Improving Indoor Location Tracking Quality for Construction and Facility Management

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Abstract –

Real-time location tracking systems (RTLS) for personnel and machinery in outdoor civil engineering environments quite often use commercially-available Global Navigation Satellite System (GNSS) technology. Although the GNSS is an important approach in outdoor positioning and logistics coordination, their signals are not able to penetrate buildings due to their signal strength. Despite some recent advances in research, reliable indoor navigation remains an unsolved problem. This work deals with a detailed study of the methods and approaches of indoor location tracking. The focus lies on systems based on Bluetooth Low Energy (BLE) technology that meet the specific requirements of construction site and facility management.

The authors develop a prototypical application with which measurements are taken using different BLE hardware. The experiments show that location tracking is only applicable to a limited extent using BLE technology and path loss model. There were great differences in the behavior of different devices observed since the environment greatly influences the signal transmission. Proposed is an alternative, holistic system for location tracking using BLE. It uses a systematic classification of the work space by positioning the BLE beacons according to the a-priori known spatial building structure from a Building Information Model (BIM). By the relative observation of the received signal strengths of the individual beacons spread on a building floor, the calibration of the receivers is obsolete so that several different or alternative device types can be used together at the same time.

Keywords –

Building Information Modelling, Facility Maintenance and Management, Human-Machine Interface, Localization, Sensing and Monitoring, Tracking, Visualization, Web-based Systems

1 Introduction

Although commercial GNSS like GPS or GLONASS is an important prerequisite for outdoor applications such as automated control of machines or an approach for logistics coordination, its signals are not able to penetrate buildings and thus its application not suitable for indoor localization. Despite recent advances in research with varying results, a reliable, inexpensive and practicable indoor localization method remains an unsolved problem in construction as well as in facility management.

This work deals with a detailed study of the methods and approaches for indoor location tracking. The focus lies on systems based on Bluetooth Low Energy (BLE) technology that meet the specific requirements of construction sites and facility management. After selecting and evaluating possible approaches, the authors introduce a prototypical application with which measurements are taken using different BLE hardware. By means of these measurements, the properties of the components are critically evaluated. Based on the results, a holistic concept is developed to meet the requirements of the chosen application. The concept contains the algorithm, utilized hardware and a cloud platform configuration for the management of the tracking data. As an important aspect in the selection of the localization algorithm, the so-called fingerprinting method will be avoided, since it is to time-intensive and therefore cannot be used in a practical application.

2 State of the Art

2.1 Real-time locating systems

Localization in RTLS can be conducted in various ways. There are different approaches used for different applications, although essentially three different approaches can be distinguished.

The most common approach is based on the measurement of distances between several base stations (with a known positions) and the device to be located. The exact position can be determined by means of multilateration or hyperbolic navigation of at least three (2D plane) or four (3D space) distance measurements. The distance measurement takes place by means of the signal transit time measurement (applied with GNSS) or by signal strength measurement and the principle of free space loss. The latter is applied in many BLE based systems [1-3]. However, the signal transit time measurement is less suitable for indoor location tracking due to multipath reception, which results from reflections on objects.

Another approach is the fingerprinting method, which is also based on the measurement of the signal strength values. However, no physical relationship between signal strength and distance is evaluated. Instead, a map is created which links the manually detected signal strengths to the respective position in the plane. The resulting matrix of signal strengths of a certain point on the plane is called fingerprint. This way, interference and damping of individual signals no longer influence the localization and relatively high measuring accuracies and repeatability can be achieved [4]. However, the creation of a fingerprint map is very time intensive and therefore not practical for larger or very dynamic work spaces.

Inertial navigation systems (INS) are the third method for localization. With inertial sensors, such as rotation rate and acceleration sensors, the direction of movement of a system can be determined very precisely for short periods of time. In preliminary work, it has been possible to develop pedometers with high accuracy, such as in [5]. However, an initial location must be assumed through other means and measurement errors continuously add up with each step. This approach is well suited when combined with a previous RTLS in sensor data fusion using the Extended Kalman Filter (EKF) or particle filter.

2.2 Bluetooth Low Energy (BLE) and beacons

BLE was introduced in December 2009 as an extension of the Bluetooth 4.0 specification. Like conventional Bluetooth, BLE also works in the 2.4 GHz range of the ISM band. It is designed for significantly lower energy consumption and cost-effective integration. Reduced transmission power and smaller data packets or shorter data transfers contribute to low power consumption, so that button cells can be used to enable BLE connectivity of a device for months or even years. BLE is supported by popular operating systems such as Windows, Mac OS, iOS and Android given that the system has a Bluetooth 4.0 compatible hardware.

BLE devices can send short advertising events on three separate channels. These make the device known as a participant in the radio traffic. The device then waits for a connection request. BLE beacons are devices that rely on this basic functionality. The advertising event allows the broadcasting of short data sets which can contain, i.e. identification numbers, sensor data, or short web addresses. Receivers such as Smart Devices can receive the advertising events.

Common standards for BLE Beacon communication protocols are Apple's iBeacon and Google's Eddystone. In the context of location tracking, the signal strength can be determined using the Received Signal Strength Indicator (RSSI). The theoretical distance to the device can be approximated with the path loss model.

Figure 1 shows two exemplary BLE beacons. The nRF51822 is an evaluation platform from Nordic Semiconductor with minimal dimensions, the Accent Systems iBKS 105 (shown with its case opened) is a commercially available BLE beacon.

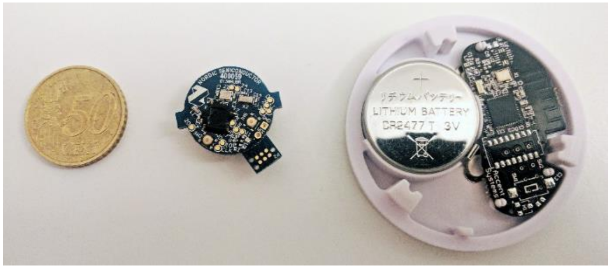


Figure 1. left to right: 50 Euro-Cent, Nordic Semiconductor nRF51822-Beacon, Accent Systems iBKS 105

2.3 Building Information Modeling (BIM) und lean management in construction

Building Information Modeling (BIM) includes methods and processes for creating and managing 3D virtual building models. Information exchange associated to a parametric model forms the core of the method. BIM acts as a central database, which contains semantic information and parameters as well as geometric data such as 3D models. BIM can be used for data exchange in the project lifecycle, including design, construction planning, construction work and facility management [6-7].

The concept of the Lean Construction Management (LCM) is the adaptation of the Toyota production system to the requirements of the construction industry. It is a continuous process for eliminating waste (in processes and resources) which is achieved by the continuous optimization of single business processes. Lean also consists of four basic principles. The flow principle, the just-in-time principle, the flexible resource control and the systematic quality control [8-9].

The application of LCM requires, above everything else, solid data to improve the business process. However, actual project data is typically not recorded in construction through digital means. Monitoring the progress of a project through technology enables BIM to become a information-driven model based on actual data.

3 Aims and Methodology

In this paper, the authors develop a holistic concept for indoor location tracking using BLE technology. The concept aims applications in the construction industry and facility management. The design of the localization algorithm excluded the so-called fingerprinting method, since it is too time-intensive and therefore cannot be used for practical purposes in dynamic work environments. For future use in the field of LCM an interface integration to BIM is proposed.

3.1 Use-case

As with every software development, it is useful to define the deployment scenario precisely for the envisioned location tracking system. In this case, the authors chose to classify the interiors of buildings into the three different classes "room", "corridor", and "atrium". A room is designed for people to stay or work in. It has a floor area of at least 10 m^2, a door and usually windows. A corridor, on the other hand, is a connecting space in a building, from which individual rooms emanate. It is characterized by long narrow passages. In contrast, an atrium is a larger and usually also high-roofed, open space. Corridor and atrium can be directly connected to one another. The examination is initially limited to elements of the class "room", as it is the most basic element. Later in the paper, the recorded preliminary results will the transferred to the other classes.

3.2 Selected hardware and software

For the selection of hardware and software, one must first and foremost decide which technology approach of localization to use. Generally, a distinction can be made between the systems which use wireless technology or inertial sensors, such as acceleration sensors, gyroscopes, or magnetometers.

The inertial sensor systems are distinguished by a high measurement accuracy. However, measurement errors are add up quickly. In addition, they need a known initialization point. An exception is the magnetometer. The method of "Magnetic Positioning" developed by the company *IndoorAtlas* is based on a fingerprinting method, which makes use of the magnetic interference of steel structures in buildings to determine the position [10]. The fingerprinting process is cloud-based and requires, in addition to a one-time mapping and a permanent Internet connection, practically no other infrastructure. However, since a fingerprinting process is to be avoided in this work and a permanent Internet connection cannot be guaranteed at a construction site, this method is not considered further.

The ultra-broadband wireless technology (UWB) offers probably the highest accuracy in indoor location tracking. UWB operates in a frequency range from 3.1 to 10.6 GHz. Although tests in construction have shown suitable applications in outdoor environments [11], this technology can only be used in one-room or wide-area-of-view solutions due to its strong damping and reflection properties [12]. Because of the relatively small market share of the technology, the costs of transmitters and receivers are very high.

Wireless technologies obviously include wireless LAN and BLE. Both technologies operate in the 2.4 GHz frequency range. Either RSSI values or using a characteristic curve to estimate the distance between sender and receiver can be used for the fingerprinting method. Both technologies are supported by many embedded systems and are widely used in PCs and smart devices. The use of wireless LAN requires an infrastructure of access points. In addition, due to a relatively large power consumption, connection to the power grid is required. Both factors are not to be expected on a construction site. In contrast, BLE beacons are very energy efficient and can operate on batteries for several months or years. In addition, they are also relatively inexpensive and do not require additional infrastructure. Therefore, a BLE-based technology approach is chosen in this paper.

BLE beacons are used as transmitting units while smart device such as a tablet or a smartphone will be the receiver. Smart devices, in addition to BLE support, also have internet connectivity (at some time during a work day) and can thus receive ambient data from an external cloud platform or upload tracking data.

3.3 Preliminary examination

In preparation for this work, several existing methods for indoor navigation were evaluated. The authors tried to reproduce positive results, which are mostly based on the path loss model and multilateration. It was evident that most results were not reliably reproducible. In addition to the affirming work, there are also some critical considerations on the theme of the path loss model.

A major criticism that has often been mentioned, are large measurement fluctuations due to interferences caused by diffraction or reflections on walls or due to interference with, for example, Wi-Fi. The measured signal strength, which forms the basis of the path loss model, varies massively when using different combinations of both beacons and smart devices, which boils down to different microchips and antenna combinations. In addition, the measured signal strength is also influenced by the parameters of air temperature, humidity, and the angle between transmitter and receiver antennas. These factors induce separate characteristic curves between signal strength and distance. These must be determined for each beacon used. For every specific model type and its specific spatial position, the combination with the respectively used receiving device and its possible antenna orientations requires careful evaluation. The characteristic curve must also be constantly adjusted to environmental influences such as air temperature and humidity.

The authors' own measurements have yielded characteristic curves which were relatively flat when the distance was greater than one meter from the concerned BLE beacon. Combined with the existing ambient signal noise, this results in large fluctuations in the distance measurement.

In some studies [1,3,13,14], these and other sources of error have been ignored. Many other systems try to limit the noise by means of filters, such as particle filters or Kalman filters [14-15]. Furthermore, sensor data fusion with inertial sensors is often used to increase accuracy. Commercial systems are regularly limited to Apple devices, since they offer limited variation in installed hardware, ultimately offering similar characteristics.

As a summary, preliminary investigations showed that the path loss model on its own offers insufficient precision. Significant efforts are necessary to find a suitable approach.

3.4 Methodology

The problems of the path loss model described in the previous section lets one discover the actual potential of BLE technology for location tracking and examine its strengths and weaknesses more closely. For this purpose, measurements are to be carried out in a realistic indoor test environment using the fingerprinting method as a reference. These fingerprints will not form a base for future tracking, but to evaluate the findings in tracking quality by other means.

For comparison purposes, the outdoor measurement scenario outdoor should be carried out again in a free plane. It serves to distinguish between the influence of reflection, diffraction, and attenuation by walls and the influence between the transmitter and receiver. The concept for developing a location tracking algorithm is not subject to the same restrictions of the path loss mode.

4 Experiments and Results

4.1 Design and implementation

The first measurements were taken in the laboratory of the Chair for IT in Mechanical Engineering at the Ruhr-University Bochum. The laboratory is located in the basement of an academic building and equipped with various demonstrators, including conveyor belts, test assemblies, partition walls, and computer workstations. The laboratory environment may serve well as a realistic test environment for indoor tracking in construction and facility management.

Part of the laboratory consist of a large room. It has dimensions of 15 x 5 m and a ceiling height of more than 3 m. The upper part of the ceiling is equipped with an open ventilation system so that the room has only a useable height of about 2.4 m. For the experiment, six beacons are distributed uniformly in space at a height of 2.1 m. A sketch of the test bed environment including its fixtures is shown in Figure 2. It shows the exact position of the beacons with their indicators in the laboratory.

For the fingerprinting process, the space is divided into 75 individual squares, each having a surface area of 1 m². A unique "fingerprint" of the received signal strengths of the individual beacons is then recorded for each individual area over the course of 30 seconds. For this purpose, a smart device is positioned in the respective quadrant using a tripod.

The smart device is then positioned centered and upright at a height of about 1.2 m in the quadrant. The orientation of the smart device remains the same throughout the entire measurement. Utilizing a self-developed app installed on the smart device, all received RSSI values of all beacons in range are recorded and stored in a measurement period of 30 seconds. The evaluation of the measurements is carried out later with a self-written MATLAB script on a PC. Figure 2 shows the division of the room in its subareas and the orientation of the smart device in a quadrant.

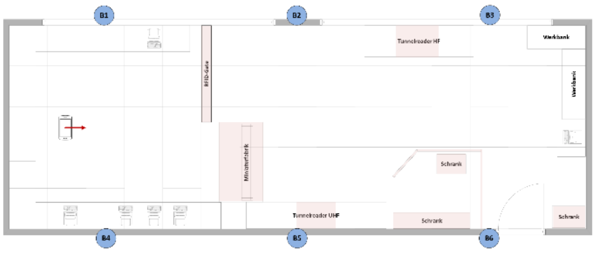


Figure 2. Floor plan of the test laboratory. Blue circles indicate the position of BLE beacons. Red spaces show objects with heights over 1.5 m.

The dimensions of the laboratory scenario are then replicated in an open field. For this purpose, a rectangle with the same dimensions of the laboratory test room was staked out on a soccer field (with an artificial turf) at the Ruhr University Bochum's campus. The beacons were positioned on professional tripods at pre-assigned positions. The positioning of the tripod with the smart device were realized with a measuring tape.

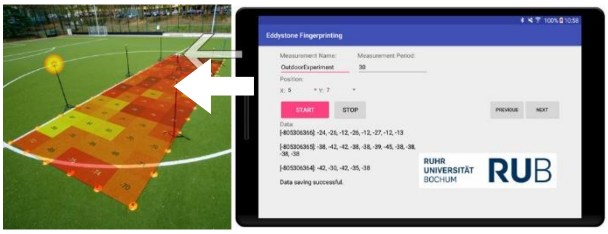


Figure 3. Android app

4.2 System architecture

For the experiment, BLE beacons from Accent Systems with the model designation iBKS 105 were used. These support both the iBeacon and Eddystone protocols, whereas the Eddystone protocol was used in the research. The beacons have been configured to send an advertising signal with a signal strength of +4 dBm, with an interval of 300 ms. These values represent the highest transmission power and the shortest possible time interval available on these specific beacons. This configuration is chosen so that possible transmission errors have as little influence on the measurement as possible. The transmitting advertising signal contains, among other things, a unique identification number (UID), whereby the recorded signal strength can be unambiguously assigned to the respective beacon.

The measurements in the experiments are carried out with two smart devices. The first is the Nexus 5X (powered by Google, OEM is LG) and the second is the Xperia Z4 from Sony. Both devices are equipped with the Android 6.0 operating system. Android provides support for BLE from version 4.3 on, but in these outdated versions it lacks performance and reliability. Since version 5.0, the BLE API has been reworked from scratch.

4.3 Software implementation

To systematically record measurement data, the authors implemented a mobile app specifically for the experiment. The app offers the possibility to name the experiment and to define the measuring period for each quadrant. A 2D coordinate system identifies the currently selected field of the measurement. A text field displays the current measurement data for a brief overview. After the measurement run finishes, the measurement data is stored as a text file. The process is repeated for each quadrant in the field to create a robust fingerprint.

A specifically programmed Matlab-Script evaluates the stored data after completion. The script reads the measured data automatically from the text file and stores it in a nested matrix structure. Algorithmically, the median value for each beacon in each quadrant is determined iteratively from the RSSI values measured over the measurement period. The specific RSSI mean values are then visualized graphically as heat maps for the individual beacons and can thus be evaluated objectively.

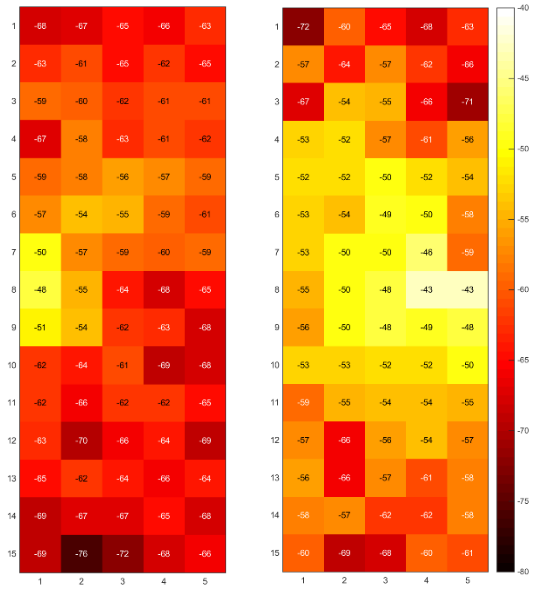
4.4 Evaluation of measured results

For the systematic evaluation of the experiment, the results for the outdoor test are analyzed first. By performing the experiment in the open field, the influence of interfering signals, as well as diffraction and reflection on objects or walls is at a negligible level. The reflection of the ground cannot be excluded. The measurement results show, according to the path loss model, a steady decrease in the signal strength with an increase in the transmitting distance.

However, the measured signal strength is also strongly dependent on the alignment angle between BLE beacon and the smart device. Since the alignment of the smart device in each quadrant remains the same, the angle between smart device and beacon changes for each quadrant. From the results it appears as if there is a characteristic drop in the signal strength from a given orientation angle. This observation is evident when comparing Figures 4b and 5b.

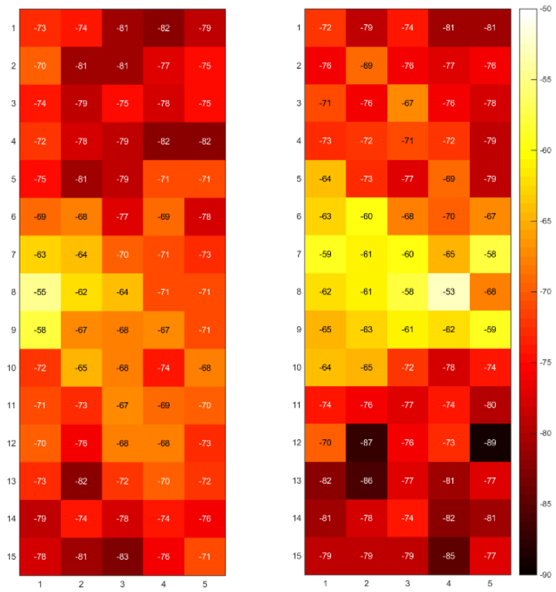
Evidently this angle is specific for each device/beacon combination as the comparison between the used smartphone and the tablet show (cp. Figures 4b and 5b). The Sony Xperia Z4 tablet is much more sensitive to the alignment angle. This becomes evident at very close measurement ranges of the tablet to the beacon. A large drop in the signal strength is observed. This is due to the relatively high angle of inclination between beacon and tablet. It is also noticeable that the signal strength drop for Beacon 4, 5 and 6 is severe. A possible explanation is that the antennas in the smart devices were installed on the right side, which therefore also affects the alignment angle between the transmission devices.

The test results in the indoor test show a similar effect, except for the last-mentioned phenomenon. In addition to the decrease in the signal strength over the transmitting distance, the characteristic drop in the signal strength from a specific alignment angle can also be observed here. In addition, some effects are attributable to the spatial design and geometry of the laboratory room. In general, damping effects by large superstructures can be detected. Contrary to the observation made in the outdoor scene, the signal strengths for beacons 4, 5, and 6 are significantly stronger than those of beacons 1, 2, and 3. This is probably due to a highly reflective surface at the ceiling of the laboratory room. A channel for cables made out of metal runs along the long side of the laboratory wall. A variety of materials mounted at or inside the reinforced concrete walls of the laboratory may contribute to this effect. In addition, relatively strong signal strengths were measured within the metal partition walls placed in the room. This again illustrates the reflection characteristics of metallic objects or walls.



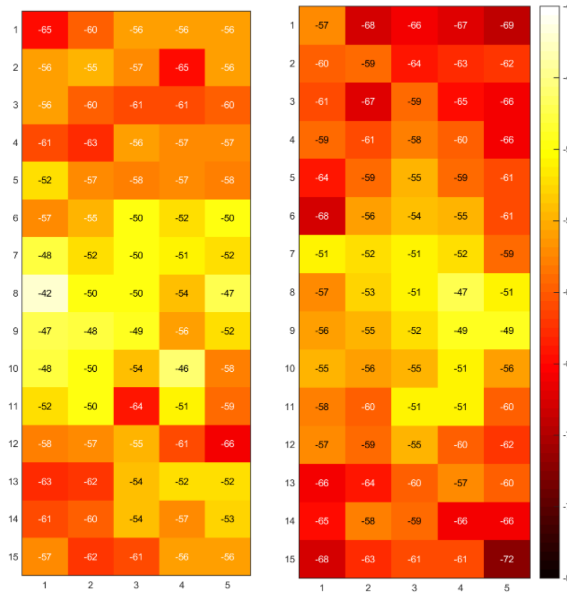
(a) Beacon 5 (b) Beacon 2

Figure 4. Selected heat maps of RSSI-median-values from the **outdoor experiment** with **Nexus 5x** Device



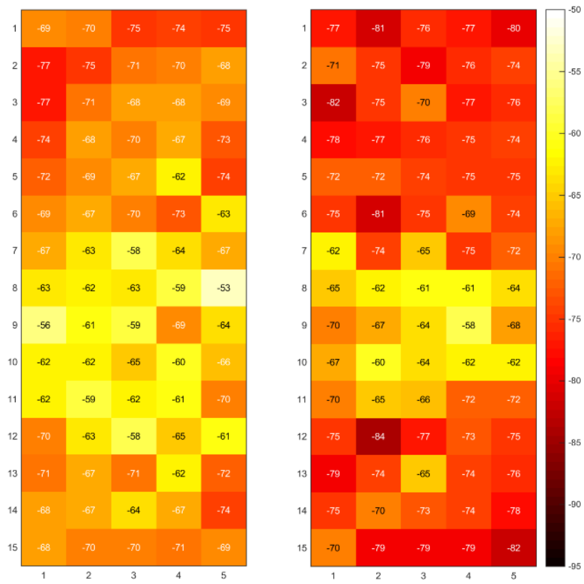
(a) Beacon 5 (b) Beacon 2

Figure 5. Selected heatmaps of RSSI-median-values from the **outdoor experiment** with **Xperia Z4** Device



(a) Beacon 5 (b) Beacon 2

Figure 6. Selected heatmaps of RSSI-median-values from the **indoor experiment** with **Nexus 5x** Device



(a) Beacon 5 (b) Beacon 2

Figure 7. Selected heatmaps of RSSI-median-values from the **indoor experiment** with **Xperia Z4** Device

5 Resulting Concept

Accuracy of existing location tracking methodologies, such as with GPS or a UWB systems, is favorable for construction applications, however focus on outdoor or wide area field-of-view applications and the necessary calibration and adaptation measures to the different system variants are, in practice, far too complex and require too much effort [16-17].

As an alternative, this work evaluated through experimental results with BLE that its signal propagation depends on two factors: the spatial environment and on the measurement devices applied.

This work found, that an alternative positioning method can be realized based on the BLE technology. Sector-location that fit this purpose, divide a space into sectors while one or two beacons are positioned in the respective sector. The measurement principle assumes that the beacon/s has/have the strongest signal strength in their corresponding sector. This procedure can be implemented well in the previously defined classes of "room" and "corridor". If one measures the signal strengths of several beacons relative to one another, one can thus determine the sector by the receiving signal strength of the device.

Furthermore, the transition between the different sectors can be predicted by the changing of the signal strength profile while moving. Explained in a simple example, when moving from point A to point B, the signal strengths from the beacon at point B will rise, while the one from mounted at point A will fall. This method also avoids the need for calibration for the individual receiving devices since the signal intensities are only considered relative to one another.

The size of the sectors is defined by the distribution density of the beacons used. To keep costs low and the deployment practical, it makes sense to create the sectors not smaller than 5 x 5 m. The sensitivity or accuracy of the tracking can be increased by sensor data fusion with an inertial sensor system, such as a pedometer. In the developed system concept, the sectors are calculated using the spatial data contained in the BIM.

The following steps must be taken to realize a sector oriented location tracking:

1. The user is given the appropriate positions of the beacons for the initial installation.
2. The sector allocation and beacon data are stored in a cloud platform.
3. During location tracking, the floor plan of the building is generated by BIM.
4. The sector and position data of the beacons on a smart device are synchronized with the cloud platform.
5. Due to this information, the continuously measured signal strengths and the movement data of the inertial sensor system, the sector is then calculated by the receiving smart device.
6. When an active internet connection is available, the position within the found sector is send to the cloud platform. In offline mode, the application stores the timestamp and the found sector on the device, to synchronize the data at a later point once an internet connection is established again.

The resulting system architecture is shown in Figure 8.

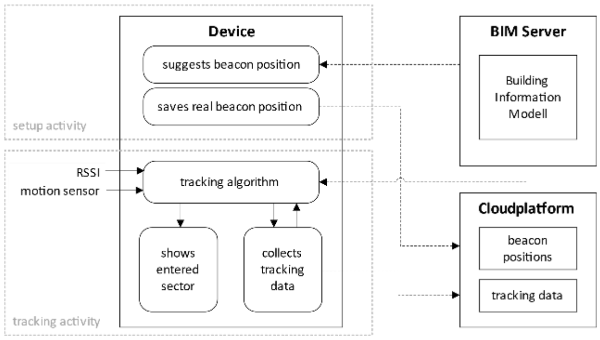


Figure 8. Proposed system architecture for the sector location tracking algorithm

6 Conclusion

The experiments carried out for this research show that location tracking is only applicable to a limited extent using BLE technology and path loss model. There are large differences in the behavior of the existing devices. Just the angle between transmitter and receiver has a rather large influence on the measured signal strengths. The experiments also show that the environment greatly influences signal transmission. To counteract these weak points in the path loss model, the authors found that complex adaptation and calibration measures would be necessary.

Based on these important findings, the authors proposed an alternative, holistic system for location tracking using BLE. It uses a systematic classification of the work space by positioning the BLE beacons according to the a-priori known spatial building structure, e.g. taken from a Building Information Model (BIM). The proposed system offers several advantages:

First, the relative observation of the received signal strengths of the individual beacons, the calibration of the receivers is obsolete so that several different device types can be used together and at the same time. Second, by combining the BLE location with the movement data of the receiving device, the accuracy of the system can be improved. Third, both, the data needed for location tracking and the tracking data are stored in a cloud platform, enable further analysis.

One of the next steps in the development of a holistic indoor tracking system is the implementation of the proposed concept along with its validation at a real construction site [18].

References

[1] Y. Wang, X. Yang, Y. Zhao, Y. Liu, L. Cuthbert, Bluetooth positioning using RSSI and triangulation methods, in: IEEE Consumer Communications and Networking Conference (CCNC), 2013: 11 - 14 Jan. 2013, Las Vegas, USA ; [including workshops], Las Vegas, NV, IEEE, Piscataway, NJ, 2013, pp. 837–842.

[2] S. Viswanathan, S. Srinivasan, Improved path loss prediction model for short range indoor positioning using bluetooth low energy, in: IEEE SENSORS 2015: November 1-4, 2015, Busan, South Korea proceedings, Busan, IEEE, Piscataway, NJ, 2015, pp. 1–4.

[3] C.E. Galván-Tejada, J.C. Carrasco-Jiménez, R.F. Brena, Bluetooth-WiFi based Combined Positioning Algorithm, Implementation and Experimental Evaluation, Procedia Technology 7 (2013) 37–45.

[4] R. Faragher, R. Harle, Location Fingerprinting With Bluetooth Low Energy Beacons, IEEE J. Select. Areas Commun. 33 (11) (2015) 2418–2428.

[5] Q. Tian, Z. Salcic, K.I.-K. Wang, Y. Pan, A Multi-Mode Dead Reckoning System for Pedestrian Tracking Using Smartphones, IEEE Sensors J. 16 (7) (2016) 2079–2093.

[6] C.M. Eastman, BIM handbook: A guide to building information modeling for owners, managers, designers, engineers, and contractors, 2nd ed., Wiley, Hoboken NJ, 2011.

[7] B. Hardin, BIM and construction management: Proven tools, methods, and workflows, Wiley Technology, Indianapolis, Ind., 2009.

[8] R.F. Aziz, S.M. Hafez, Applying lean thinking in construction and performance improvement, Alexandria Engineering Journal 52 (4) (2013) 679–695.

[9] H.R. Thomas, M.J. Horman, R.E. Minchin, D. Chcen, Improving Labor Flow Reliability for Better Productivity as Lean Construction Principle, Journal of Construction Engineering and Management 129 (3) (2003) 251–261.

[10] A. Solin, S. Sarkka, J. Kannala, E. Rahtu, Terrain navigation in the magnetic landscape: Particle filtering for indoor positioning, in: 2016 European Navigation Conference (ENC): Helsinki, Finland, 30 May 2016-2 June 2016, Helsinki, Finland, IEEE, Piscataway, NJ, 2016, pp. 1–9.

[11] T. Cheng, M. Venugopal, J. Teizer, P.A. Vela (2011). "Performance Evaluation of Ultra Wideband Technology for Construction Resource Location Tracking in Harsh Environments", Automation in Construction, Elsevier, 20(8), 1173-1184.

[11] E. Garcia, P. Poudereux, A. Hernandez, J. Urena, D. Gualda, A robust UWB indoor positioning system for highly complex environments, in: 2015 IEEE International Conference on Industrial Technology (ICIT 2015): Seville, Spain, 17 - 19 March 2015 ; [proceedings], Seville, IEEE, Piscataway, NJ, 2015, pp. 3386–3391.

[12] J. Park, Y.K. Cho, K. Kim, Field Construction Management Application through Mobile BIM and Location Tracking Technology, in: 33rd International Symposium on Automation and Robotics in Construction (ISARC 2016).

[13] Y. Gu, L. Quan, F. Ren, J. Li, Fast Indoor Localization of Smart Hand-Held Devices Using Bluetooth, in: 2014 10th International Conference on Mobile Ad-hoc and Sensor Networks (MSN): 19 - 21 Dec. 2014, Maui, Hawaii, USA, Maui, HI, USA, IEEE, Piscataway, NJ, 2014, pp. 186–194.

[14] H. Bae, J. Oh, K. Lee, J.-H. Oh, Low-cost indoor positioning system using BLE (bluetooth low energy) based sensor fusion with constrained extended Kalman Filter, in: 2016 IEEE International Conference on Robotics and Biomimetics (ROBIO), Qingdao, China, IEEE, 2016, pp. 939–945.

[15] A. Ozer, E. John, Improving the Accuracy of Bluetooth Low Energy Indoor Positioning System Using Kalman Filtering, in: 2016 International Conference on Computational Science and Computational Intelligence (CSCI), Las Vegas, NV, USA, IEEE, 2016, pp. 180–185.

[16] J. von Heyl, J. Teizer (2017). "Lean Production controlling and tracking using digital methods", Lean & Computing in Construction Congress (LC3), Heraklion, Greece.

[17] J. Melzner, J. Hanff, J. Teizer (2017). "Pattern-based Generation of 4D-Schedules for Robust Construction Management", Lean & Computing in Construction Congress (LC3), Heraklion, Greece.

[18] J. Teizer, M. Wolf, O. Golovina, M. Perschewski, M. Neges, M. König (2017). "Internet of Things (IoT) for Integrating Environmental and Localization Data in Building Information Modeling (BIM)", 34th International Symposium on Automation and Robotics in Construction, Taipei, Taiwan.