A survey of methods for location estimation on Low Power Wide Area Networks

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***Abstract*—This survey provides a comprehensive review on localization systems and algorithms for LPWAN (Low Power Wide Area Networks). In particular, we are dealing with localization techniques for sensors in LoRa network technology, and we present methods for localizing mobile objects through that kind of network using different sensor measurements. Also, methods for improving the localization error are presented. The survey concludes with research directions, and a mention at the future work and trends.**

Keywords—localization, LoRa, RSSI, LPWAN

I. Introduction

The current trend in technology focuses on applications and systems like smart-(cities, agriculture, industrial control and supply chain) [1]. Low Power Wide Area Networks (LPWAN) [1] are the most suitable in these kinds of applications compared to the other existing communication technologies, because they provide long range communication between battery sensors, low battery consumption and tradeoff low data rate. LoRa [2] [1] [3] is a LPWAN network, which provides these kinds of characteristics. In IoT applications localization of sensors can be a vital element. Localizing sensors can have great benefits in various applications like environmental monitoring, surveillance, rescue missions, traffic monitoring, etc. In most of the cases, satellite based location systems (like GPS or Galileo) are the main solution to this kind of problems, but cause of the high energy consumption or high cost of hardware this solution is not viable, forcing the research community to find other alternatives for accomplishing the task of localization sensors in LPWAN networks. There is a big amount of research works which have combined LoRa communication with several localization methods [3] [4] [5]. These localization solutions are based on distance or angle or time difference readings from sensors and with proper process of the sensor data they can provide the proper information for the localization techniques. Time of Arrival and Time Difference of Arrival requires synchronized clocks among the base stations while Angle of Arrival requires an array of antennas. Finally, RSSI is a low-cost solution for localizing mobile objects in LoRa networks.

The remainder of the paper is structured as follows. In the section II we present methods using distance measurements to localize objects, whilst in method which using angle measurements will be presented in section II. In section III, we will see the different alternatives for gaining distance measurements and in section IV we will how distance is estimated while section V presents methods about improving the accuracy in such localization systems. Finally, we conclude in section VI.

II. Methods using distance measurements

A. Intro

Several methods, based on distance measurements to calculate the location of a moving object, can be used. The most commonly used methods are the following:

- Multilateration [3] [4] [6]
- Trilateration [3] [4] [5]
- PSO algorithm [7]

B. Multilateration

"Multilateration is a navigation and surveillance technique based on the measurement of the times of arrival (TOAs) of energy waves having a known propagation speed" [6]. This method requires the receiving stations to possess synchronized 'clocks'. An object can either transmit/ receive signals to/from the receiving stations. Systems based on Multilateration technique are also called hyperbolic systems, because in order to find the coordinates of the object they used the intersection of the hyperbolas defined between each pair of base stations.

C. Trilateration

Trilateration is a localization technique based on measured distances between an object and receiving stations. For every receiving station the object communicates with, a circle centered at its coordinates with radius the estimated true

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distance between the receiving station and the object, is constructed. The circle centers and the radius provide the information to estimate the location of the object, depending on the number of the communicating receiving stations. At least three non-collinear receiving stations are required to communicate with the object in order to calculate its position which is estimated by using the intersection of those circles.

D. Particle Swarm Optimization

The stochastic Particle Swarm Optimization (PSO) as described in [7] is an optimization population-based algorithm, where the social behavior of fish schooling or bird flocking is imitated. Opposite of other genetic algorithms, PSO algorithm doesn't use evolution operators, such us crossover or mutation. It's an iterative technique, with the aim to improve a specific cost function in each iteration of a group of candidate solutions. First, a number of particles is generated randomly in the world space and then searches for optima by updating the particles position and velocity in each iteration. Every particle can learn from its best position but also from the global best position found by another particle. The algorithm is expected to move the swarm towards to the best solution.

E. Social Learning Particle Swarm Optimization

In the PSO algorithm the learning process of the particle is updated through the personal best position and global best position only. "The process of learning and imitating the behavior of better individuals in a population is known as social learning, which can be widely discovered in social animals" [7]. The SL-PSO algorithm as presented in [19] is executed on a sorted swarm, in which a particle can perform social learning. Social learning helps the particles to learn from any better particles, where a particle in the current swarm can learn and imitate the behavior of any better particles, known as demonstrator. Imitators are the particles that learn or imitate the behaviors of the demonstrators in the current swarm.

III. Methods using angle measurements

A. Triangulation

Triangulation [3] [4] [8] is the process of estimating a point's position by forming triangles to it, from known points. It is a widely used technique for many purposes, such us navigation, astrometry, binocular vision, surveying astrometry, etc. The measured arrival angles of radio signals exchanged between an object and receiving stations are used to form lines, and the position of the object is estimated at the intersection of those lines. The arrival angles of radio signals can be measured with the aid of directive antennas or antenna arrays. In order to estimate the object's location a minimum of two receiving stations is required. A disadvantage of this method is the high equipment cost to obtain accurate angle estimates.

IV. Distance estimation

A. Intro

Due to the long communication range the distance can be estimated by processing data obtained from sensors. The widely used techniques which provide information about distance are the following:

- RSSI (Received Signal Strength Indicator) [5] [9] [4] [10]
- TOA (Time of Arrival) [3] [4]
- TDOA (Time Difference of Arrival) [3] [11] [4]
- TOF (Time of Flight) [4] [3]

B. RSSI

Received Signal Strength Indication (RSSI) is one of the most commonly used characteristics for the localization. It is based on measuring the power present in a signal between receiving station and objects. RSSI readings observed at the receiving stations can be used to estimate the corresponding distances from the receiving stations with the use of path loss models, the relationship between the transmitted and received signal strengths can provide information in order to approximate the distance. Each corresponding distance defines a circle on which the object is located on the circumference and essentially the object's location can be inferred from the intersection of those circles. The formula as shown in which describes the RSSI is the following:

$$Z = Z_0 + 10 * n * log_{10}\, d + A \quad (1)$$

where Z is the signal strength which the receiving station receive by the object, Z_0 is the signal strength which the receiving station receive by the object in one-meter distance, d is the distance we want to calculate, n is a variable called Loss exponent and A is a zero-mean Gaussian random variable that represents the background noise. Another formula that describes the RSSI is the following:

$$Z = 10 * n * log_{10}\, P_t - 10 * n * log_{10}\, P_r \quad (2)$$

where P_t is the signal strength which the object sends to the receiving station and P_r is the signal strength which the receiving station receive by the object. So, for every receiving station (denoted by indicator i) who communicates with the object we can form the following equation:

$$Z_i = Z_0 + 10 * n * log_{10}(d_i) + A \quad (3)$$

Using the above types, we can calculate the distance of the object to the corresponding receiving stations:

$$d_i = 10^{\frac{(Z_0 - Z_i + A)}{10 * n}} \quad (4)$$

But the distance can also be expressed from the well-known Euclidean formula (where the 3d uneven earth surface is mapped to a flat 2d surface) as:

$$d_i = \sqrt{(x - x_i)^2 + (y - y_i)^2} \quad (5)$$

Now we can create equations of for every receiving station:

$$-2x_i x - 2y_i y + R = 10^{\frac{(Z_0 - Z_i + A)}{10*n}} - R_i \quad (6)$$

where x,y are the coordinates of the object and x_i, y_i are the coordinates of the corresponding receiving stations:

$$R_i = {x_i}^2 + {y_i}^2 \quad (7)$$

$$R = x^2 + y^2 \quad (8)$$

C. Time of Arrival

The time of arrival (TOA) of a radio signal measures the propagation time of signal from transmitter to receiver, in order to estimate the distance between them. The propagation speed in most of the occasions is the speed of light, which means that in order to achieve precise measurements very accurate timers are required. It is very crucial for the object and the receiving stations to have synchronized 'clocks'. The distance between the can be obtained by the following type:

$$d = c * (t_{ar} - t_{se}) \quad (9)$$

where c is the signal speed, t_{se} is the time the signal transmitted and t_{ar} is the time the signal received. Another requirement is that the location of every receiving station must be known, If the object communicates with at least three receiving stations, we can estimate the position of the object.

D. Time Difference of Arrival

This method uses time differences of the signal the object sends to the receiving stations in opposite to the TOA method, which use distances between the receiving station and the object. This method requires only the receiving stations to have synchronized 'clocks'. Through a correlation analysis of the received signals, the location of the object can be obtained by:

$$t_i = \frac{1}{c} * \Delta d_i \quad (10)$$

$$\Delta d_i = \sqrt{(x - x_i)^2 + (y - y_i)^2} \quad (11)$$

If we have N receiving stations communicating with the object, we take a receiving station as origin and we formulate N-1 equations:

$$r_i = t_i - t_0 = \frac{1}{c} * \left(\sqrt{(x - x_i)^2 + (y - y_i)^2} - \sqrt{x^2 + y^2}\right) \quad (12)$$

E. Time of Flight

Time of Flight is a measurement method that doesn't require synchronization between the object and the receiving stations, but instead it measures distance using the total time of 2-way communication between the receiving stations and the object. This method requires that the respond time of the object will be constant in order to achieve accurate measurements. The distance can be calculated by the following equation:

$$d = \frac{c*(t_{ar} - t_{se} - t_{res})}{2} \quad (13)$$

where t_{ar} is the time that the signal arrives to the receiving station, t_{se} is the time that the receiving station sends the signal to the object and t_{res} is the response time the object needs in order to send a message to the receiving station. In Table I we see the requirements of each method in terms of synchronization and receiving stations.

TABLE I.

Method	Requirements	
	Synchronization	***Receiving Stations***
TOA	RS and object	>= 3
TDOA	RS	>= 3
AOA	No	Antenna array
RSSI	No	>= 3

In Table I we see that the TOA method requires synchronization between the receiving stations and the object and provides good accuracy in terms of localization error, is related with outdoor applications. In order to localize an object three receiving stations are required to communicate with the object. The TDOA method, also focuses on outdoor applications and provides equally good performance on localization of objects with TOA method but requires synchronized clocks among the receiving stations only, and in order to localize the object a minimum of three receiving stations are required to communicate with it. On the other hand, the outdoor application method Angle of Arrival doesn't not require synchronized clocks, but extra equipment. The RSSI method in order to localize the object requires also at least three receiving stations communicate with the object, it can be used both for indoor and outdoor applications but in terms of accuracy in localization of an object in IoT is has the largest errors if we compare them with the other methods.

V. Methods for Improving Accuracy

There are several methods studied above, about improving the accuracy of the localization systems. Most of them were about locating those receiving stations who were mostly infected by noisy measurements and exclude them from the localization process or they use statistical methods to smooth the readings of the sensors or apply some filters to the data in order to remove noise.

A. Moving Average Filter

The unweighted mean of the previous *n* data is called simple moving average [12] and is given by the formula:

$$\frac{1}{n}\sum_{i=0}^{n-1} P_{m-i} \quad (14)$$

However, in science and engineering the mean is normally taken from an equal number of data on either side of a central value. This ensures that variations in the mean are aligned with the variations in the data rather than being shifted in time.

B. Exponential Moving Average

An exponential moving average (EMA) [12], also known as an exponentially weighted moving average (EWMA), is a first-order infinite impulse response filter that applies weighting factors which decrease exponentially. The EMA for a series *Y* may be calculated recursively:

$$\Sigma(t) = \begin{cases} Y_1, & t = 1 \\ (a * Y_t) + (1 - a) * S(t-1), & t > 1 \end{cases} \tag{15}$$

C. LoRa Localization using Clustering

The localization algorithm [9] locates the measurement affected by noise, using k-mean clustering and then performs the standard localization calculation excluding the receiving station with the largest estimated RSSI error. Initially, R out of N receiving stations are selected to apply the regular solution to get an estimation about location of the object. Then, they apply k-mean clustering in order to group the locations into K clusters and they find the cluster with the lowest error. For the remaining clusters they locate the receiving station which participates to most of them end they exclude him from the process of localization of the object position.

D. LoRa Localization using Minimum error nodes

This localization algorithm [9] based on the idea that if the estimated RSSI errors of the estimated location of the object to the receiving stations are small, then the localization error would be also small. Thus, they propose to select the best solution by calculating the estimated RSSI errors in all possible locations that can be estimated. Initially, R out of N receiving stations are selected to apply the regular solution to get an estimation about the location of the object. For every solution they compute the error according to the measurements, and the winner solution is the one with the lower error.

VI. Conclusions

There is a really high interest on localizing sensors in LPWAN due to the variety of applications IoT. There are many methods as alternatives to GPS to perform that task with different characteristics and requirements. In this work we present those methods. We also present methods for obtaining measurements from sensor and ways to reduce the localization error in such tasks. We focus on our future work, to search for ways of improving the accuracy of localization of objects in LPWAN using methods we presented in this work separately or even using fusion of data.

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