TECHNICAL UNIVERSITY OF CLUJ-NAPOCA

ACTA TECHNICA NAPOCENSIS

Series: Applied Mathematics, Mechanics, and Engineering
Vol. 69, Issue II, June, 2026

EVALUATION OF THE PERFORMANCE AND MANAGERIAL APPLICATIONS OF A BLUETOOTH LOW ENERGY GATEWAY NETWORK FOR ASSET LOCALIZATION THROUGH RSSI IN DYNAMIC AIRPORT ENVIRONMENTS

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Abstract: *In dynamic airport environments, optimizing asset management and operational flow is a major challenge. This study evaluates the performance of ESP32-C6-DevKitM-1 BLE gateways for real-time localization using RSSI analysis to monitor BLE beacons. Empirical tests, simulating airport operational zones, examining RSSI values under Line-of-Sight (LOS) and Non-Line-of-Sight (NLOS) conditions, varying distance, Tx Power, and environmental factors (interference, obstacles). The research also explores the optimal placement of gateways for reliable coverage and location data collection. Security and robustness of BLE IoT infrastructure in high-security public spaces are discussed. The article highlights the potential benefits of BLE for improving airport management, security, and passenger satisfaction in the context of digital transformation.*
Key words: *Bluetooth Low Energy (BLE), BLE gateway, indoor localization, RSSI, airport management, asset tracking, IoT systems engineering, smart airport.*

1. INTRODUCTION

Bluetooth Low Energy (BLE) technology is increasingly being used in airport management systems for various applications. BLE beacons can be used to create real-time indoor positioning systems for passenger tracking and security purposes [1]. These systems can provide location-based services to smartphone apps through cloud-based servers, eliminating the need for proprietary software development kits [2].

The "Digital Smart Airport" system, implemented in Russian airports, combines BLE with other technologies like GLONASS/GPS and IoT for comprehensive asset tracking and process optimization [3]. BLE gateway devices can efficiently connect BLE and Wi-Fi networks, enabling the transmission of IoT node information to servers or cloud platforms without requiring additional microcontrollers, making them cost-effective and power-efficient solutions for managing large numbers of IoT devices in airport environments [4].

Since the global airport sector is characterized by intrinsic complexity and accelerated dynamics, the efficient management of a large number of mobile assets, from ground support equipment (GSE) and baggage carts to IT and security equipment, is a major challenge for airport operators. The rapid and precise localization of these assets is vital for optimizing operational processes, reducing delays, minimizing losses and associated costs, and ensuring a continuous flow of operations. As passenger and cargo traffic continue to grow, along with the pressure for digitalization and the implementation of the "Smart Airport" concept, advanced technological solutions for asset management are essential. Bluetooth Low Energy (BLE) technology, which offers real-time localization capabilities with low energy consumption, has emerged as a cost-effective alternative. For the development of BLE

Received: 13.04.26; **Similarities**: 16.04.26: **Reviewed**: 13.04. /13.04.26: **Accepted 1**5.06.26.

gateway networks intended for passenger localization in airport environments, the ESP32-C6 platform offers integrated support for Wi-Fi 6, BLE 5, Zigbee, and Thread.

It is imperative to conduct a thorough evaluation of the performance of such an ESP32-C6-based network under realistic operational conditions to determine the managerial implications of its implementation. This is the main reason why this article addresses the main issue. The purpose is to create a solid foundation for investment and implementation decisions in airports, determining the reliability of localization based on RSSI, effective range, and factors that influence accuracy.

2. METHODOLOGY

Bluetooth Low Energy (BLE) beacons have emerged as a promising technology for crowd monitoring and control. BLE beacons can be set up in confined indoor areas to gorge the status of a crowd and how they act. While BLE beacons or less of an intrusion into privacy than passive sensing, such as cameras, to create a more facilitative atmosphere, it is found that passive sensing provides more accurate personal mobility information [5]. BLE vulnerabilities for security attacks include free riding and device spoofing. The latter can be avoided when beacons dynamically randomised the signals that they send and receive from each device [6]. BLE allows for crowds to be sensed.

As people carry devices with high physically detectability, smartphones can recognise these BLE tags either set as beacons or in the cloud, achieving up to 90% detection [5]. With more adults tethered to their smartphones than ever before, the use of BLE beacons to figure out. If there are static clusters forming within a larger group via BLE signal strength and orientational data helps assess intentions as well since. There are barely device motion activity signals that indicate when devices or actively moving versus static in relation to specific people in the crowd [7]. Nevertheless, this type of technology requires optimal placement types for maximum detection without inflating labour costs for monitoring detection [8].

The current research pertains to the airport industry and focuses on the operational and logistical management of assets within airport premises. This includes areas such as passenger terminals (check-in areas, security control, boarding gates), baggage handling and sorting areas. The proposed BLE gateway network is designed to manage a wide range of mobile assets that are tagged with BLE beacons. These assets include passengers, staff and personnel in certain operational contexts where privacy standards are upheld. This paper will be beneficial for airport operators, airlines, ground handling service providers, and other parts of the airport logistics chain. Such a system can help achieve the "Smart Airport" objectives by improving efficiency, reducing costs, and increasing the overall satisfaction of all stakeholders.

2.1. Research Stages

For the evaluation of the BLE gateway network, the proposed investigation will include some interconnected stages. For the initial testing of Bluetooth low energy connections, among the tested equipment, the most versatile and user-friendly hardware platform that can be configured, regardless of the type of operating system, is represented by the ESP32-C6, which allows the design of the firmware through the Arduino IDE software platform. The Arduino IDE platform was a good choice, as it allowed the import of several types of libraries of instructions specific to the configuration of the BLE antenna, including BLEDevice.h, BLEUtils.h, BLEScan.h. Through these libraries, the BLE antenna can be configured to operate in several modes: scanner, beacon, range extender, data repository for beacon or tag registrations.

The ESP32-C6-DevKitM-1 boards are set up as BLE beacons (transmitters) and as BLE gateways (scanner/receiver). Arduino IDE is used to develop firmware for beacons and gateways. These functions include BLE scanning, extracting RSSI, and transmitting data to a central server with data repository function.

The beacons transmission power (Tx Power), the advertising interval, and, if possible, the configuration of the physical layer (PHY), such as LE 1M PHY that is used for initial testing.

Representative testing environments in a real or simulated airport scenario, with the necessary permissions, is considered. Testing areas include open areas (LOS) and specific non-line-of-sight (NLOS) areas, such as check-in zones, hallways, and areas with metal structures.

2.2. Testing method

Initial examination at a proximity, such as one meter, for rough calibration of RSSI and detection verification is set. Precise measurement of the distance between the beacon and the gateway, which progressively increases is defined at 0.5 m, 1 m, 2 m, 3 m, 4 m, 5 m, with extended distance testing at 6 m, 7 m, 8 m, 9 m and 10 m (m=meters).

Recording detections (reliability, frequency) and RSSI values at each step for an appropriate period (time slots between 20 seconds to 60 seconds) is effectuated for identification of a credible maximum detection distance under LOS conditions. The evaluation of the impact of different types of obstacles, such as walls, furniture, and people is considered.

2.3. Data Collection and Analysis

The systematic recording of data includes the beacon name, configuration (Tx Power, range, PHY), testing environment, distance, average/minimum/maximum RSSI, detection consistency, and specific observations, like antenna positioning, the measured power constant, the environmental factor constant, statistical analysis of the relationship between RSSI and distance under different conditions evaluation of the influencing factors and RSSI variability.

Evaluation of antenna performance in LOS scenarios and the hardware and software configurations analysis via performance influence is carried out.

3. RESULTS

An experiment was conducted in laboratory conditions, in order to calibrate and measure BLE beacon configurations, by using a BLE scanner. At least two ESP32-C6-DevKitM-1 development boards will be used. One of these is configured to function as a BLE beacon (signal transmitter), while the other will operate as a BLE scanner/gateway (signal receiver). ESP32-C6 is selected due to its support for BLE 5, Wi-Fi 6, and integrated security features. For the beacon and scanner functions, conventional ESP32 BLE libraries were used in the Arduino IDE development environment. The code for the beacon ensured the periodic transmission of a unique identifier and calibration data (e.g., measured power).

The code for the scanner identifies in real-time specific beacons, records the MAC address, RSSI, and identification time, and sends them to a computer via the serial port for logging and analysis.

A strict protocol is followed for measuring distances and recording data.

The variables that were controlled include the transmission power (Tx Power) of the beacons, which set to the maximum possible value or a documented fixed value; the advertising interval, which is set to 100 to 200 milliseconds; and the physical layer (PHY – default LE 1M PHY, ideal for testing and with LE Coded PHY for extended range).

Due to LOS measurement conditions, the LE 1M PHY physical layer was used in the measurement experiment. For comparability, the gateway's scan parameters, such as setInterval(100) and setWindow(99), was kept constant.

RSSI values will be collected at different distances and under different conditions (LOS, various obstacles, antenna orientations). The reliability of detection (the percentage of packets received within a time interval) will also be noted. Precise distance measurement tools, such as a tape measure or a laser rangefinder, were used.

Figures 1 and 2 show a non-linear and increasingly low stable relationship between distance and received signal strength (RSSI), which is characteristic of Bluetooth Low Energy (BLE) measurements in real environments.

In Figure 1 were BLE RSSI over distance of 0-5 meters illustrates the behavior of the BLE signal at close distances.The Y-axis (RSSI) displays a clear decrease as the distance on the X-axis increases.

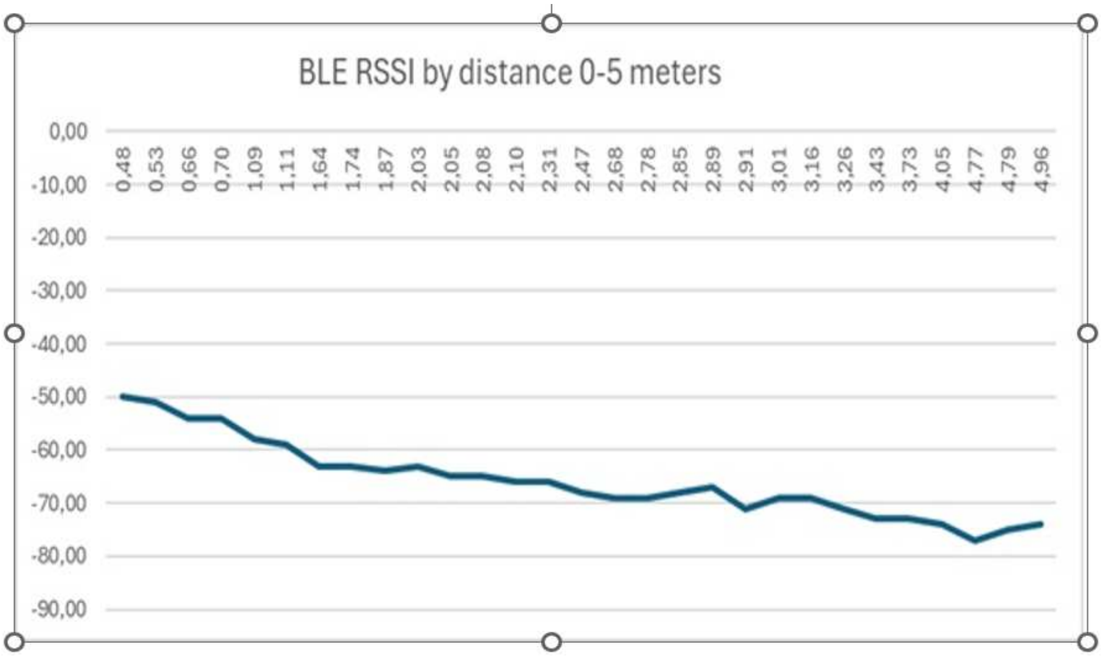

Fig. 1. BLE RSSI by distance (0-5 meters) measurement

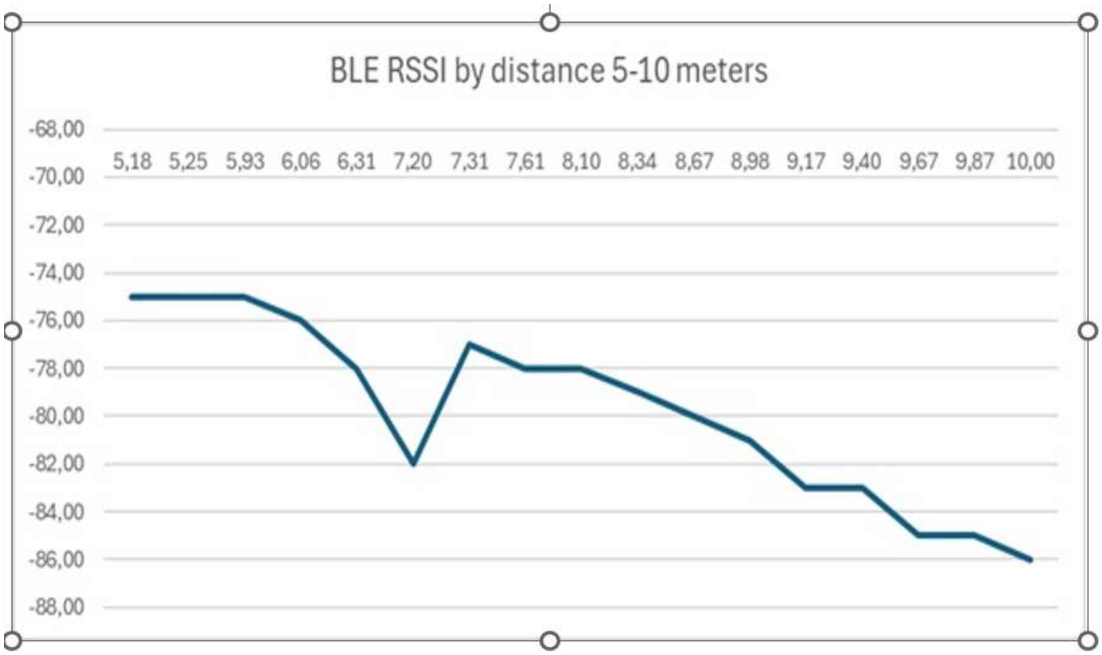

Fig. 2. BLE RSSI by distance (5-10 meters) measurement

This is a natural attenuation of radio signal. The RSSI value is stronger (less negative) at short distances and weaker (more negative) at longer distances. In the proximity area (0-2 meters) the curve has the steepest slope. At a distance of less than 1 meter (e.g. 0.48m), the RSSI is relatively strong, around -50 dBm. As the distance increases towards 2 meters, the value decreases quite steadily to around -65 dBm. This rapid and predictable decline makes the 0-2 meter range the most suitable for relatively reliable distance estimates.

In the intermediate area (2-5 meters), after the 2 meter threshold, the slope of the curve flattens considerably. From 2 to 5 meters, the RSSI value fluctuates in a narrower range, between approximately -65 dBm and -75 dBm. This demonstrates a key principle: at greater distances, a significant change in distance produces a much smaller change in RSSI value. Therefore, differentiating between a 3 meter and a 4 meter distance based on RSSI becomes more difficult and more prone to error.

The second figure, which shows the received signal strength (RSSI) between the scanner and an ESP32-C6 beacon over the 5-10 meter distance range, confirms and emphasizes the instability of the signal at greater distances.

The general trend of the RSSI value is to decrease as the distance increases, from -75 dBm at 5 meters, to -86 dBm at 10 meters. This decrease is far from linear or uniform, being characterized by significant fluctuations.

In the initial range, between 5.18 and 5.93 meters, the signal is relatively stable, maintaining a value of -75 dBm. Immediately after this threshold, a progressive attenuation is observed, reaching approximately -78 dBm at 6.31 meters.

The most prominent feature of the graph is the sudden and pronounced decrease in the signal, which reaches a minimum of -82 dBm at 7.20 meters. This abrupt attenuation, followed by an equally rapid recovery to -77 dBm at 7.61 meters, is an example of the impact of the environment. It is very likely that at this specific distance, the direct signal is obstructed or that reflected signals are interfering destructively, creating a "dead zone" or area of very weak signal.

After recovering from 7.61 meters, the signal continues its general downward trend, but it does so in an irregular, stepwise manner. Signal plateaus are observed (e.g. ~-83 dBm between 9.17m and 9.40m; -85 dBm between 9.67m and 9.87m) alternating with dips. This "stepping" behavior further emphasizes the difficulty of correlating a specific RSSI value with an exact distance. Following a comprehensive analysis of the graphs presented, several conclusions are taken.

The RSSI technology is effective for proximity detection and for a rough estimate of distance in the range of 0-5 meters. The relationship between distance and RSSI is more predictable at short distances.

The measurements confirms that, at distances above 5 meters, the BLE RSSI signal becomes very volatile.

At distances above 5-6 meters, the reliability of RSSI as a metric for calculating the exact distance decreases dramatically. Fluctuations caused by the environment (multi-path propagation, absorption, minor obstacles) become dominant.

Using a single RSSI reading to calculate an exact distance in this range is extremely unreliable. For example, a value of -78 dBm is recorded at both ~6.3 meters and ~8.1 meters.
Despite the imprecision, the system remains effective for presence detection or area localization. It can be determined with a reasonable degree of certainty whether a beacon is in the "near" (e.g. RSSI > -80 dBm) or "far" (e.g. RSSI < -80 dBm) range, which is often sufficient for flow management or crowd monitoring applications in an airport.

For an airport monitoring system, these data suggest that the technology is well suited to determining the presence of a person in a defined area (e.g. "in the baggage drop-off area" or "near security gate X") and to estimate the relative position ("person A is closer to the gateway than person B").

However, using it to create an accurate map with the precise coordinates of people (absolute location) would be extremely difficult and prone to significant errors, relying solely on RSSI.

In Line-of-Sight (LOS) conditions, with optimal Tx Power and possibly LE Coded PHY, the ESP32-C6 can have a considerable detection range – tens or even over a hundred meters, depending on the receiver's sensitivity and the actual transmission power.

4. DISCUTIONS

The BLE system operating mode for detecting, identifying and monitoring people in the public area (landside) of the airport, as presented in the block diagrams, combines a specific hardware architecture with a logical data processing flow.

The data flow and hardware components, as shown in Figure 3, are structured hierarchically.

The BLE Beacon is considered the starting point. The device is worn by each monitored person (passenger, employee). It functions as a Bluetooth Low Energy beacon, constantly emitting an identification signal.

The IoT device represents the physical implementation of the BLE beacon. It is a small electronic device (for example, a smart access card, a badge or a small dedicated tag) that contains the BLE module.

The ESP32-C6 BLE Scanner is the fixed component of the airport infrastructure. The scanners, based on the ESP32-C6 hardware platform, are strategically placed at key monitoring points (entrances, FIDS area, baggage claim area, security gates). Their role is to continuously "listen" to the signals emitted by the BLE beacons in proximity.

Fig. 3. Data processing flow.

All data collected by the scanners is centralized in a data repository (a database or a server). Critical information is stored here: the ID of the detected beacon, the location of the scanner that made the detection, the timestamp and the strength of the received signal (RSSI).

The airport management system represents the upper level of the architecture, where the aggregated data from the repository is processed, analyzed and visualized. This software system provides management, operational and security personnel with an overview of crowd flows, crowd density and security alerts, allowing informed decision-making.

The monitoring operational BLE ID system applies the following architecture (fig. 4). The logical flow of monitoring a person occurs through the following defined steps according to the schema blok generala.jpg, starting when they enter the public area until they exit security gates.

The first step is the system entry and ID assignment. Initial Detection (BLE Scan Entry) takes place. A person entering the airport is detected first by an ESP32-C6 scanner at the entrance of the airport via their IoT device (BLE beacon).

The next stage involves the random ID assignment (BLE ID attribution). To ensure privacy and anonymous person traking on a continuous basis, the central system does not link to anyone's hardware ID of the device. It creates a random BLE ID that will be attributed to that person just for entering the public area of the airport, and only when first detected. Next, the acknowledgment & BLE ID assignment takes place.

The system acknowledges this attribution in the data store and is in an active monitoring state for the newly assigned ID.

In the following step, BLE ID is monitored at FIDS area .The system operates with scanners at certain points. When a person moves within the area and arrives in the Flight information Display System (FIDS), the ESP32-C6 scanner, operating at that location will detect their attributed random BLE ID.

If the system obtains the signal (YES branch of the BLE ID at FIDS decision), it will acknowledge this new record in the data store. This new record includes their random ID, "FIDS" listing as location, time stamp, RSSI value.

Thus, the relative location of this person is updated. If a person has not arrived at the FIDS area yet (branch "NO"), the system continues to maintain an active monitoring state (Check BLE ID assignment), validating presence must exist at one of the way points.

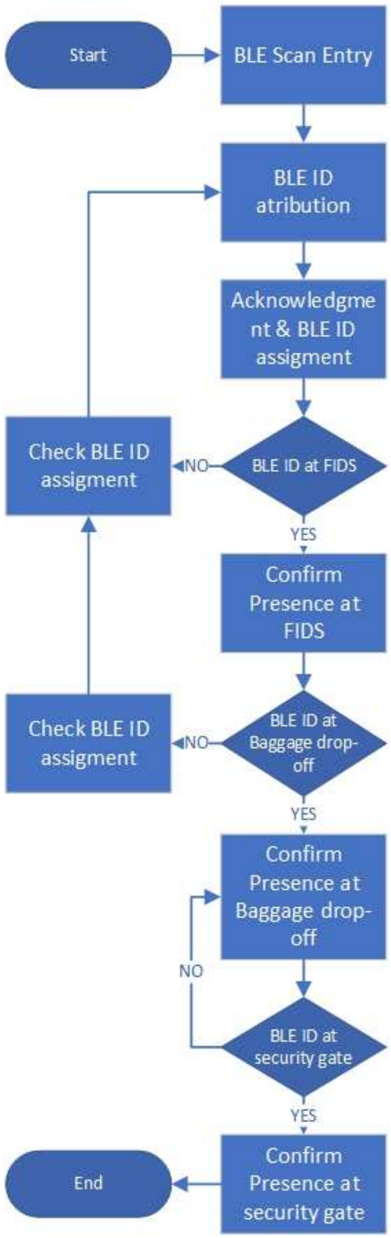

Fig. 4. BLE architecture system

The system continues to monitor at the next intermediate point, the Baggage Drop-off Area.When a person moves to baggage drop-off, and if the scanners indicate their attributed ID (YES branch of the BLE ID at Baggage drop-off decision), this means that a verification has occurred.

The "Confirm Presence at Baggage Drop-off)" phase means that another record is created in the data store, allowing awareness for their location at "Baggage Drop-off". This subsequent update allows the management system to create a tally of how long people spend in each location and how long it takes people to transfer from location to location which may indicate queuing or reasons why persons are stopped.

In the next step, the final detection takes place, during the exit from public area (Security Gates). This is the last way point in the public area (landside). When a person attains the access gates to security control, their ID is detected by the scanners situated there (YES branch of the BLE ID at security gate decision).

The confirmation of BLE ID presence at the security gate takes place. The system registers this action and acknowledges this action as an exit from their public turn.

When presence at security gates is confirmed, for that attribution ID, the cycle ends. Since this random ID is temporary, it can be deactivated or deleted from the active system thus preventing this random ID from being used to denote any future visits from the same person, while ensuring privacy. Therefore, through this hardware architecture and logical flow of operation, effective monitoring of persons in public areas is thus able to operate, allowing effective assessments for airport management while providing a fundamental measure of privacy through random and temporary IDs.

Based on the expected results and the limitations of this initial study, the following future research directions are considered.

Extensive testing in real airport environments can take place. Implementing a pilot system in an operational airport to confirm long-term performance under real traffic conditions and with a large number of labelled assets. This would allow for the evaluation of the robustness and scalability of the solution in the face of complex interferences that are specific to airports.

Integration with Advanced Localization Algorithms will be taken into account. The implementation and testing of triangulation/trilateration algorithms (requiring multiple gateways) or radio fingerprinting techniques allow overcoming the limitations of localization based solely on RSSI. experimenting with how machine learning (ML) algorithms can improve localization accuracy by learning signal propagation characteristics in specific areas.

Advanced BLE technologies will be explored. The ability to utilize the more advanced features of BLE 5.x, such as angle of arrival (AoA) and angle of departure (AoD) will be analyzed , to achieve more precise localization, although this may require specialized antenna hardware beyond the standard capabilities of the ESP32-C6-DevKitM-1. In addition, evaluate the effects of Bluetooth channel sound if it is available and supported on accessible platforms such as ESP32.

An attempt will be made to evaluate the potential effects of Wi-Fi networks (ESP32-C6 supports Wi-Fi/BLE coexistence) and other devices in the 2.4 GHz band. This happens even though it is difficult to completely isolate.

Qualitative elements will be discussed, such as BLE transmission security. BLE has security mechanisms, and the ESP32-C6 offers hardware security features such as flash encryption and secure boot.

These results underpin the previous sections regarding managerial implications and future research, providing a clear picture of the capabilities and limitations of using ESP32-C6 as BLE gateways for RSSI-based localization in airports.

The integration with other airport IoT systems can profit from the BLE localization system with existing airport IT systems, such as Flight Information Display Systems (FIDS), Baggage Handling Systems (BHS), or Enterprise Resource Planning (ERP) systems to create a unified informational ecosystem and maximize the value of localization data.

These research directions will help mature BLE localization solutions based on accessible platforms such as ESP32-C6 in the airport industry.

5. CONCLUSIONS

The study demonstrates that the ESP 32C6 platform is technically viable and cost effective for implementing a network of Bluetooth Low Energy BLE gateways in airport environments. Experimental results based on measurements within this range, the relationship between distance and signal attenuation is relatively predictable. However, the research also highlights the fundamental limitations of this method.

At this distance, beyond 5-6 metres, the volatility and instability of RSSI values increase exponentially due to environmental factors such as multipath propagation and minor obstacles. It is concluded that the system based solely on RSSI is unreliable for precise positioning with exact coordinates, but excellent for determining the presence of a person or asset in a predefined area, such as a checking area or near a security gate. Implementing such a network of BLE gateways has direct and significant managerial implications by real time monitoring, distribution and density of people like passengers, employees, operational staff in key public areas, airport management gains the superior situational awareness.

This data allows dynamic staff allocation and opening of new counters at baggage drop off or security access points based on real time crowding data, as well as directing maintenance, cleaning or assistant staff to areas where their presence is most needed.

The system transforms from a simple technical tool into a strategic support for managerial decisions aimed at increasing operational efficiency and reducing costs.

The proposed architecture uses random and temporary BLE ID's assigned upon entry into the monitored area, representing a practical approach to balance the need for operational monitoring with the right to privacy of individuals.

This method prevents persistent tracking and makes it difficult to correlate data to identify specific individuals, thus meeting data protection requirements such as GDPR. However it is emphasised that implementation in a public environment with high security requirements requires a thorough analysis of cyber risks and the integration of hardware security mechanism offered by the ESP 32C6 platforms to protect the integrity of the network.

This paper provides A valuable performance baseline and a practical framework for the adoption of BLE technologies in airports. The study paves the way for more advanced systems.

The maximum potential of this infrastructure will be reached through future research aim. At Integrating the advanced localization algorithms like triangulation and machine learning, exploring superior BLE technologies such as angle of arrival or departure and data fusion with other IoT systems in the airport.

The evaluated system is not just a point solution, but a fundamental step towards the interconnected and intelligent ecosystem that defines the concept of smart airport.

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Evaluarea performanței și aplicațiilor manageriale ale unei rețele de gateway-uri Bluetooth cu consum redus de energie bazată pentru localizarea activelor prin RSSI în medii aeroportuare dinamice

În mediile aeroportuare dinamice, optimizarea managementului activelor și a fluxului operațional reprezintă o provocare majoră. Acest studiu evaluează performanța gateway-urilor BLE ESP32-C6-DevKitM-1 pentru localizare în timp real utilizând analiza RSSI pentru monitorizarea beacon-urilor BLE. Testele empirice, simulând zonele operaționale ale aeroporturilor, examinează valorile RSSI în condiții de linie vizuală (LOS) și non-linie vizuală (NLOS), distanță variabilă, putere Tx și factori de mediu (interferențe, obstacole). Cercetarea explorează, de asemenea, plasarea optimă a gateway-urilor pentru o acoperire fiabilă și colectarea datelor de localizare. Sunt discutate securitatea și robustețea infrastructurii IoT BLE în spațiile publice de înaltă securitate. Articolul evidențiază potențialele beneficii ale BLE pentru îmbunătățirea managementului aeroportuar, a securității și a satisfacției pasagerilor în contextul transformării digitale.

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