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Indoor real-time location system for resource localization in multistory buildings

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ABSTRACT

This paper presents the practical implementation and empirical evaluation of a commercial Bluetooth low energy (BLE) based real-time location system (RTLS) within a multi-story university building, an environment characterized by significant architectural and electromagnetic interference. The study addresses a gap in existing research, which often focuses on simulations or single-story deployments, by analyzing the system's performance in a real-world, challenging setting. The system, integrated with enterprise-grade wireless infrastructure, was subjected to five test scenarios designed to assess its core functionalities: real-time tracking accuracy, reliability of geofencing and alarm features, and performance under severe interference and in a multi-floor context. The results demonstrated high reliability for room-level identification, achieving a location accuracy between 1.5 and 3.0 meters under normal operating conditions. Furthermore, location-based alarm and geofencing functions proved to be fully effective and instantaneous. However, the study identified two critical limitations: a complete failure of the system when the tracking tag was placed within a shielded metal enclosure, and an inability to distinguish between floors, which led to incorrect location projections and false alerts. The findings conclude that while BLE-based RTLS is highly effective for room-level asset management in standard office environments, its successful implementation in multi-story buildings is critically dependent on installing dedicated infrastructure on each floor and acknowledging its technological limitations in heavily shielded areas.

Keywords: indoor asset tracking, RTLS, bluetooth-based positioning, IoT in facility management, real-time location system.

INTRODUCTION

Real-time location systems (RTLS) are modern technologies supported by the internet of things (IoT) that enable precise tracking of assets, people, and operations in real-time. This translates to improved time management, optimized infrastructure utilization, and faster response in emergency situations [1]. For example, RTLS are addressing challenges such as asset tracking [2] and pathfinding in dynamic indoor environments [3]. Despite the increasing availability of technologies like BLE, Wi-Fi, UWB, and RFID, many RTLS implementations still face issues with accuracy, cost, interoperability, and adaptability to complex architectural conditions. These issues stem from factors such as signal propagation limitations, lack of standardization, and difficulties in scalable adaptation of solutions to real industrial and service environments [4, 5]. In light of these challenges, BLE emerges as a particularly promising technology [6].

Bluetooth low energy (BLE) based technology is gaining significance as an environmentally friendly communication solution, particularly in applications requiring long-term operation with limited energy resources. Thanks to its low power consumption, the possibility of implementation within existing wireless networks, and the ability to operate for many years on small batteries, BLE devices are becoming integral components of modern IoT systems in various fields. These include, among others, precision agriculture [7], environmental monitoring in smart buildings [8], asset and people localization systems in enclosed spaces such as hospitals or warehouses [9].

In the current technological landscape, BLE plays a significant role in asset tracking systems. BLE transmitters are widely used for localizing assets and individuals in enclosed spaces such as warehouses, hospitals, and offices. BLE enables precise real-time object tracking with low implementation and maintenance costs [10]. A modern example of BLE's utilization in asset tracking systems and the broader IoT is the ASSIST-IoT project. This project developed a scalable next-generation IoT architecture and implemented solutions using BLE for asset tracking and ensuring safety, which is important in real industrial and construction environments [11].

Existing RTLS solutions and technologies

BLE-Based Localization is a frequently studied approach for indoor positioning due to its low implementation cost, the energy efficiency of BLE technology, and its potential for integration with existing network infrastructure. These methods primarily rely on measuring the Received Signal Strength Indicator (RSSI), although their accuracy can be limited by environmental factors. This limitation motivates research into improving precision, for example, through channel aggregation, noise filtering, or the application of machine learning algorithms. The literature emphasizes that despite its limitations, BLE remains one of the most practical technologies for tracking assets in environments such as hospitals, universities, or industrial halls [9].

Despite the popularity and advantages of BLE devices, they are not the sole solution available on the market. The problem of asset tracking can be addressed through a variety of distinct applications, each possessing unique characteristics. Within the context of enhancing efficiency and resource management in the IoT ecosystem, various real-time location systems, such as RFID, QR codes, airtags, bluetooth, and LoRaWAN [12], merit consideration. Furthermore, entirely alternative technologies that can be used for tracking or locating can include systems based on visual place recognition (VPR) [13]**.** The integration of GPS receivers with barometric sensors is being investigated to provide vertical localisation. One study analysed the position measurement capabilities of three GPS receiver models and a barometric altitude sensor, identifying the U-blox M8N model as the most accurate, achieving an average location error of around 1.89 metres [14]. In another study also based on GPS and a barometer, building entrance detection was achieved with over 93% efficiency and floor change detection with a sensitivity of over 95% and a specificity of nearly 98%, indicating the great potential of the system in applications such as indoor navigation, security and crisis management [15]. The LOCUS project develops an innovative platform to enhance indoor localization accuracy, security, and privacy while integrating advanced physical analytics, addressing the limitations of GPS, Wi-Fi, and Bluetooth technologies in complex environments [16].

LoRa (Long Range) in RTLS systems is used to locate objects in large, dispersed spaces such as warehouses, industrial halls or open areas. Thanks to its long range (up to several kilometers) and low power consumption, LoRa allows the construction of location networks with wide coverage without the need for dense deployment of access points, but offers lower location accuracy (in the order of several metres) compared to technologies such as BLE or UWB. In RTLS applications, LoRa is preferred where long battery life and low infrastructure costs are key, with moderate precision requirements [17].

RFID technology, especially in its active version, provides highly accurate and reliable point identification in a small space. Paper [18] describes the design and analysis of a sensor area network (SAN) system based on active RFID tags for RTLS in the 2.4 GHz band. The main innovations include the use of a grid of small detection zones (RF barriers), which minimise the impact of signal multipath and improve localisation accuracy in indoor environments.

Applications of RTLS

RTLS has a wide range of applications in environments where the precise location of a person or object in real time is required, especially in complex structures such as multi-storey buildings, industrial plants or logistics centres.

Healthcare sector applications

One application example of RTLS is the healthcare sector. Hospitals manage a wide range of mobile medical equipment, and any delays in its location can affect the quality of patient care and staff efficiency [19]. RTLS, especially those based on BLE and WiFi technology, have proven to be effective tools for improving workflow. An example is a study conducted in South Korea, which evaluated the implementation of BLE and WiFi-based asset tracking for medical equipment management. The system used BLE beacons and tags and was integrated into the hospital information system. An evaluation of the system was carried out as part of a three-month pilot, yielding an average satisfaction rating of 3.7 on a scale of one to five based on the responses of 117 nurses [20]. In Italy, a different approach involved a system based on magnetic field fingerprinting and Wi-Fi signals in a hospital serving approximately 120,000 people, achieving an accuracy of around 2.5 meters [21]. Furthermore, Saritha et al. present a hospital asset tracking system that combines RFID and GPS technology, enabling real-time location of medical equipment both inside and outside the facility. By integrating these technologies, operational efficiencies can be improved, costs can be reduced and the quality of patient care can be increased by locating assets faster and reducing their loss [22]. While many implementations show promise, the review by Bazo et al. highlights other examples of asset tracking systems in healthcare, noting that some technologies exhibited poor to average accuracy and functionality, leading to general user dissatisfaction with their performance [23].

Construction site and safety applications

The nature of construction environments, including variable weather conditions, the interaction of multiple teams and the presence of heavy equipment, creates significant challenges in terms of occupational safety and asset management, justifying research into advanced IoT-based location systems in these environments [24]. As highlighted by Paul et al, advanced asset tracking systems in construction based on RFID, GPS and IoT, significantly improve asset lifecycle management and infrastructure maintenance [25]. Recognizing these needs, the Assist-IoT project (EU H2020 ICT-56-2020 development project) was established to build an employee support system. It is taking place in Poland and is being implemented by Motostal Warszawa SA, which is testing the system based on BLE in the construction area of the Marshal's Office in Szczecin. There are many uncontrollable factors in construction areas, such as weather conditions, parallel work in the area, and working in the company of heavy machinery. The Assist-IoT project is intended to increase health and safety in complex and unpredictable environments [11]. According to data from 2023, the construction sector in Poland recorded 3,600 occupational accidents, including 39 fatal incidents, highlighting the persistently high occupational risk in this industry. Although this represents a 2.9% decrease compared to 2022, the statistics highlight the ongoing need for technological solutions to improve safety on construction sites [26]. Accident reduction can be achieved by avoiding hazardous areas. The proposed system, based on BLE technology using angle of arrival (AoA), generates dynamic danger zones and sends real-time vibration alerts to workers, effectively minimising unnecessary notifications by taking into account team performance, alert expiry times and speed thresholds [27].

Industrial and manufacturing applications

In industrial environments where management of material and resources flow is important due to profits, asset tracking systems enable real time monitoring of components and product [28]. The Bendavid et al. paper discusses the use of IoT and RTLS in the context of Industry 5.0, with a focus on passive RFID as a competing technology to existing active RTLS solutions. Research and pilots at two industrial plants have shown that passive RFID-based systems can significantly improve location accuracy and asset management efficiency, offering low maintenance costs and easy scalability, and BLE is being considered as a cheaper and more flexible alternative in environments requiring moderate accuracy and simple deployment [29]. In contrast, Siwiec et al. showed that an RFID-based system for dynamic traffic control at intersections inside a factory can optimize material flow and reduce average waiting times compared to traditional sequential algorithms [30]. A practical example of RTLS implementation using Wi-Fi and BLE is a case study from the smart manufacturing demonstration centre (SMDC), where a system was implemented to track the movement of materials and semi-finished products on the production floor. It was pointed out that BLE is beneficial where cost, battery life and sufficient accuracy are the prevailing factors [9]. In another case, a BLE-based RTLS for monitoring resource flow in indoor environments was designed and tested, with a particular focus on improving location accuracy through signal processing (Kalman filter) and optimising transmission parameters. The authors developed their own transmitting and receiving equipment, analysing the effects of sampling frequency, environmental interference and BLE settings on signal quality and stability in a printing materials warehouse, obtaining a minimum measurement error of about 1.5m [31]. In order to improve container terminal operations and reduce vessel handling times, RFID-based RTLS is proving to be an effective solution as it provides highly accurate and reliable object identification. This makes it possible to optimize material flow and reduce waiting times, while passive variants of this technology additionally offer low maintenance costs and easy scalability [32].

While extensive research exists on BLE-based RTLS systems, a significant gap persists: the majority of studies primarily focus on theoretical simulations or validations in controlled, single-story laboratory settings. Crucially, there is a distinct lack of comprehensive empirical analyses of commercial system deployments within genuine, multi-story buildings. Such real-world environments present unique challenges, including prevalent architectural complexities and substantial electromagnetic disturbances (e.g., lift shafts, reinforced concrete ceilings, active server rooms) that are often not fully accounted for in simplified test cases. This study directly addresses this critical research gap. By conducting a practical implementation and rigorous empirical evaluation of a commercial RTLS solution within such a challenging, real-world multi-story university building, this paper offers novel insights into the practical capabilities and inherent limitations of BLE-based localization, extending beyond theoretical predictions and simplified test scenarios.

The motivation for the study was the lack of comprehensive analyses of commercial RTLS deployments in real, multi-storey buildings that take into account typical architectural and electromagnetic interference. The aim of the project was to develop practical recommendations for the design of BLE-based location systems and to implement a functional RTLS system in a multi-storey building infrastructure. An additional objective was to critically evaluate the implemented solution by experimentally verifying the performance parameters, in particular the localisation accuracy and the system's resistance to environmental disturbances. An important element of the research was also the analysis of the compliance of the obtained results with the RTLS system technical specifications, which enables an objective assessment of the suitability of BLE solutions in demanding operational environments. In the course of the preparatory work, an industrial building was selected that houses a great deal of electronic equipment on all floors, and in addition, an Local Multipoint Distribution Service (LMDS) antenna system is located on the roof of the building. The research was carried out in R&D laboratories with numerous working research equipment, as well as network equipment, servers and computers. In addition, server rooms are located above the floor and below the floor on which the research is conducted. The large number of metal components, fluorescent lighting, working elevators and working equipment provide an excellent environment for conducting tests on the accuracy of RTLS systems. The results and recommendations obtained can be used in the design process of RTLS systems supporting the operation of critical infrastructure systems.

RESEARCH METHODOLOGY

This chapter presents the architecture, hardware and software components of the implemented RTLS. It also describes the characteristics of the physical test environment and the test scenarios designed to verify the accuracy and reliability of the system.

Test environment and challenges

The implementation and testing of the system was carried out in the building of the Rzeszów University of Technology. This is a research and teaching facility whose multi-storey structure, reinforced concrete ceilings and specific equipment provided a demanding environment for radio technology. The implementation challenges consisted of architectural and electromagnetic interference, such as thick walls, two lifts and server rooms and classrooms with a large number of active network devices. The RTLS system was deployed on the 6th floor of the building (Figure 1), where metal rack cabinets – filled with active network equipment such as UPS units, switches, and other devices – constituted an additional source of interference in the environment under study. The diagram shown in Figure 1 is a detailed plan. For clarity, simplified diagrams were used in the subsequent parts of the study, without additional markings for computer workstations, air conditioning, or other elements. However, their positions remained unchanged during the study.

System architecture and components

The asset tracking system was integrated into the existing network infrastructure. Its architecture is detailed in Figure 2. The presented solution combines a set of commercial-grade hardware components and software utilized in accordance with the manufacturer's specifications and appropriately configured to ensure proper system operation. According to the implementation guide, the accuracy of the used asset tracking system is approximately 5 metres, and it is asserted that BLE technology alone provides sub-meter location accuracy [33].

Equipment

Access points (AP) – the infrastructure was based on 4 Alcatel-Lucent OAW 1321 access points with an integrated BLE module. Beacons - to ensure adequate localisation accuracy, 12 autocalibrated BLE beacons were used as reference points. Location tags – 1 to 3 BLE CT18-3 tags in card form were used for asset tracking. The tags were equipped with an accelerometer, which saved energy by triggering transmission only when movement was detected.

Software

Management platform - the system was managed by the OmniVista Cirrus platform, installed as an on-premise variant. It was responsible for managing network devices, collecting location data and making it available via an API.

System configuration and implementation

The deployment process involved several stages. Access points and BLE beacons were deployed on the floor plan according to the manufacturer's recommendations and the results of the signal coverage analysis (Figure 3), which showed the need for additional devices to eliminate dead zones near sources of interference. Each beacon was assigned to a specific position and its ID was imported into the management system for calibration. Tag registration was done by scanning a unique QR code. Virtual zones (GeoFences) corresponding to individual rooms were also defined in the system and assigned rules to notify when a resource leaves the zone.

Research scenarios

In order to verify the prepared RTLS system, a series of five test scenarios were designed and carried out. The scenarios were designed to reflect possible situations occurring in a multi-storey facility.

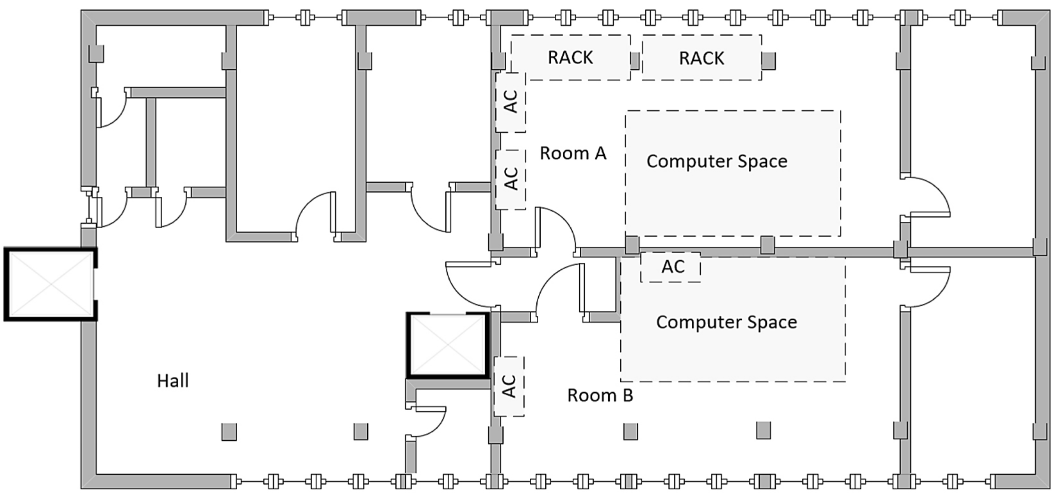


Figure 1. Floor plan of the 6th level of a multi-storey building

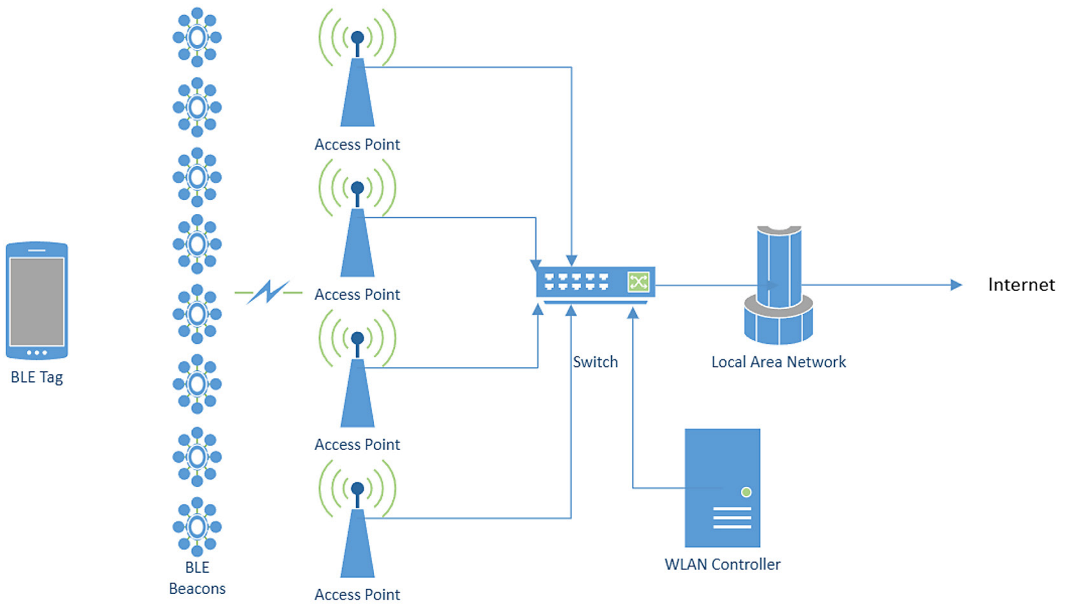


Figure 2. BLE-based architecture system integrated into existing building infrastructure

a) b)

Figure 3. Signal coverage map before (a) and after (b) adding an access point

Tracking resources on the move (Scenario 1)

The first scenario aimed to assess the accuracy of the system at room level and verify the delay of real-time position updates. As part of the test, a BLE tag, assigned to a mobile resource, was moved along a predefined path covering two teaching rooms (A and B) and a hall. In each of these areas, the tag remained stationary for a set period of time to assess the stability of the readout. Parameters measured included the effectiveness of room identification, the time it took to update the location in the system, and the stability of the reading when the object remained stationary.

This test simulates the typical use of mobile resources such as measuring instruments, medical trolleys or keys. The test verifies the most basic operational capability of the system – checking the position of resources. Its results not only allow the suitability of the system for everyday use to be assessed, but also confirm the correctness of the prepared test environment. The high accuracy and low latency can allow the implementation of more advanced features, such as the automatic inventory of equipment in individual rooms, the optimisation of staff workflows by quickly locating the tools needed, or the creation of an event log for security audits. In turn, identified errors or delays will be able to indicate the need for system reconfiguration or infrastructure compaction to achieve the required reliability.

Resistance to interference (Scenario 2)

The scenario was designed to quantitatively assess the performance degradation of the location system, including its accuracy and stability, under conditions of severe electromagnetic interference and signal attenuation. As part of the test, the localisation tag was placed inside a metal RACK-type server cabinet in which active network devices were operating. The analysis included the evaluation of indicators such as positioning error in metres, readout stability and the possibility of signal loss.

This test simulates asset storage conditions in demanding technical environments, such as server rooms or metal tool cabinets, where physical barriers and radio interference pose critical challenges for BLE-based systems. Understanding the system's behaviour under adverse conditions influences the definition of its operational limits and the development of deployment recommendations. The results can assess whether BLE technology is reliable enough for tracking high-value assets in metal enclosures, or whether denser receiving infrastructure or alternative positioning technologies are required in such cases.

Alarm function (Scenario 3)

To verify the reliability of the alarm function and qualitatively assess its speed of operation. The aim was to confirm that each alarm call is effectively recorded and transmitted to the management system. A user equipped with a BLE tag, moving around the facility, in different locations (including teaching rooms and hall), deliberately activated the alarm button. The test was repeated multiple times (20 times) to verify the repeatability and reliability of the function. A percentage was measured, indicating how many attempts to activate the alarm were correctly registered by the system. A qualitative assessment of the time elapsed from pressing the button to the appearance of the message in the admin panel (assessing whether the response is immediate or noticeably delayed). The scenario simulates emergency situations where immediate response and precise location of the person in need of assistance is crucial. This includes, but is not limited to, medical emergencies, security threats (assault, intrusion) or technical failures requiring urgent intervention. Reliable operation of this function can be important for personal safety and security (HSE) systems.

Usage GeoFencing (Scenario 4)

The purpose of the scenario is to verify the reliability and speed of the geofencing function, which automatically generates alerts when a resource enters and leaves a defined zone. A virtual zone (geofence) has been defined in the system, coinciding with the boundaries of room "Room A". The test consisted of performing two actions repeatedly (20 times):

- Moving the tag from the centre of "Room A" to the outside, to the "Hall" area.
- Moving the tag from the "Hall" area back to "Room A".

The measured parameters of the scenario are the percentage of successful attempts in which the system correctly generated a zone change alert, verification that the system correctly identifies the event as 'zone entry' or 'zone exit', and a qualitative assessment of the time from when the zone boundary was crossed to when the alert appeared in the system. The rationale for developing the scenario is that it is required to: generate an immediate alarm if valuable equipment (laptops, medical equipment, tools) is attempted to be taken outside the permitted area; automatically record that a component has entered the test area or left the warehouse; and monitor that assets requiring special conditions (e.g. cleanliness, temperature) do not leave the designated areas.

Location between floors (Scenario 5)

This test is to verify the system's ability to correctly interpret the location of a tag placed on a different floor than the one where the receiving infrastructure is installed. This scenario aims to identify the system's limitations in a multi-story architecture. The RTLS system infrastructure (access points) was installed on a single floor only. The test involved placing a BLE tag on the floor directly below, at a location corresponding to the vertical projection of Room A. It was observed where and how the system visualizes the position of the tag, which is physically located outside the monitored floor. The test also verified whether the change of floor generates false alerts for leaving or entering predefined zones. The test simulates common real-world situations such as an employee accidentally moving a resource to another floor, a deliberate attempt to 'hide' a resource in a location not covered by direct monitoring, and the test assesses whether a system with infrastructure on one floor can monitor vertically adjacent zones (e.g. just above or below) to a limited extent.

RESULTS

This section presents the empirical results obtained from the five test scenarios outlined in the methodology. The findings are reported in a clear and objective manner, providing a factual foundation for the subsequent analysis and conclusions.

Tracking resources on the move (Scenario 1)

The system demonstrated a 100% success rate in correctly assigning the tag being moved to the correct zone (Room A, Room B or hall). At no point in the test was the tag incorrectly assigned to an adjacent room. An example of this is illustrated in Figure 4, where a resource located in Room B (Figure 4a) was unambiguously located by the system within the same room in the diagram (Figure 4b). The positioning accuracy, with an error of between 1.5m and 3.0m, was fully sufficient for this task.

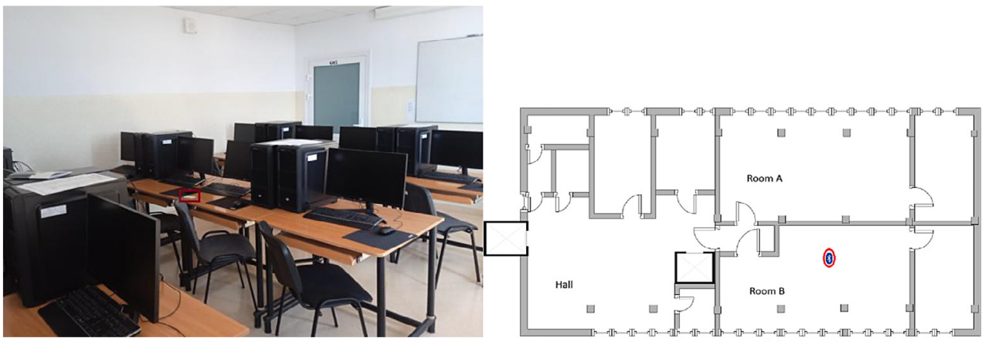
Resistance to interference (Scenario 2)

The test of placing the tag in an enclosed metal RACK with active devices showed a critical degradation in the performance of the localisation system. The localisation became completely unstable and chaotic. The recorded positioning error regularly exceeded 5.5 metres. The location indicator moved erratically between different rooms and even to other floors. This problem is illustrated in Figure 5, which shows how a tag physically placed in a server cabinet (Figure 5a) is erroneously located by the system in a completely different location (Figure 5b).

As a consequence of the errors, the system was completely incapable of correctly identifying even the room in which the resource was located. The location reported by the system was useless from an operational point of view. The results clearly indicate that the metal enclosure of the RACK, combined with interference, effectively suppresses BLE. Under these conditions, the system proved to be completely non-functional.

Alarm function (Scenario 3)

Testing of the emergency button on the personal tag demonstrated its full functionality and readiness for use in critical applications. The system demonstrated complete effectiveness. Each attempt to activate the alarm was correctly recorded and transmitted to the admin panel as a pre-set priority event. No instance of alarm loss was recorded. System response was judged to be immediate and without any apparent delay. The notification in the management system appeared virtually simultaneously with the moment the button was pressed, which was confirmed by the observer. Each emergency notification generated, in addition to identifying the user, included his or her real-time location with room accuracy. This is a key piece of information that determines the speed and effectiveness of rescue or intervention action. Tests have confirmed that the alarm function works reliably and immediately. The system can effectively



a) b)

Figure 4. Visualisation of the actual environment of the resource with its location in the system: (a) photo of room B, representing the physical test environment, (b) floor plan with the estimated location of the resource (Bluetooth point) and the actual point (red point) that correctly assigns it to Room B

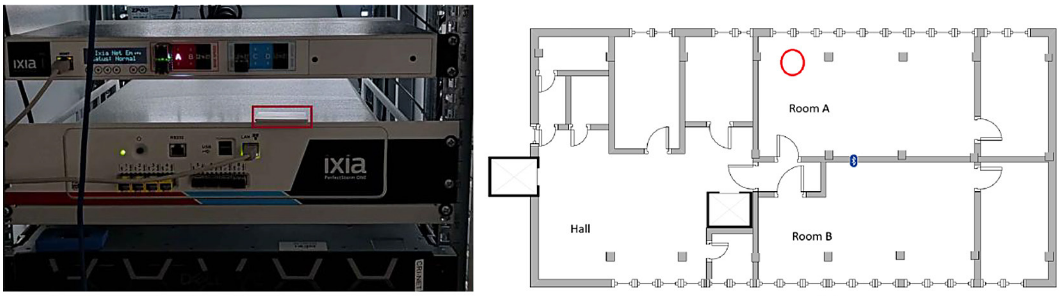


Figure 5. Illustration of total signal degradation in Scenario 2 (RACK cabinet): (a) photograph of the interior of the RACK cabinet, representing the physical test environment, (b) floor plan with the estimated location of the resource (Bluetooth point) and the actual point (red point)

provide a complete package of information (e.g. who needs help and where), demonstrating its full suitability for personnel safety applications.

Usage GeoFencing (Scenario 4)

The system demonstrated full effectiveness in generating alerts. For each attempt to cross the boundary of the 'Room A' zone, the system generated an appropriate alert. Importantly, the system distinguished the direction of movement without error, generating the correct messages: "Leaving zone: Room A" and "Entering zone: Room A". As in previous tests, the system's response to the change in resource location was immediate. Alerts appeared in the management panel as soon as the tag physically crossed the threshold of the defined zone (in practice, the door threshold), with no delay noticeable to the observer.

The geofencing function, in the surveyed environment, works reliably, immediately and precisely. The system's ability to report flawlessly and quickly on every entry and exit from a defined zone confirms its high utility in property security and logistics process automation applications.

Location between floors (Scenario 5)

The test of placing the tag on a floor not covered by the system's infrastructure showed significant limitations in its performance and confirmed the need to install receivers on each monitored floor. The system, receiving a weak signal from a tag placed on the floor below, was unable to identify the change of floor. Instead, it erroneously

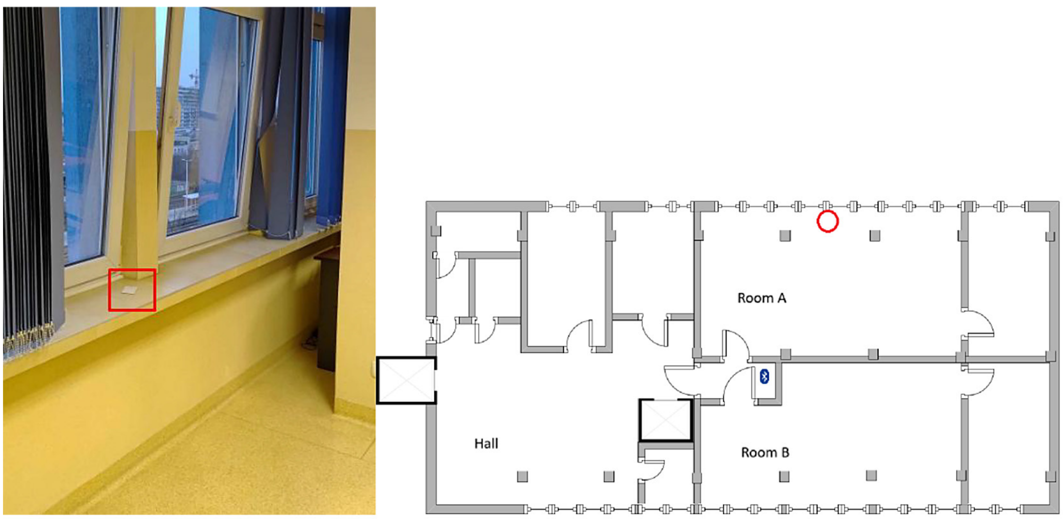


Figure 6. Illustration of a multi-floor location error: (a) actual location of the tag on a floor not covered by the infrastructure, (b) incorrect position of the asset reported by the system, which projects the location onto the monitored floor

projected the position of the tag onto the map of the monitored floor. The location of the asset was displayed at a point that was the resultant of the signal strength received by all access points, often in the middle of a hall or between rooms.

As a consequence of the misinterpretation of position, the system generated a string of false geofencing alerts. Although the resource did not physically leave the vertical projection of Room A, the system continually reported its supposed entries and exits from the zone, as the projected, unstable position moved erratically across virtual zone boundaries. This problem is illustrated in Figure 6, which shows the erroneous position reported by the system (Figure 6b) for a tag that was actually a floor below (Figure 6a). The results clearly indicate that the BLE-based RTLS system in its current configuration is not capable of distinguishing between floors. In order to properly monitor resources in a multi-storey building, it is necessary to implement a dedicated infrastructure (access points) on each floor to be covered by the system.

DISCUSSION

The research carried out provided insights not only into the performance of the RTLS system deployed, but also into the fundamental characteristics and limitations of BLE technology in indoor location applications. Analysis of the results in the context of the theoretical assumptions and the practical usability of the system allows a comprehensive evaluation of the solution to be formulated. The system manufacturer and general technical literature often declare the accuracy of BLE technology to be up to several metres (eg. 5 m) under

Table 1. Summary of BLE-based RTLS system performance and limitations

Feature / Aspect	BLE-based RTLS system in the study	Advantages	Disadvantages / Limitations
Localization accuracy	1.5–3.0 m (room level)	High accuracy for room-level identification	Insufficient for precise localization in smaller areas (e.g., a specific desk)
Function reliability	Alarm, Geofencing: 100% effectiveness, immediate response	Effective and immediate event notifications	Dependence on infrastructure (requires correctly defined zones)
Interference resistance	Complete signal degradation in RACK cabinets	Stable operation in office/ educational environments	Complete non-functionality in strongly shielded, metal enclosures
Floor detection	Inability to distinguish between floors	-	Necessity of installing infrastructure on each monitored floor. Generation of false alarms without inter-floor infrastructure
Scalability	Based on planned ”Future Work”	Potentially scalable for a larger number of tags	Requires further research under increased load conditions
Implementation costs	Low-medium, for BLE	Lower costs compared to UWB. Possibility of integration with existing Wi-Fi infrastructure	Requires dedicated Access Points and Beacons for optimal precision
Implementation complexity	Moderate, with the requirement of precise AP/Beacon planning	Simple tag configuration, intuitive interface	Requires detailed signal analysis and elimination of ”dead zones”
Applications	Room-level asset management, personnel safety	Effective in office and educational environments	Limitations in precise tracking in areas with strong interference
Data availability	Real-time, with the possibility of event logging	Rich event logs for process analysis and optimization	Requires data management and integration with other systems
Configuration flexibility	Possibility of defining zones (Geofencing)	Adaptation to changing environmental needs	Necessity of manual zone adjustme

optimal conditions. The results of test one confirmed that such precision is achievable. In more complex conditions, taking into account movement and environmental variability, realistic and stable positioning accuracy was in the range of 1.5–3.0 m.

It is important to note that the observed accuracy was adjusted for environmental factors present in the real facility, such as reinforced concrete ceilings, numerous walls, as well as electromagnetic interference generated by network devices in server rooms and teaching halls. Most importantly, the obtained precision proved fully sufficient to achieve the main goal – flawless identification of the resource at the room level, which is the basis for effective resource management.

Beyond the technical parameters, the value of RTLS lies in its usability. Visualising the location of assets on a real-time digital map is intuitive and reduces the time it takes to find them. The interface offers both passive tracking and active management through geofencing and an alert button, transforming raw location data into information to support security and logistics. The system becomes an interactive decision-making tool.

In addition to confirming the usefulness of the system in some scenarios, studies have also shown its limitations, e.g. the total non-functionality of the tag in a shielded metal enclosure and the inability to distinguish between floors for an infrastructure limited to a single storey. A summary of the key features, advantages, and limitations of the BLE-based RTLS system in this study is provided in Table 1. Another interesting direction for further research is the determination of conditions necessary for the controlled blocking of RTLS operation. Such functionality is desirable in areas where enhanced resource protection is required and precise localisation is inadvisable. Our research has demonstrated that this is fully achievable. Effective methods include physical shielding-for example, our tests confirmed that placing a tag inside a shielded metal RACK cabinet resulted in complete signal loss, rendering the system non-functional. Additionally, it is possible to intentionally design the infrastructure to create ‘dead zones’ by strategically omitting access points and beacons in selected areas. Future work could also explore more dedicated solutions, such as active signal jamming or the implementation of software-level location masking to create virtual ‘privacy zones’.

Future work could also include testing with a larger number of simultaneously monitored tags to assess the scalability and stability of the system under increased load. It would also be useful to see if a particular tag performs differently from the others for some reason, to rule out potential anomalies.

CONCLUSIONS

Based on the above discussion and empirical evaluation, a number of recommendations were made. The main aim of these recommendations is to bridge the gap between the theoretical capabilities of BLE technology and the challenges that arise when implementing it in a real, complex environment. To ensure effective monitoring of assets in a multi-storey building, it is absolutely necessary to install dedicated receiving infrastructure (access points) on each floor covered by the system. The scenarios investigated clearly showed that a system with infrastructure installed on only one floor is not able to distinguish between floors and erroneously projects the location of the resource onto the monitored map.

Before final deployment of access points and beacons, it is recommended that a detailed signal analysis is carried out to identify ‘dead zones’ and areas of increased interference. In addition, the system will not work for assets placed inside enclosed metal cabinets and areas of high interference. In such cases, it is recommended to use manual procedures (e.g. code scanning at retrieval) or to consider hybrid technologies such as RFID. Carrying out an analysis of optimal access points is a way of designing an optimal and reliable infrastructure, avoiding the situation where, once all the equipment has been installed, it turns out that the system has gaps in coverage and does not meet its objectives. Operational recommendations include the need to train users that the system is used to locate at room level (with an accuracy of a few metres) and not to pinpoint the precise location of (e.g. a specific desk). For security purposes, it is recommended to actively use the geofencing function to protect valuable assets and the alarm function to improve staff security. The event log generated by these functions should be used for process analysis and optimisation.

In order to develop and improve the usability of the system, it is advisable to collect regular feedback from staff using the system on a daily basis. This will allow targeted improvements to be made to make the tool more intuitive and better adapted to real work processes. Conducted tests confirmed that the implemented RTLS system is fully functional and effective under controlled conditions, while precisely defining the limits of its applicability. The test scenarios used effectively indicated both the potential directions of the system and its limitations. The system enables real-time asset location with an accuracy of between 1.5m and 3.0m, which is fully sufficient for flawless and reliable identification of the asset room. Location-based features such as personal alarming and geofencing have demonstrated full effectiveness and immediate response in the tested environment. Research has shown two critical limitations of the system. Firstly, it is completely non-functional when the tag is inside a metal, heavily shielded enclosure (e.g. a rack cabinet), leading to chaotic readings and a complete loss of usability. Secondly, a system infrastructure limited to a single floor is unable to differentiate between floors, resulting in erroneous position projections and the generation of false alerts. The effectiveness of the system is directly dependent on the correct design of the infrastructure. Correct monitoring of a multi-storey building requires the installation of dedicated receivers on each floor. The system provides stable and predictable performance in office and teaching environments, but its precision degrades in areas with strong radio signal interference.

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