Experimental Validation of Wireless Localization Techniques in IEEE802.15.4 Networks

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Abstract: **Localization techniques in Wireless Sensor Networks are attractive for a large set applications in which the data recorded from a device must be correlated to the exact position of the node, i.e. temperature monitoring by means of sensor devices in a wide area deployment.**

In recent years various localization techniques for IEEE802.15.4 based networks have been proposed by the research community, and their performance mainly evaluated by means of simulation studies. In this work we mainly focus on the performance evaluation of state-of-the-art localization algorithms in real testbeds. Moreover, we propose and measure the performance of a new algorithm based on the Received Signal Strength Indicator, developed for nodes localization in case of static networks.

1. INTRODUCTION

Wireless Sensor Networks (WSNs) have been developed during the years with the main goal of creating smart ambient by sampling information from the environment and in turn processing, analyzing, and diffusing data whenever required. A large number of WSNs applications are based on localization techniques, set up to create location-aware services [1, 2, 3]. In such kind of applications a random deployment of the sensor nodes is often used and sometimes required. As a result, the position of these nodes is not predetermined, thus requiring nodes collaboration in order to determine their location. This is for example the case in which sensor devices are deployed in a wide area to monitor the temperature and where the data recorded from a device make sense only if they are correlated to the exact position of the node.

The most effective technology used nowadays to determine the location of both people and devices is the Global Positioning System (GPS). However, in a WSNs scenario this kind of technology can not be successfully adopted for two main reasons. The first one refers to the strong limitations of the GPS in the indoor scenario, which is affected by heavy signal attenuation who make impossible to perform the localization step. The second one is related to the GPS equipments, which require both hardware space and energy, two big limiting factors for an integration in miniaturized sensor boards. To overcome GPS limitations several alternative or complementary localization methods have been proposed during the years, and their performance evaluated by means of simulation studies. In this work we mainly focus on the performance evaluation of state-of-the-art localization algorithms (Received Signal Strength Indicator [4] based algorithm and Monte Carlo Boxed [5] algorithm) in real testbeds, in order to identify criticalities in the localization process. Moreover, we propose and evaluate the performance of a new algorithm based on the Received Signal Strength Indicator (RSSI), the RSSI-assisted algorithm, which aims to correct the received RSSI value taking advantages of the known position of both anchor and coordinator devices.

The rest of the paper is organized as follows: Section 2 presents an overview of the localization techniques developed for static and mobile WSNs. Section 3 details the software platforms used to develop the different algorithms. Experimental results based on real indoor experiments are discussed in Section 4. Section 5 concludes the paper.

2. LOCALIZATION TECHNIQUES OVERVIEW

WSNs localization techniques can be categorized as centralized [6, 7] or distributed [8, 9, 10]. Centralized techniques require the use of a central node for computing the position of the nodes. This kind of technology is affected by two main drawbacks: high communication cost and high response delay due to the intensive computation performed by the central node. On the contrary, distributed algorithms spread the computational load within the network thus decreasing computation delay [7]. Distributed techniques are the most suitable in WSNs scenario in which applications are distributed in order to share the computational and communication load.

Range-based [11, 12, 13] and range-free [14, 15, 16] techniques present another classification of localization algorithms suitable for WSNs. The former estimates the distance between two neighboring nodes, thus requiring additional hardware to execute the localization task. Range-based techniques are mostly based on the Received Signal Strength Indicator (RSSI) [4] or Time of Arrival (ToA) [17] of signals, while others depend on more expensive technologies such as the Angle of Arrival (AoA) [17], and Time Difference of Arrival (TDoA) [18]. Range-free techniques do not estimate the absolute point-to-point distance, thus resulting to be very appealing and cost-effective solution for localization in WSNs. The key idea of range-free methods is based on the transmission in broadcast of an answer request, followed by the processing of the answers coming from location aware devices identified as anchors. Amorphous localization [19], Centroid localization [14], APIT [20], Multi-Hop, Monte Carlo Localization (MCL) [21], are some examples of range-free localization techniques. A new approach, developed in [21], is based on probability and prediction, having exploited additional information from the mobility of the nodes. In range-based techniques three schemes are possible: static nodes - moving anchors, moving nodes - static anchors, or both moving. This approach was improved by Baggio et al. using Monte Carlo Boxed (MCB) localization [5].

The aforementioned works (except MCL and MCB) assume a static networks. However, the problem of mobility is gaining interest in the WSNs scenario. Recently, researchers propose algorithms to support the mobility of both anchors and normal nodes: these methods are based on probabilistic approach, and the most successful ones are based on the filtering idea. For instance, MCL proposed by Hu et al., based on the Sequential Monte Carlo method is a range-free localization technique supporting nodes mobility. MCL represents the posterior distribution of possible positions using a set of weighted samples and uses the Monte Carlo method for sampling, filtering and estimating nodes position. MCL technique uses anchor information only in the filtering step, thus making the task of drawing samples massive and long, i.e. energy inefficient. MCB is similar to MCL but leveraging on the idea of optimizing energy consumption: in fact it uses the anchor information to constrain the area from which the samples are drawn in the prediction stage. As a result less samples are rejected by the filtering process, consequently reducing energy consumption.

3. ALGORITHM IMPLEMENTATION

In this Section we first present the software tools used to implement the different localization algorithms, then we detail the algorithms implementation with the adopted equations.

3.1 Software

3.1.1 Erika OS

All the algorithms have been developed as concurrent tasks running in the Embedded Real tIme Kernel Architecture operating system (ERIKA OS) [22]. ERIKA is an innovative real time operating system for small microcontrollers based on Application Programming Interfaces (APIs) similar to those proposed by the OSEK/VDX Consortium. The ERIKA kernel implements innovative scheduling algorithms such as fixed priority with preemption thresholds, stack resource policy, earliest deadline first, and resource reservations which can be used to schedule tasks with real-time requirements.

3.1.2 μWireless Stack

In ERIKA all the wireless communications based on the IEEE802.15.4 standard are demanded to the μWireless network stack. μWireless uses an OS-independent architecture to implement the main features of the IEEE802.15.4 MAC protocol. The current implementation of μWireless supports: beacon transmission at every beacon order; coordinator/end-device time synchronization; data transmission and reception in slotted mode including guaranteed time slot allocation and transmission. The stack currently works with ERIKA OS on the Microchip dsPIC and the Atmel Atmega128 microcontrollers. The supported radio transceivers are the CC2420 and the MRF24J40.

3.2 RSSI and RSSI-Assisted Algorithms

RSSI based algorithms perform the node localization procedure starting from the Received Signal Strength (RSS) of a localization message sent through the network. In the first step of the algorithm the localization message is sent in broadcast by the target node and received by a set of location-aware devices (anchors) that extract the RSS Indicator (RSSI) value and send the joint information RSSI-own position to the network coordinator (sink node). The second step of the algorithm is done by the coordinator, calculating the position of the target node based on distance estimation, as soon as all the anchors send the RSSI values. The received signal strength is used to measure the distance between the sender and the receiver starting from the Friis' equation [23], reported in the following in case of indoor transmission (our main target in the performance evaluation section):

$$P_R = P_T \cdot G_T \cdot G_R \cdot (\lambda/(4\cdot\pi))^2 \cdot (1/d)^n \tag{1}$$

In Equation (1) the P_R and P_T are the power of the transmitter and receiver; the G_T and G_R are the gains of the transmitter and receiver antennas; λ is the wavelength; d is the distance between transmitter and receiver; n depends on the transmission space (is in the range from 3 to 5 in an indoor scenario). The unknown variables in Equation (1) are the distance d, which we want to determine, and the received power; using the RSSI definition in Equation (2) and its value extracted from the relative incoming packet field, we can determine the received power at the receiver side.

$$RSSI = 10 \cdot \log_{10}(P_R/P_T) \tag{2}$$

Once all the distance values are extracted (one for each anchor), the multilateration [24] algorithm is used to determine the position of the target node. The multilateration algorithm working procedure is explained in the following. Lets assume 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 $d_i, i = 1, 2, 3$. The distance between the node and each anchor is:

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

The resulting set of equations can be easily solved writing them as a system of linear equations in x_u and y_u.

3.2.1 RSSI-Assisted Algorithm Overview

In case of indoor communications the RSSI value received by each anchor is heavily affected by multipath interference and obstacles, thus resulting in large errors in the position estimation. In order to compensate propagation fluctuation of the signal we developed a modified version of the previous algorithm, called RSSI-Assisted.

The main idea behind the proposed algorithm is to add a verification step before estimating the distance between target and anchor devices. The goal of the verification step is to correct the RSSI value extracted by the anchor device making use of the communication between the anchor and the coordinator, where theoretically we can determine the exact RSSI, and then to use it to correct the RSSI value of the communication between the target node and the anchor device. The RSSI-Assisted algorithm can be detailed as follows :

- The coordinator receives the packet from an anchor device, containing the RSSI value of the communication between the anchor node and the target device.
- The coordinator establishes the procedure to calculate the exact RSSI value between itself and the anchor using Equations (1) and (2).
- The coordinator evaluates a correction factor for the RSSI related to the communication between target and anchor.
- Finally the target position is evaluated using the corrected RSSI values in Equations (1) and (2).

3.3 Monte Carlo Boxed Localization MCB

In recent years researcher attentions moved from static WSNs to Mobile Wireless Sensor Network (MWSN). In such a scenario a possible algorithm for estimating the node position is the Monte Carlo Boxed. In MCB algorithm we take advantage of the anchors heard to build an anchor box where the set of samples must be drawn. In other words, this box is the region of the deployment area where the node is localized; such box does not exist in MCL where most of the samples are afterward rejected at the filtering step.

Reducing the node deployment area by building an anchor box has two sequences. First we draw samples more easily and thus faster. Drawing good samples means that we have to reject samples less often in the filtering phase, reducing thereby the number of iterations the algorithm needs to fill the sample set entirely. The second consequence is implementation dependent. The implementation of MCL sets a bound on the number of times a node can try to draw samples if its sample set does not contain the required number of samples yet. This results in avoiding that the algorithm loops endlessly if no valid sample can be drawn for a given configuration. In MCB, we make sure that the sample set is as full as possible by drawing samples that do not have to be filtered.

In MCB a node that has heard anchors - one-hop or two-hop anchors - builds a box that covers the region where the anchors radio ranges overlap. Once the anchor box is built, the prediction step of MCB algorithm is executed to draw samples within the anchor box, those samples are filtered depending on the distance between them and heard anchors.The prediction and filtering steps repeat until the sample set is full or until the maximum number of tries is reached.

4. SYSTEM DEPLOYMENT

In the following the hardware platform used in the experiments is presented prior to the performance analysis of the developed algorithms in real testbeds.

4.1 Hardware Platform

4.1.1 FLEX Board

The hardware adopted in our experiments is the FLEX Board (Base Board plus Demo Board) equipped with a MRF24J40MA transceiver, Figure 1. The FLEX Base Board is equipped with a Microchip dsPIC®-33F 16bit-microcontroller which operates at 40 MIPS and has 30 KB of internal RAM memory and 256 KB of flash memory. The board exports all the pins of the microcontroller in order to connect additional boards with different sensor devices, such as the FLEX Demo Board. The FLEX Demo Board is a daughter board suited for prototyping and laboratory experiments. The features hosted on the FLEX Demo Board are 2 DAC outputs, a 3-axis accelerometer , push buttons, LEDs, an LCD, a buzzer, a potentiometer, a thermal sensor, a light sensor, an InfraRed device, and a transceiver connector. The MRF24J40MA is a single chip IEEE802.15.4 compliant R/F transceiver operating in the 2.4 GHz band equipped with an omnidirectional antenna.

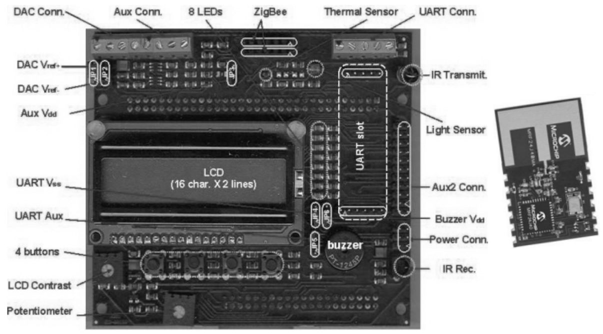

Figure 1: Flex Demo Board and MRF24J40MA transceiver.

4.2 Performance Evaluation

4.2.1 Stationary Node Localization

In the following, experimental results will be shown and discussed in order to compare the performance of both RSSI and RSSI-Assisted algorithms for various positions of the target node (Figure 2). All experiments have been performed in an indoor scenario, where three anchors plus the network coordinator have been installed in different known positions at a height of 1 m from the floor. In the room selected for the experiments (7m x 11m) the transceivers transmission power has been set as low as possible while guaranteeing a full coverage of the room surface.

In the experiments performed in Position 1, RSSI-Assisted gives an average error equal to 1.15 m, while the RSSI algorithm shows an average error equal to 6.45 m. Figure 3 shows how the estimation error is reduced using RSSI-Assisted, and

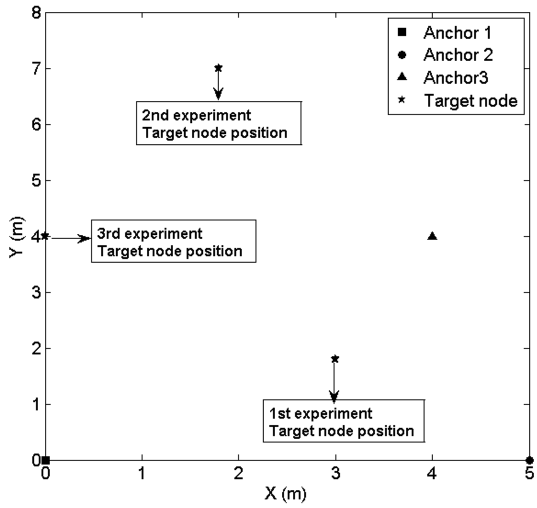

Figure 2: Experimental scenario for RSSI based algorithms.

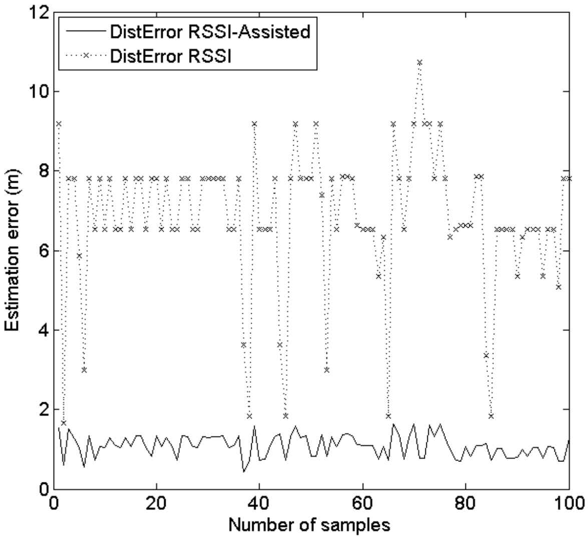

Figure 3: RSSI vs RSSI-Assisted for Position 1.

that the maximum error is less than 2 m, while using RSSI algorithm the maximum error goes up to 11 m. This improvement in error estimation is due to the modification introduced into the received RSSI value, showing the benefits of the proposed algorithm. The improvements of the RSSI-Assisted algorithm are confirmed also by the experiments performed in Positions 2 and 3. In Position 2 RSSI-Assisted gives an average error equal to 4.55 m while the RSSI algorithm shows an average error equal to 8.55 m. The behaviour of the estimation error is depicted in Figure 4. For the experiments performed in Position 3 the RSSI-Assisted error is equal to 1.33 m against the 4.29 m evaluated with the RSSI algorithm. The estimation error for this experiment is depicted in Figure 5. Table 1 summarizes the performance of both algorithms.

In all the performed experiments only three anchors have been adopted. In general the position error decreases when the number of anchors in the deployment area increases. This behaviour has been evaluated in several papers and it was out of the scope of our work. Implementing the algorithms in real devices we experienced some criticity, mainly due by the wireless transceiver. The RSSI value evaluated by each transceiver is strictly dependent on the hardware in terms of possible range of values and quantization step (not completely linear). From our experience a successful localization based on the received signal strength can be performed only with identical hardware solutions.

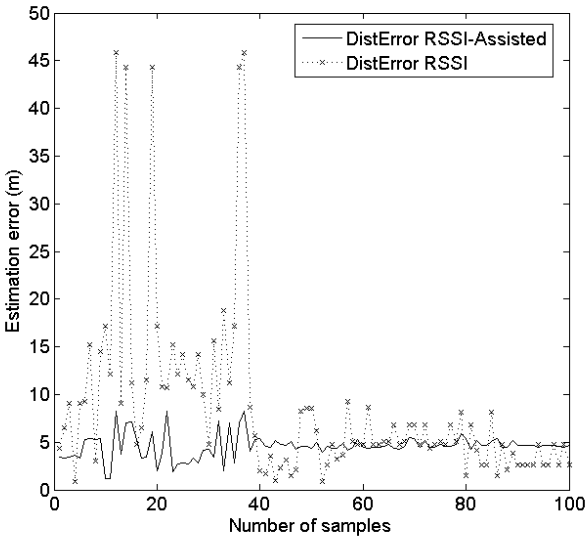

Figure 4: RSSI vs RSSI-Assisted for Position 2.

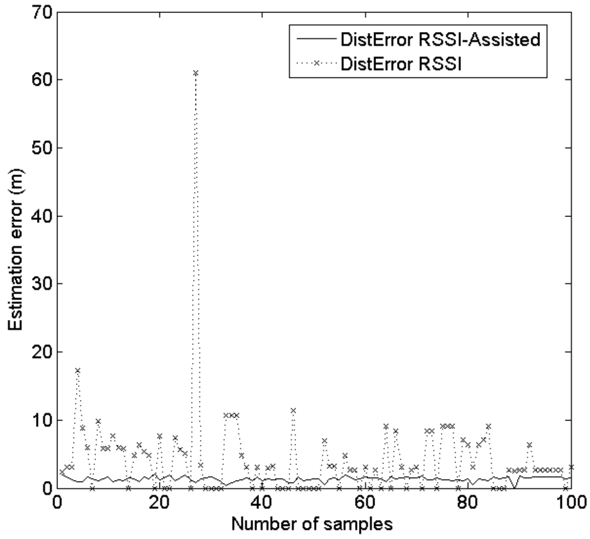

Figure 5: RSSI vs RSSI-Assisted for Position 3.

4.2.2 *Mobile Node Localization*

MCB algorithm have been tested using eight anchors in the same deployment area in which RSSI based algorithms have been tested. The radio range is set to 4 m, because this value is small enough to modify the number of anchors heard each time we modify the position of the mobile node, the nodes height is equal to 1 m. The number of samples is set to 100. Figure 6 illustrates the position of the eight anchors and one target node in the test room. The test consists in modifying the position of the mobile node to evaluate the localization protocol accuracy. Moreover as the algorithm assumes that the maximum speed is constant, we define this parameter equal to 1 m/s.

The first experiment has been performed with the target device in the position (3.6 m, 2.3 m). In this case the average localization error is equal to 0.42 m knowing that for each time interval at least three anchor devices contribute to estimate the position of the mobile node, and we execute MCB algorithm 20 times for the same target position. The second reference point is set to (3.4 m, 5.2 m) and similarly to the previous experiment we execute the algorithm 20 times. In this case we got an average localization error equal to 1.10 m with a number of anchor devices between two and three for each time interval. The last reference point is set to (4 m, 6.4 m) and the number of one-hop anchor is no more than two for each time interval. The average error in this case is 1.26 m, confirming that when the number of one-hop anchors decreases, the accuracy of the

Table 1: RSSI vs RSSI-Assisted for all the positions.

	Average Error		
	Position 1	Position 2	Position 3
RSSI	6.45 m	8.55 m	4.29 m
RSSI-Assisted	1.15 m	4.57 m	1.33 m

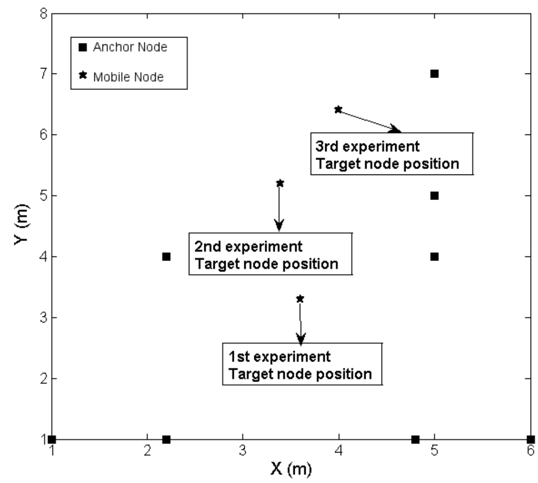

Figure 6: Experimental scenario for MCB algorithm.

whole system decreases as well.

More tests performed in different indoor scenarios have confirmed as the MCB algorithm is able to reach good accuracies even with a low number of anchors. The performance of the algorithm is completely hardware independent, but depends on the way MCB makes use of the data gathered from the anchors which permit to constrain the fiducial area of the mobile node and improve the localization process.

5. CONCLUSION

In this paper a performance evaluation of the RSSI based and MCB based wireless localization algorithms is presented in a real scenario. In case of RSSI based techniques a new algorithm, called RSSI-Assisted is presented and its performance evaluated with respect to the traditional RSSI algorithm, showing as it is able to reach better accuracies. The conducted analysis has shown as the implementation of the RSSI based techniques is strictly dependent on the adopted hardware solutions, while MCB localization algorithms developed to support node mobility are completely hardware independent and their performance mainly depends on the number of data packets gathered from the anchors in charge of constraining the fiducial area of the mobile device.

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