RSSI-Based Localization in Low-cost 2.4GHz Wireless Networks

Sorin Dincă*
Dan Ştefan Tudose†
Faculty of Computer Science and Computer Engineering
Polytechnic University of Bucharest
Bucharest, Romania
Email: *sorin.dinca@cti-pub.ro, †dan.tudose@cs.pub.ro

***Abstract*—Wireless Sensor Networks (WSNs) is a technology which is increasingly implemented in a multitude of data acquisition, data processing, and control applications. Node localization in such networks is one of the topics which is currently intensely researched. The solution proposed in this paper is based on measuring the radio waves propagation from the emitter to the receiver. A new approach will be presented, an approach oriented on respecting the requirements of a low cost network like the low energy consumption, low processing power and the lack of specialized hardware.**

Keywords*—*RSSI, Wireless Sensor Networks, Positioning

I. Introduction

Wireless sensor networks are characterized by severe limitations due to requirements such as low-cost design, low energy consumption and small dimensions. In the future, minimizing the cost and size of the nodes will lead to extended and scalable networks used in various applications, many of them location-aware.

Because of these limitations traditional localization methods like GPS or assigning each node a fixed position are almost impossible to use. Efficient, power-aware algorithms and appropriate hardware need to be developed in order to obtain satisfactory results.

Based on a number of theoretical localization methods, the goal of this paper is to present an application that takes into account the above requirements and offers localization services to a low-cost wireless sensor network.

A scalable and robust solution, based on RSSI measurement, implemented on a 2.4GHz network will be described. The solution will be implemented with minimum hardware and computation requirements, only the radio module of the sensor being needed.

II. A State of the Art in Wireless Sensor Network Localization

Localization is a relatively new research topic and only particular, platform-specific solutions have been developed. These solutions work well on one kind of network but they are difficult to adapt to another network, thus the need of developing a more general method, even though it will not provide results as accurate as the particular ones.

As presented in [1], localization techniques can be anchor based or anchor free, radio wave based, centralized or distributed.

Research in this area began around the year 2000, when American laws imposed the mobile operators to offer a tracking service for emergency calls, with an error less than 125 meters. When wireless sensor networks appeared, research results from mobile phones migrated to wireless sensor networks [2].

To the best of our knowledge, no general solution based only on the node's basic hardware has been fully developed.

III. Theoretical Principles in Localization

The following principles are presented considering a network with two kinds of nodes: anchor nodes and regular nodes. In this architecture, only anchors are aware of their global coordinates. The final goal is to obtain the spatial coordinates of each node in the network.

As shown in [3], obtaining the exact coordinates of a node implies three major steps:

- Estimating the distances between the node and its neighbors that are anchors
- Calculating node's position in respect with a global coordinate
- Refining the coordinate using results from other nodes.

A. Distance Estimation

This step depends heavily on the features available on the platform such as the node's hardware. The survey in [4] suggests the following methods:

- Angle of arrival: if the hardware provides two antennas with different orientation, by measuring the phase difference between the signals received by the antennas, the distance to the emitter can be inferred [5].
- Time Difference of Arrival: If the emitter can send two signals that have different propagation speeds, the receiver will measure the time difference between the arrival of the faster and slower signals and will deduce the distance.[6]

- Distance Related Measurements: Location dependent parameters are measured from the received signal and the distance is deduced from the level of these parameters.

In this paper, distances between nodes will be estimated with a Distance Related method which uses RSSI as a distance dependent parameter. RSSI (Relative Signal Strength Index) measures the attenuation of the received signal, usually in decibels. Knowing the electromagnetic waves attenuation law (known as Friis equation [7]), the emission power of the signal and its attenuation, the distance between the emitter and the receiver can be estimated.

Since the results obtained are only estimations, we will attempt to enhance them with empirical rules which aid in finding the most accurate form of *f(RSSI) = d* function.

B. Position Calculation

Based on the distances obtained at the first step, mathematical algorithms are applied for obtaining the node's global coordinates. Trilateration and multilateration are suitable for distance related measurements, because they involve lengths not angles.

Trilateration uses circle geometry to calculate a node's position from three other known locations (fixed nodes). Using circle geometry, coordinates of the unknown point are calculated. Ideally, three points are enough to find the exact (x,y) coordinates of a node, but considering that distances measured with RSSI method are not 100% accurate, more points will be needed in order to obtain low error rates in the calculated position. Ideally, the intersection of the three circles will be a point, but because of errors, the intersection will be a zone, as illustrated in Figure **??**.

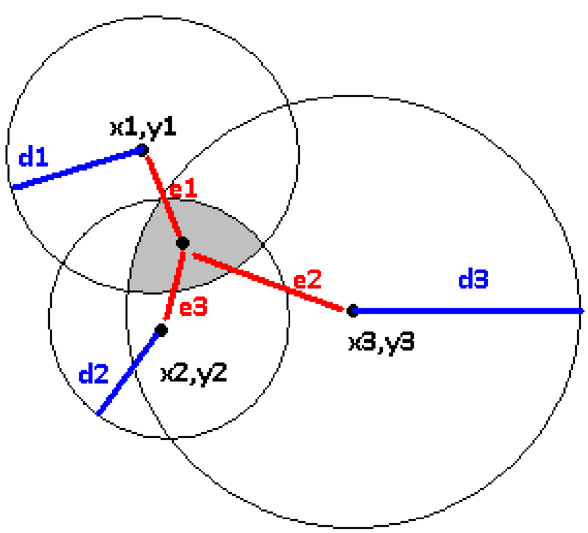

Fig. 1. Trilateration with errors at input.

Multilateration is the extended version of trilateration, using as many anchors as available. By solving a simple system of equations, the coordinates of the unknown node will be provided.

Multilateration equations are presented below:

$$(x_1 - x)^2 + (y_1 - y)^2 = d_1^2 \tag{1}$$

$$\dots$$

$$(x_n - x)^2 + (y_n - y)^2 = d_n^2 \tag{2}$$

where $x_1 ... x_n$, $y_1 ... y_n$ are anchors' coordinates; $d_1 ... d_n$ are the distances measured from the first step and *(x,y)* are the coordinates to be calculated.

This system is re-written in matrix form:

$$A = \begin{bmatrix} 2(x_1 - x_n) & 2(y_1 - y_n) \\ \dots & \dots \\ 2(x_{n-1} - x_n) & 2(y_{n-1} - y_n) \end{bmatrix} \tag{3}$$

$$B = \begin{bmatrix} x_1^2 - x_n^2 + y_1^2 - y_n^2 + d_n^2 - d_1^2 \\ \dots \\ x_{n-1}^2 - x_n^2 + y_{n-1}^2 - y_n^2 + d_{n-1}^2 - d_n^2 \end{bmatrix} \tag{4}$$

And the solution is: $X = (A^T A)^{-1} A^T B$, where $X=(x,y)$

IV. Application Architecture

To prove that RSSI method is implementable in a low cost wireless sensor network it needs to be tested with the appropriate hardware. A 2.4GHz network that respects 802.15.4 standard has been chosen. Its characteristics are low power consumption and low processing capabilities so the localization application should be adapted to these constraints. In most of the applications the user needs to know a node's position, not the node itself, so in this example the final results will be computed on the user application, not directly on the node. This saves a great amount of processing power at the sensor's level.

A. Hardware Specifications of Sensor Nodes

Each node in the network is based on an 8-bit Atmel microcontroller, a transceiver and an on-chip antenna. This architecture offers reasonable performance at a low price. The radio module has a transmit power up to 3dBm and a receiver sensitivity up to -101dBm, which is suitable to test the RSSI localization method. RSSI is obtained by the transceiver with a resolution of 3dBm. The transceiver also computes the energy level for a received 802.15.4 frame, with a resolution of 1dBm. This level will be used instead of RSSI because of the better resolution.

The antenna is the critical part in obtaining accurate results. Depending on its parameters (gain, isotropy, orientation) the test restults will vary more or less from an ideal scenario. For example, applying the wave attenuation equation to the onboard antenna, a maximum range of 100 meters is obtained. In practice, however, accurate measurements were possible within a range of only 10 meters from each sensor node.

B. Application Software

As a support for our application we used a network stack called RUM (Route Under MAC, [8]). It supports IPv6 and UDP communication with the outside world. UDP commands are sent to a node which composes the answer and returns it to the sender. At node level, the simplest and most power effective program is desired. Therefore, the node's functionality is only to send its measured radio parameters to an external application located on a computer. The computations needed to find the coordinates are executed by this external application. A graphical user interface is available to display the configuration of the network in the form of a map.

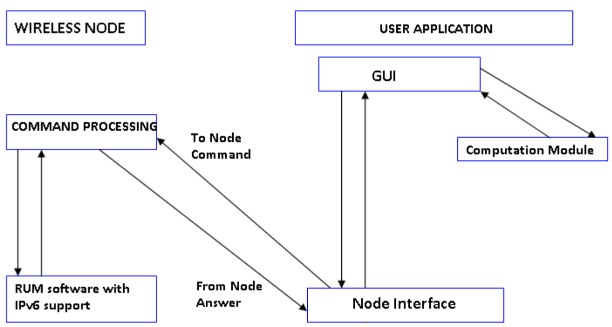

Fig. 2. Test application modules.

C. Principle of Operation

The software on the node is designed to answer commands coming from the user, via UDP packets. The available commands handle simple tasks such as gathering RSSI information, sending information back to the user, reset, etc.

When a node receives a command to gather neighbor information, it sends a number of broadcast packets to the network. A neighbor that receives a packet answers with an ACK packet. When receiving back an ACK packet, the node stores its associated RSSI value, in this form:$sender\_address, received\_packet\_rssi$. In this way, each node will form a list with all its neighbors. When the user wants to localize the node, it will request this list and do the localization if enough anchors are neighbors. The following pseudo code describes the way a node works:

```
while (TRUE)
    get_command();
    if (command == gather_info)
      send_broadcast();
      get_ACK();
      if (ACK_received)
        get_neighbor_address();
        get_RSSI();
      fi
    fi
    if (command == send_info)
      for each(address, RSSI) do
          send_to_user(address, RSSI);
      od
    fi
```

V. Experimental Results

Implementing and testing this localization method has been done in several distinct steps in order to obtain the best results:

- Testing each module's functionality: radio parameters of the node, interface between network and the user application.
- Adjusting the theoretical method with the practical conclusions.
- Evaluation of the entire application and analyzing the results.

A. Testing Radio Parameters and Adjusting the Method Used to Obtain the Distance Between Two Nodes

This step is very important in refining the results. The first measurements taken showed that only applying the theoretical formula was not enough. Large errors occured due to the varying radio environment conditions. For example, when measuring a RSSI level that corresponded to a distance of 20 meters the actual distance between two nodes was only 2 meters.

Also, when changing the orientation of the nodes but with the same distance between them, the results differed. This is mostly due to signal loss, interference with other WiFi and Bluetooth networks that were present on the test site and the deficiencies in omnidirectionality of the small chip antennas on the sensor nodes.

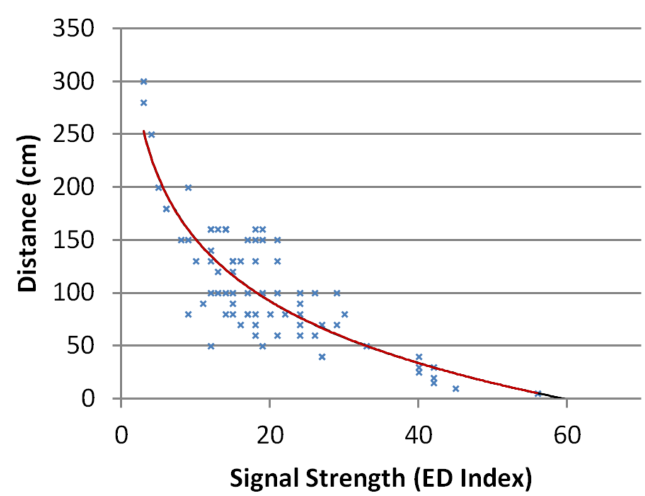

Fig. 3. Measured signal power variation with distance between nodes.

It became apparent that a semi-empirical method would yield less erors in estimating the distance than a more conventional approach. After a series of measurements of the received signal strength versus distance, a final form for the *f(Signal Strength) = distance* function was developed.

As shown in Figure 3, this function is not continuous so the errors still remain. In the range of 50-150 centimeters a great dispersion of the results is observed. Because of this, a variation in the received signal will not mean all the times a variation in the distance.

B. Test Scenarios

After testing the radio parameters, several test scenarios needed to be developed in order to understand the behavior of the localization method in different environments and with different topologies.

The following scenarios were taken into consideration:

- Indoor placement, sensors placed in line of sight one with each other, five anchors
- Indoor placement, sensors not necessarily in line of sight, variable number of anchors
- Outdoor placement, line of sight, greater distance between nodes.

For each scenario, the unknown nodes were placed in different positions, inside or outside the area formed by the anchors. Because of the low transmission powers, the maximum distance between nodes has been 10 meters in indoor scenarios and 25 meters in outdoor scenarios. Only flat surfaces have been considered, meaning the z coordinates of all nodes were equal. The method can be adapted without difficulties to obtain the (x,y,z) global coordinates for a node.

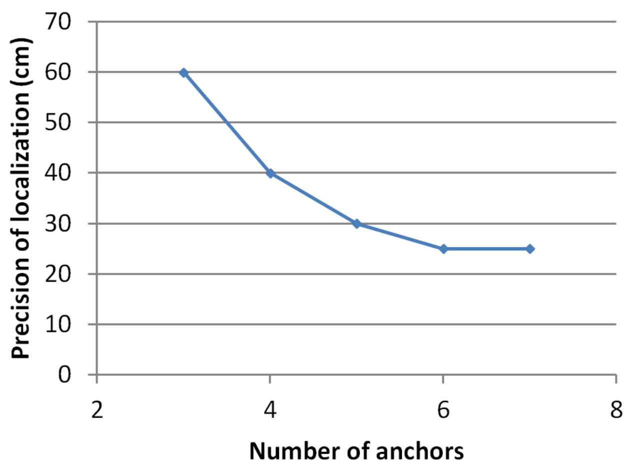

Fig. 4. Measured precision variation with the number of used anchors.

C. Result Analysis

After functional tests on each module of the application, the results were analyzed. The purpose was to check that the theoretical localization methods presented above can be used in practice. The results were dependent on the factors presented above and also on the environment where the sensor network was placed.

For each scenario and for each position of an unknown node in the network, a maximum error of 30-40 centimeters was obtained. This is a precision of approximately 90%, a good value considering that exact precision is not the main criteria in this kind of applications. The most favorable case is when a node is positioned in the area formed by the anchors, in line of sight with each of it.

We determined that the closer the nodes are, the lesser the errors. The most unfavorable case is when the node is not in the area formed by the anchors. Line of sight is an important error factor due to the way radio waves are propagating. Reflections that attenuate the signal appear between non line of sight nodes.

The most important factors that influence precision are:

- The number of anchors
- The number of anchors in line of sight
- Antenna isotropy
- Spatial configuration of the network.

The influence of these factors can be observed from the graphs below. Egregious errors appeared in all test scenarios. Their rate was significant, but decreased to a manageable level when utilizing multiple anchors, as observed in Figure 5. When localizing with more than 5 anchors, egregious errors tended to stabilize at 10% of all the tests.

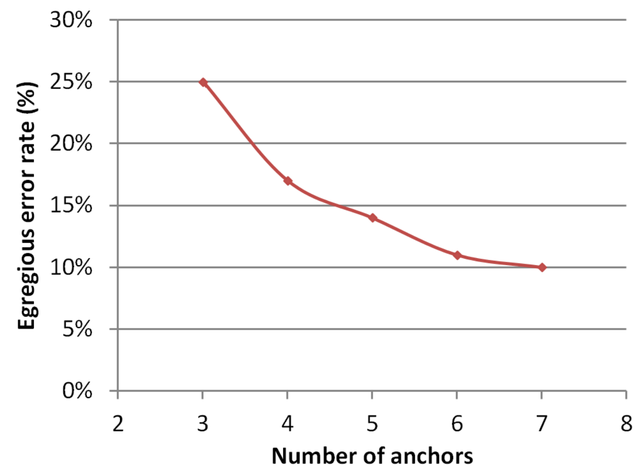

Fig. 5. Egregious error rate variation with the number of anchors.

As seen in Figure 6, non line of sight nodes are an important error source. This is due to the signal being affected by reflections and distortions that alter its strength.

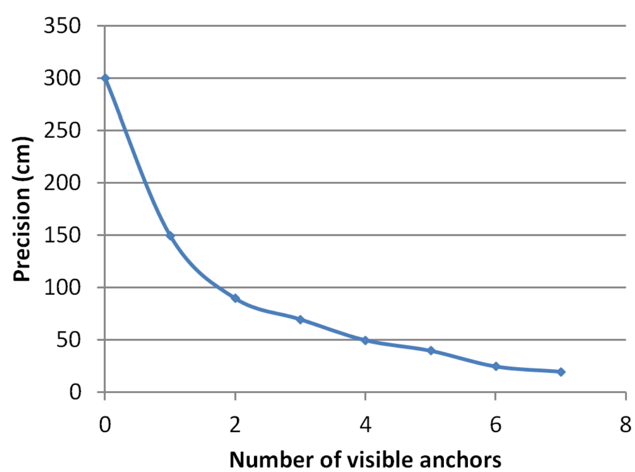

Fig. 6. Influence of line of sight anchors in the precision.

VI. Conclusions and Future Work

The needs of positioning a node in a wireless sensor network lead to searching for a robust and generic method to solve this problem. The localization method presented above proved to be an optimal solution in case an exact precision is not needed. Its advantages are that it can be implemented in any kind of network, not needing to install additional hardware.

In this paper we described an application that runs over a wireless sensor network and allows an external user to localize a node in this network. Unlike the hardware-dependent methods proposed by other authors this one offers greater applicability with the cost of a lower precision. The low power consumption requirements have been reached by moving the localization computations on the user's computer. Although RSSI is a very noisy indicator, it was demonstrated that with careful empirical estimations it can be successfully used in estimating distances between nodes.

After evaluating the application, several methods of improvement have been discovered. The main defficiency of this implementation was the node hardware, especially the radio circuitry which, due to its low cost, was unable to perform accurately. Node antennas presented a large grade of anisotropy, seriously disturbing the accuracy of the localization. Because of the small gain of the antennas, the real distances possible to measure were far smaller than the ideal ones.

The first improvement is replacing the antenna on the nodes with a better one, much closer to the ideal isotropic model. The costs are not large comparing to the increase in performance obtained.

Estimating the distances between nodes with RSSI is an indirect method that leads to errors. Another method can be used but the hardware must be changed.

This application can be considered as a base for other, more precise ones. The obtained results are above expectations, the reached performances allowing the use of this method in many industrial or research low cost wireless sensor networks.

VII. Acknowledgements

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