Cooperative Localization with 802.15.4a CSS Radios: Robustness to Node Failures

Gabriel E. Garcia*, Henk Wymeersch*, William Riblier†, and Alexandre Cazalis†
* Department of Signals and Systems, Chalmers University of Technology, Gothenburg, Sweden
† Telecommunications Department , IPB - ENSEIRB-MATMECA, Bordeaux, France
E-mail: {ggarcia,henkw}@chalmers.se, {wriebler,acazalis}@enseirb-matmeca.fr

***Abstract*—Cooperative positioning is a solution for location-aware applications where GPS-aided localization is unfeasible. In this paper, we provide a qualitative comparison between cooperative and non-cooperative localization under node-failure scenarios, in a typical indoor environment using off-the-shelf 802.15.4a radios. From our analysis, we observe the improved robustness and coverage offered by the cooperative approach in node-failure scenarios.**

I. Introduction

Location-aware technologies are currently undergoing a swift evolution, making absolute and relative position information essential to develop reliable location-based applications. Such applications include the commercial, public, and military domains [1]. For example, there exists a need to track inventory items inside warehouses [2] or medical equipment in hospitals [3]. Moreover, habitat [4] and health monitoring [5] as well as soldier tracking and battlefield surveillance [6] also rely on location information.

It is well known that existing technologies such as the Global Positioning System (GPS) [7] can help to solve the location problem in many situations. However, GPS may not be suitable or viable under certain conditions. In weak signal environments such as indoors, underground, or in urban canyons it is difficult to obtain reliable GPS location estimates.

Intense research work has been done in order to develop new techniques to solve the localization problem in environments where GPS-aided localization is unfeasible. Tangible examples include wireless ad-hoc system for positioning (WASP) [8], GSM solutions and RADAR tracking system [9]. However, there does not yet exist a widespread commercial technology. There is ongoing research at both theoretical and practical levels. One research track involves cooperation among devices, to distribute and share information over the network.

In cooperative localization the main goal of every node in the network is to be able to localize itself, in other words, to estimate its own *state* with the use of the shared information. The network consists of *anchors*, nodes with known states at all time; and *agents*, nodes with a priori unknown state information.

The *cooperative localization solution* can be broken down into two phases [10]. The first phase is the *measurement phase*, where the agents measure metrics based on the properties of the received signal from anchors and neighboring agents. Metrics take advantage of properties such as the angle of arrival (AOA) or time-of-flight (TOF), related to the relative positions of the receiver and the transmitter. The measurement phase can be affected by several error sources such as non-line-of-sight (NLOS), interference, and multipath derived from the typical indoors environment. In the second phase; *the localization phase*, the agents in the network are localized by implementing a specific localization algorithm. Cooperative algorithms rely in the concept of nodes sharing information to determine their positions regardless the type of node (anchor or agent). Performance metrics such as accuracy and coverage are increased when using cooperative algorithms [11]. Cooperative localization has gained considerable attention in research fields such as wireless communications, robotics and navigation. However, there is still a need to validate experimentally the theoretical claims that the cooperative framework offers. Related experimental validation based on Ultra Wide Band (UWB) wireless ad-hoc networks for emergency situations can be found in [12].

In this paper, an experimental setup in a typical indoors environment was implemented using Nanotron Technologies[1] nanoLOC Development Kit (DK). Although this development kit has been used in other practical demonstrations such as in [13] and [14], no cooperative processing approach has been implemented to the extent of our knowledge. This paper presents several node failure scenarios in order to show the robustness of cooperative algorithms, specifically the sum-product algorithm over wireless networks (SPAWN) [11].

The rest of the paper is organized as follows. In Section II, we describe the model and formulate the problem. A brief explanation of SPAWN is introduced. In Section III we describe the hardware and software included in nanoLOC Development Kit. In Section IV the experiment setup used for the measurement phase is described in detail. Results and simulations of the node failure scenarios are discussed in Section V. Finally, our conclusions are presented in Section VI.

II. Model and Baseline Algorithm

A. System Model

Consider a wireless network consisting of N nodes. Assume there are N_A anchor nodes with known positions (obtained via GPS or some absolute reference) and the remaining $N_u =$

[1] www.nanotron.com

$N - N_A$ agent nodes are located at unknown positions. The position of agent node i at time slot t is denoted as $\mathrm{x}_i^{(t)}$. We assume that all nodes cooperate to determine their unknown coordinates. The set of nodes from which node i receives signals at time t is denoted as $S_{\to i}^{(t)}$. Based on a ranging protocol and signal metrics received from node $j \in S_{\to i}^{(t)}$ at time t, node i calculates the distance estimate $\hat{d}_{j\to i}^{(t)}$.The localization problem is solved by means of SPAWN, which will be introduced shortly. Throughout this paper the state of the node will be treated as the two-dimensional geographical coordinates of the node. In non-cooperative localization $S_{\to i}^{(t)}$ only contains neighboring anchors.

The goal of each node is then to localize itself, in other words, to estimate its own state $\mathrm{x}_i^{(t)}$.

B. Sum Product Algorithm Over a Wireless Network

The sum product algorithm over a wireless network (SPAWN) is the cooperative positioning technique implemented in the practical scenario using Nanotron's equipment. SPAWN has been shown to surpass many cooperative (and non-cooperative) algorithms in theoretical studies. It requires little communication overhead and accomplishes robust and accurate localization [11].

The Bayesian cooperative framework on which SPAWN relies, consists of the exchange and calculation of statistical information through the use of a message passing algorithm. The statistical information consists of distributions of two-dimensional continous random variables for the case of two-dimensional positioning.

The algorithm is initialized with an a priori distribution $b_{X_i^{(0)}}^{(0,0)}(\mathrm{x}_i^{(0)})$ for each node. Since the agents have no information about their position, their a priori distribution is uniform. On the other hand, anchors have accurate information about their position and the initialization is a delta Dirac function at the anchors' coordinates.

The algorithm comprises two different steps: the *correction* and the *prediction* operation. At every time slot t, the correction operation (shown in Algorithm 1) allows the nodes to exchange their location distributions in an iterative manner until a specified number of iterations N_{iter} is achieved. At every iteration l the nodes update their own distribution, or *belief*, using the received information from neighboring nodes. From the belief, we can obtain the *maximum a posteriori* (MAP) or the *minimum mean squared error* (MMSE) estimates to deduce the position and therefore, track the agents.

The prediction operation (shown in Algorithm 2) takes place at every time slot t to account for the mobility of the node given by the model $p(\mathrm{x}_i^{(t)} \mid \mathrm{x}_i^{(t-1)})$. The algorithm can be extended to more general states and to include internal measurements.

A node failure situation occurs when there is a loss of connection caused by different circumstances such as hardware failure or manual intervention. Node failures cause a temporary loss of ranging information and location information from the failing node. In cooperative localization, we expect the impact of node failures to be limited due to the increased redundancy in the network. Note that we do not consider the impact of malicious nodes that send false information [15].

Algorithm 1 SPAWN - Correction Operation

1: for $l = 1$ to Niter
2: Broadcast $b_{X_i^{(t)}}^{(l-1,t)}(\cdot)$
3: Receive $b_{X_j^{(t)}}^{(l-1,t)}(\cdot)$
4: Convert $b_{X_j^{(t)}}^{(l-1,t)}(\cdot)$ to a distribution over $X_i^{(t)}$
$$m_{\mathrm{X}_j\to\mathrm{X}_i}(\mathrm{x}_i^{(t)}) \propto \int p(\hat{d}_{j\to i}^{(t)} \mid \mathrm{x}_i, \mathrm{x}_j) b_{X_j^{(t)}}^{(l-1,t)}(\mathrm{x}_j^{(t)}) \mathrm{d}\mathrm{x}_j^{(t)}$$
5: Compute new belief
$$b_{X_i^{(t)}}^{(l,t)}(\mathrm{x}_i^{(t)}) \propto b_{X_i^{(t)}}^{(l-1,t)}(\cdot) \prod_{j\in S_{\to i}^{(t)}} m_{\mathrm{X}_j\to\mathrm{X}_i}(\mathrm{x}_i^{(t)})$$
6: end for
7: $b_{X_i^{(t)}}^{(0,t)}(\mathrm{x}_i^{(t)}) = b_{X_i^{(t)}}^{(N\mathrm{iter})}(\mathrm{x}_i^{(t)})$

Algorithm 2 SPAWN - Prediction Operation

1: for $t = 1$ to T do
2: Nodes $i = 1$ to N in parallel
3: Prediction operation
$$b_{X_i^{(t)}}^{(0,t)}(\mathrm{x}_i^{(t)}) \propto \int p(\mathrm{x}_i^{(t)} \mid \mathrm{x}_i^{(t-1)}) b_{X_i^{(t)}}^{(0,t-1)}(\mathrm{x}_i^{(t-1)}) \mathrm{d}\mathrm{x}_i^{(t-1)}$$
5: *Correction Operation: see Algorithm 1.*
6: end parallel
7: end for

III. Nanotron System

Nanotron Technologies has developed a range of wireless products and solutions combining data transmission and localization. This section presents an overview of the nanoLOC Development Kit (DK) hardware and software components used in the experimental setup. The DK is designed for prototyping and developing ranging and location-aware wireless applications based on the nanoLOC TRX transceiver.

A. Hardware

The nanoLOC Development Kit 3.0 includes 5 nanoLOC development boards used as nodes, each containing a nanoLOC TRX transceiver and a ATmega128L microcontroller. Furthermore, the kit also includes a nanoLOC USB stick which is plugged into the base station (PC) and enables wireless communication between the PC and the development boards.

The nanoLOC TRX transceiver operates in the ISM band at 2.4 GHz. The wireless communication and the ranging protocol are integrated in the ATmega128L microcontroller.

The wireless communication is based on chirp spread spectrum (CSS), which is part of the IEEE 802.15.4a-2007 standard [16]. CSS employs pulses that are frequency modulated with a frequency that changes monotonically from a higher to a lower value (downchirp) or a lower to a higher value (upchirp). The difference between the lower and higher frequencies is approximately the bandwidth of the chirp pulse, which in

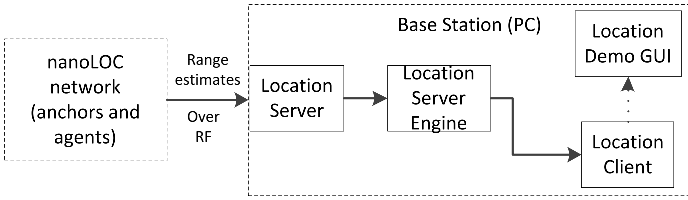

Figure 1. Off-the-shelf software system overview.

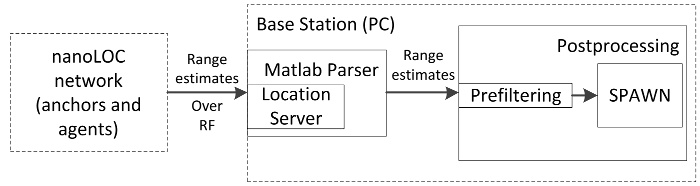

Figure 2. Modified software system overview.

our case is 80MHz. Advantages of this specific modulation technique include resistance to multipath and tolerance to clock and frequency offsets. CSS is tailored to achieve low power consumption without compromising the reliability of the transmission [17]. These advantages make CSS suitable for indoor environments.

In order to determine range estimates $\hat{d}^{(t)}_{j\to i}$ between nodes j and i, the *symmetrical double-sided two way ranging* (SDS-TWR) methodology is used [17]. The concept behind this method is to remove the requirement for clock synchronization in the network.

5.2 Software

The DK software includes two important software packages: the *Location Server* and the *Location Client*. Separately, a Matlab parser was coded in order to obtain and save real-time data for postprocessing purposes, a detailed description of which will be given in Section IV.

The Location Server is in charge of the wireless communication with the agents while the Location Client is the console program for running a location Demo and also serves as an alternative access to the Location Server. The off-the-shelf software configuration is shown in Figure 1. The Location Client or the Location Demo requests ranging. The Location Server via the base station searches for the agents. All found agents in the network perform ranging to all anchors. The data generated from the ranging procedures is transmitted to the base station. Finally, the Location Server Engine uses the latter data to perform ranging prefiltering to remove unwanted outliers and estimate the coordinates of the agent. Thereafter, the location estimates are sent to the Location Client to display them using the Location Demo GUI [17].

IV. Experiment Setup

This section gives a detailed explanation of the experiment setup. Software changes were performed in order to have a functioning cooperative network. A real indoor scenario was set up in order to obtain the range estimates for post-processing in SPAWN. The reader should be aware that even though SPAWN was performed offline, in principle, SPAWN can be run in real-time.

A. Software Modification

A Matlab parser was coded along with several modifications in the Location Server and agent's source code to achieve two goals. The first goal was to accomplish ranging between agents. Originally, every agent receives the list of addresses of the anchors from the base station. The modification in the Location Server consists of a hardcoded list including the addresses of the agents. The modification within the agents' source code consists of an address check. The agent iterates over the list of addresses sent by the base station and if the agent's own address is the next one on the list to perform ranging with, the procedure is just skipped. The second goal involves bypassing the Location Client by means of the Matlab parser in order to access the Location Server to obtain and save the ranging information for postprocessing in the PC. The Location Server Engine is replaced by the postprocessing block including the prefiltering and SPAWN algorithm. The modified system's software overview is depicted in Figure 2.

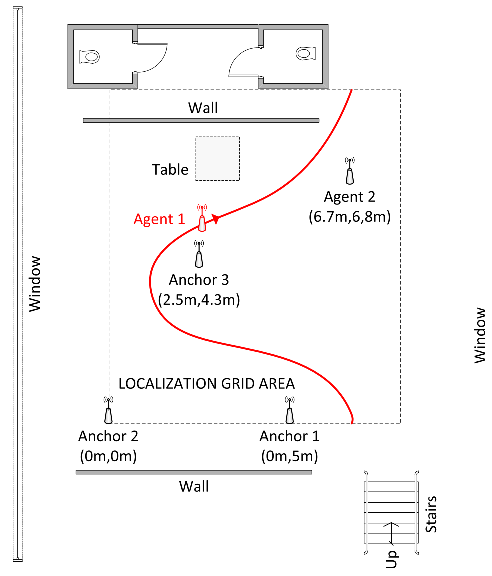

Figure 3. Scenario 1: 3 anchors, 1 mobile agent and 1 static agent.

B. Physical Setup

A series of 3 data collection campaigns for 2 different scenarios were performed in an indoor line-of-sight (LOS) environment in a common gathering (cafeteria/working) place inside the EDIT building at Chalmers University of Technology. The deployment area was 8×9 meters. Radios were carried by hand when mobile procedures were needed while for static procedures tripods were used.

The first scenario, the static case, consists of three anchor nodes, one mobile agent, and one static agent. For the mobile agent, a 23-steps predefined path was chosen while the static agent remained without motion in a specific point within the

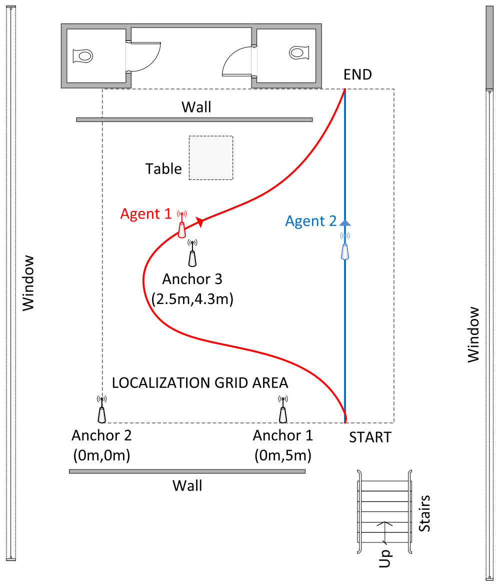

Figure 4. Scenario 2: 3 anchors and 2 mobile agents.

localization grid area. The complete physical setup for the first scenario is depicted in Figure 3. The red line shows the path followed by agent 1.

The second scenario, the mobile case, consists of three anchor nodes and two mobile agents. Once again, for one of the mobile agents, the same 23-steps predefined path was chosen while for the remaining agent a 12-steps straight line path was defined. Scenario 2 is shown in Figure 4, the red and blue lines depict the paths followed by agent 1 and agent 2, respectively.

The measurement campaigns included collecting at least 5 ranging estimates from each step for later postprocessing.

C. SPAWN Implementation

The localization coordinates are MAP estimates of each agent's belief after one iteration in the correction operation of SPAWN, where the messages are represented by a grid with a resolution of 0.15 cm. Agents' a priori distributions were uniform for both scenarios. The mobility model for agent 1 and agent 2 for both scenarios is a random walk model calculated as:

$$p(\mathrm{x}_i{}^{(t)} \mid \mathrm{x}_i^{(t-1)}) \propto \exp\Big(\frac{1}{2\sigma_{\mathrm{mob}}^2} \parallel \mathrm{x}^{(t)} - \mathrm{x}^{(t-1)} \parallel^2\Big). \quad (1)$$

The ranging model implemented for the measurements is gaussian distributed with unity variance calculated as:

$$p(\hat{d}_{j\to i}^{(t)} \mid \mathrm{x}_i, \mathrm{x}_j) \propto \exp\Big(\frac{1}{2\sigma_{\mathrm{r}}^2}\big(\hat{d}_{j\to i}^{(t)} - \parallel \mathrm{x}_i{}^{(t)} - \mathrm{x}_j{}^{(t)} \parallel\big)\Big), \quad (2)$$

where $\sigma_{\mathrm{r}} = 1$m according to our measurements.

V. Results and Discusion

In this section the node failure schemes are presented along with the results, making it possible to compare the coverage and robustness of cooperative and non-cooperative localization.

For both physical scenarios presented in the previous section a node failure scheme was simulated for each one of the anchors. Anchor failure was induced after the first 9 steps and 5 steps out of the 23 steps of agent 1 for the static and mobile cases, respectively. The distance estimates corresponding to the anchor presenting a failure were not included in the algorithm for both cooperative and non-cooperative localization.

A. Static Case

The results for the static experiment with three anchors nodes, one mobile agent, one static agent with a failure in anchor 1 are shown in Figure 5. The results for the same scenario with an induced failure in anchor 2 are depicted in Figure 6. The scenario for the failure in anchor 3 is not presented in the paper since the results are similar to the ones from anchor 1. The mobility model was calculated for agent 1 using $\sigma_{\mathrm{mob}} = 0.6$ m, given the average difference in distance from each step in its predefined path and for agent 2 using $\sigma_{\mathrm{mob}} = 10^{-15}$ m, since it is static within the localization grid area.

We can observe agent 1 follows the ground truth without problems within the first 11 steps at the beginning of the path. After the eleventh step, for the non-cooperative scenario agent 1 stops following the ground truth due to the ambiguities that arise from having measurements only from anchor 2 and anchor 3, making it difficult to localize itself. On the other hand, in the cooperative case, even though anchor 1 is down, agent 1 is still able to follow the ground truth. The improvement is more noticeable when there is an induced failure in anchor 2. This is because the distance estimates from anchor 2 particularly for this experimental campaign were significantly worse than for anchor 1. The latter caused a positive bias in the distance estimates that later on were mostly discarded by the prefiltering stage.

B. Mobile Case

The results for the mobile experiment setup, with three anchor nodes, two mobile agents with an induced failure in anchor 3 are shown in Figure 7. The results for the mobile scenario but this time with a failure in anchor 2 node are depicted in Figure 8. As with the previous results, the failure scenario for anchor 1 is not included in the paper since the results are similar to the ones from anchor 3. The mobility model for this case was calculated for agent 1 using $\sigma_{\mathrm{mob}} = 0.6$ m and for agent 2 using $\sigma_{\mathrm{mob}} = 0.35$ m given the average distance differences from each step in the predefined paths.

We can observe that for the first part of the predefined steps agent 1 follows the ground path without problems. However, after the sixth step, when the failure is induced, and abrupt change in comparison with the ground truth is noticeable.

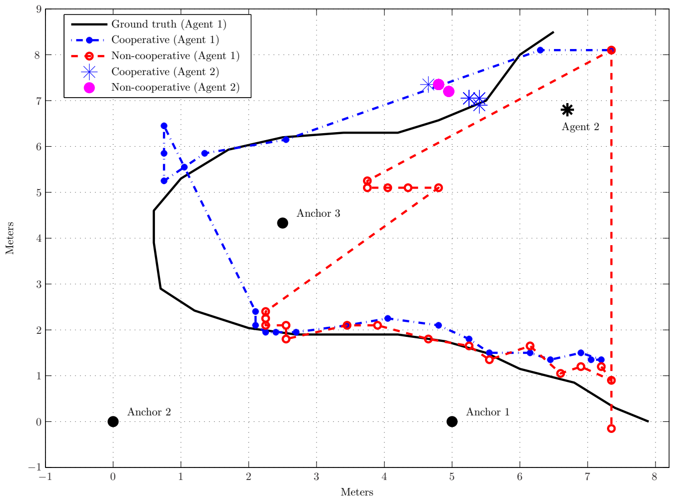

Figure 5. Static case, node failure simulation for anchor 1.

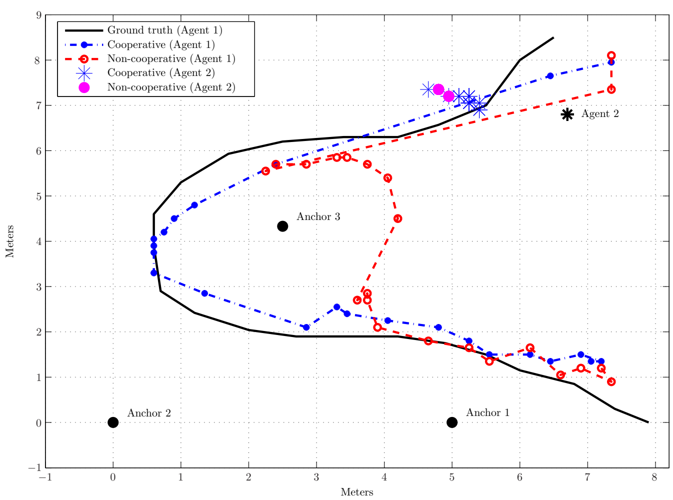

Figure 6. Static case, node failure simulation for anchor 2.

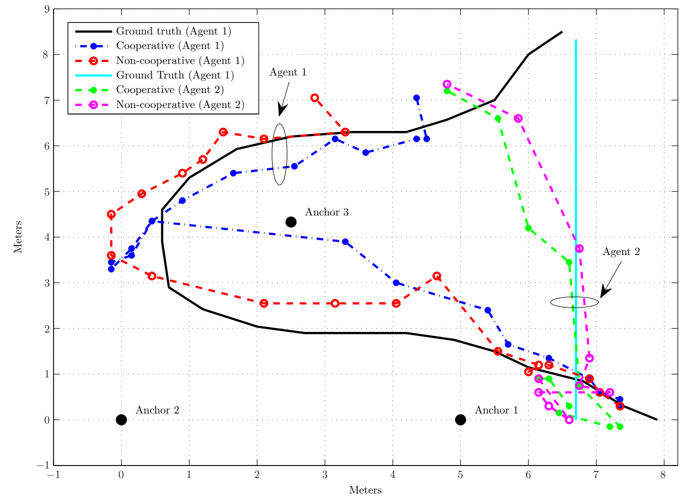

Figure 7. Mobile case, node failure simulation for anchor 3.

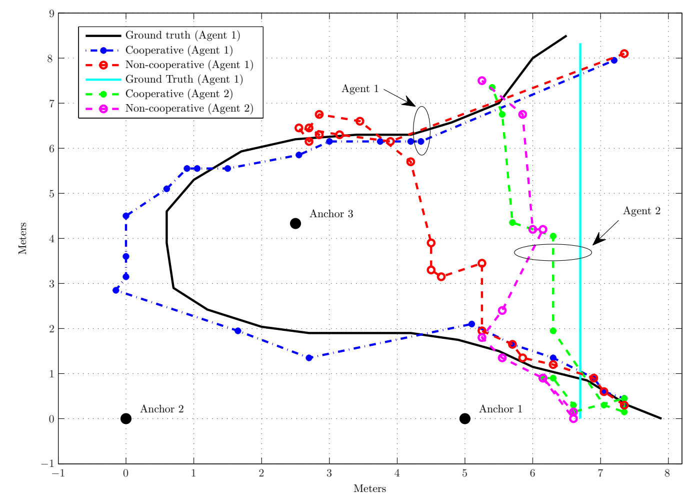

Figure 8. Mobile case, node failure simulation for anchor 2.

Once again, the cooperative case shows a qualitative improvement in coverage and robustness, since it is able to localize the agents in the presence of node failure scenarios. As with the static case, the improvements are more noticeable when the induced failure is present in anchor 2.

VI. Conclusions and Future Work

Many current and future applications of wireless networks require the need for positioning information. Cooperative localization offers improved robustness, accuracy and coverage, boosting the localization performance. In this paper we have shown how cooperative localization can be implemented in a practical scenario using off-the-shelf hardware and software from Nanotron Technologies in a typical indoor environment. We have performed a experiment that has demonstrated how coverage is improved under node failure scenarios where non-cooperative techniques are not capable of solving the localization problem.

Localization within indoor environments propose several future work and research challenges that need to be addressed. The use of other available radio frequency technologies might be used for communication and ranging, such as UWB, which offers robust capabilities against multipath and interference among other advantages; fusion and integration of different available information is another important issue in both the measurement and localization phase; non-line-of-sight (NLOS) indoor environments; high mobility cases, and robust prefiltering.

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