used and the amount of objects in-between. As one could realize, the initial spread is narrowed down and brought close together simulating a better estimate. The final outcome depicted towards the user will be the output of the accuracy function.

IV. Use case

Having explained one of the two post-processing filters for improving the location estimate proposed in this work, we will see now a specific use case. University faculties are a plausible and perfect place to apply indoors localization using beacons. A clear example of this is also described in [8] where they take another approach (k-Nearest Neighbors) for position estimation. In what follows, the use case described here was

	Namespace (10B)	**Instance (6B): floor + id**
FF:7C:FA:0D:B0:29	0xa7ae2eb7a749bac1ca64	0x000004 000001
D0:FD:BA:AB:4B:B9	0xa7ae2eb7a749bac1ca64	0x000004 000002
CD:4D:EB:60:7B:60	0xa7ae2eb7a749bac1ca64	0x000004 000003
C6:1F:A8:28:B8:4E	0xa7ae2eb7a749bac1ca64	0x000004 000004

TABLE I: Extract of beacons' configuration.

tested in the faculty of engineering where the authors work. Professors usually are found through extranet facilities or other internal services of a given university. In our case, a public website is accessed to find the professor one wants to contact with. It is not easy though, so a mobile application might come in handy here. The project developed in the university used as the example, with the idea of using beacons as the main and unique resource to locate people, gives the chance of searching for a professor or staff personnel quickly (just typing the name and taping the result row) at the same time that it allows checking his/her office or place of work. The latter is shown in an interactive map where an orange dot marks the professor's office (or even a laboratory, meeting point etc.). Meanwhile, the user is being located thanks to the beacons surrounding him/her and the position displayed on the map too.

A. System architecture

The mobile application was developed as a Phonegap/Apache Cordova app (hybrid) which determined the future decisions. For instance, the framework used to design the app, the application internal architecture etc. The beacon format selected was Eddystone[8], there was not a special reason for this apart from having ready-to-use plugins for Phonegap to work with Eddystone format (even though iBeacon could have been an affordable choice too). The company easiBeacon[9] provided us the beacons (with ranges up to 30 or 70 meters depending on the model). In server-side a node.js web server is run along with PouchDB[10] (NoSQL) as the data source for information regarding rooms, offices, beacons and staff.

The overall picture is a 2-tier and 2-layer architecture, where a single server processes all requests from client-side and issues them the appropriate data. Every client has each own local database obtained and updated from server. The idea is to guarantee the availability of the data even offline. The client app is a Single Page Application (SPA) implemented with jQuery Mobile with some customization.

B. Configuration

A sample of a given configuration for your suite of beacons can be seen in Table I. Shows the identification pattern that was assigned to the set of beacons. Note that the instance number (6 bytes) is at the same time divided logically in two fields to simulate the major and minor features of iBeacon format. The first three bytes represent the floor where the beacon is at, whereas the following three bytes are the identifier for each

[8]https://developers.google.com/beacons/eddystone
[9]http://www.easibeacon.com/
[10]https://pouchdb.com/

beacon. This manner, we can identify each device on each floor, now given their coordinates in advance and the distance estimates (based on RSSI), trilateration can be applied. On the other hand, the namespace act as a filter to avoid capturing data from other BLE devices. As a programmer, those BLE signals that don't match known devices' MAC addresses can be skipped.

C. Enhancing trilateration: corrective function

Following the use case presented here, one might probably want to delimit the visual representation (e.g. dots on a map) obtained out of all previous mathematical calculations. In this specific use case, the estimated position is drawn on a schematic plain map of the building which far from being sophisticated, in the core, it is an image that can be moved around with the finger across the smart phone's screen. Moreover, the point displayed on the map doesn't know much of physical restrictions of building's walls, aisles etc. The purpose of this corrective function is simply to prevent the point from been drawn in illogical coordinates on the map. The idea behind it is adjusting the coordinates so that the estimated position's landmark remains enclosed within the building's walls. This process implies knowing the X and Y boundaries for each map presented to the user, thus, avoiding the printed dots from escaping the hypocenter of user's movement.

V. Privacy and security considerations

Locating someone using trilateration is plausible and depending on the specific application, a certain user can be tracked in an indoor environment and his/her data be sent to a server. With respect to BLE devices (beacons), the majority of them are provided with a built-in password (which usually can be changed) that tries to guarantee that beacons' configuration is not externally tampered maliciously. Nevertheless, more often than not, the usual form factor of a beacon is a coin battery powered small case (alternating colors, shapes, sounds etc.) rather than USB plugged, meaning that depending on the region the device might be manipulated within hand's reach. Smart homes and ubiquitous IoT devices are hype nowadays, and owing to that fact, security considerations should go hand in hand with innovation. [15] concentrates on privacy problem location aware sensor networks, and provides a couple of examples of home healthcare activity monitoring applications bringing up again the healthcare topic. Apart from that, in the context of aforementioned use case, regarding professor's fear of been localized, there is nothing to worry about because no further information is disclosed apart from the public knowledge of his/her office number or contact details.

VI. Evaluation and measurements

In order to shed light on the reliability of the location estimation, we conducted an evaluation apart from the daily measurements and tests during development process. A Nexus 5 was the phone used to capture the data. The beacons were placed roughly over 7 meters from each other, more or less. Which turned out to be covering an area of approximately $110m^2$. Do not forget that trilateration requires to have contact at least with 3 beacons, therefore they should be scattered not so far from each other. The testing involved applying trilateration as the main indoors localization technique. Two distinct approaches were tested: **1)** one of them with just vanilla trilateration. **2)** On top of trilateration the **accuracy** as well as the **corrective** function were also applied giving as a result the best approach to real location under current surrounding conditions and within our technological research center. Note that in the test, the real person coordinates were **(1842, 320)** for X and Y axes.

Vanilla trilateration (px)		**Euclidean distance**(m)	**Accuracy + Corrective**(px)		**Euclidean distance**(m)
X	**Y**		**X**	**Y**	
1785.56	317.75	**2.259**	1785.96	305.28	2.3173
1785.40	-78.56	16.1025	1786.14	300.81	2.3624
1785.47	-71.99	15.8420	1786.08	315.51	2.2438
1785.55	313.02	2.7466	1786.38	162	6.7000
1864.67	95.95	9.0074	1786.24	162	6.7019
1866.94	82.23	9.5628	1788.91	312.97	**2.1419**
1943.24	423.38	5.7880	1788.01	233.31	4.0849
1943.24	424.02	5.8062	1788.09	188.81	5.6732
1846.60	136.98	7.3227	1786.23	233.33	4.1221
1840.60	151.76	6.7296	1800.32	242.09	3.5338
Mean		8.1166	Mean		**3.9813**
SD		4.7469	SD		1.8159

TABLE II: Error margin between a sample with non-filtered and filtered position estimate outcome.

The data shown in Table II is based on a map image which shows the user the estimate position, that's the reason why the unit is pixel. Independently of the value itself, the notorious thing here is to depict the difference between the real position and the estimate. The Euclidean distance (error margin) columns outline the mentioned difference in meters. The mean is computed too and the Standard Deviation help us to conclude which estimates are normal. In the sample taken, the values were captured on a short period of time and overall they are very close to each other, with slight differences but influential at the end. Despite the taken sample, several more rounds were conducted with greater sample size than 10. Particularly, four more rounds were executed with up to 80 samples each. The corresponding mean and standard deviation values can be seen in the Table III. The outcome varies accordingly to what we thought at the beginning given the irregularities of the BLE signals. We'd like to remark the fact that a different handheld (Huawei Nexus6P) device was also bore in mind just to contrast the obtained results so as to not be biased. Again with 80 samples each time, the computed mean and SD values were similar to the first mobile device, so we did not find special relevance to depict the results here.

A. Restrictions and lessons learned

It is worth mentioning the findings achieved in [14], proves that the signal variation retrieved from beacons are far from

Samples	No data treating Mean	SD	Post-processed with filters Mean	SD
2nd round	14.6929	4.6074	5.6656	1.5590
3rd round	12.5438	5.6159	5.8698	1.5869
4th round	8.7553	6.1211	3.7136	1.9086
5th round	8.7245	6.3779	2.9910	1.2127

TABLE III: Euclidean distance mean and Standard deviation (SD) calculations between applying or not accuracy and corrective functions

estimating an accurate, reliable and robust distance measure. According to them, the RSSI values vary significantly across different beacons vendors, indoor/outdoor environments factors, and obstacles. From their understanding, the challenges for designing an indoors localization system are not trivial. Indeed, different factors slow down and/or interfere the communication between the device and the beacon (radio frequency interference) such as thick enough walls, other devices transmitting in the same frequency or simply because an average weight person is in the middle, among others. Besides, external anomalies like absorption and diffraction can influence radio waves making different properties of the beacon fluctuate. With regards to beacons deployment, given the trilateration formula employed, no three beacons can be placed in a row. The reason is that, if such thing happens, then a certain mathematical division within the process of estimating the position will give zero, consequently harming the consecutive calculations. The best solution for this is to deploy the beacons so that no three beacons are placed in a row in the same axis (alternating them works well), no matter the scenario is 2D or 3D, for instance, Fig. 5. The best approach to have sharp and clear signal reception is to place the beacons in places such as the false ceiling or similar. This way, the position estimate will be more accurate. Signal reception is manufacturer-dependent property and usually one would expect detecting the BLE device from 70 meters. It is relevant to stick out that any object (for instance, human body), or metal surface is likely to alter the signal's strength and affect the calculations (if any).

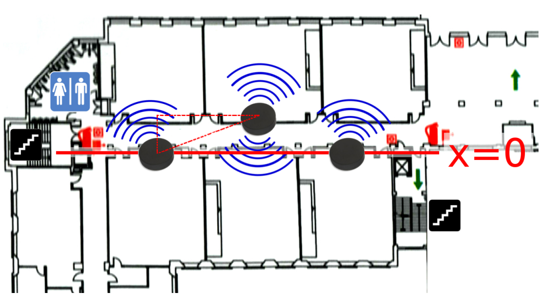


Fig. 5: Example of a correct placement of a set of three beacons

VII. Conclusion

Indoors localization is feasible depending on the technology used. Should any person tackle this application in the future might be advisable to be clear about the unpredictable distance estimate calculated based on the RSSI values of the broadcasted signal from beacons. Note that some beacons are USB powered rather than a coin battery which means that no power decreasing will happen over time. Trilateration might be one of the easiest ways of estimating someone's position within a building. It is highly recommendable to apply different others filters or data processing after initial distance estimates due to latter's inaccuracy, thus easing localization. The good news is that all these data can be dumped to a smart phone making things easier for a user and his/her whereabouts.

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