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Time Difference of Arrival Localization Study for SAR Systems over LoRaWAN

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Abstract

Over the last years we have seen a rapid expansion within the area of Internet of Things (IoT) applications. For many applications' use cases, such as rescue monitor systems, the problem of localization (i.e. determine the physical location of nodes) is critical. This paper studies and evaluates the usage of mathematical model of multilateration algorithms using Time Difference of Arrival (TDoA) as a solution for positioning over Long Range Wide Area Network (LoRaWAN). The research is carried out using simulations in Python by configuring the constant positions of the Gateways inside an outdoor area. The proposed algorithms can be integrated in application for tracking people at any time and especially routing people from vulnerable groups. Through multilateration and algorithm's prediction, we can have an accuracy of 40-60m in location positioning ideal for search and rescue use cases.

Keywords: IoT; wireless network; lorawan; TDoA; search and rescue application; mulilateration;

1. Introduction

With the emergence of the Internet of Things (IoT), a growing number of low-cost devices intended to operate on their own for extended periods of time, often far away from WiFi access points. For this reason, Low Power Wide Area Network (LPWAN) technologies have attracted a lot of research attention from companies and global

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organizations. Practically the above technology allows such devices to communicate across large distances (up to 20km under good conditions), using comparatively low power. The ability to geolocate such device is often on interest on many use cases such as rescue monitor systems of vulnerable groups in need. In its basic implementation, it involves the generation of a set of geographic coordinates and is closely related to the use of positioning systems. Such an application service built-in using LoRaWAN can be useful for area-based location positioning, with the advantage of requiring fewer and low-cost devices with long-lasting batteries. LoRa operates in various frequencies depending on the region, such as 868 MHz for Europe and 915 MHz for North America.

Geolocation can also be achieved through Global Positioning System (GPS) [1], but such a module can be enough costly. Furthermore, a GPS module can also increase power consumption, making some applications unfeasible to be used in everyday life or in area with buildings or interference factors. In a Search And Rescue (SAR) use case the goal is to locate people in need such as track them as they move or by creating geo-fences, for example, sending an alert if the person in need moves outside a defined area, like a child in a neighborhood. For localization of IoT devices, the state of the art technology, in terms of accuracy, is GPS. In most modern GPS modules, an accuracy of less than 10m can be observed in an open outdoor environment. Based on this the above solution is quite attractive for Search and Rescue Systems. Using GPS IoT modules consumes more than 10 times the energy of LoRa, when localization packets are sent to the same rate [2]. The difference can even be up to 20 times, if LoRa is configured in an efficient way on both Spreading Factors and Bandwidth Factors. In addition to a GPS module, a device will also require an extra module for communication. Having this in mind, it would be more appealing to use a Low-Power Wide-Area Network (LPWAN) for the communication and localization [3].

Two technologies that can be used in a LPWAN are LoRa and Sigfox. Sigfox is an Ultra Narrowband (UNB), wireless communication technology owned by a company of the same name. Sigfox, is aimed at IoT devices thus, one of the services it offers is Geolocation. The localization algorithm that it uses is trilateration with RSSI ranging. Many times, Sigfox use machine learning techniques in order to improve the accuracy of the position. However, this technology is able to locate devices with an accuracy precision (<500m), using information from nearby Wi-Fi access points which is compared to crowd-sourced data. In this research, a position accuracy improvement has been introduced within a radius of 200m. Similar results have been achieved, where LoRa is used for positioning, using RSSI. They achieve an accuracy of less than 20m in a small area. SigFox and LoRa are both capable of communication over many kilometers even in Line of Sight (LoS) or not. However, in this research we test localization algorithms of in terms of multilateration able to be integrated in SAR systems as an extension to localization methodologies from previous studies.

In this paper, we describe our approach based on IoT devices and on the deployment of various LoRaWAN gateways from localization perspective. Through the estimation of the behavior of a LoRaWAN channel and using multilateration, the localization of a person inside an area can be obtained within a small range (about 40-60m). The proposed approach is a low power and cost solution, and with a good possibility to operate even though in indoors cases such as universities, playgrounds or even shopping malls [4][5]. Both solutions Triangulation, Trilateration and Multilateration are presented as a suitable candidate for such systems. In this study, we start by finding the state-of-the-art tracking algorithms using multilateration that could be integrated in SAR systems. After that these algorithms are evaluated for position localization in terms of position accuracy as well as per cent distance error on estimation.

The rest of this work is organized as follows: The next section introduces the Localization techniques whereas Section 3 refers to the SAR topology and algorithms study on multilateration scenario. Section 4 describes the performance experiments and results analysis. Section 5 includes the conclusions as well as discusses the future work and remarks on the implemented system.

2. Localization

In the world of real time location systems, a number of loosely woven technologies have been introduced in order to track people and objects in real time. Location tracking is not at all a recent phenomenon. One major aspect of a location tracking system is the basic mathematical computation that determines the exact location. These days, navigation techniques remain relatively similar, replacing stars and landmarks with satellites and radio towers. Fortunately, there's not one but three major ways of determining a location - namely, triangulation, trilateration and multilateration.

2.1. Triangulation

In out of the three techniques, triangulation is the only one that measures angles rather than distance, and it is a preferred technique by the surveyors and researches. Building a SAR system through triangulation starts by initiate two points (point 1 and point 2) with a known distance between them, which is established as the baseline. From these two points, the researchers measure the angle made by lines from distant points intersecting with the base line using a device called Theodolite. These angles are then used to determine the unknown distances and thus locate the distant points.

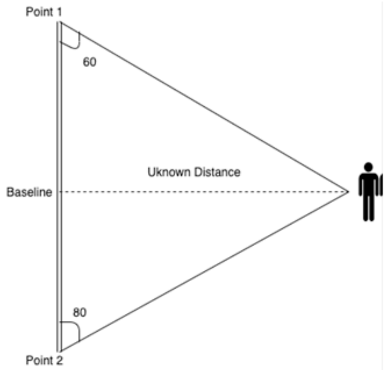

Fig. 1 Geolocation based on triangulation

If the known points are replaced with anchors in terms of a SAR system, at least 2 anchors are required to determine a location in a Two-dimensional (2D) space and at least three anchors would be required to determine a location in a Three-dimensional (3D) space. Triangulation as a methodology, mostly finds use in Navigation, Metrology and Astrometry. It is also an ideal candidate when surveying a hilly area due to the ease of establishing stations at appropriate distances and areas, the LoS (Line of Sight) is hugely impacted and can only be overcome by the use of towers, which escalates the cost to a high degree [6].

2.2. Trilateration

Trilateration is a more popular technique that is also used by the traditional GPS. Trilateration pinpoints a location by measuring distance. The general idea is that a satellite broadcast a signal for a GPS receiver to pick up. This is how the distance between a satellite and a GPS receiver is known. Similarly, when 3 such satellites come into contact with the GPS receiver, the exact location is determined. In Fig. 2, it can be seen that each satellite is at the center of a circle. The intersection of the circles gives the location of the GPS receiver. As the GPS receiver moves, so does the point of intersection of the circles.

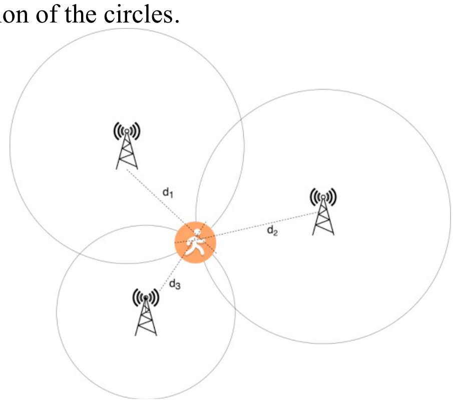

Fig. 2 Geolocation based on trilateration

In real-world scenario, the circles become spheres, and thus 4 satellites are required to pinpoint the location with better accuracy. Following our previous research on trilateration for a SAR system, we used the multiple associations that a LoRaWAN node establishes with surrounding GWs. The GWs in our area receive a packet from a LoRaWAN IoT device and forward it to the network server. This leads the network server to have multiple copies of the same package. Next step was to filter the duplicate copies and send a unique copy to the application service. The above data can be extracted through the application service by developing a simple API. Message Queuing Telemetry Transport (MQTT) [7] can be used to obtain the above information. The basic concept is the deployment of a broker, publishers / subscribers and topic creation. The critical condition in a SAR system is that in any position inside an area the client has connectivity with a minimum of three GWs so that we can benefit of trilateration. The locations of the GWs inside a SAR system are to be installed and the total number of required GWs is strongly dependent on the context in which the localization process has to take place. The setup of the LoRaWan GWs has to be done into consideration of factors like the size of the area that we want to cover, the number of devices that can be tracked and any buildings that may be inside [8].

2.3. Multilateration through TDoA

Multilateration relies on the time difference in the arrival of signals to various base stations. Through the literature on positioning systems this technique used for indoor and also outdoor positioning in confined regions [9]. For this reason, we extend our previous research about trilateration by integration Multilateration in a SAR system. The popular positioning methodology known as Time Difference of Arrival (TDoA) uses multilateration in which the base stations (LoRa GWs) need to be synchronized. In this method, the end-nodes (people in need) send out data packets with their information that are received by the established GWs. The difference in the time of reception between the GWs is the basis of the distance calculation and, ultimately, the calculation to locate the object. The principle behind multilateration is similar to trilateration, except that there's no circle or sphere here; TDoA is known as one of the most accurate and power-optimized technique for localization. This method does not require the exact distance from an end-node to each GW but rather, only the differences in distance from each gateway to the device. The difference in distances can be calculated with the TDoA of a signal from a device to the GWs. [10].

TDoA is a popular technique for localization as it does not require the transmitter to be synchronized with the receivers. This is because TDoA only requires the differences between the timestamps of a transmission. Let us give a SAR scenario where we have to locate an end-node (person in need) in a unknown distance from our established GWs. When a LoRa signal is transmitted from a device, it is received by n gateways (where n is the number of established GWs). These gateways will be our anchor points because we know their exact locations (longitude and latitude). Each gateway will be at a slightly different distance to the device therefore, they will receive the LoRa transmission at different instances in time. Because TDoA uses the difference in time, there is one measurement for each possible pair of GWs. The total number of possible pairs is a binomial coefficient: $\binom{n}{2}$. For each GW pairs, the TDoA can be presented by $\Delta t_{i,j} = t_j - t_i$, where $1 \leq i < j \leq n$ and, t_i and t_j are the timestamps of the GWs. By using the time difference from all the possible gateway pairs, we can calculate the position of the transmitter if the signal was received by at least three GWs. The time differences can be referred as the TDoA measurement and the distance as TDoA distance. The distance is extracted from the mathematical formula below: $\Delta d_{i,j} = c\Delta t_{i,j}$, where *c* is the speed of light through air. By using TDoA for distance calculation we can create a hyperbola consisting of all the possible points of where the end-node (person in need) could be. The general 3D range equations for source localization using TOA and TDOA are: TOA: $st_i = [(x-x_i)^2 + (y-y_i)^2 + (z-z_i)^2]^{1/2}$ (1)

and TDOA: $$s\Delta t_{ij} = [(x-x_i)^2 + (y-y_i)^2 + (z-z_i)^2]^{1/2} - [(x-x_j)^2 + (y-y_j)^2 + (z-z_j)^2]^{1/2}, \quad i,j = 1,...,N$$ (2) where *s* is the signal propagation velocity, t_i is the signal traveling time from the source to GW, and Δ_{ij} the time difference as described above. The terms *x,y,z* are the coordinates for the position of the person in need in the SAR system. The possible location of the person in a SAR system is given by a hyperbolic Line Of Position (LOP) in which the focal points of the hyperbola are the positions of the two receivers used in the TDOA computation. Because TOA and TDoA have measurements errors, the location of a person in need in a SAR scenario may be estimated by propagating the errors through the computation and estimating the location along with errors in the estimates. In the 3D case, where we build our simulation, a hyperboloid is defined by each TDoA, and at least three TDoAs need to intersect at a unique point to identify a person in SAR system. Intersection of LOPs, a geometric construct is the most basic and intuitive method for position estimation. Our research is based on the well-known methods that have been studied, developed, validated and published in literature [11].

3. SAR Topology and Algorithm Literature

3D localization and tracking of people in a SAR system, requires at least four different GWs to form the necessary nonlinear localization equations. From TDoA equation described above, the precision of the estimation of a person can be estimated as a function of the errors in the measurements of GWs locations, TDoA, and signal velocity [12]. In our research on the above algorithms we start by configure four different LoRa GWs in a specific area of Western Greece (view positions in Fig. 3). The position of the person in SAR scenario was at (38.282200, 21.787980). The above locations that we view in Fig. 3 were used in the performance analysis that we studied in which we try to estimate the position of a person using the algorithms in Table 1.

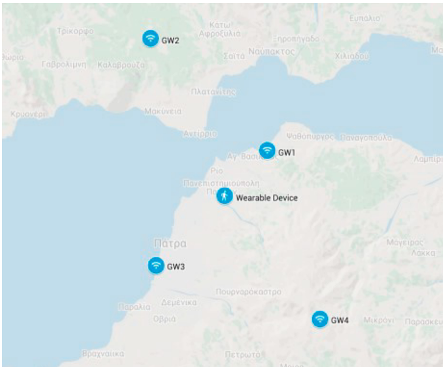

Fig. 3 Actual position of GWs and Wearable in SAR scenario

Table 1. Summary of TDoA Localization Algorithms in LoS Condition

Author, Year	Algorithm	Advantages/Disadvantages
Schmidt, 1972	LOCA: Location on the conic axis, an alternative geometry to the hyperbolic intersection plane (PX). Provide a plane in 3 dimensions of people position in SAR system	The GWs appear on the conic rather than at foci and thus the person's location appears at foci rather than on a hyperbola.
Friedlander, 1987	Weighted LS method	Derived a linearization algorithm to estimate person's velocity from TDOA.
S. Robinson, 1987	Spherical Intersection (SX) method	Requires a priori solution for the actual position range.
Foy, 1976	Taylor-series, an iterative Gauss-Newton method, gives LS solution	Requires an initial guess, not a start in application Convergence is not proved. Is computationally expensive. Useful in solving multiple-measurement, mixed-mode problems

4. Performance analysis and Results

The technique used in our research uses TDoA data measured at 4 synchronized GWs with known locations. Following Schmidt algorithm introduced in 1972, appears person's location at foci rather than a hyperbola [13].

From the other hand Friedland introduced a Least Squares (LS) method, where a linearization algorithm is used to estimate person's position from TDoA [14]. Solutions like Robinson's and Foy using Taylor Series, require a priori solution or guess in order to estimate the actual position of an object or a person. Using the above algorithms we start by studying the positioning accuracy and error as it emerged from the simulations in Python [15][16].

4.1. Positioning Accuracy

Table 2 includes the prediction of position estimation using the algorithms from Table 1. For the whole simulation the position of the GWs is fixed. Using the mathematical model of each algorithm we are tried to estimate the position of an IoT device in SAR use case.

Table 2. Results of Algorithms estimation about the position of person in SAR system.

Algorithm	Calculated Longitude	Calculated Latitude
Actual Position	38,28220	21,78798
schauAndRobinson3	38,18953	21,86329
schauAndRobinson	38,32114	21,74945
friedlander3	38,26205	21,79862
friedlander	38,28242	21,78848
taylorSeries	38,27241	21,78800
schmidt	38,26232	21,78856

Via the Friedlander algorithm the calculated position of the person in need in the SAR use case as we can see is (38.282424, 21.788484). The calculated position seems to be very close to the actual position. The other algorithms seem to calculate the position of the IoT device with a deviation from the actual position. The worst accuracy with the biggest deviation from the actual position is the prediction of the schauAndRobinson3 algorithm (38.18953, 21.86329).

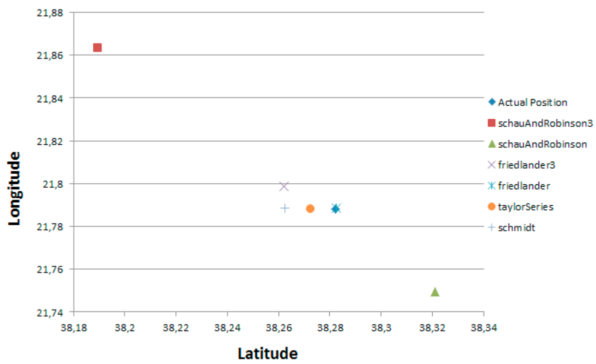

Fig. 4 TDoA Position estimation based on algorithms

The natural significance of the above results is that the method of calculating the position using multilateration in the case of the friedlander3 and taylorSeries calculates the position of a person more accurately. The location of base stations or better GWs must be fixed in order to be accurate. Upon improving positioning accuracy, LoRa shields offer great energy efficiency and make them an ideal choice for quick transmitters that can continuously operate for over a week on a small battery bank. This is very useful in emergency situations such as people with high probability to get lost as the accuracy of the position should be as high as possible.

4.2. Positioning Error

Fig. 5 depicts the distance error as calculated in our simulation using the algorithms from Table 1. The results in this research vary based on factors used such as initial guesses, base stations positions, etc. As we can see from the diagram below, the Distance Error of Friedlander is some meters from the actual position of the IoT device (50.6 meters). Next, taylorSeries estimation had a distance error of ~200 meters, while Friedlander3 and Schmidt approached the error on about 1Km relative to the actual position. The worst cases seem to be schauAndRobinson3, schauAndRobinson where the distance error is increasing to 6-7km.

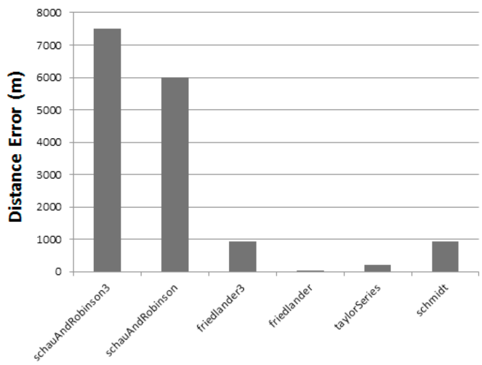

Fig. 5 Distance statistical error on meters

As we mentioned in the case of position accuracy, our goal here is to reduce the margin of error in calculating the position of a person or an IoT device. Fig. 6 shows the percent distance error in each different algorithm. As we can see friedlander calculates the distance with the minimum error in comparison with schauAndRobinson and friedlander3 whose error per cent is about 95-99%. This is very important in SAR cases while the accuracy of the position must be a few metres, for familiar but also police or emergency services, fire brigades which must be immediately called to the site [17].

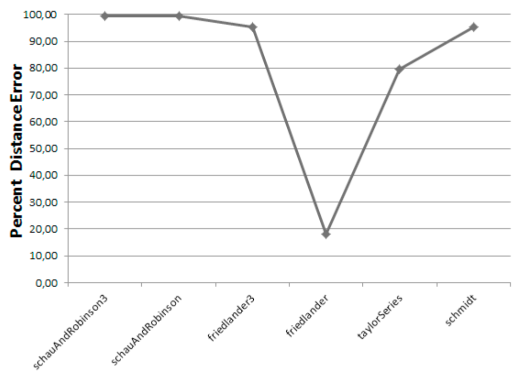

Fig. 6 Percent Distance error

The above research is based on mathematical models and algorithms, so a practical study with real time information could be also beneficial for our next steps. Some improvements on GWs positions, interferences from close devices or improvements at transmission power, and improved path-loss model with similar LOS could lead to better results. The above solutions could achieve even better localization accuracy as well as reduce the distance error.

5. Conclusions and Future Work

This research has reviewed localization algorithms that apply TDoA in transmitter and receiver technologies for a SAR case study. Compared with other signal source localization approaches and triangulation and trilateration, TDoA is appropriate for applications that require high accuracy. For this reason, we focus on the simulation and research study of some of the most known algorithms. We came to the result that many factors can influence the performance of localization algorithms in specific applications like SAR. Among these are the GWs positions, actual size of the person in need, IoT limitations (lost connection to GWs, synchronization, channel structure, battery life), mobility in network, environmental conditions as well as uncertainties in propagations (e.g Non Line Of Sight (NLOS), multipath, sound speed variation and etc.). Despite that companies and research studies focus on the development and improvements on both software and hardware the challenges on location estimation still exist as they try to achieve high performance and accuracy with economical solutions on both hardware and software. Next steps in our research study are the integration of the above algorithms on the development of the hardware running on the SAR end-node so as to verify our research in practical experiments.

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