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Is RSSI a good choice for localization in Wireless Sensor Network?

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***Abstract*—Numerous localization protocols in Wireless Sensor Networks are based on Received Signal Strength Indicator. Because absolute positioning is not always available, localization based on RSSI is popular. More, no extra hardware is needed unlike solutions based on infra-red or ultrasonic. Moreover, the theory gives a RSSI as a function of distance. However, using RSSI as a distance metric involves errors in the measured values, resulting path-loss, fading, and shadowing effects. We present experimentation results from three large WSNs, each with up to 250 nodes. Based on our findings from the 3 systems, the relation between RSSI and distance is investigated according to the topology properties and the radio environment. We underline the intrinsic limitations of RSSI as a distance metric, in terms of accuracy and stability. Contrary to what we assumed, collaborative localization protocol based on Spring-Relaxation algorithm can not smooth the distance-estimation errors obtained with RSSI measurements.**

I. Introduction

Wireless Sensor Networks (WSNs) are formed by hundreds or thousands of low cost and low energy sensor devices. Recently, WSN has been brought into reality with the effective deployment of sensors.

Localization is an important issue in the field of WSNs and the location estimation is required in numerous WSN applications. The interest in this aspect in WSNs will probably grow with the proliferation of WSN applications. Thus, this topic has been widely investigated especially by simulations.

In this paper we focus our analysis on Received Signal Strength Indicator (RSSI) based localization. The RSSI is an indication of the power level being received by the antenna: higher is the RSSI level, stronger is the radio signal and then closer is the destination. Generally, radio component reports the current RSSI value each time a valid packet is received.

However, other strategies based on radio propagation properties are proposed for localization in WSN. They estimate the distance by observing the time of propagation (ToA [6]), using different radio interfaces (TDoA, [15, 23]) and considering either propagation time or the angle of arrival (AoA, [13]). However, these solutions generally require dedicated hardware and do not consider the energy consumption.

The most wireless devices have the capability of measuring the received signal strength. As a result, the RSSI-based localization algorithms are very popular. Generally, the signal strength received by a sensor from another one is considered as a monotonically decreasing function of their distance modeled by the Friis transmission equation [8]:

$$P_r(D) = P_t + G_t + G_r + 20log_{10}(\frac{\lambda}{4\pi D}) \quad (1)$$

where P_t and P_r are the transmission and reception power antenna respectively in dBm, G_t and G_r are the antenna gains of the transmitting and receiving antennas respectively, λ is the wavelength, and D is the distance between the antennas.

However, studies [3, 16] have recently revealed that most of localization protocols based on RSSI, once deployed in real platforms, have worse behavior than what predicted by simulations. Equation 1 is an ideal case for a source point and the signal often decays at a faster or slower rate. Practically, it's hard to determine antenna gains and a simplified form of the relation between distance and receive power is often used:

$$P_r(D) = P_{r1} - K.log_{10}(D) \quad (2)$$

where P_{r1} is the received power in dBm at one meter, K the loss parameter and D the distance between the transmitter and receiver. The values of P_{r1} and K are generally determined empirically. Equation 2 is illustrated by Figure 1.

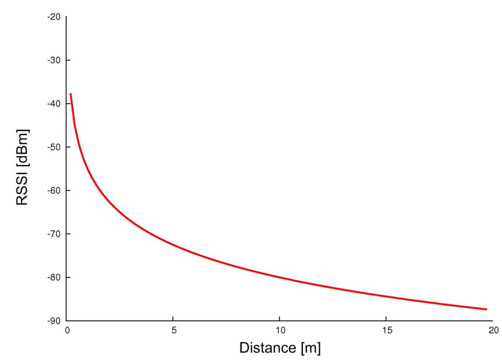

Fig. 1. Expected relationship between RSSI and distance ($K = 25$, $P_{r1} = -55dBm$)

Contributions. The goal of this study is double: firstly, the distance-RSSI-ratio hypothesis is investigated and we underline the intrinsic limits of distance estimation based on

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RSSI in WSN with a set of experimental studies. Secondly, the performances of a collaborative localization protocol based on Spring Relaxation Algorithm (SRA) is investigated in case of distance evaluation is not accurate. To this end, experiments using three different platforms with different topologies and different materials are conducted. The originality of this study is the importance of empirical results, obtained using more than 700 wireless sensors (with sub-1 GHz transceiver and 2.4 GHz IEEE 802.15.4 compliant transceiver).

Structure of the paper. The rest of the paper is organized as follows. In Section II, a survey on RSSI-based localization algorithms is presented. Section III introduces problem statement and and IV introduces methods and materials used for the experiments. Section V presents the experimental results in highlighting inaccuracy ratio between distance and RSSI and the dynamics in RSSI measurements. Section VI presents an application of a collaborative localization protocol and studies this ability to get through the distance-estimation errors obtained with RSSI measurements. Finally, we summarize the results and conclude with some future work directions in Section VII.

II. Related work

RSSI measurement is supported by actual sensors (Imote2, TelosB, MicaZ, WSN430, etc.) and 802.11 [20] and ZigBee [19] standards. RSSI is available during a packet reception with no additional hardware, no impact on energy consumption nor throughput. Moreover, this metric seems intuitive: stronger is the received signal, closer is the transmitter and weaker is the received signal, further is the transmitter. RSSI is also used in several standards to determine when the amount of radio energy in the channel is below a certain threshold at which point the node is clear to send. These reasons make RSSI-based techniques very attractive. As a result, they have been widely investigated and the literature on the RSSI is quite huge. A survey on this topic is clearly not the aim of this work. A more complete overview can be found in [14]. However, in this section, we introduce two main categories of RSSI-based techniques: range-free and range-based. We discuss on RSSI limitations in a third section.

A. RSSI-based and range-free protocols

The range-free algorithms do not estimate the distance between sensors. They generally use connectivity information to identify the nodes in their radio range and then estimate their position. A particular category of the range-free localization techniques uses the RSSI profiling [4, 12]. These algorithms construct a RSSI map in the deployment area. The map is previously obtained offline by measurements or online using dedicated sensors (*sniffers*) deployed at known locations. Each entity, non-sniffer and non-anchor, measures the received signal strength from each anchors and provides a vector. This vector is a kind of "fingerprint". This fingerprint is compared to the map in order to determine the sensor position.

B. RSSI and range-based protocols

The range-based protocols use RSSI as a distance metric. According to this distance estimation, they generally try to determine node position.

A common position estimation method uses the *multilateration*. From the estimated distances d_i between unknown position of the node $(x; y; z)$ and known positions of the anchors $(x_i; y_i; z_i)$ we derive the following system of equations:

$$\left.\begin{array}{ccc} (x_1-x)^2+ & (y_1-y)^2 & +(z_1-z)^2 = {d_1}^2 \\ & \vdots & \\ (x_n-x)^2+ & (y_n-y)^2 & +(z_n-z)^2 = {d_n}^2 \end{array}\right\}$$

The authors in [21] propose to localize a target node with several anchor nodes. The positioning protocol is based on the minimum mean square error (MMSE) estimator. It is a common measure of the estimator's quality. In order to minimize the variance of the estimation error, this method needs an important number of anchors. Indeed, the experiment gives a significant positioning error according to the size of the deployment field.

The notion of proximity is used by [17] to improve the localization accuracy. They define proximity as the capacity of a node to correctly transmit a packet to a neighbor. However, the experiment is limited to very short distances ($0.25m$), without interferences.

C. RSSI limitations

All these studies have difficulties to establish a relationship between the distance and the received signal strength. In other words, in real deployments, it is hard to map RSSI to the distance and obtain a function close to the one shown in Fig. 1. [10] highlights that the signal strength is affected by three phenomena: path-loss, fading and shadowing.

- Path loss is the reduction in power density of an electromagnetic wave as it propagates through space. This attenuation is represented by the path loss exponent, whose value is generally in the range from 2 to 6. In free space, we consider the path loss exponent equals to 2, and 4 for relatively lossy environments. In some environments, such as buildings or other indoor environments, the path loss exponent can reach values in the range from 4 to 6.
- Fading is deviation of the attenuation that a signal experiences. The fading varies with geographical position, time and radio frequency. It is often modeled as a random process. As a result, fading can create either destructive or constructive interferences, amplifying or attenuating the signal power seen at the receiver. The authors in [17] propose to measure RSSI under several frequencies to reduce the fading effect.
- Shadowing is the loss of signal due to obstacles (walls, buildings, trees, cars, people, etc.) between a transmitter and a receiver. The shadowing induced by the walls or the buildings will not temporally evolve. However, authors in [22] study the signal level (with a 2.4 GHz frequency) and shows that the movements of people create an important

shadowing (up to -21 dB of variation with the average) in a unpredictable way. A possible solution will be then to realize an important averaging to smooth these variations.

III. Problem Statement

Sensor positioning enhances the utility of collected data by determining the location from where each data is obtained. As seen previously, localization can be done using RSSI-based algorithms. Such algorithms assume that RSSI can be used to determine distances between sensors.

In this paper, we investigate the relationship between the RSSI level and the physical distance as described in Section I. In other words, we show how is the RSSI in a real environment. In this way, several large-scale experiments on real sensor networks are conducted. We experimentally measure **RSSI as a function of distance** between sender and receiver, **standard deviation** and **asymmetry** of links to illustrate dynamism and investigate the sensor radios radiation (i.e. **isotropic** properties). Of course, due to the random nature of propagation, we expect this relationship not straightforward to predict.

However and despite prediction errors, is it possible to estimate, with a good accuracy, the sensors location using a collaborative algorithm? In order to answer to this question, the SRA [9] is implemented and we investigate how this algorithm is impacted by these errors. The average **localization error** and **algorithms cost** in terms of computation rounds, according to the number of anchors.

IV. Methodology and materials

A. platforms description

SensLAB[1] is a group of 1000 sensor nodes available as a testbed for distributed embedding sensor network applications and distributed systems' research. In this study, we used 3 SensLab platforms, each composed by more than 250 nodes: the INRIA Grenoble SensLAB and the Lille SensLab testbeds where nodes are randomly deployed and the University of Strasbourg SensLAB testbed where nodes are deployed in a regular cubic grid. The three platforms are in an indoor environment. SensLAB nodes are composed of 2 wsn430 boards (one open node and one control node) connected by one gateway board. The purpose of the control node and the gateway board is to offer the essential SensLAB features: firmware deployment on open node; radio environment and power monitoring; configurable sensor polling on control node (temperature, light); remote software update ability for control nodes and gateway. In other words, each node is connected in an "out-of-band" fashion, to a node handler using testbed infrastructure. We are able to monitor a set of metrics (packet sent or received, RSSI, noise level, temperature, light or energy level) without using wireless communications nor back end data collected by a sink. The open nodes are notably composed by:

- MSP430 core (MSP430F1611, offering 48kbyte ROM, and 10kbyte RAM);
- Texas Instrument CC1101 radio chip which operates in the $868MHz$ ISM band and emitting between -30 and $5dBm$ (0.001 and $3.16mW$) with maximum transmission rate of $250kbps$ on Grenoble and Strasbourg platforms.
- Texas Instrument CC2420 which is a single-chip $2.4GHz$ IEEE 802.15.4 compliant RF transceiver and emitting between -25 and $0dBm$ (0.003 and $1mW$) with maximum transmission rate of $250kbps$ on Lille platform;
- Omnidirectionnal PCB antenna;
- Varta Polyflex 383562 rechargeable battery.

For more details, we invite reader to consult [1] and [2].

B. Experiment parameters

As medium access control, the nodes use an OS-free implementation of XMAC MAC protocol. XMAC is a preamble based and an energy-efficient MAC protocol developed by [5] in 2006. Nodes periodically send "*hello*" packets with their id each 30 seconds and maintain a neighborhood table. We do not investigate MAC nor routing protocols. Each experiment lasts 3 hours. It represents more than 2 millions exchanged packets. Thanks to the "out-of-band" infrastructure, each packet sent or received and the associate RSSI value is monitored. We vary the transmission power level and test the system behaviors.

The SRA is used with a RSSI-based distance estimation. The algorithm details are given in Section VI.VI-A.

Table I sums up the essential experiment parameters and platform description.

	INRIA Grenoble	University of Strasbourg	INRIA Lille
Environment	Indoor	Indoor	Indoor
Node position (3D)	Random	Regular cubic grid	Random
Number of nodes	256	256	256
Radio chip	TI CC1101	TI CC1101	TI CC2420
Transmission power	-30 dBm to 5 dBm	-30 dBm to 5 dBm	-25 dBm to 0 dBm
Frequency	868 MHz	868 MHz	868 MHz
Experiment duration	3 h	3 h	3 h
Hello packet period	30 s	30 s	30 s
MAC protocol	XMAC	XMAC	XMAC
Positioning protocol	SRA	SRA	SRA

TABLE I
Summary of the experiment parameters.

V. The RSSI limitations as a distance metric

A. The RSSI-Distance Ratio

Figures 2a, 2b and 2c are obtained with more than 2 millions measures on Strasbourg, Grenoble and Lille platforms respectively. Each sensor periodically exchanges packets with neighboring nodes and notifies RSSI. The figures represent

[1] http://www.senslab.info

the RSSI measurements, the average RSSI and the theoretical RSSI against distance. Theoretical RSSI is obtained by Equation 2. Several phenomena are highlighted:

- The RSSI measures are strewn between -30 dBm and -100 dBm whatever the distance;
- The average and the theoretical RSSI are rather close on Lille platform and on Strasbourg and Grenoble platform for short distances;
- The average RSSI-distance ratio is different on three platforms: except in medium distance, the distance between the three average RSSI is at least equal to 3 dBm.

These phenomena are due to different deployment environment: in Strasbourg platform, all nodes are displayed on a tridimensional grid without obstruction with material (line-of-sight), while on Grenoble and Lille platforms sensors are randomly deployed in a room with people and robotic area.

B. *Asymmetry*

Symmetry properties of the radio links (i.e. signal strength from node A to node B is roughly equal to signal strength from node B to node A) are studied as well. Note that a bidirectional link can be asymmetric in terms of RSSI. Figure 3a shows the RSSI measured by both nodes of a bidirectional link for all the bidirectional links on Strasbourg platform. The majority of links seems quite symmetric, but a significant part of the links are clearly not. For a power transmission equal to -15dBm, more than 10% of the bidirectional links are not symmetric (i.e. a difference more than 3dBm). Note that an increase of 3 dBm represents roughly doubling the power. As a result, a difference of 3 dBm is clearly significant. This behavior is similar on all platforms.

Moreover, more than 40 % of links in the network are unidirectional. And among the bidirectional links, a significant part is unbalanced: in a link between a node A and a node B, the number of packets received by B from A is larger than the number of packets received by A from B (Fig. 3b). It is greatly asymmetric. There are large variations in the number of packets received by both nodes. This suggests that the link quality is not symmetric even if the measured RSSI is similar. The same behavior is observed on Grenoble platform.

However, on Lille platform, a large proportion of links is balanced and more than 95% are bidirectionnal whatever the transmission power. It can be explained by the technology used (TI CC2420 as radio) and the associate frequency (2.4 GHz).

C. *Isotropy*

In order to use RSSI as a distance metric, isotropic radiation is supposed: antenna broadcasts power equally in all directions. An isotropic radiation has the same intensity regardless of the measurements direction. The isotropic properties are investigated on the 3 platforms.

As shown on Fig. 4, Printed Inverted F Antenna (PIFA) of WSN430 sensors have been specially designed to be compact and they have good radiated performances [7]. However, on a real deployment, different propagation properties are observed according to the direction. Figures 6, 7 and 8 shows the average RSSI distribution on Strasbourg, Grenoble and Lille Platforms. Transmission power is modified and we observe the RSSI of received packets from a central node (node 110 on Strasbourg platform, node 91 on Grenoble platform and node 158 on Lille platform). On each case, the same phenomena is observed: decorrelation between the received signal strength and the distance. In addition, in some cases, a close node does not lead to a link presence. This suggests a severe anisotropic radiation and it explains both asymmetric and unidirectional links. A node failure hypothesis is not relevant to explain this behavior: all sensors used in the experiment correctly send and receive packets. The impact of collisions can be excluded as well because of the MAC layer used (XMAC), the low throughput considered, the important duration of experiments and the reproduction of all experiments we done.

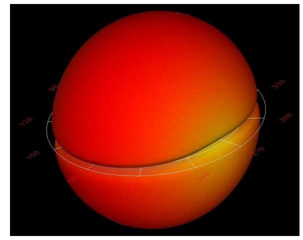


Fig. 4. WSN430 radiation pattern for a 868 MHz frequency [7]

D. *Dynamics*

Figures 5a and 5b show RSSI standard deviation of the links on Strasbourg platform. The 3 curves are obtained with a 0 dBm, -15 dBm and -30 dBm transmission power, respectively. These figures represent the links' *quality* in terms of RSSI stability. The Grenoble platform has a significant number of links which have a unstable behavior, while on Strasbourg platform a major part of links have a relative RSSI stability. Note that, if a link has a RSSI standard deviation equal to 1, it has a high probability (95%) to be ranging from -2 dBm to $+2$ dBm around the mean. In other words, we observe on Strasbourg and Lille platforms a band of received RSSI equal to 4 dBm around the mean.

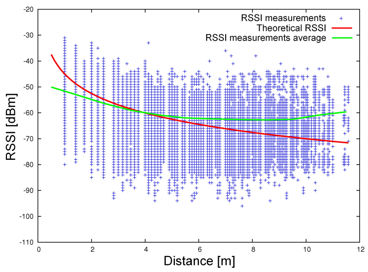
Again, the difference of behavior is related to a different deployment environment: while Strasbourg platform is in a dedicated room without obstruction, Grenoble platform is composed by sensors randomly deployed in a room with people and material.

VI. Localization algorithm

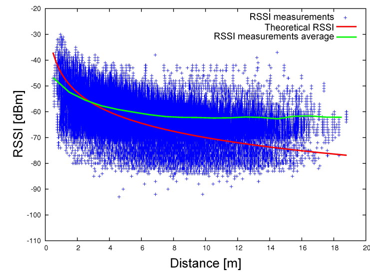
As previously investigated, RSSI-based ranging is affected by errors due to the unpredictable radio propagation behavior. In this section, we investigate how the SRA is impacted by theses errors.

A. *Spring Relaxation Algorithm*

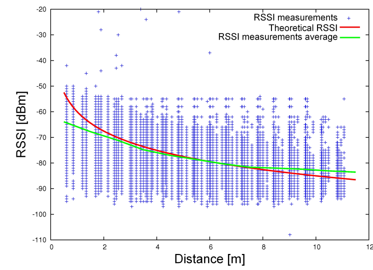
In this section, we use the Spring-Relaxation technique, a force-based algorithms [9]. The force-based algorithm position the nodes by assigning forces among the set of edges and the



(a) Strasbourg platform

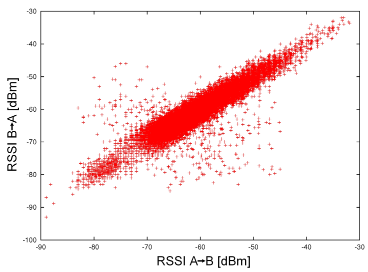


(b) Grenoble platform

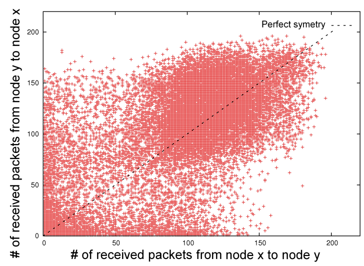


(c) Lille platform

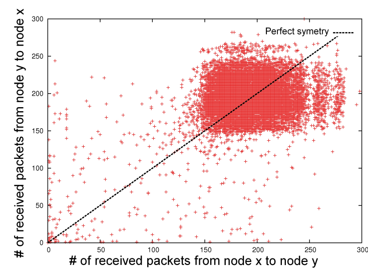
Fig. 2. The RSSI measurements and the theoretical RSSI against distance on the three SensLAB platforms



(a) View of symmetric RSSI on the Strasbourg platform (0 dBm)

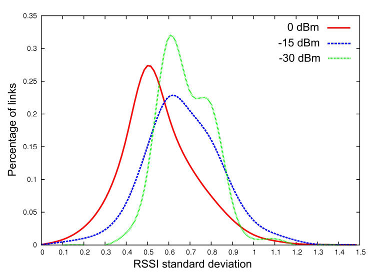


(b) Illustration of asymmetric rate on the Strasbourg platform (0 dBm)

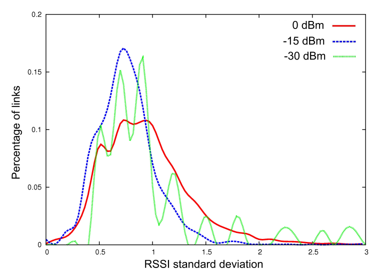


(c) Illustration of symmetric rate on the Lille platform (0 dBm)

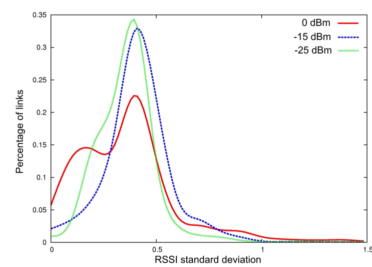
Fig. 3. Symmetry properties of WSN links



(a) Strasbourg platform



(b) Grenoble platform



(c) Lille platform

Fig. 5. RSSI standard deviation for 3 power transmissions on 3 sensLab platforms

set of nodes. The forces are applied to the nodes, attract them closer together or repulse them further apart. The process is repeated iteratively until the system reaches an equilibrium state.

The SRA is chosen because it exhibits several advantages:

- Simplicity: SRA is simple and it could be easily implemented. Moreover, since it is based on physical analogies of common objects like springs, the behavior of this algorithm is quite intuitive;
- Flexibility: it can be easily adapted and extended to work with directed and dynamic graphs;
- Local computation: each node only needs information on its 1-hop neighborhood (distance and position estimation) to compute its own position. It is especially relevant for large WSN context;
- Good-quality results despite the distance approximation.

However, two drawbacks can impact its efficiency: an important running time and local minima. The SRA has a time complexity equivalent to $O(n^3)$ (where n is the number of nodes of the network). The number of iterations is $O(n)$, and in every iteration, all pairs of nodes need to be visited to compute the force applied to the node. The goal of SRA is to find a graph minimizing ”energy” (i.e. minimize springs extension or compression). As a result, the local minima can be found and be considerably worse than a global minimum, which is translated into a low-quality positioning.

The spring-relaxation technique is initially used for localization by Priyantha *et al.* in [18] and then modified by Zhang *et al.* in [24]. Spring-relaxation technique is a cooperative localization algorithm i.e. each node computes locations relative to the locations advertised by their one-hop neighbors. The computed locations are then broadcasted back

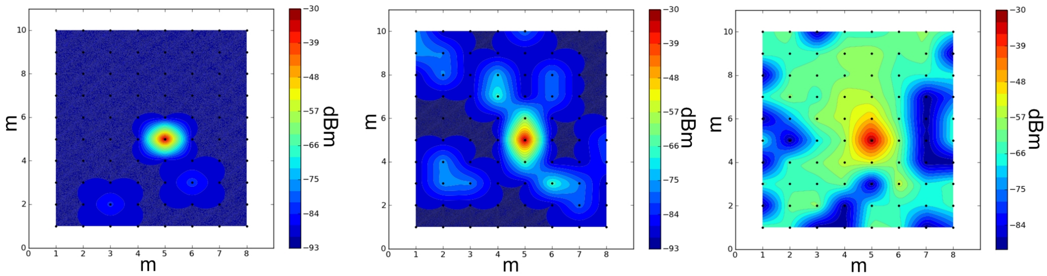


Fig. 6. RSSI propagation on Strasbourg Platform (-30, -15 and 0 dBm)

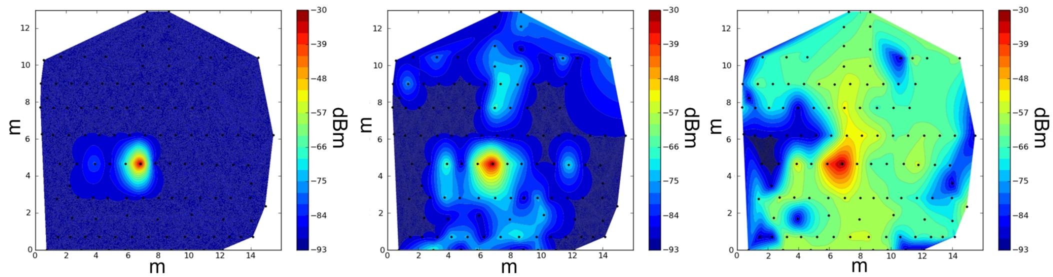


Fig. 7. RSSI propagation on Grenoble Platform (-30, -15 and 0 dBm)

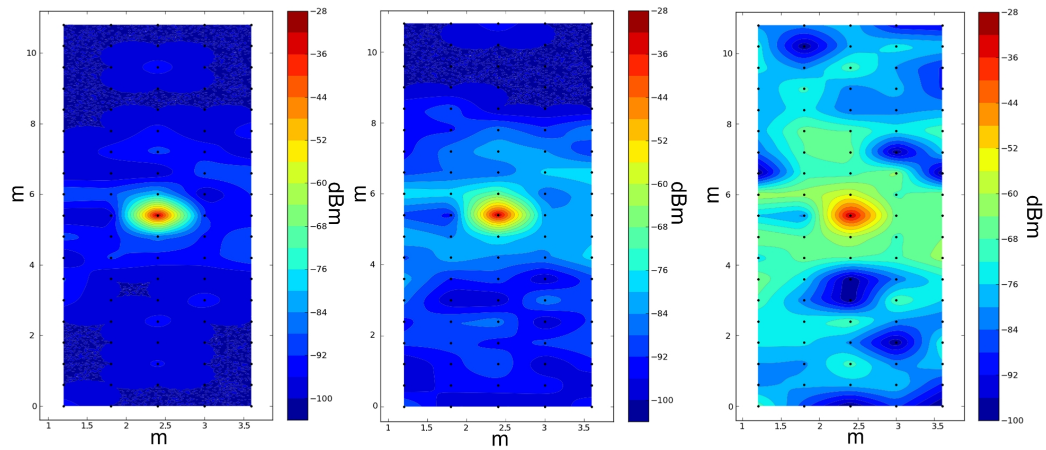


Fig. 8. RSSI propagation on Lille Platform (-30, -15 and 0 dBm)

to their one-hop neighbors for refinement, until the computed locations converge. We assume that a percentage of sensors, called anchor, knows their absolute location. SRA is based on two phases. In the first phase, sensor locations are coarsely estimated by using RSSI-ranging to the anchors: each sensor makes an initial random assignment of its location (Fig. 9) and uses the estimated distance from neighboring anchors to iteratively refine this initial guess. Second phase improves location approximation by using inter-sensor estimated distances.

SRA is driven by several parameters: τ is the maximal magnitude of the force $\vec{F_i}$ applied to the node i and δ is the the step size which controls the proportion that sensor updates its location according to the net force in each iteration. We set $\tau = 0.005$ and $\delta = 0.001$ according to values found in [24].

B. Performances

The localization algorithm accuracy is defined as the position difference in meters between the real position (x_r, y_r, z_r) and the estimated position (x_e, y_e, z_e) of a node. The Position error is given by the following equation:

$$Error = \sqrt{(x_e - x_r)^2 + (y_e - y_r)^2 + (z_e - z_r)^2} \quad (3)$$

RSSI used to compute distance estimation is obtained by averaging measures obtained with 3-hour experiments. To estimate the distance with RSSI, parameters minimizing the estimation error are used. We assume that each node knows the deployment area limits and chooses random coordinates inside this area. The anchors are chosen randomly and localization performances are studied under different transmission power (from -30 dBm (cc1101) or -25 dBm (cc2420) to -0 dBm). Thus, we use advantageous conditions to evaluate localization algorithm performances.

The initial random assignment of nodes location gives an initial error comprised between 5 and 8 meters on each platforms. Higher errors are obtained on Grenoble platform due to a larger deployment area and a poor distance estimation.

The average degree has an important impact on accuracy and the best results have obtained with the maximum transmission power (i.e. when the average degree is maximal). With a minimal power transmission, the best localization error obtained is 4 meters whatever the platform. In the following, only results obtained with the best conditions (i.e. with the maximum power transmission) are exposed.

Contrary to what we assumed, increasing the number of anchors does not necessary lead to a better average accuracy. Figure 10 shows that more than 50 anchors deteriorate the average accuracy. This deterioration can be explained by the poor distance estimation.

Observations indicate the same general behavior on the 3 platforms. However, there are several minor differences:

- The worst performances are obtained on Grenoble platform (estimation error close to 3 meters). It can be explained by a larger deployment area that leads to a worst initial random location.
- The comparable performances are obtained on Lille platform despite a large deployment area. It can be explained by a better distance estimation as shown on Fig.2c (average RSSI is close to theoretical RSSI).

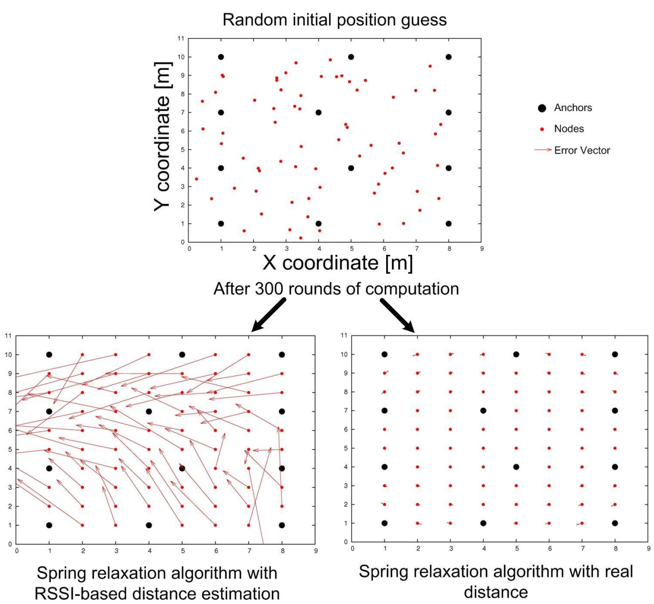


Fig. 9. Localization map obtained with spring relaxation algorithm

Finally, even in very good conditions (RSSI-distance ratio determined according the platform, distance estimation only based on average RSSI values, important average degree, important number of anchors, information on deployment area size), the localization estimation is relatively poor regarding to the deployment area. Figure 9 illustrates, in 2 dimensions and on Strasbourg platform, the differences between localization using real euclidean distance or using RSSI-based distance estimation: the localization error obtained with RSSI is close to 2 meters when the localization error obtained with euclidean distance is less than several centimeters.

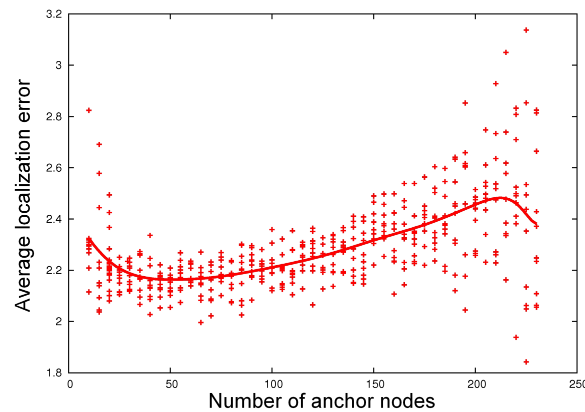


Fig. 10. Localization error according number of anchors

VII. Conclusions and further work

In this paper, we conduct a study on 3 large wireless sensor networks, each with up 250 nodes deployed in different environments and topologies. The contribution of this study is twofold:

- We present important empirical results underlining intrinsic limits of RSSI in terms of stability and reliability. To the best of our knowledge, this work is the first to study the RSSI on more than 700 sensors deployed in 3 different sites, using both TI CC1101 (low-cost sub-1 GHz transceiver) and TI CC2420 (2.4 GHz IEEE $802.15.4$ compliant RF transceiver).
- Collaborative localization protocol, based on Spring-Relaxation algorithm, have been studied. In particular, we study its ability to get through the distance-estimation errors obtained with RSSI measurements. One of the particularity of this part is considering 3D positioning.

Experimentations have conducted on real environments with dynamics. In our point of view, WSNs deployed should face to these type of environments. However, according to the state-of-the-art, in order to obtain a stable and accuracy RSSI, there is necessary to:

- measure RSSI on several frequency;
- average an important number of RSSI measures to be able to smooth variations;
- caliber sensor radios to obtain a comparable emission power and reception sensitivity;
- have a high-quality antenna;
- be able to minimize interferences and network environment dynamics (mobile objects, rain, doors, electronic equipments, etc.).

In our opinion, theses constraints are not compatible with the most of WSNs applications:

- frequency hopping is not available on all sensors;
- the time needed to smooth RSSI variation depends on environment dynamics. This manipulation leads to a latency and energy consumption increase;

- the scenarios generally taken (smart building, environment monitoring, etc.) as available for wsn deployment are often highly dynamic.

This study reveals that RSSI-based localization in real environment and using standard sensors is not enough accurate. In this work, we focused on an original spring-relaxation technique. However, spring-relaxation accuracy can be impacted by local minima, the initial guess of the node location could be crucial. It would be interesting to investigate localization improvements as Kamada-Kawai have proposed in [11].

In conclusion, according to this study, RSSI is not a good candidate to estimate distance in WSNs. Moreover, range-free algorithms can give useful metrics instead of using RSSI-based distance estimation. A future work will investigate these type of algorithms using 2-hop connectivity information.

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