INDOOR LOCALIZATION WITH WIRELESS SENSOR NETWORKS

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Abstract—Wireless Sensor Networks (WSNs) have attracted a great deal of research interest during the last few years. Potential applications make them ideal for the development of the envisioned world of ubiquitous and pervasive computing. Localization is a key aspect of such networks, since the knowledge of a sensor's location is critical in order to process information originating from this sensor, or to actuate responses to the environment, or to infer regarding an emerging situation etc. Indoor localization in the literature is based on various techniques, ranging from simple Received-Signal-Strength (RSS) to the more demanding Time-of-Arrival (ToA) or Direction-of-Arrival (DoA) of the incoming signals. In the context of several EU research projects, various WSN platforms for indoor localization have been developed, evaluated and tested within real-world emergency medical services applications. These platforms were selected in order to deal with all principal localization techniques, namely RSSI, ToA and DoA. Deployment and real-world considerations are discussed, measurements results are presented and overall system evaluation conclusions are drawn regarding indoor localization capabilities of WSNs.

1. INTRODUCTION

Wireless Sensor Networks (WSNs) are a class of distributed computing and communication systems that are an integral part of the physical space they inhabit [1]. Albeit low profile, limited computational power and sparse energy resources, their most

interesting feature is the reasoning of and reaction to the world that surrounds them. Smart environments represent the next evolutionary development step in building, utilities, industrial, home, shipboard, and transportation systems automation [2]. This bridge to the physical world has enabled a growing bouquet of potential services, ranging from commercial (environmental monitoring, industrial sensing and diagnostics, context-aware computing etc.) to military (infrastructure protection, battlefield awareness, on-field navigation etc.) applications [3].

Information about location of wireless sensors is crucial for the successful deployment and operation of such networks. Passing over the case of pre-recorded location, which is cumbersome and impractical in mass-scale WSNs, there is a growing interest in wireless sensor and WSN-based localization. Location information is considered to add many potential applications to telecommunications systems, such as fraud protection, fleet management, location-aware network access, person/asset tracking, navigation etc. Furthermore, Ambient Assisted Living (AAL) platforms strongly rely on an accurate underlying localization system, in order to provide timely and reliable services to elderly users. Furthermore, first responders' reaction quality is considered to be improved to a large extent in the case where location-related information is available.

In this paper, we aim at demonstrating evaluation results regarding implementation, measurements and real-world experience of WSN-based localization for AAL platforms. More specifically, in the context of the "EMERGE" EU research project, a variety of localization systems has been tested under the scope of providing real-time emergency medical services to elderly users [4–11]. The breadth and depth of the presented results aim at providing information on hands-on experience with promising technologies for indoor localization to interested researchers and developers.

In the following, a short discussion about localization techniques precedes a detailed presentation and analysis of the experimental systems and results presented herein. For this analysis, the template proposed by Jedlitschka et al. is used [12], in order to comply with a well accepted format for documents of similar scope. Finally, a short discussion about real world deployment considerations is cited before concluding the paper.

2. LOCALIZATION TECHNIQUES — OVERVIEW

Several localization techniques have been proposed in the literature. The Global Positioning System (GPS) provides global coverage but

specialized equipment is needed, which is energy inefficient and mostly ineligible for WSNs, except for the case of limited number of sensors with extended battery capabilities. Furthermore, GPS is not capable of operating indoors, because of the large attenuation introduced by buildings' walls and ceilings; therefore it cannot comprise a ubiquitous localization method.

Radio frequency techniques have been alternatively suggested in order to locate wireless units. Radio frequency position location systems are classified into two broad categories: Direction-finding (DF) and range-based (RB) systems [13]. DF systems utilize antenna arrays and Direction-of-Arrival (DoA) estimation techniques in order to locate the Mobile Station (MS), and are mainly used in areas with limited clutter [14–20]. On the other hand, RB systems measure the distance between the MS and a number of Base Stations (BSs), and then the MS's position arises as the intersection point of the corresponding curves. The range of the MS is calculated using either Time-of-Arrival (ToA) or Received Signal Strength (RSS) measurements [15, 17, 21, 22].

DoA and ToA measurements are not available to inexpensive systems [23], due to the need for antenna arrays or time synchronization respectively. Also, DoA and ToA measurements may be degraded due to shadowing and multipath. However, Ultra WideBand (UWB) ToA systems are most efficient and robust, due to the extended capabilities of rejecting multipath. Unfortunately, UWB-ToA is the most expensive and energy consuming localization technique known today.

On the contrary, RSS indicating-capable equipment is widely available and provides a cost-effective means of position location. RSS based distance estimation may also be degraded due to shadowing as well as multipath, but small-scale fading may be smoothed out by averaging over time or equivalent distance and frequency band [24]. Also, RSS based positioning may be performed by using Scene-Analysis (SA) like in the indoor cases presented in [25–29]. The resulting indoors accuracy is considered to be satisfactory, but onsite calibration measurements are not practical, and some times not possible. Alternatively, onsite RSS propagation model estimation may be used in order to leverage indoor accuracy [15, 30, 31]. In outdoor cases, topographical maps and propagation-prediction tools, as well as statistical modeling, neural networks and particle filters have been used instead of RSS pre-measurements [2, 14, 22, 32, 33–38]. Furthermore, specialized techniques for WSNs have been introduced in order to enhance localization accuracy and reduce uncertainty [22, 39]. Concluding, RSS-based positioning is ubiquitous and inexpensive and such techniques are well eligible provided that they demonstrate

satisfactory accuracy and require little or not at all offline calibration, prior knowledge of the environment etc..

Under the scope of WSN applications, the criterion of accuracy may be deemed less important and then RSS-based localization seems to be the most eligible technique. However, in AAL applications accurate localization may grow to a very important factor, e.g., in cases where mobility patterns or fall detection of the user are required. Thereupon, the entire range of different localization techniques has been evaluated and tested, and results are presented hereinafter. More specifically, we have evaluated and tested the following systems:

i) *The Cricket system*, which is based on Radio-Frequency (RF) and Ultra-Sonic (US) ToA measurements,

ii) *The Ubisense platform,* which is based on a hybrid combination of DoA and UWB-ToA measurements, and

iii) *The WAX system (Wireless-sensor network using Arduino and XBee)*, which is an in-house developed prototype, based on the XBee (ZigBee-enabled) radio modules and Arduino microcontrollers, and performs localization using RSS-SA techniques (Scene Analysis with Received Signal Strength).

3. BACKGROUND, PROBLEM STATEMENT AND RESEARCH OBJECTIVE

3.1. Background

The main motivation for proposing and implementing AAL platforms is the observed increase of average age in modern societies. Together with this increase in average age goes an increase in chronic illnesses as well as an observed increasing rate of coexisting morbidities. The need for assistance and healthcare to the elderly is becoming more and more necessary for social as well as for economic reasons. In many of the existing AAL platforms there are issues such as late or false notifications, as well as lack of reliable information, meaning that sensor fusion of different types of sensors is not widespread yet. Together with a reported low user acceptance, it is safe to conclude that — currently — the preventative assistance to the elderly is incomplete and of low added value.

The EMERGE project aims at implementing an Ambient Assisted Living Platform (AALP) for offering such medical and healthcare services, with a specific target on emergency medical services. The AALP will be based on recording user location and trajectories in order to recognize the daily routine of a person. Based on daily patterns deviations, critical situations will be detected in order to initiate
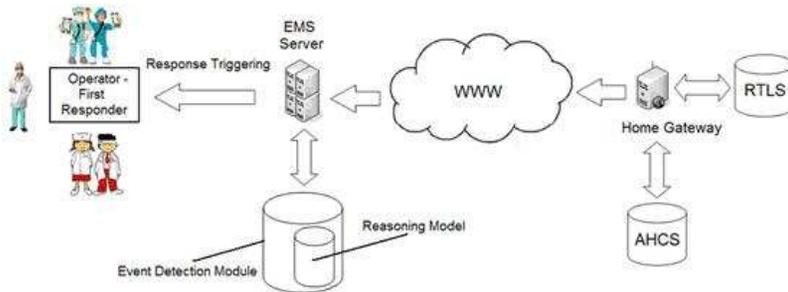
Figure 1. The AALP platform for emergency medical services.

adequate countermeasures. The AALP platform is illustrated by Fig. 1. The Real-Time-Location-Server Module (RTLS) is responsible for collecting all location information regarding the user and forwarding it to the Home Gateway. On the other hand, there is the Ambient Health Care System Module (AHCS), which effectively monitors the health status of the elderly and consists of vital, environmental and activity sensor packs. The data from location and other sensors are aggregated by the Home Gateway and forwarded via the WEB to the Emergency Medical System (EMS) server. The EMS Server feeds the Event Detection Module with data from the RTLS and the AHCS modules. The Event Detection Module includes a Reasoning Model, which detects deviations from typical behaviors using ontologies and AI techniques. In case of an emergency or abnormal behavior, the Event Detection Module triggers the EMS server, which in turn responds by sending an emergency notification to the First Responders Operation Dispatcher. The loop of emergency medical service is closed by doctors, nurses, paramedics etc. who rapidly arrive to the site of the elderly.

Within this context, accurate and timely localization measurements provided by the RTLS module were the primary objective of the research work of our team within the EMERGE EU project.

3.2. Problem Statement

The problem: localize the assisted person in an indoor environment, with an accuracy and performance high enough to reliably monitor his activity and detect falls/injuries, taking also into account ergonomics and minimizing intrusiveness on the user.

3.3. Research Objective

The research objective concerning the RTLS module was to develop, evaluate and test various WSN-based indoor localization platforms and systems. Besides the standard Cricket, Ubisense and WAX systems, the experiments also evaluated proposals for further improving the accuracy, such as a proposed sensor fusion technique as well as preservation of clear Line-of-Sight (LoS) between transmitter and receiver, as described in the following sections.

4. HYPOTHESES, PARAMETERS AND VARIABLES

The following parameters were calculated for evaluating the accuracy performance of the proposed localization techniques and techniques:

- **Average accuracy (m)**: the arithmetic mean value of observed accuracy measurements; gives a straightforward value for the accuracy performance.

- **Median accuracy (m)**: the value of accuracy below which 50% of observed accuracy measurements fall.

- **67th percentile (m)**: the value of accuracy below which 67% of of observed accuracy measurements fall; a performance metric which includes most normal observations and circumstances in general.

- **95th percentile (m)**: the value of accuracy below which 95% of of observed accuracy measurements fall; a performance metric which excludes infrequent peaks.

- **2D accuracy**: the 2D accuracy in each case is calculated using Pythagoras theorem, namely: $d = \sqrt{(x_{est} - x_{real})^2 + (y_{est} - y_{real})^2}$, where d denotes the 2D-accuracy and $x_{est}, y_{est}, x_{real}, y_{real}$ denote the estimated and real values of positioning coordinates respectively.

- **2D relative accuracy**: the 2D relative accuracy is defined in order to provide a common basis for the comparison among different systems deployed at different environments. The 2D accuracy is calculated as the ratio of a circular area of $\pi \cdot d^2$, where d denotes the 2D-accuracy, vs. the area, A, of the deployed network, i.e., length times width of the indoor area where the network is deployed. The relative accuracy, d_R is calculated by $d_R = \frac{\pi \cdot d^2}{A}$.

5. EXPERIMENTAL DESIGN

5.1. Cricket Localization System

The Cricket localization system consists of a number of wireless nodes (the so-called "crickets"), which may be set to act as either beacons or listeners. Beacons are static nodes acting as anchored reference points and are typically attached to Line-of-Sight (LOS) spots, such as on a room ceiling. They periodically transmit an ultrasonic pulse, together with an RF pulse bearing a beacon identifier, position coordinates and other useful data. On the other hand, listeners are attached to fixed or mobile objects that are to be localized. They listen to beacon transmissions and calculate their distance to a nearby beacon using the difference between the ToA of RF and ultrasonic pulses. The distances to nearby beacons are then used in order to calculate the listener's position coordinates by triangulation [6, 40]. Evidently, while in a typical ToA–based localization system expensive beacon-listener RF synchronization equipment is needed, with Cricket the need for RF synchronization is eliminated due to the combined usage of RF and ultrasonic pulses; at the same time, the system relies on ToA measurements, thus being expected to yield highly accurate position estimation results.

In order to develop a model of the Cricket sensor-performance characteristics, a simple testbed was setup as illustrated in Fig. 2. This testbed is used in order to evaluate the measured Distance-to-Beacon (DtB) from a listener, denoted by y_i, assuming a single listener sensor is used. The beacon and listener are placed parallel to one another, at a manually adjusted ultrasonic transmitter-receiver distance and misalignment angle. Listener DtB measurements are propagated to the EMERGE Home Gateway via a Bluetooth wireless link. When the beacon transmitter and listener receiver face each other directly, the respective misalignment angle is defined to be $0°$. The DtB is measured for different misalignment angles, ϕ, within the interval $(0°, 180°)$ and with a step of $10°$, and true DtBs (denoted by x_i) equal to $20\,\text{cm}$, $1\,\text{m}$, $2\,\text{m}$, $3\,\text{m}$ and $4\,\text{m}$.

For any given (x_i, ϕ) the corresponding measurements are time-dependent as denoted by

$$y_i(t) = f(x_i, \phi, t), \tag{1}$$

where $f(.)$ is a (generally non-linear) function corresponding to the outcome of the underlying sensor measurement. The temporal average of these measurements is given by

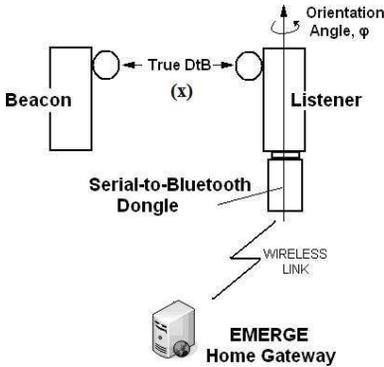$$\bar{y}_i = \frac{1}{T} \sum_{i=1}^{T} y_i(t) = \frac{1}{T} \sum_{i=1}^{T} f(x_i, \phi, t), \tag{2}$$

Figure 2. Cricket DtB measurements with respect to true DtB, x, and misalignment angle, φ.
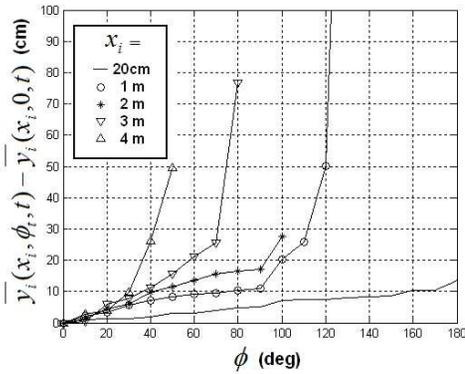
Figure 3. Measured DtB error with respect to DtB measured at $\varphi = 0°$, for Cricket beacon-listener pairs.

where T denotes the observation period. In our analysis herein, we assume that x_i and ϕ remain constant throughout the observation period T (static case) so that time averaging is meaningful as a means of smoothing out noise.

The average $\bar{y}_i$ vs. ϕ, for various x_i is displayed in Fig. 3, for a sample size equal to 80. It is observed that there is a monotonically increasing difference between $\bar{y}_i$ and x_i as well as between $\bar{y}_i$ and ϕ. This increasing error is expected, since increasing x_i or ϕ causes decreasing ultrasonic pulse RSS, which in turn causes higher detection circuits' response time, resulting in an increasing positive error. The increasing measurement error may as well be due to other factors besides the decrease in the ultrasonic pulse RSS, e.g., environmental factors, such as air humidity, pressure and temperature, or hardware factors, such as timing and arithmetic quantization, or errors in detecting ultrasonic signals and variable RF-triggered interrupt service routine delays. Other environmental factors in practical applications may include multipath propagation as well.

Furthermore, the ultrasonic transmitter and receiver radiation patterns of the Cricket sensors are directional and consist of one main directional lobe with a 3 dB-beamwidth of about 90°, while relative side lobe level remains under 20 dB. Therefore, the RSS as well as transmitter and receiver sensitivity drop along directions different than $\phi = 0°$, resulting to monotonically increasing errors. Thereupon, regardless x_i, the most reliable DtB measurements are considered to be the ones corresponding to $\phi = 0°$. Moreover, by Fig. 3, it is observed
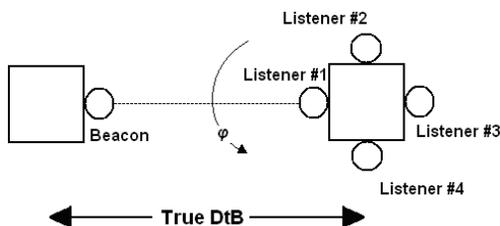
Figure 4. A Cricket beacon and a multi-sensor Cricket bundle of listeners.

that for some beacon-listener distances the ultrasonic pulse RSS drops under the receiver sensitivity for misalignment angles larger than a specific value, e.g., for $x_i = 2$ m no measurements could be obtained for $\phi > 100°$.

The above measurements constitute a performance model for the underlying sensors of the Cricket system. Based on this, a sensor fusion approach is introduced, in order to achieve satisfactory accuracy in the case where Cricket sensors are used as building-blocks of a localization system [6]. More specifically, since a single sensor may yield large errors on y_i measurements, a multi-sensor Cricket bundle consisting of 4 listeners attached to each other at $90°$ angle is proposed in order to achieve accurate range measurements and, thereupon, position estimates. As illustrated in Fig. 4, four Cricket listeners form a symmetrical configuration which covers the horizontal plane with 4 ultrasonic radiation patterns of $90°$ 3 dB-beamwidth each; thus the need for minimum correlation among radiation patterns and complete horizontal plane coverage are simultaneously satisfied. Each listener is identified by a subscript k, $k = 1, 2, 3, 4$; thereupon a measurement of x_i by the k-th sensor is denoted by $y_{k,i}(x_i, \phi, t)$.

According to the proposed approach, all 4 listeners capture the incoming RF and ultrasonic pulses and measure the corresponding DtB. A group of beacons is then selected for triangulation. Since smaller y_i measurements correspond to smaller range estimation errors, the beacons corresponding to smaller y_i measurements are preferable. Thereupon, in the case where the multi-sensor bundle collects DtB values from more beacons than the number needed for triangulation, only the beacons that correspond to the smallest measured DtB values are used. Moreover, the bundle sensors may collect more than one DtB values for a specific beacon; in this case the minimum recorded DtB value for this beacon is used. As will be discussed in following Sections, the performance improvement in the case where the proposed technique is used is spectacular.
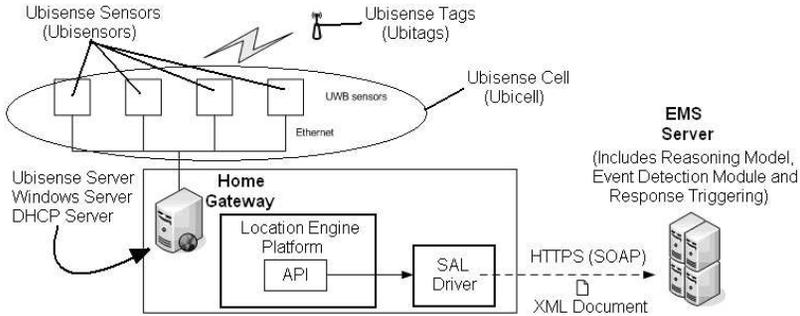
Figure 5. The Ubisense localization platform — overview.

5.2. Ubisense Localization Platform

The Ubisense UWB positioning system mainly consists of three components: battery powered tags (Ubitags) transmitting UWB pulses used to determine their location, plug powered sensors (Ubisensors) mounted on fixed infrastructure which receive and evaluate Ubitag signals, and a software platform which aggregates positioning data, analyses, presents, and communicates information to users and relevant information systems, as illustrated in Fig. 5.

Localization is based on measuring UWB-ToA and DoA from Ubitags to Ubisensors. Ubisensors are grouped into cells, which are typically rectangular in shape, while in each cell a master sensor coordinates and communicates with all tags and remaining sensors. Position information is sent via standard Ethernet cable or WiFi to the Location Engine Platform of the Ubisense server, while data and information are passed to an external application via an API. Furthermore, since all Ubisensors have to be synchronized, each slave sensor is connected with the master sensor via a timing cable too.

The frequency of Ubitag beacon reading depends on the respective desired frequency of user position estimating/tracking, and strongly affects the Ubitag battery life. However, with a typical Ubitag communication frequency of 4 times per second, the Ubitag's battery will last for months according to Ubisense product specifications [41].

Initial data analysis indicated that the Ubisense localization platform exhibits satisfactory performance in general; however there are cases where accuracy degrades substantially, especially with respect to estimating the Ubitag's y-coordinates. It is considered that, these results are due to the fact that the Cell area is fragmented; hence Line-of-Sight (LOS) conditions do not exist simultaneously for all Ubitag-Ubisensor combinations. Furthermore, strong multipath is caused by

the existence of heavy clutter, such as metallic furniture, hardware equipment etc. Multipath propagation severely affects ToA- and DoA-based localization systems, since in both cases multipath components may be mistakenly interpreted as direct path signals. However, LOS existence will generally improve the performance of such systems since the LOS component arrives earlier (for ToA systems) and is of greater power (for DoA systems) with respect to multipath components; thus the probability of false ToA or DoA calculation is lower. In this context, it is considered that, due to the fragmentation of the Cell area, inaccurate measurements may occur by detecting incoming signals from reflections. On the contrary, in the cases where LOS exists between transmitter-receiver, it is expected that the corresponding ToA and DoA measurements will be more accurate.

Based on the above considerations, it is proposed that the localization procedure using Ubisense be completed in three steps. First, the Cell area is partitioned under the criterion that each partition must retain LOS for at least two Ubisensors. Then, an initial position measurement takes place and the system estimates the partition in which Ubitag is located. Finally, a final position measurement is performed, but this time only sensors known to have free LOS to the selected partition are used. The proposed technique is named "LOSSLES" by "LOS-based Selective Location EStimation" [7].

5.3. WAX Localization System

Unlike the preceding localization systems, WAX is an in-house custom-designed WSN platform for both environment sensing/triggering and localization. The core of the WAX platform is a hardware combination of an XBee radio [42] and an Arduino microcontroller platform [43]. The XBee radio module by Digi is responsible for interconnection and wireless communication among the WSN nodes. Furthermore, XBees incorporate the well-established ZigBee protocol as well as a custom-developed MESH network routing protocol. On the other hand, the Arduino microcontroller is used in a limited number of nodes in order to provide computing and processing capabilities. Both node types are equipped with digital and analog inputs and outputs, making it easy to load them with sensors, actuators etc. Additional hardware was also used to provide extra functionality and interface the main components, such as the Arduino XBee Shield, buttons and wires, additional omni-directional antennas etc..

In the context of the EMERGE project, the proposed WSN is focused on providing localization services for mobile users. In order to offer a scalable network, a room-based architecture is proposed. More specifically, wireless sensors are grouped in cells, each of which covers
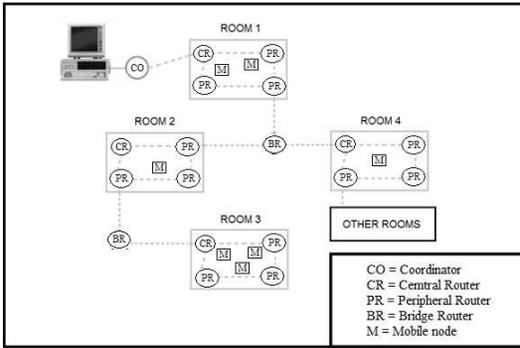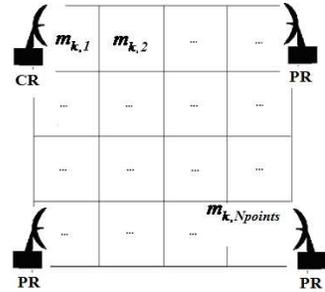
Figure 6. Proposed WAX architecture.

Figure 7. RSS-SA technique used in WAX.

an entire room, as illustrated in Fig. 6. For larger rooms, two or more cells may be used in order to provide adequate signal strength across the entire area. Each cell consists of a Central Router (CR) and a number of no more than three or four Peripheral Routers (PR). The CRs, besides incorporating XBee modules, are also equipped with an Arduino microcontroller which stores information regarding the PRs of the room as well as room properties, such as room coordinates and offline RSS measurements, as will be discussed later in this section. Furthermore, Bridge Routers (BR) are located in between rooms in order to preserve network consistency — from the most faraway room up to the Coordinator (CO). The Coordinator (CO) of the WSN is connected to a sink-server, which is responsible for managing the entire network and storing information about the cell layout, network topology, rooms' coordinates, backup data regarding room properties etc. Finally, each user is equipped with a Mobile node (M), which initiates the localization procedure on request.

Furthermore, a software platform has been developed, in order to integrate XBees, Arduinos and localization services in a fully functional localization platform. The software platform controls the wireless nodes of the network and collects data regarding the location of users. The layout of the WSN coverage area is represented in a GUI, which also displays the locations of users and wireless nodes. The localization technique used is a Scene Analysis based on Received Signal Strength (RSS-SA).

The RSS-SA technique used by WAX is based on performing offline RSS measurements at each room and storing the respective data to the corresponding CR. More specifically, a grid of N_{points} offline measurements points is applied on each room, as illustrated in Fig. 7.

At each grid point, RSS measurements are collected by the M node from the CR and the PRs of the specific room. The RSS from the k-th router (CR or PR) to the i-th grid point is denoted by $m_{k,i}$. Then, a database of these measurements is uploaded to the CR of the specific room. The procedure is repeated for each new room added to the network.

The first time that a M node request to be located, a simple cell-id procedure is used in order to estimate the room in which it lies. Then, the M node downloads the database of measurements from the CR, and launches a typical SA localization procedure [44, 45]. More specifically, it collects the RSS from all room nodes (CR and PRs), denoted by μ_k. Then, the distance in signal space from each offline point, e_i, is calculated, and the M node's position is estimated by the least-distance offline point in signal space, $\min \{e_i\}$. Further improvement on localization accuracy may be achieved by calculating weighted averages from multiple offline points. It is noted that the M-node is located with respect to local room coordinates; in case geolocation is required the room coordinates may be downloaded from the CR or the CO and taken into account during localization.

6. OTHER DESIGN CONSIDERATIONS

6.1. Sample/Test Persons

For purposes of experiment repeatability, the analysis of results was based on measurements from tags mounted on a tripod on specific heights. However, measurements from tags carried by users were also collected in order to examine how they interfere with system performance. All users were volunteers from the staff of NCSR, selected from a pool of persons not familiar with the localization system, in order to avoid potential biased results.

6.2. Instrumentation/Data Collection Tools/Forms/ Templates

Within the EMERGE architecture, the *Sensor Abstraction Layer (SAL)* is the module enabling access to sensor data, addressing the different challenges and constraints connected to WSNs. SAL is a product of Microsoft's Sensor and Context Management technology [46], which was adopted in EMERGE. Specifically, the SAL provides the following features:

- *Web Service Interface* — the Sensor Abstraction Layer enables programmers to discover, access, and consume sensors

data through standard web services protocols (WS-MetaData Exchange, WS-Eventing, WS-Discovery). Those protocols are open to non. NET applications compliant to the WS Specification [47–49].

- *Sensor Abstraction* — the sensor specific details (e.g., communication technology, protocols etc.) are hidden from application programmers in order to allow for an easier integration of sensors into software applications and a flexible use of sensor inside an application. Thus, in the case where different sensor hardware of the same class is used (e.g., temperature sensor), it is not necessary to modify the application. In other words, the same application is able to use sensors from different vendors interchangeably.

- *Different Sensor Access strategies: Pull, Push, Stream* — depending on the sensor data, different access idioms for the data are provided. Reading a temperature value is efficiently done by pulling the data from the sensor. Exceeding a temperature limit can easily be signaled to the application using events. In this case the application does not need to wait for the event to happen, but gets a notification when it occurs. An application focused on a time series of temperature values is best served by a streaming approach.

- *Targeting heterogeneous sensor technologies* — the SAL platform allows the interoperability with different types of sensor platforms such as TinyOS, BSN Nodes, and many others by offering the option to add plug-in modules for those platforms.

- *Extensible* — the sensor field is rapidly changing. New sensor nodes, sensor values, sensor applications, networking technologies, communication protocols will be created. By providing a modular approach for sensor plug-in, the SAL architecture is extendable towards these changes.

- *Distribution of Computation* — computation such as situation recognition, sensor data filtering, or monitoring can be distributed between all components of the sensor network (sensor nodes, sensor gateways and applications). This is important in the context of limited resources. E.g., computing activity data from raw sensor data on the sensor node might be more power efficient than sending the whole video stream constantly to another node.

- *Support of IP and Non-IP based communication technologies* — sensor networks are using different networking technologies, which are not necessarily IP based. Providing IP communication facilitates platform and application implementation.

7. PREPARATION — EXPERIMENT RUN

7.1. Preparation

7.1.1. Cricket Localization System

The proposed Cricket-based sensor fusion and localization algorithm was experimentally evaluated via measurements conducted within the premises of the Institute of Informatics and Telecommunications (IIT) of the National Center for Scientific Research (NCSR) "Demokritos", Athens, Greece. A total of 6 Cricket beacons were attached on the ceiling of a typical office room, at coordinates as shown in Fig. 8 and facing towards the floor, while the room area is $A_{Cricket} = 6.5 \times 5.1\,\mathrm{m}^2$ (length/width). Then, the Cricket localization system and the proposed fusion technique performance were evaluated via sample test measurements at predetermined listener locations within the specified area.

7.1.2. Ubisense Localization Platform

The LOSSLES technique for accurate indoor localization using the Ubisense platform was experimentally evaluated via measurements conducted within the IIT, NCSR "Demokritos". This time, the measurements area included a typical office room, a meeting room
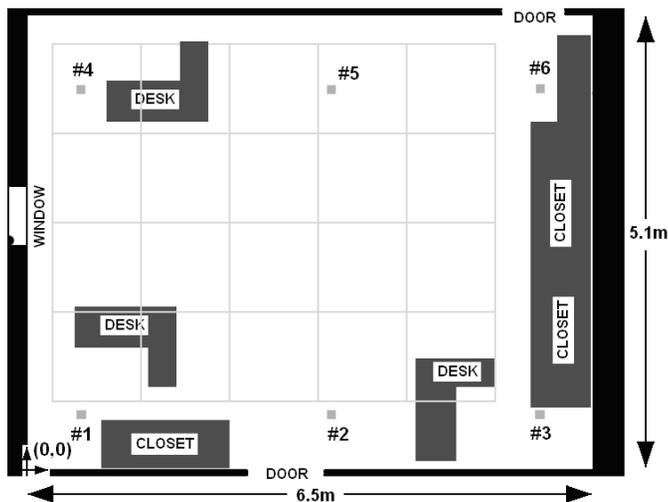

Figure 8. Layout of the measurements area for the Cricket localization system.
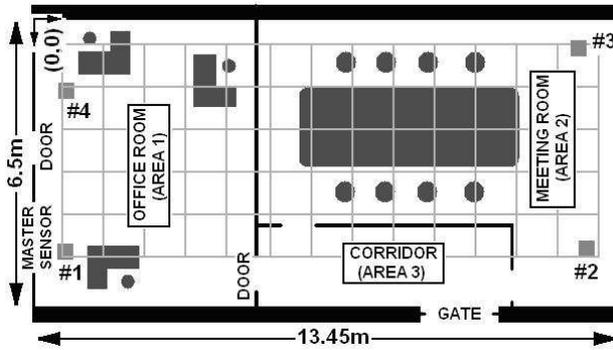
Figure 9. Layout of the Ubisense measurements area.

and a corridor, as illustrated in Fig. 9, in order to demonstrate the capability of the proposed technique to combat Non-los occurring situations. The Ubisensor coordinates were (5.25, 0.70, 2.57), (5.24, 12.53, 2.52), (0.55, 11.86, 2.52) and (1.62, 0.70, 2.54), all units in meters. The area of the room is equal to $A_{Ubisense} = 13.45 \times 6.5\,\mathrm{m}^2$ (length/width). A few calibration measurements were needed during the preparation phase, in order to synchronize time-of-arrival to all four ubisensors. Then, the Ubisense localization platform and the proposed LOSSLES technique performance were evaluated via sample test measurements at predetermined listener locations within the specified area.

7.1.3. WAX Localization System

The proposed WAX localization system and network topology were experimentally evaluated within the premises of the IIT, NCSR "Demokritos", in another typical office room, as illustrated in Fig. 10. The offline measurements points' grid is displayed in the figure, together with the positions of the CR, the PRs and the BRm while the area of the room is equal to $A_{WAX} = 5.4 \times 3.9\,\mathrm{m}^2$ (length/width). After collecting offline measurements and configuring the network (CR, BR, PR, CO and M nodes), a series of tests was performed in various points within the room, including both grid and non-grid points.

7.2. Experiment Run

7.2.1. Cricket Localization System

A number of beacon-listener distance measurements were collected over a grid of points with dimensions $1\,\mathrm{m} \times 1\,\mathrm{m}$, as illustrated in Fig. 8.
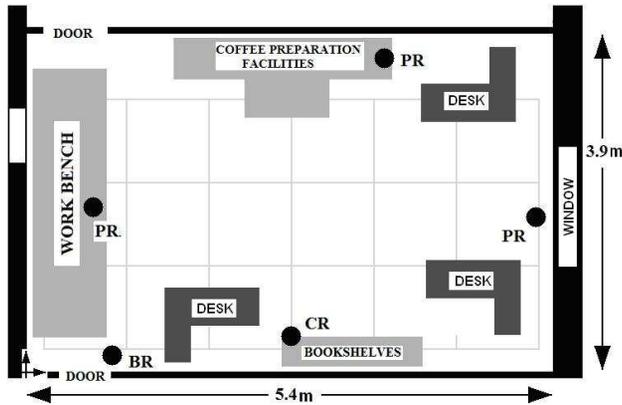
Figure 10. Layout of the WAX measurements area.

At each grid point, measurements were collected for four different listener orientations (North, South, East and West as in Figure) at a height of 1 m above floor level, while listeners were kept vertical with respect to the floor surface. Also, in order to evaluate a typical single-sensor system, further measurements were collected by placing a single listener at the same height and horizontally orientated with respect to the floor surface, since in a single-sensor Cricket system listeners are typically horizontally orientated with respect to floor surface and facing towards the ceiling. Finally, at each grid point the best-achieved-accuracy vertical sensor orientation is selected and compared to the multi-sensor and typical single-sensor accuracies. The measurements for the analysis were collected from tags mounted on a tripod at specific heights, in order to ensure experiment repeatability. Furthermore, a large amount of measurements were obtained, in which tags were carried by users, in order to investigate the effect of user interference in the system performance.

7.2.2. Ubisense Localization Platform

A number of localization measurements were collected over a grid of points with dimensions 1 m × 1 m, as illustrated in Fig. 9. At each grid point, the position of the mobile Ubitag was recorded using all four available Ubisensors. From this initial measurement, the exact area of the Ubitag is determined, and then the LOS-free Ubisensors are defined. Then, the location measurement procedure is repeated, but this time only the LoS-free Ubisensors are used. Thus, both the typical Ubisense as well as the proposed LOSSLES technique are evaluated

and compared to one another, within the same environment and under the same data set. Again, the measurements for the analysis were collected from tags mounted on a tripod at specific heights, in order to ensure experiment repeatability. Furthermore, a large amount of measurements were obtained, in which tags were carried by users, in order to investigate the effect of user interference in the system performance.

7.2.3. WAX Localization System

The proposed WAX system was evaluated in a series of grid and non-grid points during online localization measurements. More specifically, we evaluated 5 grid and 5 non-grid points; at each point the position of the M node was calculated 50 times in order to collect accurate statistics regarding the behavior of the proposed localization system. As expected, the achieved accuracy was affected by the selection of grid and non-grid points, as will be discussed later in the results Section. Again, the measurements for the analysis were collected from tags mounted on a tripod at specific heights, in order to ensure experiment repeatability. Furthermore, a large amount of measurements were obtained, in which tags were carried by users, in order to investigate the effect of user interference in the system performance.

8. RESULTS AND ANALYSIS

8.1. Cricket Localization System

Based on distance measurements from various beacons described in Section 7.2.1, the multi-sensor bundle's as well as the single-sensor listener's position were calculated via triangulation. It was found that, in the case where the single-sensor listener is used, there are numerous grid points for which no position estimate may be calculated, because no ultrasonic pulses from an adequate number of beacons for triangulation were detected. On the other hand, in the case where the proposed multi-sensor Cricket bundle and fusion algorithm are used, the number of points for which no position estimate may be calculated is drastically reduced, as tabulated in the third row of Table 1. Regarding the grid points for which position estimation was feasible, Table 1 demonstrates the respective mean accuracy and the 95th accuracy percentile. It is noted that, with the single-sensor approach, position estimation was feasible for less than 45% of points, while the mean accuracy and 95th percentile for these points was 11.68 m and 27.17 m respectively. These uncommonly large values appear due to the large number of outlier DtB measurements when using a single

Table 1. Summary measurements results for the Cricket localization system and the proposed sensor fusion technique.

	1 Listener only (Calibrated)		4-Listener Cricket Bundle
	Horizontally Positioned	Best Vertical Orientation	
Number of grid points for which position estimation was (not) feasible	13 (17)	21 (9)	28 (2)
Mean accuracy	11.68 m	10.81 m	0.30 m
Relative Mean Accuracy	12.92	11.07	0.0085
95th accuracy percentile	27.17 m	40.17 m	0.82 m

listener. These outliers are efficiently detected and rejected by the proposed method. Indeed, in the case where the proposed approach is used, position estimation was feasible for over 93% of points, while the corresponding mean accuracy and 95th accuracy percentile are 0.44 m and 0.96 m respectively. These data lead to the conclusion that the proposed method dramatically reduces errors in ranging estimation and localization. Finally, it should be noted that there were some points for which the achieved accuracy was better than 5 cm.

Furthermore, the Cumulative Distribution Functions (CDFs) of the accuracy of the single-sensor and multi-sensor configurations are illustrated in Fig. 11 in a logarithmic horizontal scale. In the case of a single-sensor configuration the accuracy CDFs for either a horizontally or a vertically placed Cricket are displayed, while in the case of a multi-sensor configuration the accuracy CDF is displayed. From Table 1 and Fig. 11, it is evident that the proposed fusion and localization technique exhibits dramatically superior performance with respect to a typical single-sensor Cricket localization system.
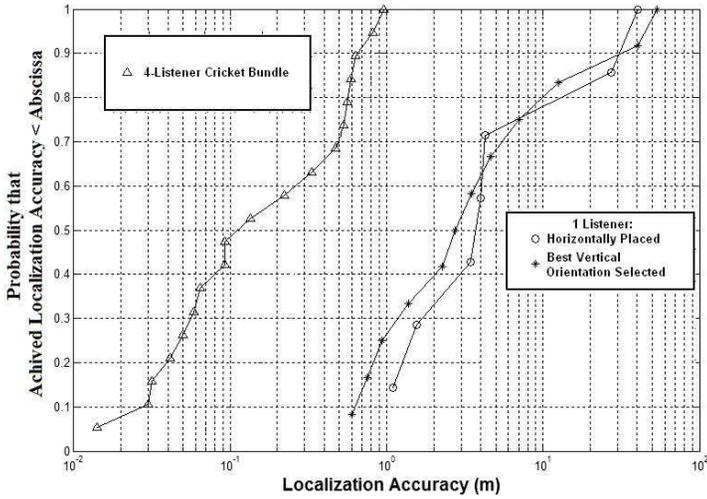
Figure 11. Cumulative distribution functions of the achieved accuracy for the Cricket localization system and the proposed fusion method.
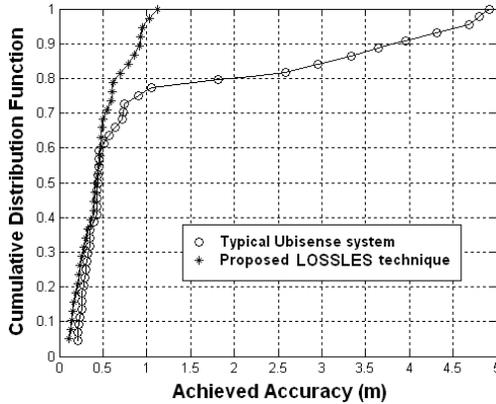

Figure 12. CDF of the achieved 2D- accuracy for a typical Ubisense system and the proposed LOSSLES technique.

8.2. Ubisense Localization Platform

Position measurements are conducted within the Ubi-Cell of Fig. 9, using either the typical Ubisense platform or the proposed LOSSLES technique. Fig. 12 illustrates the achieved 2D-accuracy Cumulative Distribution Function (CDF) for both cases.

Table 2. Performance results for a typical Ubisense and the proposed LOSSLES technique.

	2D accuracy (m)		x-axis accuracy (m)		y-axis accuracy (m)	
	Typical Ubisense	LOSSLES Technique	Typical Ubisense	LOSSLES Technique	Typical Ubisense	LOSSLES Technique
Mean	1.23	0.48	0.34	0.14	1.16	0.45
Relative Mean	0.0544	0.0083	-	-	-	-
Variance	2.40	0.08	0.29	0.01	2.15	0.08
Median	0.44	0.44	0.10	0.11	0.44	0.40
67-th Percentile	0.56	0.48	0.13	0.13	0.52	0.47
90-th percentile	3.80	0.91	1.26	0.28	3.76	0.87
95-th Percentile	3.95	0.95	1.38	0.33	3.94	0.91
99-th percentile	4.86	1.08	1.78	0.37	4.52	1.03

Figure 12 demonstrates that both approaches yield similar median accuracy values, but the proposed approach exhibits significantly lower average and excess percentile values (90th, 95th and 99th percentiles), as further tabulated in Table 2. In addition, Table 2 points out that the proposed LOSSLES technique is more reliable, since the variance of the position estimates is significantly lower. Furthermore, it was detected that inaccuracies with respect to the y-axis are the main reason for the deterioration of 2-D accuracy in a typical Ubisense system and the specific layout area. By applying the proposed technique, the impact of y-axis inaccuracies is significantly decreased; however, the relative contribution of y-axis inaccuracies with respect to x-axis inaccuracies to the overall system performance is still overbalanced. Furthermore, initial Ubitag velocity and acceleration measurements have been conducted using the presented localization platform, and future work involves the development of further data acquisition capabilities for feeding the EMERGE reasoning model. Concerning measurements from tags carried by users, we discovered there is little effect on Ubisense performance from user interference.

8.3. WAX Localization System

The achieved localization accuracy of the WAX system is illustrated in Fig. 13, for a grid a non-grid point. The 90-th percentile of the achieved accuracy is below 0.8 m for the grid point and below 0.9 m for the non-grid point. As expected, the estimated position is more accurate in the case of a grid point, since offline measurements were performed on such points. However, the achieved accuracy is satisfactory in both cases, thus turning the proposed system into a competitive alternative for indoor localization.

Furthermore, Table 3 tabulates certain statistical results of the achieved accuracy for the WAX platform.
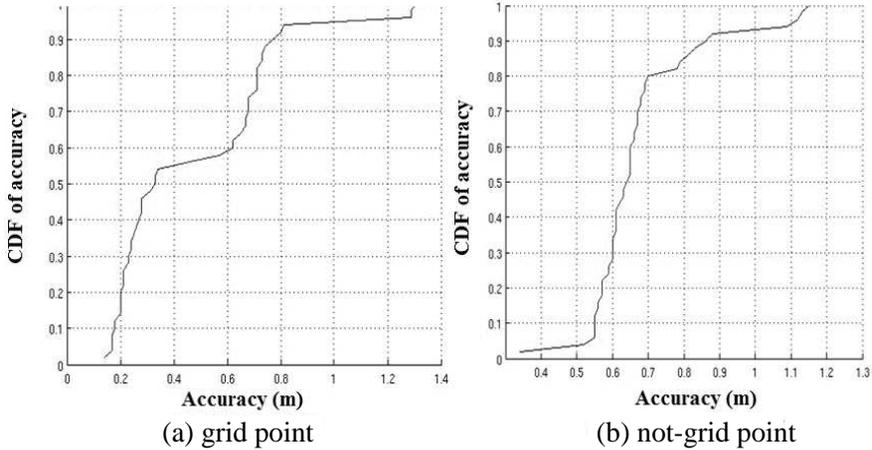

(a) grid point   (b) not-grid point

Figure 13. CDF of the achieved accuracy using the WAX system on a (a) grid point and (b) a non-grid point.

Table 3. Performance results for the WAX platform.

	2D accuracy (m)
Mean	0.83
Relative Mean	0.1028
Std Deviation	0.72
67-th Percentile	1.00
90-th percentile	1.58
95-th Percentile	1.81

9. INTERPRETATION

9.1. Cricket Localization System

1 Listener only: After initial measurements, it was found that, the accuracy in the ToA measurement rapidly deteriorates with increasing true distance and misalignment angle with respect to beacon. For example, the DtB estimation error for a misalignment angle equal to $120°$ and a true DtB equal to $1\,m$ is found to be larger than $1\,m$ (100% error). For larger true DtBs and angles the error is even greater, while the beacon cannot be detected in the case where the angle is larger than $90°$ and the true DtB larger than $3\,m$.

4-Listener Cricket Bundle and proposed fusion method: Although with this setup the accuracy and overall performance of the system is quite satisfactory, the solution is unacceptable from an ergonomics and user requirements point of view, due to the dimensions of the 4-listener bundle. Furthermore, tag measurements carried by users have shown that user presence greatly deteriorates the system performance. Based on these results, the Cricket sensors have been marked as inadequate for the EMERGE platform.

Finally, regarding the compared performance of this system vs. the other two ones, its 2D relative accuracy is equal to 0.0085, which is very close to the Ubisense one.

9.2. Ubisense Localization Platform

The Ubisense system has been tested and found to operate according to product specifications. The accompanying software has been installed in a Windows Server, the Ubisensors deployed over an indoor environment, while Ubitags have been localized inside the Ubicell with adequate accuracy. More specifically, the test Ubicell dimensions were equal to $6.5 \times 13.45 = 87.4\,$sq.m. The achieved average and 90th percentile of accuracy were equal to $1.23\,m$ and $3.80\,m$ respectively. The 2D relative accuracy of the Ubisense system is equal to 0.0083, which is the smallest among all systems considered herein.

In the case where the % accuracy is defined by

$$\% \text{ accuracy } = 1 - \frac{\pi \cdot \text{accuracy}^2}{\text{Cell\_Area}} = 1 - \frac{\pi \cdot \text{accuracy}^2}{87.4}, \qquad (3)$$

the corresponding accuracy percentage ratios for the average and the 90th percentile are equal to 94% and 49% respectively. Moreover the Ubisense system has proven itself a robust solution, with a performance resistant to user interference. Based on these results, the Ubisense systems is marked as adequate for the EMERGE platform.

Furthermore, in the case where the proposed LOSSLES technique is used, the corresponding average and percentile of accuracy drop to 0.48 m and 0.91 m respectively. Thus, the corresponding percentage accuracy ratios become 99% and 97% respectively, thus demonstrating the applicability of the proposed technique.

9.3. WAX Localization System

The WAX system was successfully tested in a typical indoor office room, and the achieved accuracy was found to be below 1 m in all cases. For larger spaces with more rooms, it is expected that the achieved accuracy will remain in below 1 m levels, since location estimation is performed at room level and is not affected by the network size. The achieved accuracy is comparable to the Ubisense one. On the other hand, WAX mobile nodes are still heavier and bulkier than the Ubisense ones, but lighter and more compact compared to the Cricket ones. We are currently working on developing a WAX mobile node that will be lighter, more compact and more ergonomic. Finally, the 2D relative accuracy of the WAX platform is equal to 0.1028, which is quite large compared to the Ubisense and Cricket ones. However, it is noted that the WAX platform is highly scalable, meaning that the absolute accuracy will remain relatively constant for larger environments (with the cost of extra sensors).

Furthermore, the WAX system is resilient in user presence, provided offline measurements are performed with a user carrying the M-node tag. Also, the proposed WAX solution is the only among the three presented that also offers extended sensing and acting capabilities, as it is based on a microntroller and ZigBee radio hardware core. Therefore, it is marked as adequate for the EMERGE platform, but also considered to be the most competitive solution, since it offers scalability and expandability beyond the scope of the EMERGE project.

9.4. Threats to Validity

Threats that might have an impact on the validity of the results are discussed in this section.

Construct/Environment validity: A possible threat is ignoring the interference of specific environment/construct elements, if the experiment is run in an area convenient for system operation, missing possible elements found in the actual end- user environment. The lab room used for setting up the experiments is an actual active office in the NCSR premises. Namely, all sorts of materials (e.g., wood, metal, plastic, glass) and interfering equipment, objects and persons are found

in this room. Therefore results can be safely assumed to be valid across many types of environments.

Internal validity: Selection: Volunteers for the experiment were used from NCSR staff. This is seen as a threat because they might be more aware of technical issues than the average population. However, having this threat in mind, the people that were chosen had totally different domains of expertise and were unfamiliar with related localization systems. Moreover, the use of a tripod for user-free measurements provided with useful information regarding a repeatable localization process. No other internal threat was identified as people simply carry around the beacons, not interacting with the system at any other point.

External validity: Although the setting was not in an actual end-user environment and the test users did not belong to the addressed population, it is claimed that the results can be generalized. Regarding the former, environment validity was justified above within this section. As far as end-users are concerned, their participation is considered in this system passive, with the minimum requirement to carry/wear the beacon on them. As far as user interference with the measurements is concerned, this was actually considered a priori as an experiment parameter under examination, ergo not a threat for the experiment.

Conclusion validity: Reliability of measures and reliability of data processing, quality of data: calibration of measurements in the preparation phase of the experiment as well as use of a different set of tags per experiment run, ensure reliable measurement and processing as well as high quality of data. The use of tripod for measurements in our analysis ensured experiment repeatability and validity of conclusions.

10. REAL-WORLD DEPLOYMENT CONSIDERATIONS

In this section, main real-world deployment considerations are presented for the experimental platforms used.

In Table 4, the *cost* for each platform setup is calculated, given also documentation, support and software provided upon purchase of related products. In the cost calculated there, is also a significant overhead for hardware, software and support needed for development. This extra cost will not apply in the case of mass production. In this case, it is estimated that Cricket and WAX systems would be around 500€ per room for one user while the corresponding cost for Ubisense would be around 5000€. It is evident that, the Ubisense Localization Platform has a relatively extreme high cost compared to the other platforms, prohibiting the platform from being

Table 4. Cost analysis for indoor localization experimental platforms.

System	Details	Price (€) (incl. VAT)
Cricket localization System	The MCS series kit has all of the components needed to develop, test and implement a wireless location system. The kit includes: • 8 Cricket Motes (433 MHz) • 1 MIB510 Programming and Serial Interface Board with DB-9 (Male - Female) RS - 232 Cable • Cricket Support Tools CDROM • User's Manual and TinyOS Getting Started Guide (PDF format)	2.400,00
Ubisense localization Platform	4 Ubisense - Sensors series 7000, 5 Ubisense - Tags (slim tags or compact tags), Ubisense Enterprise software Ubisense Visual Developer, Ubisense Simulator One year's maintenance and support for the software components to include: • software updates to support continuous improvement of the Ubisense product; • support hotline, via email, fax or telephone to aid using and solving problems with Ubisense; Shipments will be CIF (Cost, insurance, freight) destination.	12.500,00
WAX localization System	Besides additional development software and documentation, hardware included: • 6 XBee Wireless ZB RF OEM modules • 3 XBee Boards • 2 Arduino Duemilanove microcontroller • 2 Arduino XBee Shield • 5 AC adapters • 1 Breadboard • Extra electronic equipment	2.500,00

suitable for home applications and users. However, in a professional environment, organizations could consider such a cost when accurate indoor localization is essential. The other platforms offer a solution with a significantly lower budget, however the cost could still be considered as high for most home users. As an overall conclusion regarding cost, inexpensive indoor localization is still a research challenge.

Besides cost, real-world concerns for deploying each proposed solution also include the *ergonomics* of the sensors carried/worn by the user as well as the *intrusiveness* of the corresponding infrastructure.

Cricket: Regarding intrusiveness, 6 Cricket beacons were attached on the ceiling of the room. These are placed in a way where free line of sight can be established with the listener carried by the user, and are therefore clearly visible (as shown in Fig. 14). However, ceiling
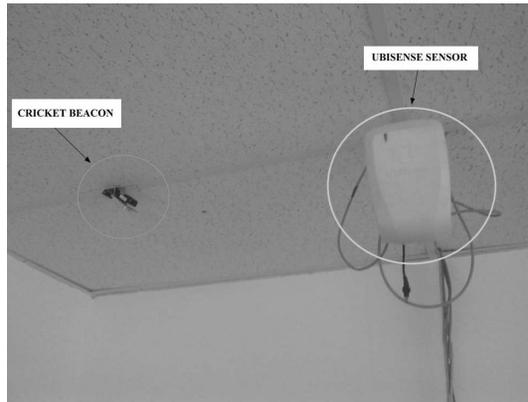

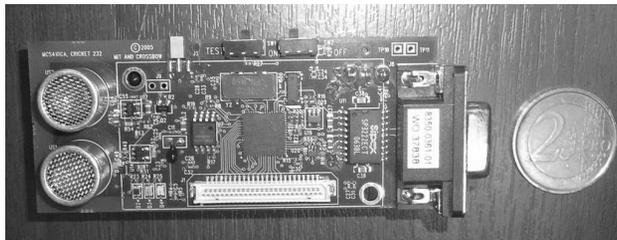**Figure 14.** Example deployments of Cricket (orange) and Ubisense (yellow) sensors.

Figure 15. A Cricket hardware unit; can function as either a beacon or a listener.

Figure 16. Ubisense S7000 Sensors (left) and tags (right) [41].
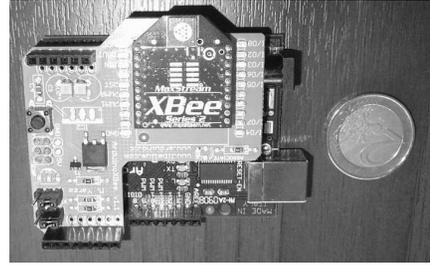
Figure 17. WAX system hardware unit carried by user.

infrastructure is quite compact and small in relative to other solutions with bulky listeners/readers, while power or cat 5 cables are not required. The Cricket beacon is shown in Fig. 15, having dimensions: $88\,mm \times 35\,mm \times 30\,mm$. The ergonomics of the Cricket device carried by the user are quite poor: as shown earlier, in order to achieve an acceptable accuracy the user should carry 4 of these units. Moreover, the cricket unit is in need of proper casing and miniaturisation.

Ubisense: Ubisense hardware units are by far the more mature commercial products from all solutions experimented with. As shown in Fig. 16, sensors and tags are properly cased, and the compact tag measures only $38\,mm \times 39\,mm \times 16.5\,mm$. However, the four sensors attached on the ceiling (Fig. 14) are substantially larger than those of other solutions, measuring $20\,cm \times 13\,cm \times 6\,cm$. Moreover, sensors need both cables for power and Ethernet connection.

WAX: As with the Cricket solution, the WAX system hardware units also need proper casing and miniaturisation before they are released as commercial products. The unit carried by the user actually includes XBee Wireless ZB RF OEM module connected with an Arduino microcontroller via an XBee Shield adaptor. It measures $52\,mm \times 67\,mm \times 27\,mm$ and it also has a small antenna embedded to it, as shown in Fig. 17. Although ergonomics are currently poor for the research version of the user hardware unit, units attached to the ceiling actually consist of the same small-sized XBee board, connected with an external antenna for improved performance while a central unit also contains the Arduino microcontroller. As communication is based on a wireless technology (Zigbee) no cables are required for this purpose.

Finally, *autonomy* and *robustness* factors were considered. Currently, the Ubisense tags have the best autonomy, with a battery life expectancy of more than four years. The corresponding ceiling

infrastructure is connected to AC power, so once deployed no need for further maintenance should be needed. The same applies for the WAX and Cricket hardware units on the ceiling, but these two also offer the option of rapid deployment with no power cables in the case where shorter life expectancy is tolerated.

On the other hand, the WAX battery operated unit on the user has a life expectancy of a few months, depending on the usage. The same life expectancy applies for the user unit of the Cricket system, which is entirely battery operated.

11. CONCLUSION

WSN-based localization is investigated in this paper, by implementation, deployment and experimental evaluation of various localization systems. The depth and breadth of the presented results range through the most popular localization techniques (UWB, ToA, DoA, RSS, SA), while different indoor environments are examined. The well-established Ubisense and Cricket systems were investigated, while new approaches on localization using these systems are proposed (namely, LOSSLES and a custom sensor fusion approach, respectively). Furthermore, the in-house WSN-based WAX system was developed and tested in the context of user localization. Results and conclusions are drawn regarding accuracy performance, but also real-world considerations, such as maturity, intrusiveness, validity threats, autonomy and robustness etc.. The WAX system is found to offer sufficient accuracy for most AAL-platform requirements, while also offering scalability, versatility and expandability, since it can be used for environment sensing and actuating as well.

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