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A Node Localization Scheme for Zigbee-based Sensor Networks

Ernesto Navarro-Alvarez
Computer Science Departament
CINVESTAV-Unidad Jalisco
Zapopan, Jalisco, Mexico
enavarro@gdl.cinvestav.mx

Mario Siller
Computer Science Departament
CINVESTAV-Unidad Jalisco
Zapopan, Jalisco, Mexico
msiller@gdl.cinvestav.mx

***Abstract*— The localization problem consists in estimating the position of the nodes within the network. This is a crucial issue for location-dependant applications. This paper presents an implementation of a localization scheme based only on the received signal strength (SS) in a Zigbee-based sensor network. This is done by taking advantage of the inherent radio communication capability present in each node. The algorithm is intended for an outdoor environment. It is based in a model, which infers distance between neighboring nodes using the SS. A coordinate system is then derived employing a multidimensional scaling (MDS) technique. The signal power level variability due to ground reflection is approached using Lloyd Effect (from optics) and incorporated in the model.**

***Keywords*—IEEE 802.15.4, Zigbee, Sensors, Wireless networks, multidimensional scaling.**

I. INTRODUCTION

Pervasive computing is derived from the availability of different devices with processing power which vary in size and in many cases with networking capability. Sensor nodes are part of this technology. They are relatively cheap and able to communicate wirelessly with low power consumption. Sensor nodes also have data storage capability and sense different types of physical variables. These devices are used to build networks for different applications. These networks are referred to as wireless sensor networks (WSN). In [1] a WSN is defined as "a network where small sensors with limited hardware capabilities communicate wirelessly with each other". Nodes are physically located and distributed in a given geographical area. The localization problem consists in estimating the position, spatial or geographical coordinates of the network nodes. This location information is used by the applications for different reasons. In tracking applications, it could be used to report the geographical origin of events, to assist in target estimation, products quality monitoring and to locate rescue teams in disaster areas. In health applications, sensor nodes can be used to monitor patients and assist disabled patients. In the military applications, they are used for intelligence, surveillance, reconnaissance such as sniper location, etc. For a detailed review of WSN applications see [2].

The simplest but not the cheapest way to solve the localization problem is to add a GPS device to every node. For some of the applications price and energy consumption would be a drawback for this solution. An alternative way of solving this is to use connectivity information such distances estimated using the power level of the received radio frequency (RF) signals. In this work the estimation is carried out from the strength of the received signal. This is referred to as LQI in the 802.15.4 standard. According to Friis equation [3] the signal power is attenuated as the distance between the transmitter and receiver increases. However, the radio signal propagation tends to be non-uniform. This uncertainty of the signal power level due to ground reflection is approached in this work by using Lloyd Effect (from optics) to model the reflections. Last, a probabilistic approach and a multidimensional scaling (MDS) technique are used to estimate the node coordinates in a coordinate system.

The rest of the paper is organized as follows. Section II presents a review of location techniques that use only signal strength to measure distances between nodes. The end of the section is focused on localization solutions with the Zigbee protocol. Section III presents the experimental methodology used to study the signal strength vs. distance relation. In section IV theoretical background of signal propagation is presented. It includes different effects affecting the signal propagation and specially a reflection phenomenon known as Lloyd effect. In sections V and VI the proposed model is introduced. In section VII results obtained are presented. Finally, section VIII presents conclusions.

II. RELATED WORK

There are three main techniques based on radio signals: *Time of arrival*, *Direction (angle) of arrival*, and *Signal Strength based.* Some other solutions can be derived from or the combination of them. *Time of arrival* is based on signal travel time measurements between nodes. The distance is derived from the arrival time difference between two electromagnetic signals. A different approach based on signal arrival employs both an electromagnetic and an ultrasound signal. This is referred to as *Time Difference of Arrival (TDOA)*. The main drawbacks related to Time of arrival techniques are synchronization of the nodes and the mathematical computations to obtain the nodes positions. Also *TDOA* requires additional hardware and it is energy consuming. *Direction (angle) of arrival* is a technique in which the node location is estimated using signal angle arrival between the unknown location node and an array of beacon nodes. The main drawback is that a digital compass is required

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per node. This can be expensive for large scale sensor networks. On the other hand, the Signal Strength based technique uses the received radio signal power to estimate distance. Although these techniques do not obtain accurate results, they are widely used because its simplicity and does not requires additional hardware. Next, various implemented solutions that relay on signal strength are reviewed.

A. RADAR and SpotON

RADAR System [4] and Spot ON [5] are two indoor location systems. RADAR uses signal strength (SS) measurements from multiple receivers to triangulate the user's coordinates. The receivers are positioned to provide overlapping coverage in the area of interest. Spot ON is based on a RFID technology. It uses a long range ID badge from a company named RF Ideas INC to implement the localization solution. Similar to RADAR, signal strength measurements and node distance estimation are provided by multiple base stations. These values are then triangulated by a central server to estimate the node location using the following function:

$$SS \approx 0.0236*d^2 - 0.69*d + 4.781 \qquad (1)$$

This function is derived from empirical data analysis mapping basestation distance to signal strength estimate. SS is given in abstract units. Other solutions such as the Cricket Location System [6], the Bat system [7], or Active Badge system [8] are discarded from this classification because they use additional hardware such as ultrasound or infrared devices.

B. Probabilistic Approach

The estimation on this approach is based on an a priori probabilistic density function (PDF) [9]. This function is derived from signal strength vs. distance experiment. Signal strength measurements at different distance are considered as a random variable because of the effects of environmental conditions, errors, noise, fading, disturbs, etc. Under [9] this PDF follows a Gaussian distribution. The algorithm is as follows. Each unknown node estimates an initial position. This estimate is updated as new packets are received from fixed beacons or from neighbors nodes. If the new estimate improves the previous one then it is broadcasted to its neighbors after a certain period of time *T*.

C. Multidimensional Scaling

This approach is based on Multidimensional Scaling (MDS). This data analysis technique was originated in psychometrics [10]. MDS is a set of procedures for data analysis which aims to display the structure of distance-like data in a Euclidean space (graphical plot). The basic principle consists in transforming a distance matrix into a cross-product matrix in order to find its eigen-descomposition using principal component analysis (PCA) [11]. This MDS algorithm was applied to the localization problem in [12] by Shang *et al*. This solution is called MDS-MAP. A 2-D (or 3-D) relative map is obtained and it can be transformed into an absolute map using geographical positions of enough anchor nodes. A main disadvantage of this technique is that it takes *O (n3)* time for a network of n nodes [12].

D. Weigthed Centroid Localization

In [13] an algorithm designed for Zigbee-based networks is presented. In a first stage sensor nodes estimate their position by centroid calculation from beacons. Weights are empirically defined to improve the localization estimation. These are assigned as a function of distance and the node sensor receiver characteristics. These values are inversely related to the distance between the node and the beacons. The LQI in Zigbee devices and Friis' free space transmission equation are used to estimate theoretical distances. An experimental plot of LQI versus real and theoretical distance is also presented.

III. FIELD EXPERIMENTS METHODOLOGY

One of the main advantages of Signal Strength based approach is that it can be implemented in any transceiver. However, the main limitation derives from the nonlinearity of outdoors signal strength values in relation to the distance. Other constraints are multipath effect, environmental effects, reflections on ground, presence of people, and environmental conditions. These effects produce the nonlinearity relation.

Similar to [13], [14], [15], and [16] a field experiment was conducted to study the signal strength vs. distance relation. For this a Zigbee network with only two sensors was formed in the middle of a soccer field. The experiment was setup as follows: a) a sensor transmitter is placed at a reference point and connected to a laptop running a measurement program. This sensor is called coordinator; b) a second sensor is placed 1 meter away; c) the second sensor is set in low power mode and wake up every 5 seconds to send an identification number to the coordinator; d) a 30 measurements sample is taken and logged in the laptop; e) the second sensor is moved incrementally 1 meter away from the reference point; f) the coordinator is moved to 1,2,3,4 and 5 meters height; g) steps 4 and 5 are repeated until a 70 meters range is reached; h) for all distances and tested heights the sensors are placed horizontally and in different antenna orientations. Since the transmitter-receiver orientations cannot be foreseen 4 orientations are considered: 0, 90,180 and 270 degrees. For all orientations the average signal strength value and standard deviation were computed. For example, average received at 1 and 2 meters were -44.795, -47.964 dBm and the standard deviation values were 3.690, 4.546 dBm. For each experimental distance measurement a histogram was obtained. The resulted statistics observed a normal distribution. This can be verified by comparing proposed pdf to the observed SS. This is done using a quantile-quantile (QQ) plot, as shown Figure 1. The points fall approximately along the 45-degree reference line. This proofs that the two sets correspond to a population with a similar distribution. Thus the obtained *SS* is a r.v. that follows a normal distribution.

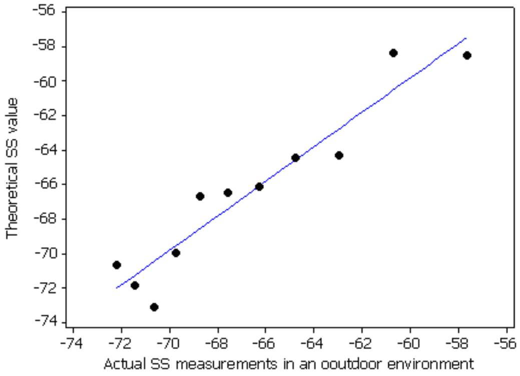

Figure 1. Quantile-Quantile plot.

From the experimental data it is observed a decreasing power results in low LQI measurements. It means that distance *d* is indirect proportional to LQI. In Figure 2 the average measured power derived from the different antenna orientation positions and each testing height is presented.

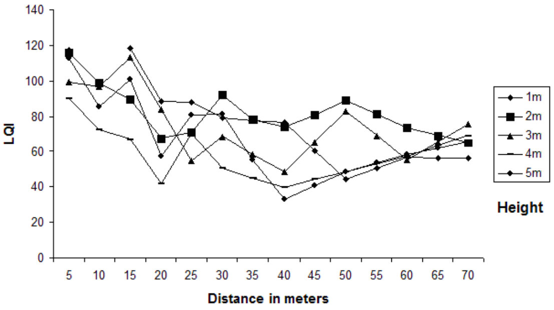

Figure 2. Experimental data.

IV. FRIIS PROPAGATION MODEL

Signal Strength based algorithms use a signal propagation model to map signal strength values to distance estimates. A general free space transmission model, but not necessarily accurate, is the Friss model. It states that signal strength decreases quadratically with the distance to the transmitter. The model predicts a value when the transmitter and receiver have a clear and unobstructed line-of-sight path between them. This model is classified as a small-scale or fading model. This is because it characterizes fast signal strength fluctuations over short travel distances and time durations. The model is expressed in the following equation:

$$P_r(d) = \frac{P_t G_t G_r (\lambda)^2}{(4\pi)^2 d^2 L} \qquad (2)$$

Where *Pt* is the transmitting and *Pr(d)* the receiving power. The latter is a function of the distance between the transmitter and receiver *(d)*, transmitter antenna gain *(Gt)*, receiver antenna gain (*Gr*) system loss factor (L, $L \geq 1$) and the wavelength in meters *(λ)*. In the particular case of the of the 2.5 GHz zigbee frequency *λ* is 0.12 meters.

V. PROPOSED SS VS. DISTANCE MODEL

In the proposed model there are two important sources of variability of the signal strength considered: *reflection on the ground* and *the antenna radiation pattern.* This is based on the previous experimental results shown in Figure 1. The observed reflection can be explained considering the common Lloyd's mirror phenomenon from the area of optics. This consists of a flat surface of dielectric material (ground) which serves as a mirror from which one portion of the wave is reflected and the other portion proceeds directly to the screen [17]. As shown in Figure 3 an electromagnetic wave from one source at point A is detected by a receiver at point C. If radiation from A is reflected off a mirror at point B, the reflected wave will also be detected by the receiver. Due to the reflection from the mirror, the reflected wave will be out of phase with respect to the incident wave. When the two waves meet at the receiver, constructive and destructive interference can occur. Maximum signal strength will be detected when the two waves reach the detector in phase. The optical path length of the reflected signal is defined as AB+BC whilst for the un-reflected signal is just AC. The path length varies as the transmitter and the receiver moved away from each other. The resultant signal strength in C from both signals can be obtained from the total Irradiance formula (eq.3).

$$I = I_1 + I_2 + 2\sqrt{I_1 I_2}\cos\delta \qquad (3)$$

Where I_1 is the un-reflected signal strength whilst I_2 is the reflected one. The δ is the phase difference angle between the two signals. It is calculated from the transmitter-receiver distance and heights as follow $\delta = ay\pi / s\lambda$. At different points in space, the resultant strength can be greater (*constructive interference*), less than (*destructive interference*), or equal to $I = I_1 + I_2$.

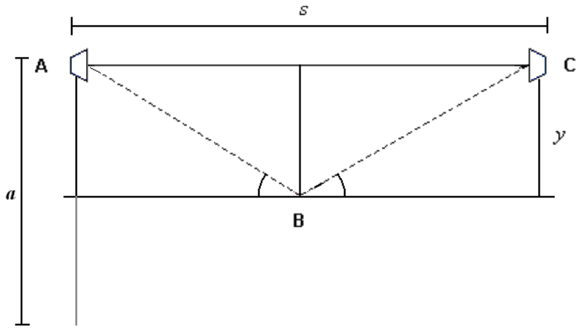

Figure 3. Lloyd phenomenon.

In addition to Lloyd effect, the transmitting antenna characteristics and orientation significantly impact the received average signal strength [15] (see also Figure 1). The MC1321x sensor family is equipped with printed (microstrip) F-antennas. This is a monopole antenna, which is a variant of a dipole, where one half of the antenna is reflected in an infinite ground plane. Both antennas are used widely in short-range radios because they are compact, easy to produce and have a simple design. The gain pattern of the F-antenna is shown in Figure 4. It can be seen that the value recorded at the receiver for a given pair of communicating nodes at a given distance varies as the antennas orientations are changed. The gain G_t and G_r depends on the orientation of the transmitter and receiver nodes and are considered as random variables in the proposed model.

Based on the Friis's free space transmission model, the Lloyd's effect and the radiation pattern of the F-antenna a function for the signal strength for a given distance is proposed as follows:

$$SS_i \approx P_{r1}(S_i) + P_{r2}(S_i) + 2\sqrt{P_{r1}(S_i)P_{r2}(S_i)}\cos(\frac{ay\pi}{S_i\lambda}) \qquad (4)$$

SS_i is the theoretical signal strength predicted values at a given distance *i*; this function depends on three random variables (r.v.): distance between the transmitter and receiver *(d)*, transmitter antenna gain *(Gt)*, and receiver antenna gain *(Gr)*. In the proposed model the irradiances of Lloyd's formula were replaced for received power at the distance *i* by a receiver. SS_i is expressed in dBm and *i* is the distance expressed in meters. Hypothesis Testing (HT) (significance level 0.05) is then performed to match observed SS to the theoretical model. If the hypothesis is accepted a distance estimate is obtained from the SS measurement. If it is rejected the significance level is changed up to 0.1 in steps of 0.01. If no matching is obtained SS re-sampling is performed. Thorough this mechanism distance estimates between all pair of neighbor nodes are calculated.

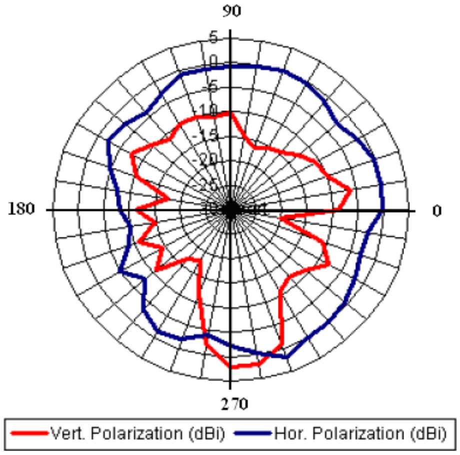

Figure 4. Printed F-antenna Radiation Pattern. Image taken from [18].

VI. POSITION ESTIMATION

Once distances between all nodes are estimated with the proposed model in section V, each node coordinates (x and y) can be derived using any localization algorithm such as: centroid determination [19], weighted centroid [20], triangulation [21], etc. In this work MDS [10] was employed given that it can be applied with or without beacon nodes. Note that the position estimation accuracy is directly linked to SS vs distance relation which represents the main contribution of this work. The MDS algorithm to transform distance into coordinates is detailed next. An adjacency matrix is used to represent the network as an undirected graph A (G) = [a_{ij}]. In this adjacency matrix a_{ij} is associated with the estimated distance between sensors *i* and *j*, if nodes *i* and *j* have a communication link. Based on this adjacency matrix a second (distance) matrix is generated to represent the shortest path distances between all pair nodes (D = M_{nxn}). Here the well-known Floyd-Warshall algorithm is used to find a shortest path from *i* to *j* for every pair of vertices *i* and *j*. Last, Singular Value Decomposition [11] is applied to D to obtain the eigen-decomposition D = UVU^T. To obtain the coordinates matrix X = M_{nxn} we compute X = $UV^{1/2}$. As we want to get the 2 dimension of the solution, we denote the matrix of largest 2 eigen-values by V_i and U_i the first 2 columns of U. Then, the coordinate matrix is $X_i = U_iV_i^{1/2}$. The 2-D relative map obtained is shown in Figure 5.

VII. RESULTS

This section is divided in two parts. Section *A* presents the results of the algorithm when using beacons; second one shows results without beacons. Beacons are nodes whose coordinates are known a priori (Coordinates can be hard coded or obtained through some additional hardware such as a GPS) and help the unknown node to estimate its position. On the other hand, in Section *B*, an unknown node calculates its position using other unknown nodes.

For evaluating the performance of the algorithm the *location error* is defined using the Euclidean distance formula: $d(P_2^A, P_1^E) = \sqrt{(x_2^A - x^E{}_1)^2 + (y_2^A - y_1^E)^2}$, where P_2^A and P_1^E are the actual and estimated location respectively. The algorithm is repeated several times to obtain an *average location error*.

A. Beacons

To carry on the first experiment, a full equipped sensor network was set up in a soccer field. This experimental testbed had dimension of 62 m by 25 m. (an area of 1,550 sq. m.) enclosed by 8 beacons. Beacon sensors (also called anchor nodes.) were placed at aligned around the field and had a distance of 20 m. to each other. A Cartesian coordinate system with origin (point 0, 0) is centered in the middle of the field. Any unknown node can be located within this coordinate system. A 9th (unknown location) sensor is randomly placed in different locations inside the soccer field area (See figure 5). This sensor is always awake and receives the packets coming from the beacons. The sensors calculate the SS based on LQI of the received packets and send it to a gateway. This gateway is connected to a computer with the logging program. The send packet includes an identification number of the beacon and the calculated SS. The identification numbers are 1, 2... 8. The experiment was repeated several times for the different locations of the unknown node. Table I summarize the statistics for the *location error* (expressed in meters).

B. *Without Beacons*

The experimental testbed is, again, the soccer field of 60 m by 20 m. (an area of 1200 sq.m.). For this experiment 4 unknown nodes were deployed inside this area. For this case no beacons nodes were used to help derive location. The positions were chosen randomly according to the layout of the soccer. (See Figure 6). When no beacons are used the algorithm produces a configuration of point that preserves neighbor relationships and distance estimates between nodes. The experiment was repeated several times with different positions for each unknown node. Table II summarize the statistics for the *location error* (expressed in meters).

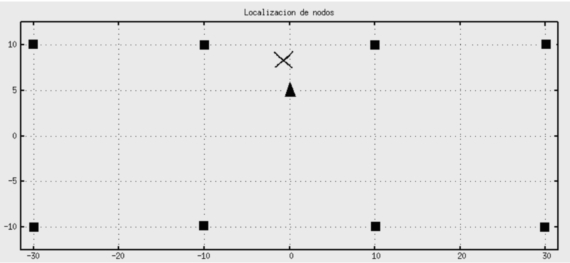

Figure 5. Localization on the 2-D map. Triangle represents the position obtained by the scheme. The X represents the physical position of the node. Black squares represents beacon nodes

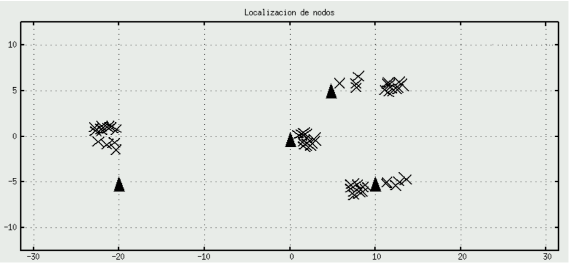

Figure 6. Localization on the 2-D map. Triangles represent the actual positions of the nodes. The X represents different estimates for the 4 unknown nodes. Notice there are no beacons.

TABLE I.

Location Error	***Mean***	***StDev***	***Min***	***Max***
Unknown node	10.59 m	6.03 m	3.36 m	18.56 m

a. Statistic for the location error. Beacon case.

TABLE II.

Location Error	***Mean***	***StDev***	***Min***	***Max***
Sensor 1	5.66 m	0.92 m	4.24 m	6.66 m
Sensor 2	1.81 m	0.20 m	0.36 m	2.60 m
Sensor 3	8.67 m	3.93 m	2.86 m	11.71 m
Sensor 4	9.19 m	3.38 m	1.17 m	11.40 m

b. Statistics for the location error. Without beacons.

For both experiments, an analysis was performed on the error distance results. The conclusions are discussed next.

VIII. CONCLUSIONS

In this paper major localization algorithms were reviewed. Many presented solutions consider assumptions which are made to simplify the problem, such as the radio frequency propagation model and probability distribution. However, these assumptions may not be necessarily accurate to the physical scenario. An implementation scheme was proposed. The proposed scheme is *Signal Strength based* and produces a relative coordinate system, which can be later converted to a global coordinate system by using positioning nodes. The scheme was tested in two different contexts: with beacons and without beacons.

An empirical study was conducted of the signal strength behavior in an outdoor environment using MC1321x Zigbee radios. The study was conducted in an open space due to minimal multipath effect. As a result a model for the signal propagation is proposed. This model is based on Friis free space propagation equation and experimental data. Also an important ground reflection phenomenon for 2.4 GHz ISM band signal was quantified and modeled: the Lloyd's effect. A summary of basic theoretical and practical facts concerning the signal strength analysis also were presented.

Most paper´s simulations reports distance error of centimeters. For example, [22] reports estimate locations within 20 cm. of the actual location of the nodes. Although this implementation does not produce errors of centimeters (maximum value 18.56 meters, minimum value 3.36 meters), it is reasonable to think that these simulations achieve similar results when are implemented for real conditions.

It is observed from the result analysis that the further away a node is located from neighbor node (beacon or unknown), the bigger the error estimated is. This is proved with the experimental data.

Better precision estimation may be achieved by improving the accuracy of proposed model. In fact, formulation of better propagation models it still is an opened research area.

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