Optimization Algorithm for Positioning Estimation in Wireless Sensor Networks

Mare Srbinovska[1], Cvetan Gavrovski[2], Vladimir Dimcev[3]

Abstract – **Location discovery or localization of nodes is one of the fundamental problems in distributed wireless sensor networks that form the basis for many location-aware applications. The main goal of localization procedures is to deduce, as accurately as possible, the location of a node from the partial information obtained from a set of nodes, which already know their location. In this paper the localization system estimates the distance between sensor nodes by measuring the RSSI (received signal strength indicator) at an appropriate number of sensor nodes.**

Keywords – **Localization system, Wireless sensor networks, RSSI, sensor nodes**

I. INTRODUCTION

Wireless sensor networks (WSNs) are networks of tiny, battery powered sensor nodes with limited on-board processing, storage and radio capabilities.

Wireless sensor networks can monitor large areas and be applied in a variety of fields, such as monitoring the environment, air, water and soil. Sensor networks can also offer sensing data for different applications that adapt to the user's circumstances in a ubiquitous computing environment. If appropriately designed, sensor nodes can work autonomously to measure temperature, humidity, pressure, and so on. In the future, sensors will be cheaper and deployed everywhere, thus, user-location-dependent services and sensor locations will become more important.

In sensor networks, nodes are deployed into an unplanned infrastructure where there is no a priori knowledge of location. The problem of estimating spatial – coordinates of the node is referred as localization. The main practical objective is to locate each node as accurately as possible with a given information with a certain amount of error about the distances between a subset of nodes [8] in wireless sensor networks. To identify the coordinates of sensor nodes (also called unknown nodes) requires measuring a distance e.g., measuring time of arrival (ToA) or time difference of arrival (TdoA). Difficulties concerning time measurement result from synchronization of involved devices as well as the high mathematical effort to calculate the position.

The measurement of the received signal strength (RSS) offers a possibility to determine distance with minimal effort.

The reminder of this paper is organized as follows: section II gives basic solutions of the possible localization techniques, III and IV discusses the theoretical background and mathematical basics of the model. The results are presented in section V, followed by the conclusion which closes this paper.

II. LOCALIZATION AND POSITIONING

For a node in wireless sensor network is useful or even necessary, to be aware of its location. This information is useful for tracking or detecting functions in wireless sensor networks. There are few basic methods how to solve this problem.

The basic solution is with integrating Global Positioning System (GPS) device in nodes. But, the fact that GPS does not work indoors, that power consumption reduces the life time of a node, which General Positioning System implies the cost factor and the fact that a GPS antenna increases the size of a node are simple examples to explain why GPS is not considered as a possible solution.

Other option is to define the coordinates of the nodes during the installation. This is a low cost, but unpractical solution, especially if the network is consisted of hundreds or thousands of nodes. In some cases, mobility of the nodes is required, so the initial topology becomes unuseful and new algorithms for determining the positions of the unknown nodes are necessary.

III. LOCALIZATION ALGORITHM FOR ESTIMATION OF DISTANCE

This method uses the proximity to an anchor to determine the localization or position of a node. This simple technique enhances increasing the number of anchors; using the proximity information of many overlapping anchors a node can approximate its position. When a node is in the proximity of another node it implies that there is a connection between them, so it helps in some uncertainties of the wireless channel.

The proximity information between nodes often helps to determine their geometric relationship. The distance between them or angle of a singular triangle can be easily estimated.

Once we measure the distances between an object and a number of beacons, we also need a way to combine the measurements to find the actual position. The most common methods to combine the distance measurements from three or more beacons are triangulation, simple trilateration and multilateration.

Triangulation is a method for finding the position of a node, when the angles are measured by Angle of Arrival technique.

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[1] Mare Srbinovska is with the Faculty of Electrical Engineering and Information Technologies, Karpos 2 bb, 1000 Skopje, R. Macedonia
E-mail:mares@feit.ukim.edu.mk

[2] Cvetan Gavrovski is with the Faculty of Electrical Engineering and Information Technologies, Karpos 2 bb, 1000 Skopje, R. Macedonia
E-mail:cvetang@feit.ukim.edu.mk

[3] Vladimir Dimcev is with the Faculty of Electrical Engineering and Information Technologies, Karpos 2 bb, 1000 Skopje, R. Macedonia
E-mail:vladim@feit.ukim.edu.mk

An example of such a procedure is shown in Figure 1.a. The object X measures its angles with respect to the beacons A1, A2 and A3. The measured angles form three straight lines along the directions XA1, XA2 and XA3. The intersection between the three lines defines the location of the node X. The accuracy of this technique is heavily dependent upon the accuracy of the employed angle measurement technique.

Simple trilateration is used when we have an accurate estimate of distances between a node and at least three beacon nodes. This simple method finds the intersection of three circles centered at beacons as the position of the node. The scenario is shown in Figure 1.b.

Multilateration is accepted as the most appropriate way to determine the location of a sensor node based on locations of beacons. An example is shown in Figure 1.c, where the nodes A1, A2, A3, and A4 are beacons, with known estimates of their locations, while the node X estimates its location using a multilateration procedure. The procedure attempts to estimate the position of a node by minimizing the error and discrepancies between the measured values.

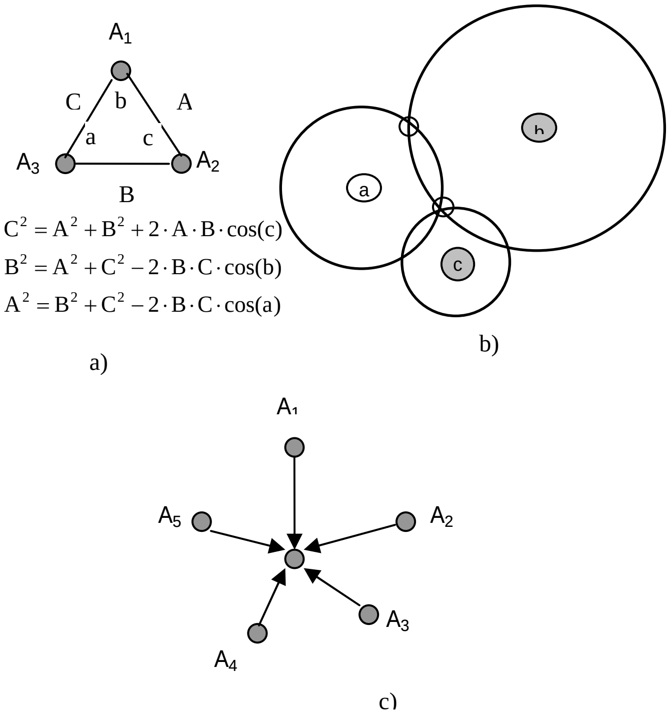


Figure 1. Localization Basics a) Triangulation
b) Trilateration c) Multilateration

This ranging process ideally leverages the facilities already present on a wireless node, in particular, the radio communication device. The characteristics of wireless communication are partially determined by the distance between sender and receiver, and if these characteristics can be measured at the receiver they can serve as an estimator of distance. The most important characteristics are Received Signal Strength Indicator (RSSI), Time of Arrival (ToA), and Time Difference of Arrival (TdoA).

III. 1 RECEIVED SIGNAL STRENGTH INDICATOR (RSSI)

One possibility to acquire a distance is measuring the received signal strength of the incoming radio signal. The idea behind RSS is that the configured transmission power at the transmitting device (P_T) directly affects the receiving power at the receiving device (P_R). The relationship between RSS and transmitter-receiver (T-R) distance is described as a propagation model.

According to Friis' free space transmission equation, the detected signal strength decreases with factor n (n is usually two) with the distance to the sender.

$$P_R = P_T \cdot G_T \cdot G_R \cdot \left(\frac{\lambda}{4\pi}\right)^2 \cdot \left(\frac{1}{d}\right)^n \qquad (1)$$

P_T and P_R are the power of the transmitter and receiver, G_T and G_R are the gains of the transmitter and receiver antennas respectively. The path loss exponent describes the influence of the transmission medium. In free space, the path loss exponent is theoretically two, which describes the equal power distribution from an isotropic radiator on the surface of a sphere.

In embedded devices, the received signal strength indicator (RSSI) is defined as ratio of the received power to the reference power. Typically, the reference is $P_{Ref} = 1\text{mW}$.

$$\text{RSSI} = 10 \cdot n(\log_{10} d) + A \quad [\text{RSSI}] = \text{dBm} \qquad (2)$$

A is received signal strength at a distance of 1 meter, n is the propagation path-loss exponent, d is the distance between the transmitting and receiving node.

In practical scenarios, the ideal distribution of P_R is not applicable, because the propagation of the radio signal is interfered with a lot of influencing effects e.g.

- Reflections of metallic objects
- Superposition of electro-magnetic fields
- Diffraction at edges

III. 2 TIME OF ARRIVAL (TOA)

When the speed of propagation in a medium is known, the distance can be estimated, using the transmission time. Receiver and sender must be synchronized to calculate the time of arrival of a transmission at the receiver. There is always a need of at least three anchors to determine the location of unknown node correctly.

To produce acceptable accuracy depending on the transmission medium, this technique requires high resolution clocks.

The sound speed propagation depends on external factors (temperature and humidity), therefore a careful and unobvious calibration is needed. Generally, the fact that the receiver and the sender must be synchronized are the disadvantages of this technique.

III. 3 TIME DIFFERENCE OF ARRIVAL (TDoA)

The problem of ToA is the fact that the receiver and the sender must be synchronized. TDoA uses two transmissions mediums of different propagation speeds to generate and implicit synchronization.

The sender spread simultaneously two signals with different propagation speeds. Obviously, one of these signals arrives first at the receiver. This first signal is used to measure the time of arrival of the second one. In this way, the propagation time of the first signal is ignored.

This method uses two types of sender and receivers on each node and this is an obvious disadvantage of TDoA.

IV. MATHEMATICAL BASICS OF THE LATERATION PROBLEM

Multilateration [5] is one of the most popular techniques for positioning applied in WSNs. Let us assume that there are three anchors with known positions (x_i,y_i), i=1,2,3, a node at unknown position (x_u,y_u), and perfect distance values d_i, i=1,2,3. From the Pythagoras theorem, follows:

$$(x_i - x_u)^2 + (y_i - y_u)^2 = d_i^2 \quad i = 1,2,3 \tag{3}$$

To solve this set of equations, it is more convenient to write it as a set of linear equations in x_u and y_u:

$$2 \cdot \begin{bmatrix} x_3 - x_1 & y_3 - y_1 \\ x_3 - x_2 & y_3 - y_2 \end{bmatrix} \cdot \begin{bmatrix} x_u \\ y_u \end{bmatrix} =$$

$$\begin{bmatrix} \left(d_1^2 - d_3^2\right) - \left(x_1^2 - x_3^2\right) - \left(y_1^2 - y_3^2\right) \\ \left(d_2^2 - d_3^3\right) - \left(x_2^2 - x_3^2\right) - \left(y_2^2 - y_3^2\right) \end{bmatrix} \tag{4}$$

The real challenge for triangulation arises when the distance measurements are not perfect, but only estimates $\tilde{r}$ with an unknown error ε are known. The intuitive solution [7] to this problem is to use more than three anchors and redundant distant measurements to account into an overdetermined system of equations, written in matrix form:

$$2 \cdot \begin{bmatrix} x_n - x_1 & y_n - y_1 \\ \vdots & \vdots \\ x_n - x_{n-1} & y_n - y_{n-1} \end{bmatrix} \cdot \begin{bmatrix} x_u \\ y_u \end{bmatrix} =$$

$$\begin{bmatrix} \left(d_1^2 - d_n^2\right) - \left(x_1^2 - x_n^2\right) - \left(y_1^2 - y_n^2\right) \\ \vdots \\ \left(d_{n-1}^2 - d_n^2\right) - \left(x_{n-1}^2 - x_n^2\right) - \left(y_{n-1}^2 - y_n^2\right) \end{bmatrix} \tag{5}$$

For such an overdetermined system of linear equation, a solution can be computed that minimizes the mean square error, that is, the solution is the pair $\left(x_u, y_u\right)$ that minimizes $\left\| \mathrm{Ax} - \mathrm{b} \right\|_2$, where 0.5A is the left-hand matrix, $x = \left(x_u, y_u\right)$ a shorthand for the vector describing the unknown position, and b the right-hand side from equation (5). Minimizing this expression is equivalent to minimizing the mean square error. As a function of x, its gradient has to be set to zero:

$$\mathrm{A}^{\mathrm{T}}\mathrm{Ax} = \mathrm{A}^{\mathrm{T}}\mathrm{b} \tag{6}$$

Equation (6) has a unique solution under certain conditions.

V. EXPERIMENTAL RESULTS

In order to create an experimental setup for a ZigBee network, 2.4GHz 802.15.4 development kit belonging to the Silicon Laboratories is used. The board is shown in Fig. 2.

Each board features a silicon laboratories C8051F121 microcontroller and a Chipcon CC2420 [6] 2.4 GHz 802.15.4 transceiver. Support components include a USB interface, JTAG programming interface, a variety of pushbuttons and LED's and a voltage regulator. The data transfer rate goes up to 250kBps, the radiation power is 1mW (low power version) or 40mW (high power version).

Fig. 2 Sensor node

We conducted an experiment to investigate the relationship between the measured RSSI and the distance between nodes. All of these measurements were performed in a free space at the area near the Department of metrology at AGH University in Krakow, Poland, on a sunny day to minimize the interferences.

In order to estimate the RSS-to-distance curve a set of sensor nodes has been positioned as in Fig.3.

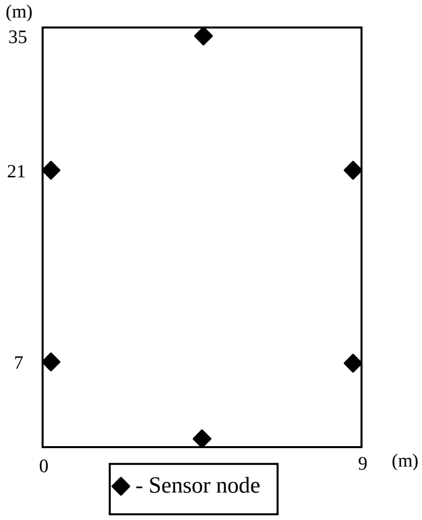


Fig. 3 Positions of sensor nodes in free space

RSSI – based ranging methods require the knowledge of the RSS-to-distance curve as follows:

$$d = 10^{\left[\frac{RSSI-A}{10n}\right]} \tag{7}$$

Where d denotes the transmitter-to-receiver distance, n is the propagation path-loss exponent, A represents the RSS value measured by a receiver that is located 1m away from a transmitter, and RSS is the actual measured value at distance d. The RSS-to-distance reference curve in (7) is obtained via a least-square linear fitting from several RSS measured values (approximately 1200 RSSI values are collected). The obtained result is shown in Fig.4 along with real measurements. Note that in Fig. 4 i) the RSS values are represented in dBm as provided by the receiver nodes, ii) the distance d in x-axis is normalized to the reference distance of 1m, and iii) the fitting parameters are A=-77.26 and n-=1.7346. Obtained result for the path-loss exponent compared to the theoretical value (n=2) is due to the fact that receiver nodes are located very closed to huge buildings, which provides constructive reflected propagation path in addition to the direct one.

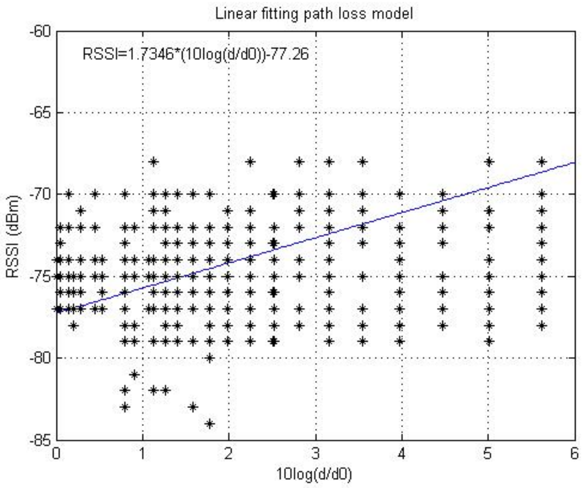
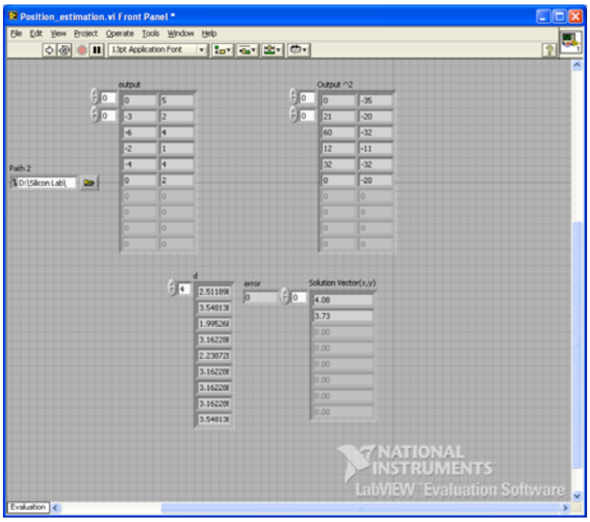


Fig. 4 RSS-to-distance model



output

0	5
-3	2
-6	4
-2	1
-4	4
0	2
0	0
0	0
0	0
0	0

Output ^2

0	-35
21	-20
60	-32
12	-11
32	-32
0	-20
0	0
0	0
0	0
0	0

d: 4
2.51189
3.54813
1.99526
3.16228
2.23872
3.16228
3.16228
3.16228
3.54813

error: 0

Solution Vector(x,y): 0
4.00
3.73
0.00
0.00
0.00
0.00
0.00
0.00

Fig. 5 Front panel of the estimated distance

The algorithm (Fig.5) for estimating the distances is entirely developed using programming language Labview [1]. We used the multilateration technique for positioning the nodes in Wireless Sensor Networks. The mathematical approach was explained in section IV.

Although the positioning algorithm does not yet provide the desired results very exactly, the presented algorithm in combination with Zigbee offers lots of advantages. The most important advantage is the simplified implementation process due to already defined fundamental functions within the provided protocol suite of Zigbee.

VI. CONCLUSION

Wireless sensor networks are widely applicable to many practical applications including environmental monitoring, military applications, etc. in which sensors may need to know their geographical locations. This paper has summarized theoretical and practical facts concerning the analysis of RSSI measurements. The algorithm for positioning the nodes and its realization is illustrated. Localization system that uses RSSI in a sensor network based on the Zigbee standard is implemented. The distance measurement accuracy of our technique through actual experimental results is evaluated. The positions of the nodes using the Labview software were estimated.

. REFERENCES

[1] M.Srbinovska, C. Gavrovski, V.Dimcev, “Localization System using RSSI Measurement of Wireless Sensor Network based on Zigbee Standard”, XLIII International Scientific Conference ICEST, Nis, 2008

[2] Shashank Tadakamadla, “Indoor Local Positioning System for Zigbee based on RSSI”, Mid Sweden University, 2005

[3] Dimitrios Lymberopoulos, Quentin Lindsey and Andreas Savvides, “An Empirical Characterization of Radio Signal Strength Variability in 3-D IEEE 802.15.4 Networks using Monopole Antennas, Yale University, New Haven, USA, 2005

[4] Marina Petrova, Janne Ruhijärvi, Petri Mähönen and Saverio Labella, “Performance Study of IEEE 802.15.4 Using Measurements and Simulations”, RWTH Aachen University, Germany, 2004.

[5] Holger Karl and Andreas Willig, “Protocols and Architectures for Wireless Sensor Networks”, John Wiley & Sons, 2005

[6] Datasheet for chipcon CC2420 2.4 GHz IEEE 802.15.4/ZigBee RF Transceiver

[7] E. Callaway, P. Gorday, L. Hester, J. A. Gutierrez, M. Naeve, B. Heile, and V. Bahl, “Home Networking with IEEE 802.15.4: A Developing Standard for Low-Rate Wireless Personal Area Networks,” *IEEE Communications Magazine*, vol. 40, no. 8, pp. 70–77, August 2002.

[8] Jason Lester Hill, “System Architecture for Wireless Sensor Networks”, PhD Thesis, University of California, Berkeley, 2003

[9] Kazem Sohraby, Daniel Minoli, Taieb Znati, “Wireless Sensor Networks: Technology, Protocols and Applications, 2007