Locating sensors with fuzzy logic algorithms

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***Abstract*—In a system formed by hundreds of sensors deployed in a huge area it is important to know the position where every sensor is.**

This information can be obtained using several methods. However, if the number of sensors is high and the deployment is based on ad-hoc manner, some auto-locating techniques must be implemented.

In this paper we describe a novel algorithm based on fuzzy logic with the objective of estimating the location of sensors according to the knowledge of the position of some reference nodes.

This algorithm, called LIS (Localization based on Intelligent Sensors) is executed distributively along a wireless sensor network formed by hundreds of nodes, covering a huge area.

The evaluation of LIS is led by simulation tests. The result obtained shows that LIS is a promising method that can easily solve the problem of knowing where the sensors are located.

I. Introduction

A wireless sensor network (WSN) consists of many small devices deployed in a physical environment. Every device, called a node, has special capabilities such as communications with its neighbours, sensing, data storage and processing. The nodes can make a mesh network of devices than can collaborate amongst themselves. These features allow the implementation of distributed solutions to solve complex problems.

Typically, a WSN consist of very small devices with several restrictions: low power consumption, low weight (especially for mobile devices), low cost, low data storage and processing and low radio range.

Generally, among all the node components, the greatest energy consumption is dissipated in the radio transceiver. This is the reason why idle-activity schedules should be implemented, as well as a minimization of transmitted and received packets.

Several protocols for hibernation have been proposed [1] [2] [3] looking for power consumption reduction. The main problem of these protocols lays in setting the clock synchronization in every node; otherwise a node can send a message when all its neighbours are in idle stage, losing information.

WSN has been widely used in several areas [4], such as environmental monitoring [5] and control [6], healthcare and medical research [7], national defence and military affairs [8] [9], etc.

In some of these applications the information gathered from the nodes is not relevant without the knowledge of the associated position, for example, in a system for wildfire tracking [10] based on the determination of specific situations (temperatures, humidity, wind direction, etc). In this case, the position of the sensors that describe these situations should be known.

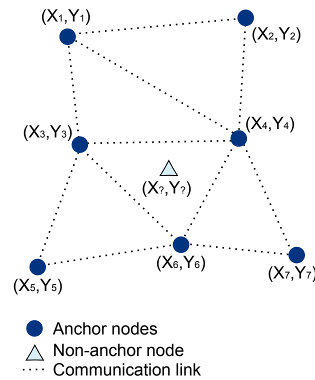

Fig. 1. Example of WSN for localization.

On the other hand, some applications required the position of the node itself, for example, a vehicle tracking system [11].

This is why localization is one of the crucial issues in WSN research.

In many cases it is impossible to use specific localization devices, like a GPS, because these devices have huge energy consumption and significantly reduce autonomy. In other applications it is necessary to have nodes inside buildings, where GPS technology does not work correctly [12].

The main contribution of this paper is the presentation of a novel localization algorithm based on fuzzy logic processing, called Localization based on Intelligent System (LIS). The proposed protocol takes into account the need to keep the power consumption low. As a result of this, the presented algorithm implements a hibernation protocol for non-anchor nodes that can save power energy from these devices.

The rest of this paper is organized as follows: Section II sums up the state of the art about localization. Section III describes LIS. The outcome of LIS performance is developed by simulations in section IV. Finally, in Section V we present concluding remarks and provide discussion for future works.

II. Localization techniques

For localization applications, a typical network consists of two types of nodes:

- **Anchor nodes:** located on a fixed and known position.
- **Non-anchor nodes:** mobile nodes.

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The essence of the localization lays in obtain the position of non-anchor nodes, using information provided by anchor nodes.

The proposed algorithms in the literature can be classified into these two categories:

A. Range-based techniques

These techniques estimate the distance between all the nodes point-to-point.

With this information the absolute position of the non-anchor nodes can be estimated using techniques as multirateration [13], triangulation or other graph theory.

There are many distance measurement methods . The most common ones are Received Signal Strength Indication (RSSI) [14], Time Of Arrival (TOA) [15], Time Difference Of Arrival (TDOA) [16] and Angle Of Arrival (AOA) [17] [18].

Nowadays, new algorithms based on these classical methods for the improvement of accuracy continue appearing, for example, based on AOA [19] [20], TOA [21] or TDOA [22].

Amongst all of these, RSSI presents the advantage of no hardware extra cost, because all the current transceivers provide this feature by default.

However, RSSI techniques could be sensitive to noisy signals. Consequently the use of RSSI measurements requires calibration on every node in order to obtain high accuracy. Moreover, the calibration could change according to the environmental conditions. The determination of how to measure the improvement of accuracy of RSSI techniques is nowadays an important research area [23] [24] [25].

B. Range-free techniques

Localization algorithms based on range-free techniques obtain the position of non-anchor nodes according to the information provided by anchor nodes. This information is usually composed by different aspects, such as:

- **Radio coverage membership.** An anchor node detects whether a non-anchor node is in its radio coverage. Using this information, the system can estimate the non-anchor node position according to the intersection of coverage areas of every anchor node in its radio coverage. Figure 2.A shows an example on intersection of coverage areas between two anchor nodes.
- **Number of hops to an anchor-node.** If there is no connectivity with an anchor node, a non-anchor node can estimate its position knowing the number of hops to every anchor node. An example of that is represented on figure 2.B. Node B is two hops distance from anchor node one, three hops distance from anchor node two and two hops distance from anchor node three.

The mechanisms employed to obtain the information are usually based on messages exchange. These messages are commonly called beacons. The handicap of implementing these mechanisms is the energy waste due to radio communication. In this sense, it is necesary to obtain a trade-off between battery life and localization accuracy. Despite having range-free techniques based in radio messages exchanges, the average energy consumption using this kind of techniques is less than in range-based ones due to the energy cost assumed by this specific hardware. Moreover, the use of additional hardware for localization increases the economic cost and weight of the solution.

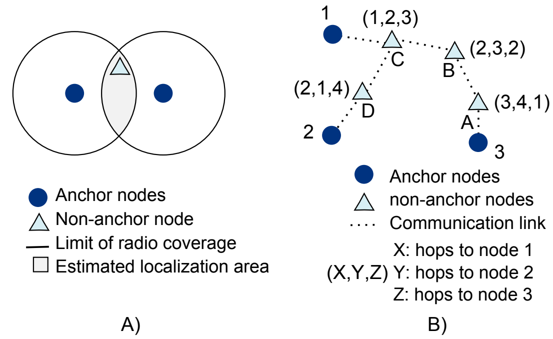

Fig. 2. Range-Free thecniques: A) Radio coverage membership. B) Number of hops.

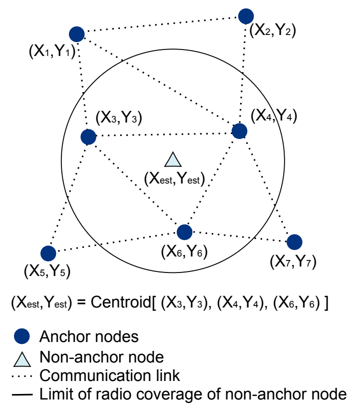

Fig. 3. CL algorithm.

Examples of classical range-free localization algorithms are Centroid (CL) [26], DV-Hop [27], Convex [28], APIT [29], etc.

CL is based on the estimation of the position of a non-anchor node obtaining the centroid of the position of all its non-anchor node neighbours. Figure 3 represents an example where the beacon is received by anchor nodes 3, 4 and 6, obtaining the estimated position of the centroid of coordinates of these nodes.

Modifications of CL algorithm are nowadays an important research area. Many authors continue proposing modifications that offer better accuracy using weight obtained either with the RSSI [30] or with the LQI [31]. Other authors are focused on the reduction of energy consumption. For example, Behnke [32] proposes modifying CL algorithm without the use of complex mathematical operation for low resources microcontroller, such as the square root. There are also authors that study the specifications of CL algorithm to determine the areas where there are big errors [33].

Nowadays new range-free algorithms continue appearing in the literature. Some of them are focused on determining new aspects of the networks that can give information about the localization, such as the intersections of a simplified coverage area [34], or modify the power transmission of beacons in order to obtain the smallest area where it is more likely to locate the non-anchor node [35].

The uses of computational intelligence have been proposed in several journals, Rajaee [36] uses probabilistic neuronal networks, Xiufang [37] uses fuzzy system and Chiang [38] uses neuron fuzzy, considering in general inputs related to positions estimated beforehand.

III. LIS ALGORITHM

Although range-free and range-based algorithms have been studied extensively, as detailed in section 2, there are some aspects that nowadays continue to be a challenge:

- Some of them need additional hardware or need a lot of beacons for localizations.
- The localization is based on a centralized processing on Base Station that requires a large amount of transmission messages to send all the information to this device or operates the localization algorithm over the non-anchor node, substantially reducing the battery of this device, because in that case it cannot put the transceiver in idle mode.
- Some of them are not easily extendible to big sensor networks.

In order to solve these problems, we propose a novel algorithm called LIS (localization Based on Intelligent Systems). LIS has been designed to obtain the following goals:

- It is easily extendible to big sensor network. The proposed localization methods can work on any network, regardless of its size.
- It keeps low consumption, obtaining big autonomy, especially on non-anchor nodes. It can be done because the non-anchor node and its radio transceiver are on idle state most of the time.
- It is lighter in weight and lower in cost. There is no additional hardware used in order to design a cheaper, smaller and lighter node. As a result of this, power consumption is minimized.

LIS is a range-free technique that determines the localization using a fuzzy system. The fuzzy system employs the estimation of the measured RSSI to the non-anchor node as inputs, offering a robust behaviour against the noise, which is the biggest problem of RSSI techniques.

A. Network processing

LIS estimates the position with the combination of two added algorithms, a distributed algorithm executed in every anchor node and a centralized algorithm executed in the Base Station.

LIS is composed of four steps, which are listed on table I.

Localization starts when a non-anchor node sends a broadcast message (fig. 6.A).

Non-anchor nodes do not participate in the localization algorithm. Because of this, they can be hibernating all the time with the radio transceiver off, except during the beacon transmission. Consequently, it is possible to obtain a very long battery lifetime.

Step	Description
Step 0:	Anchor nodes wait for non-anchor node beacons.
Step 1:	Non-anchor node sends a beacon.
Step 2:	Anchor nodes on the coverage area of the non-anchor node execute the distributed processing.
Step 3:	Anchor nodes send its partial solution to the Base Station, where the estimated position based on the centralized processing is determined.

TABLE I
STEPS OF LIS ALGORITHM.

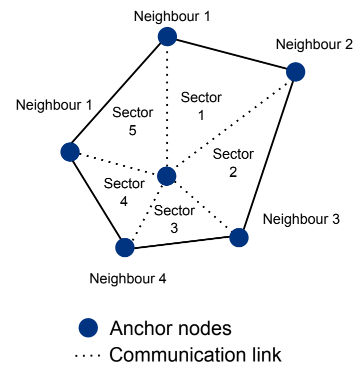

Fig. 4. Example of node with 5 neighbours.

The beacon frequency can be determined by the application, and can be modified by external conditions such as the remaining battery in the non-anchor node, a diary schedule or with information registered by external sensor such as an accelerometer. In this way, the battery lifetime is improved.

1) Distributed Processing: LIS uses the measured RSSI of a node and its neighbours to determine the representative area where the non-anchor node could be located. This algorithm is based on a fuzzy system distributed on every anchor node of the network. This method does not require additional hardware, because the measured RSSI can be obtained directly by most current radio devices.

The node must execute the algorithm for every sector formed between the current node and its neighbours, as represented in fig 4. The central node has five neighbours, according to its radio coverage. In this case, the fuzzy system is executed five times. In this figure, the space around the central node is divided by its neighbours in triangular areas. These triangles, formed by the central node and two adjacent neighbours, are the representative areas considered by the distributed processing for the localization of the non-anchor node.

Every node that receives a beacon measures the RSSI. Then, these nodes send a broadcast message to their neighbours with their estimation of the RSSI (fig. 6.B). With this information, the closest anchor nodes elaborate a table with the information related with the measured RSSI obtained by themselves and the measured RSSI provided by its neighbours. All the nearby

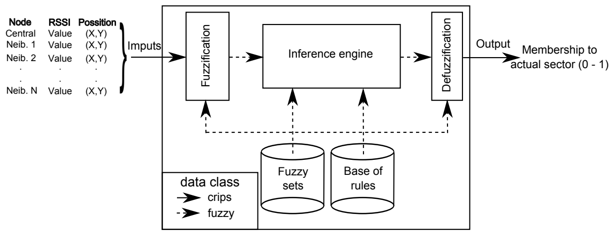

Fig. 5. Inference fuzzy system.

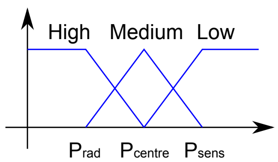

Fig. 7. Sets of the fuzzy imputs.

nodes have a table with the information of the RSSI estimate by themselves and the estimation of their neighbours.

The RSSI table is the the fuzzy system input, executed in every node which has received the beacon of the non-anchor node. This fuzzy system is evaluated in every node that belongs to a sector to determine the representative area (fig. 5). It is extendible to a node with an arbitrary number of neighbours.

As a function of the fuzzy system outputs, the representative area can be made as the union of one or various sectors formed by the area between neighbours nodes (fig. 6.C). If all of the output values of a node are very low, the node discards this information, not sending a message to the Base Station and consequently saving energy.

Representative areas are those which give an output of a fuzzy system higher than a threshold. This value can be adjusted experimentally. In the executed simulation, detailed in section IV, the chosen threshold has been 0.1.

This information is sent to the Base Station, which calculates the position as a function of the local solution estimated in different nodes (fig. 6.D).

Inputs of the fuzzy system:

The inputs of the system are all the measured RSSI of a node and its neighbours. Every input has three fuzzy sets which represents high RSSI, Medium RSSI and low RSSI.

- The fuzzy set that represents low RSSI is a trapezoid with a value of 1 for all power below the theoretical sensibility of the node which sends the RSSI measured. After sensibility, the fuzzy set decreases linearly to 0 in medium RSSI point.
- The fuzzy set that represents medium RSSI is a triangle with a value of 1 for the RSSI which represents the midpoint. The corner of the triangle is the sensibility and the power transmission. The value which represents medium RSSI can be determined for every sector with Friis formula using the RSSI that the node reads if the device is in the centre of the sector.
- The fuzzy set that represents high RSSI is a trapezoid with a lineal increase from 0 to 1 from the medium RSSI point to the theoretical RSSI of the power transmission.

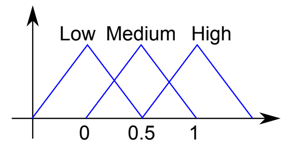

Fig. 8. Sets of the fuzzy output.

Outputs of fuzzy system:

The system offers an output for every sector that ranges between 0 and 1.

The defined output fuzzy sets are:

- Output low is defined as a triangle with the central point in 0 and the corners in -0.5 and 0.5.
- Output medium is defined as a triangle with the central point in 0.5 and the corners in 0 and 1.
- Output high is defined as a triangle with the central point in 1 and the corners in 0.5 and 1.5.

Inference engine

The inference motor has a Mandani's knowledge rule base with a centroid concresor and a singleton input fuzzificator.

The fuzzy engine evaluates the antecedent of every rule as the intersection of the fuzzy inputs, using the minimum function for the AND operator and the maximum function for the OR operator. The implication between the inputs and the outputs is made with the minimum function.

The proposed system has a base of rules that need to be evaluated for every sector formed between the node and its neighbours. The rules used in the proposal system are summed up on table II, where the current sector is the area considered in one of the execution of the inference engine.

2) Centralized processing: In the Base Station all the partial solutions in the estimated position are added. This process is called a centralized algorithm and it is executed in the Base Station.

The proposed centralized algorithm is a variation on the centroid algorithm, where it is used for the calculation, instead of the position of anchor nodes, the points that represent the areas chosen by the non-anchor nodes that submit their partial solution to the Base Station. It improves the accuracy of the system.

The centralized processing is made up by the next steps:

- Base Station waits to receive a partial solution for any anchor node.
- When a partial solution is received, it stores this on a table and starts a timer.

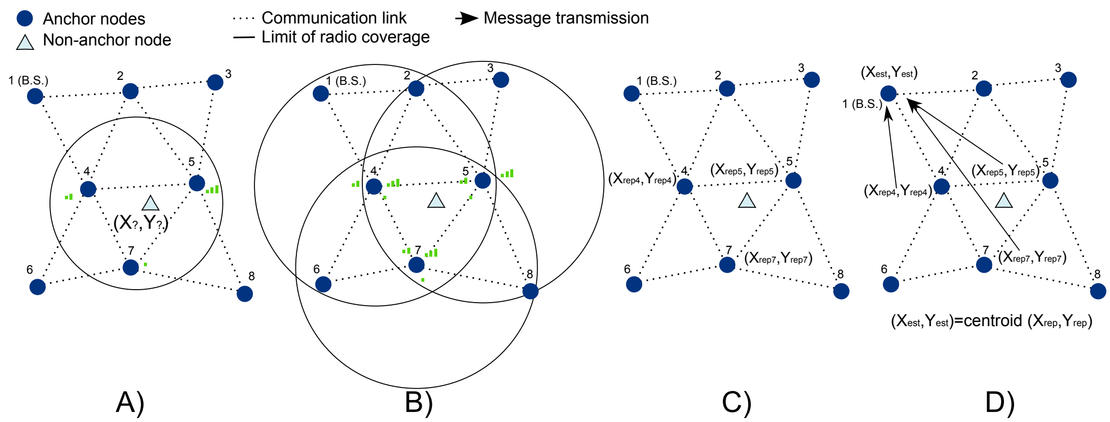

Fig. 6. Steps of LIS algorithm.

High.	All medium.	High
Low.	All low.	Low
Medium.	All medium.	High
Medium.	All low.	Low
High.	All high.	Medium
Medium.	Medium in current sector. Low in the rest.	High
Medium.	High in any sector except the current one. Low in the rest.	Low
High.	High in a neighbour of the current sector. Low in the rest.	Medium
High.	High in a neighbour, except on the current sector. Low in the rest.	Low
Medium.	Medium in a neighbour of the current sector. Low in the rest.	Medium
Medium.	Medium in a neighbour, except on the current sector. Low in the rest.	Low

TABLE II
RULES OF THE INFERENCE ENGINE.

- While the timer is running, all the partial solutions that receive the Base Station are stored into the table.
- When the timer has expired, the system combines all the partial solutions stored in the table using the centroid between all these partial solutions.
- After that, the system clears the table of the partial solutions and restarts the cycle, waiting to receive a new partial solution.

With this algorithm, the Base Station always needs to be active, waiting to receive any message from the nodes. It determines that the Base Station is going to consume more than the other nodes. This is not critical because the Base Station acts as a gateway between the sensor network and the external network. Because of this, it needs to be placed in an area without power restrictions.

IV. Experimental results

The localization system was designed to be developed in a wireless sensor network, called ICARO, designed to test an environmental monitorization algorithm. ICARO was placed in the Doñana Biological Reserve (DBR), a part of the National

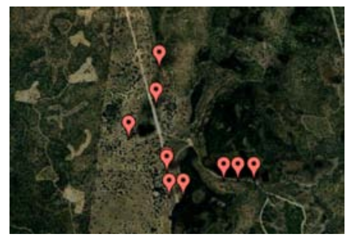

Fig. 9. Deployment of the project ICARO.

Park of Doñana. It is located in Andalusia and covers 543 km^2, of which 135 km^2 are a protected area. The park is an area of marshes, shallow streams and sand dunes.

Doñana Biological Station is a Research Institute of the Spanish Council for Scientific Research (CSIC). Some of its main goals are conservation and improving the quality at research in DBR, which was declared humanity patrimony by UNESCO in 1994 and considered one of the most important natural protected landscapes in the world. In fact, this year, DBR was included inside the great scientific infrastructures of European Union.

Icaro consists of ten wireless sensor deployed between the zone of “El Ojillo” and “El Zacallón”, working on 2.4 GHz ISM band with IEE 802.15.4 Protocol. Figure 9 shows a map with the current system deployment. This network is based on two kinds of devices:

- **Base Station:** It is the device that acts as a gateway between the remote measurement sensor and the communication infrastructure of Doñana. It permits the collection of information and allows centralized processing and data fusion. This system is based on a wireless sensor attached to an Industrial PC.
- **Remote Measurement Sensors:** They are the devices that permit the acquisition of environmental information. They are powered by solar panels. These devices allow to execute distributed and collaborative algorithms. These devices permit the utilization of data fusion and aggregation for reduce the usage bandwidth. These devices are shown in figure 10.

Fig. 10. Remote measurement sensor of the project ICARO.

Fig. 11. Example of non-anchor node for tracking animals.

Fig. 12. LIS Simulator.

Our goal consists of using the ICARO infrastructure as an anchor node, developing a low weight device, with high autonomy as a non-anchor node for tracking animals in Doñana Natural Park, such as the device shown in figure 11.

To do this, the Base Station can be used to execute the centralized algorithm of the localization, while the remote measurement sensor executes the distributed algorithm.

We have compared the obtained results with the classic CL algorithm with an ad hoc simulator designed for testing localization algorithm. In this chapter we describe the simulator and the results obtained with it.

The system simulates a square grid of 25 anchor devices with 200 meters of distance between them. In these tests, a coverage area of 200 meters with a radial pattern in the non-anchor node is used.

A. Description of the simulator

In order to test localization methods, a specific simulator on C++ named LIS simulator was designed.

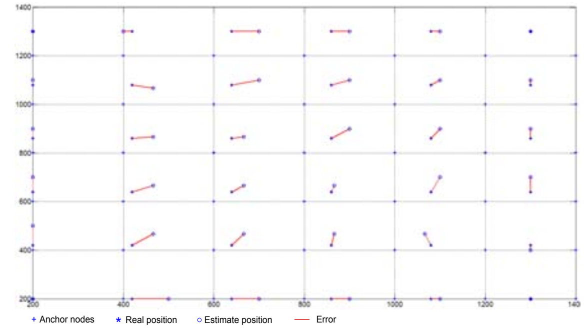

Fig. 13. Possition error of centroid algorithm.

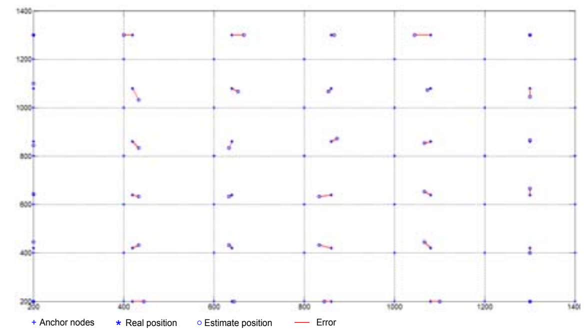

Fig. 14. Possition error of LIS algorithm.

In this simulator a grid of a maximum of 25 anchor nodes can be displayed and only one non-anchor node that can be moved through the scenery.

This simulator permits the adaptation of the coverage area of the tag, the noise, the position of the anchor node in the map and the form of the radiation pattern.

The model used to calculate the received RSSI is based on a free space Friis formula. Disturbances on this simulator can be added to the system with the addition of a Gaussian noise with adjustable mean and variance.

With this simulator we have made comparisons between classic CL algorithm and the proposed algorithm.

B. Error vs. Position

This experiment shows the absolute error vs. position. These experiments are done without adding noise.

For these tests the tag has been moved along an area, obtaining the results shown in figures 13 and 14.

In the graphics, the proposed method presents less error than the classic CL.

C. Error vs. coverage

In this test we have increased the coverage area of the non-anchor node, maintaining the same distance between anchor nodes.

In this scenario the noise has not been considered.

Figure 15 shows the results of changing the coverage. This result shows how increasing the number of non-anchor nodes that beacon receives affects the accuracy of the localization.

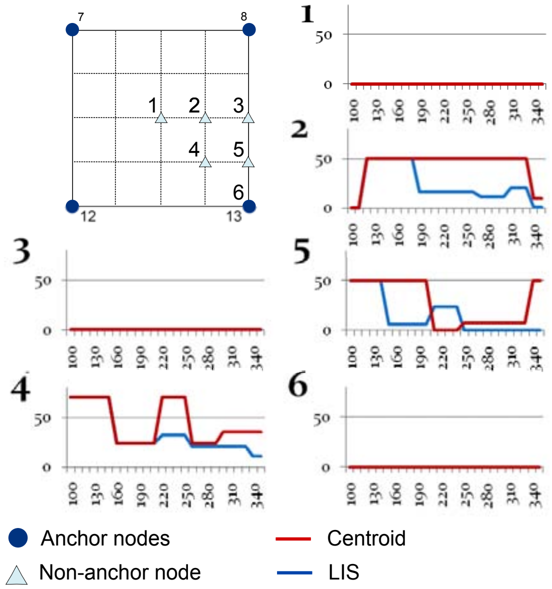

Fig. 15. Localization error vs. the coverage radio area of non-anchor node.

Generally, the proposed method obtains better results than the centroid method.

Similar results can be obtained maintaining the coverage area of the non-anchor nodes constant and reducing the distance between anchor devices.

D. Error Vs. Noise

In this test we have analysed the error obtained in a fixed position of the non-anchor nodes when changing the variance of the noise. All analyses use a coverage area of 200 m for the non-anchor node.

To obtain this result we have made 1000 analysis at every point.

The error vs. variance figure (fig. 16) represents how the noise affects the accuracy of the system. Centroids shows a good behaviour on points of symmetry with respect to the anchor nodes (such as point 1, 3 and 6), but it has worse behaviour on the resting point. Moreover LIS offers similar responses in any localization, obtaining good results on non symmetry points.

The number of errors (fig. 17) represents the number of absolute errors bigger than 100 m (1/2 of the coverage area) obtained in the localization. If the tag is situated in the center of the square, this error represents the number of results that situate the device out of the square.

As it can be seen, always LIS has less number of errors bigger than 100 m than the classic CL algorithm.

V. Conclusions and Future Work

LIS is presented in this paper as a new fuzzy algorithm for localization.

LIS has been tested with its own simulator software designed with C++. With this simulator we demonstrate that the proposed method obtains less localization errors than the original algorithm without a very high computation requisite or an extensive use of radio, it permits the use of it on devices with limited resources, like the typical nodes of Wireless Sensor Networks.

Currently, we aim to increase the accuracy of the system versus the noise, acting in the next lines:

- Using a filter to reduce the variability of the measurement: We are working on the evaluation of the advantages of using filters to RSSI Measures in order to increase the accuracy.

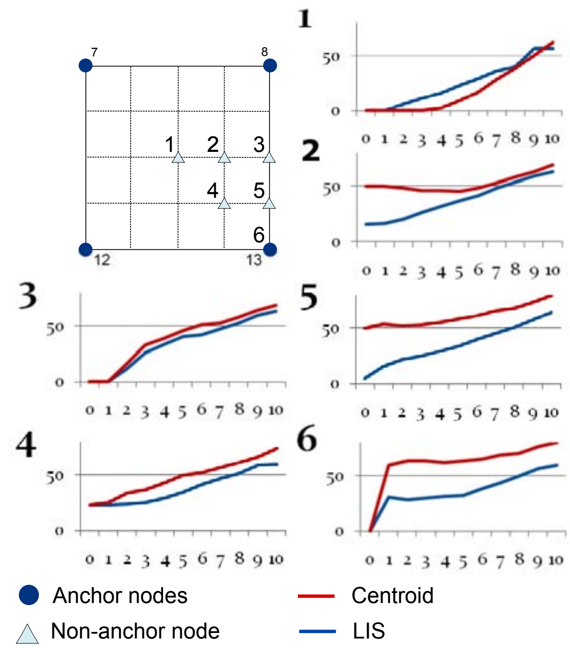

Fig. 16. Localization error vs. the noise.

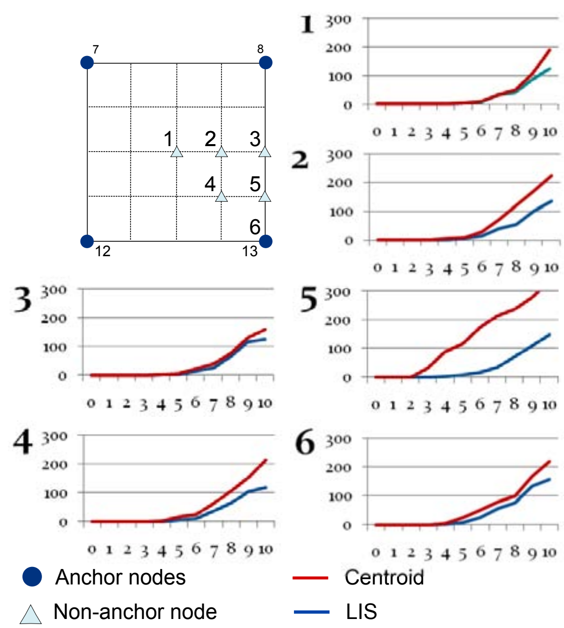

Fig. 17. Number of error bigger than 100 m.

- Use additional RSSI information between Nodes: Current radio devices can provide RSSI information for every message than the radio can intercept. For example, we can use the radio messages sender between anchor nodes in the localization to model the environment without adding traffic between devices.
- Use temporal information: The current proposed method only uses the information obtained in a predetermined instant, it does not have past memory. We are working on a modification to the current algorithm which improves its performance using this information.

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