The iLoc Ultrasound Indoor Localization System at the EvAAL 2011 Competition

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Abstract. iLoc is an ultrasound ranging based indoor localization system which is deployed at the iHomeLab laboratory. For example, the system can be used for visitor tracking: Visitors get an electronic name badge comprising an ultrasound transmitter. This badge can be localized with an average accuracy of less than 10 cm deviation in its spatial position, by means of reference nodes distributed in the lab rooms. Depending on the position update rate, a small battery may suffice for several month of tag operation. Other advantages when compared to existing ultrasound ranging systems (like CRICKET, CALMARI, BAT) are for example the simple deployment with its 2 wire "IPoK" bus system. In this paper we report on the system itself and on the participating of iLoc at the first EvAAL indoor localization competition.

Keywords: Real-Time Locating Systems, Indoor Localization, Ultrasound, Ambient Assisted Living, Wireless Sensor Networks.

1 Introduction

Ultrasound time-of-flight measurement is a proven technology for indoor ranging and has already been successfully applied to indoor localization systems in the past. Prominent ultrasound based localization projects are for example the CRICKET, CALAMARI and BAT systems ([1–3]). They provide high and reliable accuracy, achieved with moderate effort. The known ultrasound systems are now some years old and the capabilities of embedded systems have evolved considerably since that time. The newly developed iLoc system takes advantage of developments among others in energy consumption, hardware size, cost, deployment effort and accuracy.

The iLoc ultrasound ranging based indoor localization system (Fig. 1) comprises badges (name tags), detector nodes and a position server, as well as network infrastructure. The name tags (Fig. 4) are equipped with a microcontroller, a radio transceiver and an ultrasound transmitter. They emit ultrasound pulses

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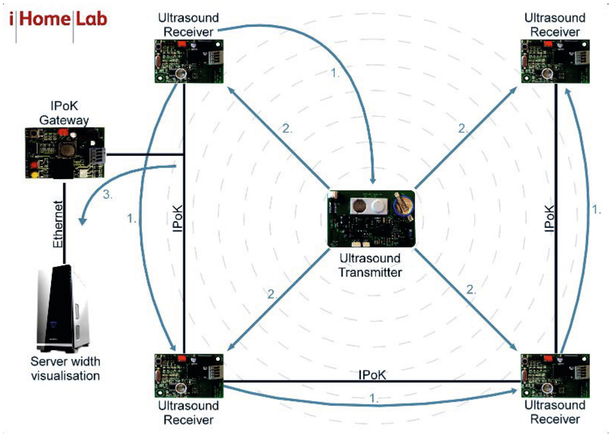

Fig. 1. Setup overview: Four reference nodes are shown. The upper left receiver sends out a synchronization signal (arrows labeled "1") by wire ("IPoK") to the other reference nodes and by radio to the mobile node (center). The mobile node emits an ultrasound pulse (arrows "2") and the reference nodes record the reception time.

at a configurable rate, for example 2 Hz, with a duration of 1 ms. These pulses are received by some of the detectors.

The detector nodes, also called reference nodes, are located at known fixed positions. They comprise a microcontroller and an ultrasound receiver as well as a 2-wire network connection to exchange data and time synchronization information. The nodes record the reception times of ultrasound bursts transmitted by the badges and transmit this information to an IP gateway via the 2 wire bus ("IPoK", [4]). A server calculates position estimates from the received data by multilateration. In the iHomeLab, the position data is used among others for visualization of visitor positions (see Fig. 3). An overview of some iLoc features is described in [5].

A more detailled system layout is sketched in fig. 2: The detector nodes are combined in groups of 10..15 devices (4 each drawn in the figure) to form one IPoK segment, linked with a "foxboard" embedded linux system to an ethernet infrastructure. Position calculation takes place at the iLoc server, from where the data is accessed by applications, for example the visualization. Synchronization and communication with the interactive badges is decoupled from the iLoc server and performed by a dedicated communication server, to increase reliability of the system.

2 Hardware

2.1 Interactive Badges

The interactive badge (Fig. 4) comprises the following hardware blocks: a CC2430 Texas Instruments microcontroller including IEEE 802.15.4 radio transceiver,

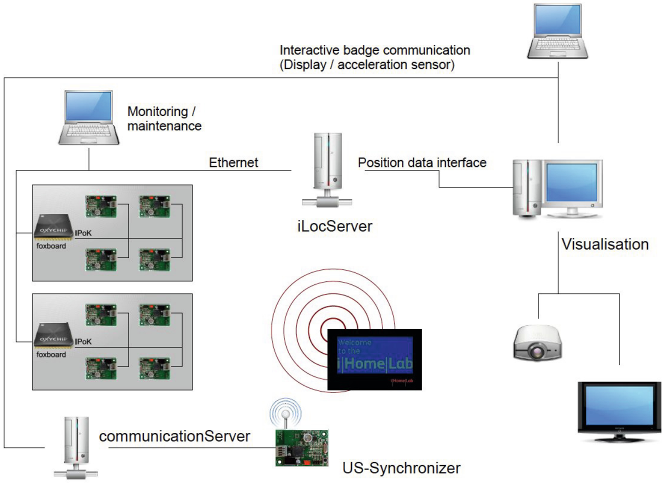

Fig. 2. System architecture: a badge emits an ultrasound burst. Reference nodes measure reception times and send them via IPoK to ethernet gateways labeled "foxboard". From there they are sent to the iLoc server. The server calculates the badge positions and offers a position data interface, which can be queried by remote applications. In the figure, a visualization client uses this interface. The badges and the receiving nodes are synchronized by the US-Synchronizer. This Synchronizer additionally implements a bidirectional communication link between the badges and interested applications, allowing sending of text to the badges LCD display and reading of acceleration- and battery state from the badge. The link is relayed by the optional communicationServer.

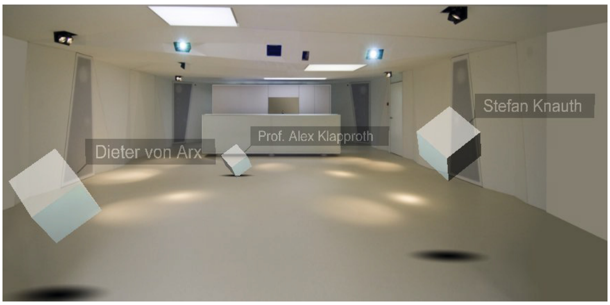

Fig. 3. 3D visualization of visitor positions in the iHome Lab. The positions are given as "hovering" cubes indicating the name of the badge bearer, embedded in a 3D visualization of the iHomeLab.

antenna and HF matching network, a Bosch SMB380 triaxial acceleration sensor, a charge pump chip to generate a higher voltage (20 V) to drive the 40 kHz piezoelectric ultrasound transducer, the transducer itself, the LCD unit, a rechargeable 25 mAh lithium battery as well as an inductive charging circuity. The power consumption of the badge hardware is in the range of 1..10 μW in standby mode and raises to about 50 mW in operational mode, with transition times < 1 ms. The microcontroller comprises a 32 kHz crystal-based wake up timer. The RF design and the sensor circuity is adopted from our WeBee ZigBee

Fig. 4. Name badge with IEEE802.15.4 radio transceiver, ultrasound transmitter and LCD

radio module described in [6]. The LCD carries its own controller and is connected with a serial interface. Power of the display can be switched off by the microcontroller, while the content of the display remains visible. We observed that, depending on the environmental conditions (temperature, vibrations), the display content may actually decline. Therefore a display refresh should occur from time to time, for example once a day. Display- and g-sensor related data communication is carried out between the badges and the communication server by listening and answering to synchronization radio packets which are described later.

The badges are equipped with an inductive battery charging circuity, comprising a coil (part of the PCB layout), a rectifier and overvoltage protection. The badges are charged when put into their storage box, without the need to establish any electromechanical connections, for example by plugs or contacts. The storage box comprises two charging coils operating at a frequency of 125 kHz.

2.2 Reference Nodes

The reference nodes are line-powered and minimal power consumption is not as crucial as for the badge. On the other hand, a large number of these devices have to be deployed and therefore installation and wiring shall be as easy as possible. Therefore the design is considerably different from that of the badges, notably is for example the use of a different microcontroller. The reference nodes comprise a Freescale HCS08GB60 Microcontroller.

For communication between the nodes we chose “IPoK” (IP over Klingeldraht), a protocol developed by us for easy networking of small (in size and cost) embedded devices. The idea behind IPoK is to use a 2 wire multipoint connection as for example RS485, and also supply power via the lines. The IPoK bus carries a 7..30 Volt supply, which is decoupled from the lines by inductors and then converted to 3.3 Volts with a DC-DC converter. The data TX signal is directly coupled in from the Microcontroller. The HCS08 series of controllers offer a 20 mA line driver for the included UART such that the controller can directly drive the line via a capacitor. When not sending, the UART line can be switched to high impedance and no external driver is necessary. For RX, the signal is AC coupled to a comparator or even easier to a pair of standard HC14 Schmitt-Triggers. This leads to a minimum hardware effort for the bus interface circuity.

3 Operation, Timing and Synchronization

The maximum detection range of the iLoc ultrasound signal is about 15 meters corresponding to a maximum ultrasound pulse “livetime” of less than 50 msec. This live time is given by the transmitter ultrasound amplitude, the sound path loss, and the receiver sensitivity, and is a consequence of the specific iLoc device parameters and the used sound frequency of 40 kHz.

There exist several design approaches for ultrasound localization systems with multiple mobile nodes. It is important to avoid ultrasound interference between the nodes (see for example [1]). One commonly used approach is to let the fixed infrastructure emit the pulses and send radio packets identifying the sending node. This has some advantages, for example privacy. The mobile node can detect its position without the system knowing that the mobile node exists. Also the number of mobile nodes is not limited in this case as they are passive. A disadvantage of this approach is that the mobile node has to listen for a certain time to radio and sound messages before being able to detect its position.

A main design goal of the iLoc system is that the mobile nodes (currently the name badges) shall consume as little energy as possible. Therefore we chose the opposite approach, using active mobile nodes and a passive detection infrastructure. The mobile nodes themselves emit the ultrasound pulse. For each node a 50 ms time slot is allocated, corresponding to the maximum lifetime of the propagating ultrasound pulse. The time needed for the position determination of n nodes is therefore $T = n \times 50\text{ms}$. A typical number of nodes in our lab is $n = 20$, so the position update rate for the nodes is 1 Hz. Other update rates are configurable, for example 10 Nodes with an update rate of 2 Hz each.

To allow the TDMA operation, the whole system is synchronized. As mentioned, the fixed nodes communicate via the “IPoK” two wire cabling. The system comprises several “IPoK” segments, each connected via ethernet to the iLoc server. Within the segments, the nodes are synchronized by data packets via IPoK. Each segment comprises a dedicated node which receives radio synchronization messages from a central time information transmitter, driven by the communication server.

The central synchronization radio signal is also used by the mobile nodes (name badges) for synchronization. To achieve a synchronization accuracy of about 50 μs, the mobile nodes need to resynchronize every 2-5 seconds. Actually the operation is as follows: The synchronization signal is sent with the slot rate, i.e. every 50 ms, containing also the number of the badge that shall send a pulse in the current slot. For $n = 20$, the nodes therefore wake up every second just prior to the moment when they expect their next synchronization signal. They listen for the synchronization packet, readjust their clock, emit their pulse and go to sleep again. The whole sequence takes about 5 ms, leading to a duty cycle of 1/200. The electric current in active mode is about 20 mA, leading to an average current of about 100 μA, at a voltage of 2.5 .. 3 V, enabling operation times of 10 days with a small lithium coin cell, and one update per second. The following table lists some operational times:

Battery type	Duty cycle	operational time
Lithium coin 25 mAh	1 sec	10 days
	10 sec	3 month
Lithium 500 mAh	1 sec	1/2 Year
	10 sec	> 2 Years
AA 2000 mAh	1 sec	2 Years

4 Deployment in the iHomeLab

Basically, 3 range measurements from 3 different reference positions allow the determination of the tag position. Given the above mentioned 15 meter iLoc maximum ultrasound range, these conditions would be fulfilled for example by deploying the reference nodes in a lattice with a spacing of about 10 meters. Practically, depending on the desired accuracy, the density of reference nodes should be much higher such that the distance to the furthermost node does not exceed approximately 5 meters. Then every point in the room is in the ultrasound range of more than 5 reference nodes, increasing the stability of the system against ultrasound interference for example by noise emitted from machinery or people. The ultrasound signal needs a line-of-sight for propagation, which can get lost by a shading caused by the body of the wearer of the tag or by other visitors in the same room. Also reflections have to be taken into account.

In the lab currently more than 70 nodes are arranged in 6 IPoK bus segments (fig. 5). Typically an emitted pulse is detected by about 5–15 receivers. Inconsistent range reports are rejected by the multilateration algorithm with a simple but computing intensive procedure: From the reported ranges for all permutations of 3 readings a position value is calculated. By stepwise removing of calculated positions lying outside of the mean value, the most probable readings are selected for the final trilateration [7].

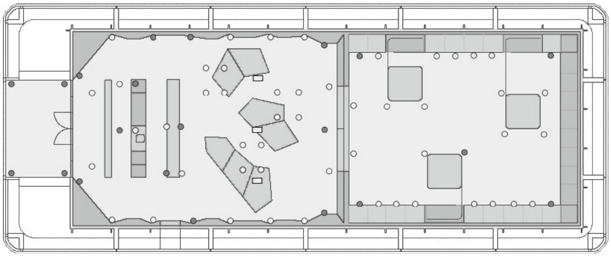

Fig. 5. Positions of the 70+ ultrasound receivers in the iHomeLab. The inner gray rectangle indicates the covered area (about $10m \times 30m$). The iHomeLab is located at Lucerne University of Applied Sciences at Campus Horw.

The deployment effort is kept at a reasonable level by using a 2 wire bus system providing power supply and communication to the nodes. Such two wire systems are commonly used for building automation purposes, and are often referred to as “fieldbus”. There exist a variety of standards and vendors. As mentioned we did not opt for an existing fieldbus system but used our own implementation (“IPoK”) to keep the bus interface hardware on the nodes simple.

In order to achieve a high accuracy of the system, the positions of the ultrasound receivers need to be accurately determined. Actually only a fraction of the positions have been laser measured. For the remaining positions only estimations have been entered to the database. Then the estimations have been adjusted by reference measurements: A mobile tag (name badge) was placed at a grid of known reference positions and time-of-flight results were recorded by the receivers. The position data of the reference receivers was then adjusted until the measured range values for a particular reference node matched best with the calculated distances. This fitting process was performed by minimizing the sum of the squared differences between measured range and calculated range.

Another possible automatic reference position determination solution is “leapfrogging” [8], especially feasible for temporary deployments: Here the position of some reference nodes for example at a corner of the deployment area is determined manually. Then a subsequent node is localized by the system using the already localized nodes, and so on. This mode requires the ability to use a given ultrasound transducer of a node not only as receiver, but also as transmitter. The feature is currently going to be implemented for future deployments.

5 Applications

Acceleration sensor data is used by the fall detection application: If the badge measures unusual acceleration values, it reports these values to the system. The fall detection application acquires position data from the iLoc server, analyzes the data and situation and decides whether a fall alert shall be generated. A sample of such an alert screen is shown in fig. 6. Also long term motion patterns of bearers can be recorded and analyzed to detect unusual behavior of persons

Fig. 6. Fall detection application: The name badges transmit acceleration sensor data to the system. In case of a fall, an alert is generated, indicating the location of the incident.

like changed wake up time, slower motion speed, etc. which may indicate a medical threat.

In a setup where the system is used in a hospital or a retirement home, context-relevant information may be indicated by the badges display such that a nurse nearby may immediately see relevant emergency medication or illnesses of the patient which may have to be considered in the emergency treatment. Of course, the system may also be used without display, allowing the employment of smaller tags.

Another application in the area of assistance systems is finding of assets. For example, the medicine box, telephone, or glasses may be equipped with an ultrasound tag. If the owner cannot remember where he had placed these things, he may by some modality be informed about the current position of his belongings.

6 Competition Negotiation at CIAMI Living Lab

6.1 Setup

For the competition a setup with 28 receiver nodes arranged in 3 IPoK lines has been chosen. This leads to roughly 2.5 m^2 coverage per node. It was a requirement that the system had to be installed within one hour. This ruled out the common deployment approach where first the nodes are placed and later the positions of the nodes are determined. Instead, the positions of the nodes were defined prior to the physical installation. Positions where chosen such that they lay in junctions of the lattice structure of the Living Lab ceiling (fig. 7).

This allowed physical node placing to be performed without having to use any measurement equipment like laser devices or a tape measure. The nodes were placed on certain predefined positions of the ceiling grid, by means of double-sided adhesive tape. Of course, this approach relies on a grid or other alignment structure, which is not normally given in a typical home. The three IpOK lines

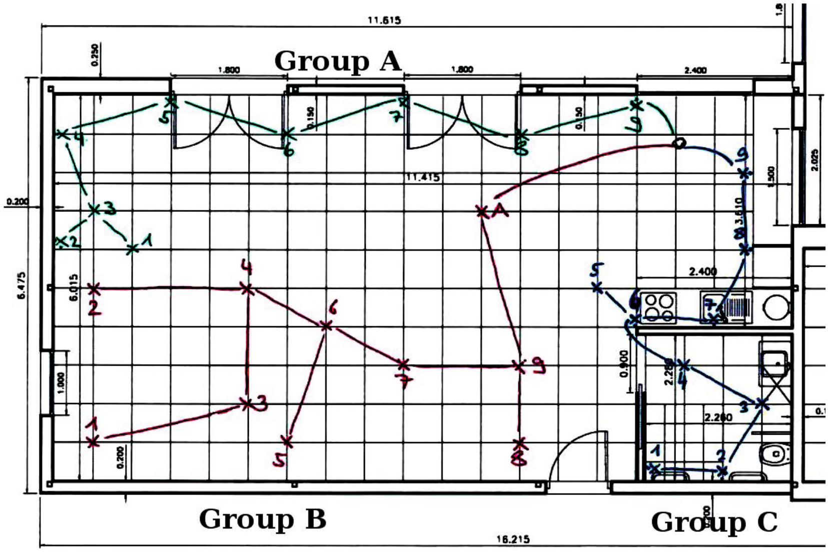

Fig. 7. Positions of the 28 iLoc receivers at CIAMI Living Lab. The nodes are arranged in 3 wiring groups, as indicated in the image.

had been wired already at our workshop such that no wiring had to be performed on site. The setup time for the system at CIAMI Living Lab was about one hour, and was mainly caused by the taping of the pre-wired nodes.

6.2 Accuracy

The score evaluation procedures were defined and published by the EvAAL technical committee, well before the competition run. We will discuss here mainly the accuracy score, which comprises a tracking run and an AOI (area of interest) detection. The rule for the tracking accuracy is to look at the individual error for each position measurement. This is the distance between the real position and the position reported by the localization system. The overall error is defined as the highest of the lower 75 percent of reported error values. From this overall error value, a score is calculated.

The obtained accuracy score for iLoc was 8.8 which means that 75 percent of the measurements were better than 80 centimeters. A typical result is shown in fig. 8. The figure indicates that the accuracy performance of the system was quite position-dependent. The walk of the test person starts in the sleeping room. Here the error is above 1 meter. After leaving the sleeping room, the track traverses the living room towards the bathroom. In this phase the deviation from the actual track is well below 50 cm, despite some outlying points which might have been induced by acoustic or electromagnetic noise. The situation changes again when entering the bathroom. Here the path in the room again shows derivations of above one meter, the final position is then detected well.

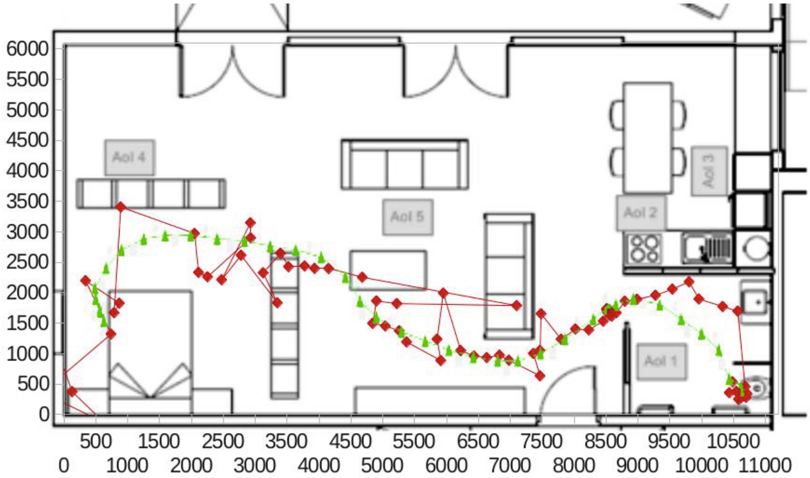

Fig. 8. Positions obtained for a specific test during the competition at CIAMI Living Lab. Bright/yellow triangles indicate real path, dark/red diamonds indicate iLoc results.

In order to detect a position value, a minimum of 3 nodes have to receive a direct ultrasound signal. If more nodes receive a signal, the quality of the position reading is increased among others by the ability to detect and ignore reflected signals [7]. The sleeping room and the bathroom were equipped with 4 receivers (fig. 7). As the badge mostly transmits in front of its bearer, it is possible that direct transmission occurs only to two receivers, degrading considerably the performance. The performance in the quite open living area was considerably better since more nodes had line-of-sight with the transmitting badge.

The score for the AOI detection is derived from the ratio “number of correct reports” divided by “total number of reports”. iLoc obtained score was 71 percent, meaning that 71 percent of the measurements where assigned the correct AOI respectively “no AOI”. The AOIs were squares with a size of 60 times 60 cm. Fig. 9 allows a qualitative discussion: Most of the AOIs have been detected well. Actually the final AOI positions were slightly different from those indicated in the figure, but still AOI 5 (in front of the sofa) was not detected correctly, and also AOI 6 (the right AOI in the kitchen area) was somewhat shifted. A possible reason could be a misalignment of receivers. In the case of AOI 5, the values were heavily disturbed and spread. This might be attributed to the sound produced by the metronome, which was used to synchronize the movement of the person walking on the path.

7 Results and Outlook

The iLoc indoor localization systems currently tracks for example 10 mobile nodes with a position update rate of two measurements per second per node,

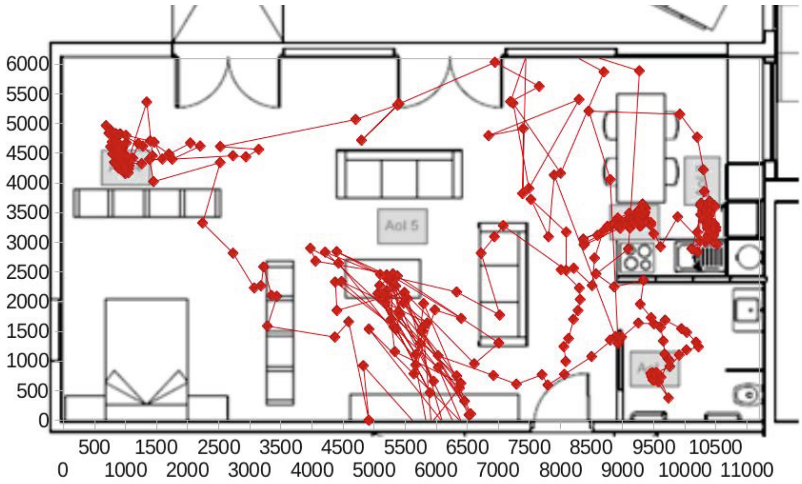

Fig. 9. Positions obtained for the AOI detection during the competition at CIAMI Living Lab

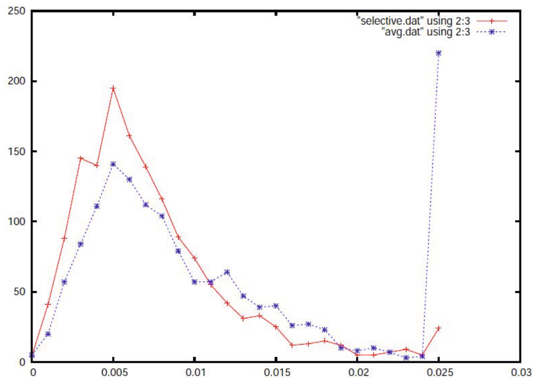

Fig. 10. Observed position error in a lab environmet after careful adjustment (not the EvAAL setup): dashed line (blue, *) indicates positions which were obtained by multilateration. Solid line (red, +) indicates positions calculated with trilateration and a selection algorithm. X-Axis: error [meters], Y-Axis: number of samples [7].

with an accuracy below 10 cm, for single measurements with no temporal averaging applied. Fig. 10 shows data from a set of about 1500 subsequent measurement cycles, with at most 8 out of 9 reference nodes reporting time stamps. The rightmost values include all measurements lying outside of the graphs X-Axis. During the recording of the observations, the sound propagation was intentionally disturbed by noise, i.e. people walking around thereby shielding the ultrasound reflectors. The high overall accuracy of the reported position values (95% within <2 cm) has been achieved by careful determination of the sound velocity and position data of the reference nodes. Under "real world" conditions, the error is typically still be well below 30 cm, provided that the alignment of the nodes has been performed with respective care.

The 2011 EvAAL competition allowed to compare the system with other competitors and technologies under identical conditions close to a real AAL scenario. We found that

- The obtained accuracy results were among the best in the competition.
- The room affiliation to bathroom, living room, sleeping room etc. was always correct.
- The installation effort was high compared to other competitors. It was still possible to set the system hardware up within 1 hour.
- User acceptance and software integration capabilities should be increased.

The results of the event strongly influenced the further development of the system. Currently the system is changed to comprise a battery powered wireless infrastructure. This, together with an automatic calibration procedure, considerably decreases installation effort. The abandonment of the wiring also increases user acceptance as the system is visually less present. The overall accuracy of the iLoc system is higher than the one obtained by the participating radio signal strength based systems. We especially propose the iLoc indoor localization system for situations where accurate positioning and tracking and an accurate room affiliation is needed in a particular AAL application.

The installation of the system is possible with moderate effort in typical indoor housing, warehouse or laboratory environments. The development includes the basic ranging electronic setup, firmware, system aspects, the timing- and multilateration algorithms, middleware and application software. Current applications of the system are visitor tracking and fall detection. The two way radio communication enables, among others, applications in the field of ambient assisted living. Long term battery operation is ensured by strict TDMA operation. The iLoc system is installed at the iHomeLab (www.iHomeLab.ch) at Lucerne University of Applied Sciences. The focus of further applications in the iHomeLab will lie in the sector of ambient assisted living.

We were glad to participate at the first EvAAL competition on Indoor Localization and experienced the EvAAL initiative with its combination of scientific workshop and real system competition as very encouraging and fruitful.

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