Localization System Supporting People with Cognitive Impairment and Their Caregivers

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Abstract—**Localization systems are an important component of Active and Assisted Living (AAL) platforms supporting persons with cognitive impairments. The paper presents a positioning system being a part of the platform developed within the IONIS European project. The system's main function is providing the platform with data on user mobility and localization, which would be used to analyze his/her behavior and detect dementia wandering symptoms. An additional function of the system is localization of items, which are frequently misplaced by dementia sufferers.**

The paper includes a brief description of system's architecture, design of anchor nodes and tags and exchange of data between devices. both localization algorithms for user and item positioning are also presented. Exemplary results illustrating the system's capabilities are also included.

Keywords—**Active and Assisted Living, Bluetooth Low Energy, dementia, Internet of Things, localization, UWB**

I. Introduction

RAPIDLY progressing aging of European populations means that the diseases typical for older people will become a growing problem in the years to come. One of the most prominent problems are different variants of cognitive disorders ranging from light forms to severe dementia. People with cognitive impairment require monitoring, diagnostics and support in the early stages of the disease and intensive care in the more advanced stages [1]. The caregivers can be supported in the above tasks by localization systems installed in the homes of the elderly people.

The localization data supplied by such systems can be used for assessment of person's health and wellbeing. Such systems allow to evaluate person's activity [2] and detect anomalies in person's behavior as described in [3]. The solution, which enables assessment of the person with cognitive impairment condition is described in [4].

In case of persons in later, more severe stages of dementia, another symptom known as wandering often occurs. Wandering behaviors typically include aimless persistent walking, eloping behaviors and spatial disorientation. Localization data can be used to detect such incidents and prevent their, sometimes severe, consequences. Proposals of localization systems equipped with such functionality can be found in [5] and [6].

Another problem common for people suffering from dementia is distraction and forgetfulness, which often causes

them to mislay their important personal belongings. According to the survey results presented in [7] the repercussions of that problem do not affect the patients only. Over 50 % of the caregivers admitted that they typically spend almost half an hour a day helping the patients to find their personal belongings. This problem could be solved by using the systems to localize not only the user but also their most important items. An example of the item localization system is presented in [8].

Positioning systems for AAL applications should fulfill many specific requirements [9]. First of all due to low technology acceptance by the elderly people they should be as unobtrusive for the tracked person as possible. The localization results should be reliable and their accuracy should fit the system's intended use. In the majority of the applications the positioning accuracy should allow for determination of the room, where the person is located. However, for wandering detection, localization precision should allow for unambiguous tracking.

There are plenty of technologies that can be used in localization systems for AAL (Active and Assisted Living) purposes. Radio, ultrasound, laser and infrared based solutions have been proposed in literature. Some technologies should be avoided because they typically do not gain elderly persons' acceptance. Vision and sound recording systems are examples of such solutions.

The proposed and widely tested solutions are dominated by radio localization systems, which offer sufficient range and localization accuracy. Additionally, thanks to propagation of signals through walls, it is possible to reduce their infrastructure and thus lower their cost and simplify their deployment. The majority of the radio localization systems are based on popular and low cost narrow-band radio interfaces complying with BLE (Bluetooth Low Energy) [10], ZigBee [11] or WiFi [12] standards. Almost all solutions exploit information on radio signals levels. The collected measurement results are typically used for distance determination or in fingerprinting based methods.

The performance comparison of systems based on BLE, WiFi, ZigBee technologies is presented in [13]. The typical localization errors obtained with such systems range from one to several meters. Such accuracy might be insufficient for some applications. The performance of the narrowband systems can be improved by using hybrid techniques, which utilize additional data obtained with different technologies. An example of such solution is a system where fusion of BLE data with WiFi based fingerprinting is implemented [14]. The system merging radio technology with inertial sensors

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is presented in [15]. The accuracy of the localization in the chosen, significant places can be also improved through the use of proximity sensors [16].

Only a few publications describe application of UWB (Ultra Wideband) technology in AAL applications [4], [17]. UWB provides high positioning accuracy up to a dozen centimeters. However, the those solutions are more complex and overall costs of UWB based systems are higher than of their narrowband counterparts.

Currently, localization systems supporting people with cognitive impairment are mainly the subject of research carried out under various projects and these solutions are not offered on the market. The paper presents the localization system implemented as a part of the AAL - IONIS project [18], which aims to design and deliver an ICT platform supporting people with cognitive impairment and their carers. The developed system targets both individual elderly persons living independently and inmates spending their time in the long term care facilities.

In case of its application for individual users, the system gathers information on persons mobility and behavior in order to detect potentially dangerous wandering incidents. Therefore, the localization accuracy and precision of the user should be as high as possible and for that purpose UWB technology is used. An additional function of the system is item search support. The system allows also to localize tags attached to important daily use objects, which are often being misplaced by dementia sufferers. The item search support is accomplished with a dedicated tablet application, which takes patient's cognitive information into consideration. The interface is simple and the application provides only the information on the room, where the sought item is located. Thus localization accuracy does not have to be very high and the tags can be localized using more energy efficient BLE technology. The tags for item localization are additionally equipped with a blinking light and a buzzer, which help to locate them in the indicated room.

The main objective of the system version intended for use in long term care facilities is determining the areas, where the patients are located, which significantly lowers the accuracy requirements and it can be realized using less expensive BLE modules. The mobility and behavior of the patients are analyzed by the personnel as a part of the daily routine.

In both of the applications an important, partially independent function is fall detection. The tags are equipped with inertial sensors, which allow to detect falling down accidents. In case of an incident the platform would send an alert to the caregiver.

The paper describes the localization system being a part of the IONIS platform. Section II describes the system architecture, presents the devices and basic operation principles. The algorithms used for user and item localization are presented in Section III. The results of experiments verifying systems capabilities are presented in Section IV.

II. LOCALIZATION SYSTEM

A. System architecture

The system functional architecture is shown in Fig. 1. It is a multilateral solution in which the tags worn by the monitored users or attached to the localized objects are the source of packets sent using UWB and BLE radio interfaces. The role of the anchor nodes which form the infrastructure is to determine UWB packets' arrival times, measure BLE signal levels and process data from the received packets. The measurement results are transmitted to the system controller over a WiFi network. Based on the received results, the controller calculates the locations of the particular tags and provides the results to the applications implementing location-based services. The use of wireless connection between the controller and the anchor nodes allows for easier installation of the system.
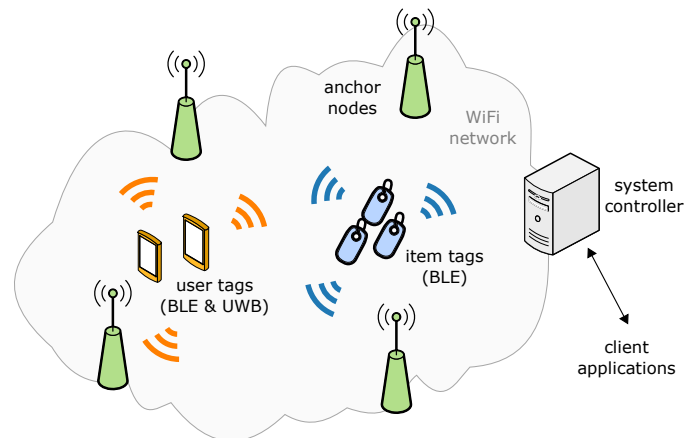

Fig. 1. Localization system architecture

The localization algorithms implemented in the system are TDOA (Time Difference of Arrival) and RSSD (Received Signal Strength) based. In order to correctly calculate TDOA values the anchor nodes need to be synchronized. It is achieved by having one of the anchor nodes periodically transmit synchronization packets. The data sent in that packets allows to synchronize the internal counters operating in the nodes, while measurements of the reference periods between consecutive packets allows to correct the deviations of anchor nodes' clocks.

B. Anchor nodes

The block diagram of the anchor node is presented in Fig. 2. The anchor operation is maintained with a TM4C123GH6PZI microcontroller [19] from the Texas Instruments Tiva family with an ARM Cortex-M4 processor. The node contains four radio modules:

- DWM1000 [20] ultra-wideband module compliant with the IEEE802.15.4a standard, which task is to receive and measure the times of arrival of synchronization packets and packets sent by the tags,
- two BL652 modules from Laird [21] compliant with the Bluetooth 5.0 standard - they are used for communication with tags and measurement of the levels of signals transmitted by them; the use of two modules allows for the reduction of the effects of multipath propagation on the measurement results,

- Digi XBee Wi-Fi [22] module from Digi International used for communication with the system controller.
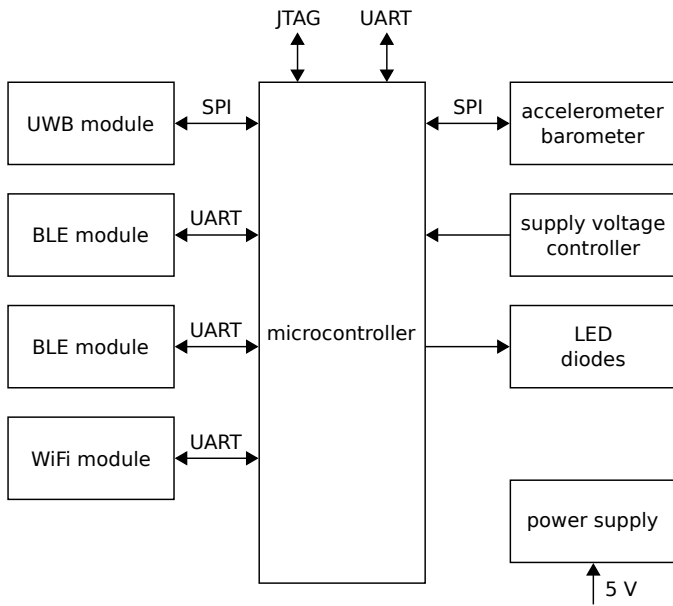

Fig. 2. Block diagram of the system node

There are two MEMS (Microelectromechanical System) sensors mounted on the anchor node's board: a barometer and an accelerometer. The role of the barometer is to determine the reference atmospheric pressure at the premises where the system is installed. In case of multi-floor buildings, by comparing this value with the measurements made by the tags, the difference in the height can be obtained, which would allow for the determination of the floor on which the tag is located.

The accelerometer is used to detect potential displacement of the node. Since the localization algorithm's accuracy depends on the accuracy with which the locations of the anchor nodes were determined, the signal from the accelerometer informs that the anchor was moved and re-determination of its coordinates might be needed.

The node is powered from an AC adapter. The task of the supply voltage control system is to detect and report potential problems with the power supply.

C. Tags

In the IONIS indoor localization system two types of tags are used:
- user tags used for person localization
- item tags attached to frequently sought belongings.

The block diagram of the user tag is shown in Fig. 3. The tag is equipped with two radio modules: UWB and BLE of the same models as those used in the anchor nodes. The UWB module is used only for localization purposes, whereas the BLE module allows the transmission of small amounts of data to the nodes.

Two MEMS sensors (an accelerometer and a barometer) from Bosch Sensortec were installed in the tags. The BMI160 accelerometer [23] allows for the detection of rapid changes in acceleration, which are typical for falling down events. The

BMP280 barometer [24] is used to detect the increase of the ambient pressure which is an another factor related to falling down. In case of the fall detection, an alarm is sent in the BLE packets. Additionally, the button installed in the tag allows the monitored person to call for help in other life-threatening situations.

The tags are controlled by the energy-efficient MSP430FR2155 microcontroller [25] from Texas Instruments. A simple SBW (Spy-Bi-Wire) interface was used to program the microcontroller. Due to the high energy requirements of the used UWB radio module, it was necessary to supply the tag with a battery, that can be charged from an external charger.
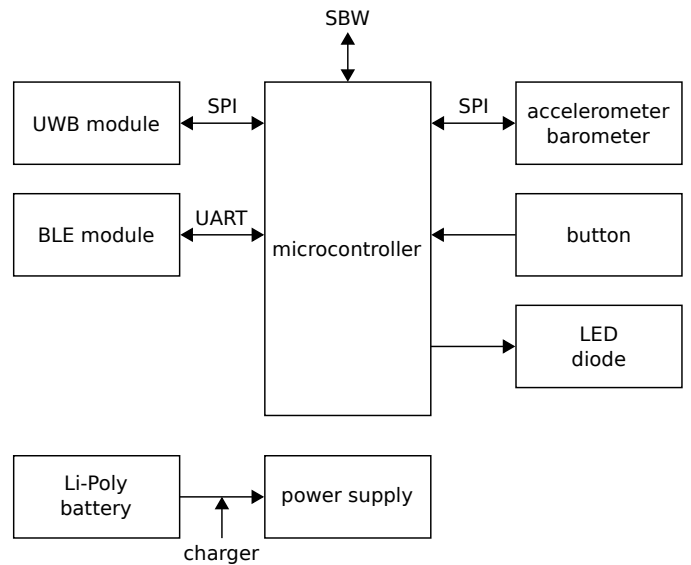

Fig. 3. Block diagram of the user localization tag

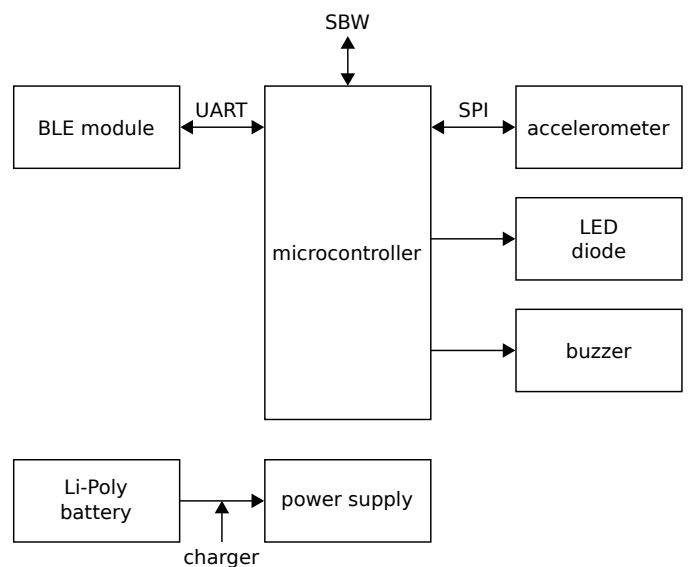The construction of the tag for the localization of objects is a bit simpler (Fig. 4).

Fig. 4. Block diagram of the item localization tag

In order to the extend the tag's lifetime without the need for recharging the battery, the ultrawideband module was removed. As a result, item localization is based solely on the measurements of the BLE signals levels, which results in lower accuracy of position calculation, but is acceptable for the intended use of those tags. The tag is equipped with a LED diode and an acoustic indicator, which can be activated after initiating the search for the object (tag). The buzzing and blinking of the tag would lead the user to the exact sought item location.

The accelerometer (BMA280 [26]) allows for detection whether the tag is moving or is stationary. In the latter case, BLE packets emission may be limited in order to preserve battery. The use of the lithium polymer battery is necessary, as the acoustic sounder operating at the frequency of roughly 1 kHz (CMT-1411R [27]), can consume up to 90 mA of current during signal emissions.

D. System controller

The role of the system controller can be performed by any computer using either Windows or Linux operating system. Research conducted as a part of the project showed the possibility of even using the Raspberry PI minicomputer for this purpose. The system controller's software structure with the most important data flows marked is presented in Fig. 5.
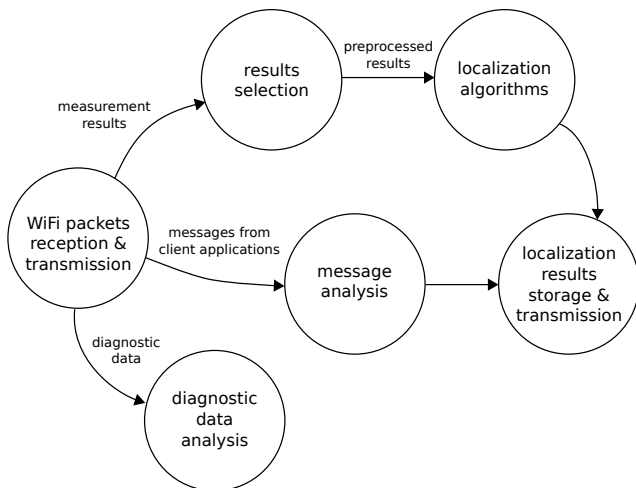

Fig. 5.   Basic controller software workflow

During normal operation the server application is waiting for the packets transmitted by the anchor nodes over the WiFi interface. Packets are sent by the anchor nodes in the intervals of around 1-2 seconds. They may contain results of both, UWB and BLE signals' measurements performed for many different tags. This results in the need of complicated parsing to properly group results from different radio interfaces, tags and anchor nodes. After a set of results from at least 4 different anchor nodes is collected, the localization algorithms are initiated. The algorithms implemented in the system are based on the Kalman filtration [28]. Depending on the software configuration, localization results can be stored and/or transmitted to external applications. In the presented

scenario, the results are transmitted to the IONIS platform server and are analyzed there.

The system controller periodically receives also service messages containing diagnostic data from each of the anchor nodes (including information about the state of the nodes, atmospheric pressure etc.). The software analyzes this data, saves it and can send it to an external server. Access to this data enables the remote supervision of the system.

Applications running on any external devices, e.g. those related to the user interface, can also communicate with the controller and utilize the data provided by it. Messages sent by them are processed in the dedicated module. As a result, the system controller may for example transmit information on the localization of the selected tags.

III. LOCALIZATION ALGORITHMS

In the system, the users and the items are localized using two different algorithms. The users are tracked using an UWB based algorithm utilizing Time Difference of Arrival (TDOA) values. The items are localized based on Received Signal Strength Difference (RSSD) measurements performed in the BLE radio interface.

A. User tracking algorithm

The users are tracked using an extended Kalman filter [28] based algorithm. In this algorithm, the localized user is described with a state vector containing information on his location x, y, and velocity v_x, v_y.

The algorithm consists of two phases: time update and measurement update. In the time update phase the current user location is predicted using an assumed movement model based on his previous location and velocity. It is described with the two following equations

$$\hat{x}_{k(-)} = F\hat{x}_{k-1(+)} \qquad (1)$$

$$P_{k(-)} = FP_{k-1(+)}F^T + Q \qquad (2)$$

where $\hat{x}_{k(-)}$ is the predicted state vector value, $\hat{x}_{k-1(+)}$ is the previously calculated state vector, $P_{k(-)}$ and $P_{k-1(+)}$ are the corresponding covariance matrices. The assumed movement model is specified with the state transision matrix F and the process noise covariance Q, which values were chosen in accordance to the Discrete White Noise Acceleration model (DWNA) [29].

In the measurement update phase, the obtained prediction is modified based on the TDOA measurement results supplied by the system infrastructure. This phase was implemented using the following dependencies:

$$K_k = P_{k(-)}H_k^T \left(H_k P_{k(-)} H_k^T + R_k\right)^{-1} \qquad (3)$$

$$\hat{x}_{k(+)} = \hat{x}_{k(-)} + K_k \left(z_k - h_k(\hat{x}_{k(-)})\right) \qquad (4)$$

$$P_{k(+)} = \left(I - K_k H_k^T\right) P_{k(-)} \qquad (5)$$

$$z_k = \begin{bmatrix} TDOA_1 & \cdots & TDOA_n \end{bmatrix} \qquad (6)$$

$$h_k(x) = \begin{bmatrix} TDOA_1(x) & \cdots & TDOA_n(x) \end{bmatrix} \qquad (7)$$

where z_k is the measurement vector containing TDOA measurement results of covariance R, $h_k(x)$ is the sensor model function allowing to estimate measurement results, which would be obtained for a tag located in point x, H_k is its linearization and K_k is the Kalman gain. The updated state vector $\hat{x}_{k(+)}$ and its covariance $P_{k(+)}$ are the final result of the algorithm and are used as input data in the next iteration.

B. Item localization algorithm

The items are localized using Received Signal Strength Difference (RSSD) based method, which consists in localizing the tags based on the difference of signal power levels measured by the anchors. In case of the assumed exponential path loss the received signal strength (RSS) is described as:

$$RSS = RSS_0 - 10\gamma \log_{10} \frac{d_i}{d_0} + \beta_i \quad (8)$$

where RSS_0 is the power received at the reference distance d_0 (typically 1 m), γ is path loss exponent and β_i is a log-normal random variable corresponding to attenuation present due to the shadowing and multipath effects. Thus the RSSD value for two anchors i and j can be expressed as:

$$RSSD_{ij} = RSS_i - RSS_j = 10\gamma \log_{10} \frac{d_j}{d_i} + \beta_i - \beta_j \quad (9)$$

Assuming that the tag transmits the signals to the both anchors with the same power, RSSD method does not require any information on its value. It is a significant advantage, which in comparison to RSS ranging based systems, increases resistance to situations, when the tag is covered or transmission power is lower due to its battery discharge. Additionally it allows to utilize different tag models in the system without a need for individual calibration.

The RSSD value contains information on ratio of distances between a tag and two anchors. In case of the 2D localization problem and the assumed propagation model, RSSD value specifies a set of points placed on a circle:

$$(x - a)^2 - (y - b)^2 = r^2 \quad (10)$$

where:

$$a = \frac{x_2 - c^2 x_1}{1 - c^2} \quad (11)$$

$$b = \frac{y_2 - c^2 y_1}{1 - c^2} \quad (12)$$

$$r = \frac{c\sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2}}{1 - c^2} \quad (13)$$

$$c = 10^{RSSD/(10\gamma)} \quad (14)$$

where x_1, y_1 and x_2, y_2 are the coordinates of the anchor nodes, $RSSD$ is received signal strength difference measured for those anchors and γ is the path loss exponent. An exemplary geometrical representation of an RSSD value for the assumed model in 2D coordinates is presented in Fig.6a.

Power measurements performed in indoor environments, due to complex propagation conditions are burdened with high uncertainty. In such case, the uncertain RSSD value would specify an area, where the tag might be located rather than
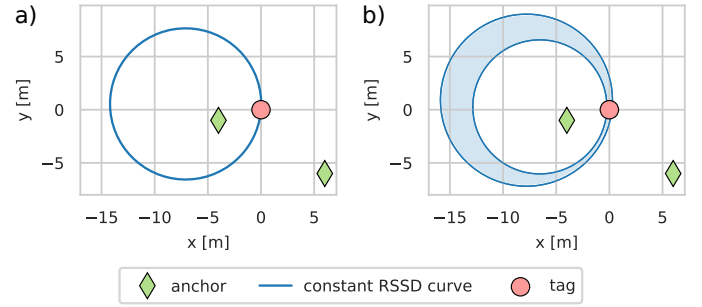

Fig. 6. Tag localization in RSSD method when the measurements are: a) accurate b) uncertain

points placed on a circle. As it can be seen in Fig.6b that area has a shape of an asymmetric ring. The localization uncertainty would be lowest when the tag is located directly between the anchors. On the opposite side, the uncertainty is much higher. Therefore, in order to achieve high localization accuracy, the anchor pairs for RSSD calculation should be chosen with care. An illustration of this problem is presented in Fig. 7.
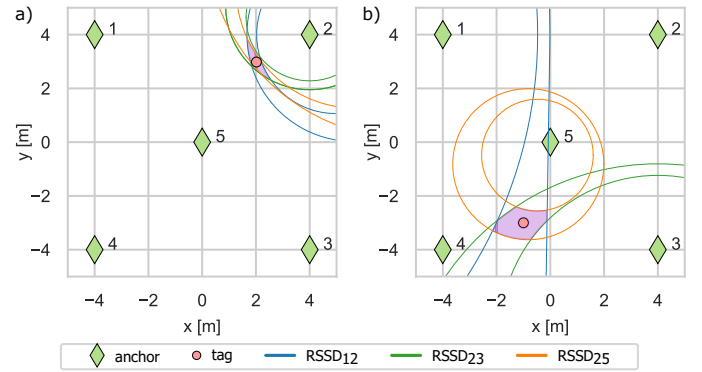

Fig. 7. An impact of RSSD anchor pairs selection on localization uncertainty: a) high, b) low accuracy

For both situations presented in Fig. 7 tag localization was calculated based on RSSD values calculated for the same set of anchor pairs: 1-2, 2-3, and 2-5. For tag and anchors geometrical configuration shown in Fig. 7a localization uncertainty is low. In case of the tag located in a different place (Fig. 7b) uncertainty is much higher. In that case it would be better to utilize different RSSD pairs (e.g including anchor 4).

The item tags are localized using an Extended Kalman Filter [28] based algorithm. The EKF implementation is almost the same as in case of user localization (1- 5). The only difference is content of the measurement vector z_k, which includes RSSD values and the form of the sensor model function h_k:

$$z_k = \begin{bmatrix} RSSD_1 & \cdots & RSSD_n \end{bmatrix} \quad (15)$$

$$h_k(x) = \begin{bmatrix} RSSD_1(x) & \cdots & RSSD_n(x) \end{bmatrix} \quad (16)$$

In the assumed sensor model, the RSSD values are calculated based on exponential path loss model (9). The γ parameter (path loss exponent) is the same for all of the anchors and is chosen at system deployment to fit the propagation conditions in the area, where the system is installed.

In order to achieve high localization accuracy, the pairs, for which the RSSD values are calculated are chosen adaptively. In the proposed method, the area where the system is installed is divided into smaller zones (as in Fig. 8). Each of the zones contains at least one anchor. For each of the zones a different set of RSSD pairs is defined. The EKF localization is preceded by determining in which zone, the tag is located (it is assumed that the tag lies in the zone containing the anchor which registered the highest signal level). Then appropriate RSSD values are calculated and the tag is located more accurately.

IV. EXPERIMENTS

The presented localization system was tested experimentally in a typical, fully furnished apartment. The tests consisted of two experiments verifying user and item localization accuracy. The plan of the apartment and the layout of the utilized system infrastructure are presented in Fig. 8.
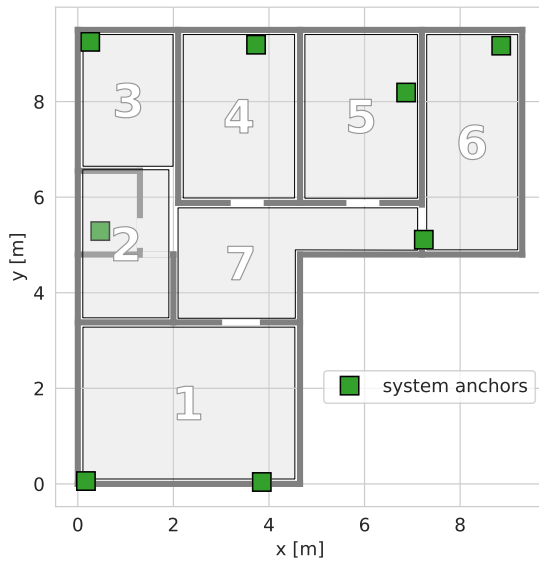

Fig. 8. Plan of the test site and placement of the system infrastructure. The grey areas and corresponding numbers indicate zones, for which different RSSD pairs for item localization are specified

The infrastructure used in the experiment consisted of 8 anchors, which were placed in such manner that each of the rooms contained at least one anchor. They were fixed to the walls or pieces of furniture trying to put them as close to the border walls of the apartment as possible. Placing the anchors in such a manner would allow to avoid situations, in which the tag is placed in the areas where the RSSD localization uncertainties are high (Fig.6).

For the purpose of item localization algorithm and RSSD pairs adaptive selection, the apartment was divided into 7 zones. Each of the zones covered either one room or a small area and contained at least one anchor. The path loss exponent in the localization algorithm was set to 3 which is a typical value for NLOS channels at 2.4 GHz frequency.

The first part of experiments consisted in testing the system's user monitoring capabilities. During a test, which took 10 minutes the user was asked to walk around the apartment, while wearing the tag on a lanyard. The results of user localization are presented in Fig. 9.
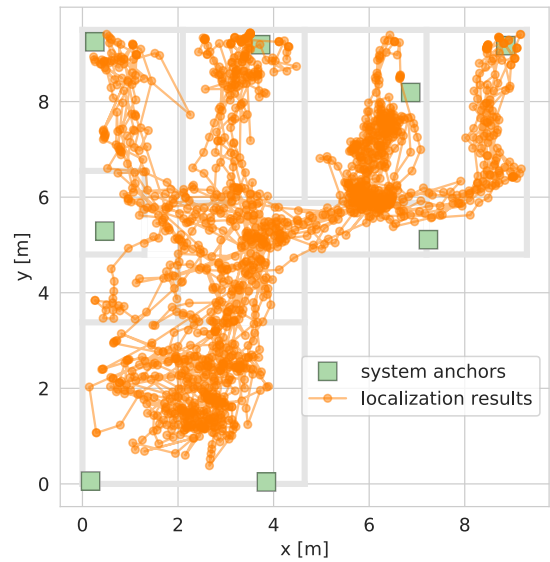

Fig. 9. User localization results

The presented system allows to determine the room, in which the user is present and estimate movement trajectory. Localization accuracy is efficient to localize the user in the vicinity of crucial or potentially dangerous objects such as a toilet or a gas stove. The obtained localizations can also be used to estimate user's movement trajectory. The accuracy is sufficient to observe signs of repetitiveness and the results might be used to detect wandering incidents.

The second part of the experiments consisted in localizing item tags placed in various places around the apartment. During the experiments the item tags were placed in a total of 40 different locations at different heights (shelves, tables, floor etc.). The tags were localized with the RSSD based method presented in Section III. The localization results are presented in Fig. 10.
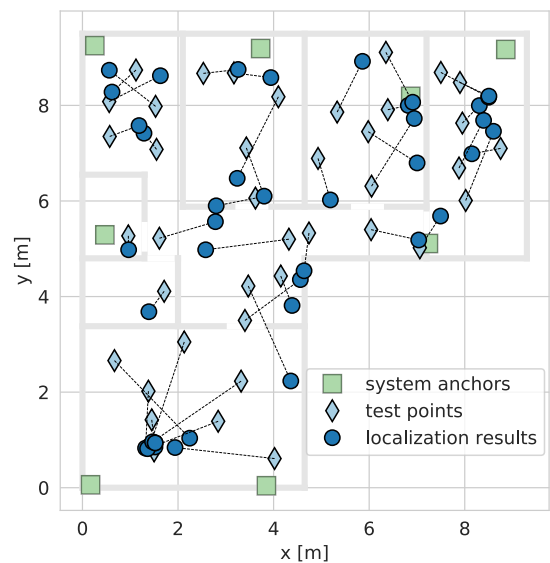

Fig. 10. Item localization results

The localization accuracy of the item tags is at a sufficient level. The room, in which the tag was located was determined correctly in case of 38 out of 40 test points. In other cases, the tags were localized in the neighboring rooms Given that the tag is additionally equipped with a bright blinking LED and a buzzer, providing the elderly person with just a room name should be enough to find the missing object.

V. Conclusions

The article presents a localization system supporting people with cognitive impairment and their caregivers. In the proposed solution the localization is supplied using two technologies: BLE and UWB which allows to fit the system to the specific application and installation environment (individual patient's home or long-term care facilities).

The system allows for localization of persons and frequently sought items. The user localization is performed based on TDOA measurement results performed in UWB interface. Item localization is performed using more energy efficient BLE technology.

The developed system was tested with experiments verifying its capabilities in terms of movement trajectory analysis and item localization. The accuracy of user localization is high enough to estimate his movement trajectory and observe patterns, which would indicate wandering incidents. The BLE based tags intended for item search support allow for room resolution localization, which is enough given that they are equipped with additional light and sound signaling devices.

The results of the performed experiments confirm that the system can be used for monitoring and supporting people suffering from cognitive impairments.

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