Smart Sensing Framework: A Custom Beacon Architecture for Mobile Data Logging

David Díaz-Jiménez[1](✉), José L. López-Ruiz[1], Joaquín Torres-Sospedra[2], Miguel Matey-Sanz[3], and Macarena Espinilla[1]

[1] Department of Computer Sciences, University of Jaén, Jaén, Spain
{ddjimene,llopez,mestevez}@ujaen.es

[2] Valencian Graduate School and Research Network of Artificial Intelligence, València, Spain
Joaquin.Torres@uv.es

[3] Institute of New Imaging Technologies, Universitat Jaume I, Castellón, Spain
matey@uji.es

Abstract. This work presents a fully customized Bluetooth Low Energy (BLE) beacon system, developed using the Zephyr real-time operating system (RTOS). The beacon broadcasts structured, application-specific data through the Manufacturer Specific Data field, enabling a level of customization not offered by standard BLE profiles. A cross-platform mobile application, built with Flutter, has been designed to detect and interpret these customized signals in real time, providing a clear and interactive representation of the transmitted data. The complete system offers a lightweight, low-cost, and adaptable alternative to commercial solutions, particularly suitable for context-aware environments, smart infrastructures, and experimental research. The proposed architecture bridges embedded BLE development with mobile technologies, offering an open and scalable framework for customized wireless communication.

Keywords: Bluetooth Low Energy · Zephyr RTOS · Custom Beacon · Flutter App · Embedded Systems · Context-Aware Systems · IoT

1 Introduction

The proliferation of smart environments has driven significant interest in wireless technologies for location-aware services and asset tracking. Fields such as healthcare, education, tourism, and industrial automation increasingly rely on the ability to identify the position of people and objects indoors, where GPS is ineffective. Among various technologies explored for this purpose, Bluetooth Low Energy (BLE) beacons have emerged as a compelling solution due to their affordability, minimal energy requirements, and widespread compatibility with mobile devices [4,10].

J. Bravo et al. (Eds.): UCAmI 2025, LNNS 1818, pp. 443–449, 2026.
https://doi.org/10.1007/978-3-032-16992-1_42

BLE-based systems operate by periodically broadcasting small data packets that nearby receivers can detect. From these signals, the received signal strength indicator (RSSI) can be used to estimate proximity, often enhanced through techniques such as trilateration, probabilistic filtering, or fingerprinting [1,3,5,7,11,12]. This principle supports applications like indoor navigation in museums, access control in smart buildings, or real-time monitoring in hospital wards and elderly care. However, despite their wide adoption, many off-the-shelf BLE beacons provide only basic configurability. Parameters such as transmission power, advertising intervals, and—critically—advertising channel selection are often fixed or severely limited [6,13].

Recent investigations have demonstrated that BLE performance is highly sensitive to these configuration parameters. Differences in propagation characteristics across advertising channels (37, 38, and 39) due to multipath and shadowing effects are significant. When signal processing ignores channel origin, localization accuracy tends to suffer. Conversely, approaches that consider channel separation, or even leverage extended channels beyond the default three, show improvements in robustness and granularity [2,8,9].

Given these limitations, a custom BLE beacon (BASIA) has been developed in this work. It allows dynamic control of transmission power and advertising channels, and is built with an optimized antenna layout to reduce RSSI fluctuations. This device is intended for both real-world applications and experimental research where fine-tuned beacon behavior is essential. Additionally, a cross-platform mobile application was implemented using Flutter to detect, decode, and visualize beacon signals in real time. This paper focuses on the design, configuration, and evaluation of the proposed system, analyzing the implications for context-aware localization applications.

This paper is structured as follows: Sect. 2 introduces the beacon's hardware and firmware architecture. Section 3 describes the experimental procedures used for characterization. Section 4 presents results and comparative analyses. Finally, Sect. 5 outlines the main conclusions and future research directions.

2 System Architecture

This section describes the architecture of the complete system, which consists of two core components: a custom Bluetooth Low Energy (BLE) beacon programmed using the Zephyr Real-Time Operating System (RTOS), and a cross-platform mobile application developed in Flutter.

2.1 Embedded Beacon Design

The custom beacon, Fig. 1, was developed on a low-power microcontroller platform and programmed using the Zephyr Real-Time Operating System (RTOS). Zephyr enables fine-grained control of the Bluetooth Low Energy (BLE) stack, power management, and peripheral integration.

Fig. 1. Custom beacon.

The beacon broadcasts advertising packets using custom Manufacturer Specific Data (MSD), structured to include the following fields: transmission power, advertising channel, battery level, supply voltage, temperature, and status flags (e.g., charging state), Table 1. This format provides a flexible and compact mechanism for context-specific data dissemination.

Table 1. Structure of the Manufacturer Specific Data Payload

Offset	Size (bytes)	Type	Name	Description
0–1	2	`uint16_t`	`company_code`	Bluetooth Company Identifier (e.g., 0x0059 for Nordic)
2	1	`int8_t`	`power`	TX power level in dBm (e.g., −20, −8, 0, +4, etc.)
3	1	`uint8_t`	`channel`	Advertising channel identifier (e.g., 37, 38, 39, etc.)
4	1	`uint8_t`	`battery`	Battery level as percentage (0–100)
5–6	2	`uint16_t`	`supply_mv`	Power supply voltage in millivolts (e.g., 3700)
7	1	`uint8_t`	`temperature`	Device temperature in Celsius (integer)
8	1	`uint8_t`	`flags`	Bitwise status flags (bit 0: charging, bit 1: low power)

BLE behavior is dynamically configurable at runtime. The system includes:

- **Transmission power control:** cyclic adjustment across levels from `-20 dBm` to `+8 dBm`.
- **Channel switching:** rotation through BLE advertising channels 37, 38, 39 and optional custom modes.

Physical buttons on the device trigger interrupts, each associated with specific work routines (e.g., changing TX power, switching channels, displaying battery level). These tasks are managed using Zephyr's work queues and kernel timers, enabling low-latency asynchronous execution.

2.2 Mobile Application Design

A cross-platform mobile application was developed using the Flutter framework, enabling native deployment on both Android and iOS platforms. The application is responsible for scanning, decoding, and visually presenting the data transmitted by the custom BLE beacon.

Each detected beacon is filtered by name and decoded using its `Manufacturer Specific Data` payload, which is parsed to extract key fields such as:

- Transmit power (dBm)
- Advertising channel identifier
- Battery level (%)
- Supply voltage (mV)
- Internal temperature (°C)
- Charging status flag

The decoded data is rendered in dynamically generated, providing a user-friendly summary per device. Additionally, a detailed view includes a real-time RSSI chart, which updates with each scan interval and allows signal stability monitoring over time.

3 Methodology

To evaluate the detectability and robustness of the beacon signal under varying operating conditions, a series of experimental tests were conducted using multiple instances of the custom BLE beacon (denoted as *anchors*). The primary objective of the methodology was to assess how changes in transmission power and advertising channel influence the signal's reception performance in real-world scenarios.

3.1 Experimental Setup

One anchor was deployed across a controlled indoor environment with minimal interference. The mobile application described in Sect. 2 was used as the receiver, scanning continuously and logging information. Signal data was recorded for a fixed time interval (typically 60 s) to obtain a representative sample of the signal quality and stability.

3.2 Test Parameters and Metrics

Two main variables were independently manipulated in the beacons:

1. **Transmission Power:** The power level was varied across the supported discrete values $\{-4, +4\}$ dBm. For each power setting, a complete distance sweep was conducted.
2. **Advertising Channel:** The beacon was configured to transmit on specific BLE advertising channels—namely 37, 38, and 39—as well as combined or custom modes. This was achieved by modifying the Zephyr advertising parameters at runtime via button interaction.

Each combination of power level and advertising channel was tested independently, resulting in a matrix of configurations. All tests were performed in a single session to ensure environmental consistency (e.g., temperature, ambient RF noise, human movement). The key metric under observation was detectability of the beacon signal, measured as RSSI distribution. Mean and standard deviation of the signal strength at each distance point.

4 Results

This section analyzes the signal stability of the BASIA beacon under different advertising channel configurations and transmission power levels. The evaluation is based on the statistical behavior of the Received Signal Strength Indicator (RSSI), focusing exclusively on the mean and standard deviation of the signal across all tested conditions. Table 2 summarizes the results obtained during the experimental campaign.

The configuration using advertising channel 37 at `+4 dBm` yielded the strongest average RSSI (`-49.91 dBm`), indicating favorable propagation conditions in the test environment. This was followed by channel 39 under the same power level (`-52.24 dBm`). As expected, reducing the transmission power to `-4 dBm` led to a general decrease in signal strength, with the lowest mean observed in the all-channels configuration (`-62.41 dBm`).

Regarding signal stability, the standard deviation values reveal a clear contrast between multi-channel and single-channel modes. The all-channel configurations produced the highest signal variability, with deviations of `7.30 dBm` at `+4 dBm` and `6.96 dBm` at `-4 dBm`. In comparison, single-channel settings demonstrated significantly more stable behavior. Notably, channel 37 at `-4 dBm` had the lowest standard deviation (`1.16 dBm`), followed closely by channels 38 and 39. These results suggest that broadcasting over multiple advertising channels introduces greater RSSI dispersion, while single-channel transmission favors more consistent signal reception.

Table 2. Mean and Standard Deviation of RSSI by Advertising Channel and Transmission Power.

Configuration	Mean RSSI (dBm)	Standard Deviation (dBm)
All channels +4 dBm	−53.74	7.30
All channels −4 dBm	−62.41	6.96
Channel 37 +4 dBm	−49.91	2.83
Channel 37 −4 dBm	−58.25	1.16
Channel 38 +4 dBm	−58.99	2.88
Channel 38 −4 dBm	−58.57	1.24
Channel 39 +4 dBm	−52.24	3.19
Channel 39 −4 dBm	−58.81	2.57

5 Conclusions

This work presented the design and implementation of a custom Bluetooth Low Energy (BLE) beacon system combined with a cross-platform mobile application for structured wireless data broadcasting and visualization. The architecture's modularity and low-power design make it particularly well-suited for smart environments, prototyping platforms, and experimental setups where control, customization, and monitoring are critical. Additionally, the system is being explored for use in context-aware localization applications, such as indoor navigation in museums, patient flow tracking in hospitals, and other location-based services that benefit from lightweight and infrastructure-independent solutions. Future work will explore integration with cloud platforms, data logging features, and extended sensor inputs to further broaden the system's applicability.

Acknowledgments.
This work has been partially supported by grant PID2021-127275OB-I00 funded by MICIU/AEI/10.13039/501100011033 and by "ERDF A way of making Europe" and grant PDC2023-145863-I00 funded by MICIU/AEI/10.13039/501100011033 and by "European Union NextGenerationEU/PRTR".

Disclosure of Interests. The authors have no competing interests to declare that are relevant to the content of this article.

References

1. Alsmadi, L., Kong, X., Sandrasegaran, K., Fang, G.: An improved indoor positioning accuracy using filtered RSSI and beacon weight. IEEE Sens. J. **21**(16), 18205–18213 (2021)
2. Andreev, P., Aprahamian, B.: Analytical comparison of bluetooth low energy beacons. In: 20th International Symposium on Electrical Apparatus and Technologies (SIELA), pp. 1–4 (2018)
3. Bai, L., Ciravegna, F., Bond, R., Mulvenna, M.: A low cost indoor positioning system using bluetooth low energy. IEEE Access **8**, 136858–136871 (2020)
4. Botler, L., Spörk, M., Diwold, K., Römer, K.: Direction finding with UWB and BLE: a comparative study. In: 2020 IEEE 17th International Conference on Mobile Ad Hoc and Sensor Systems (MASS), pp. 44–52. IEEE (2020)
5. Dinh, T.M.T., Duong, N.S., Nguyen, Q.T.: Developing a novel real-time indoor positioning system based on BLE beacons and smartphone sensors. IEEE Sens. J. **21**(20), 23055–23068 (2021)
6. Gentner, C., Günther, D., Kindt, P.H.: Identifying the BLE advertising channel for reliable distance estimation on smartphones. IEEE Access **10**, 9563–9575 (2022)
7. Mackey, A., Spachos, P., Song, L., Plataniotis, K.N.: Improving BLE beacon proximity estimation accuracy through Bayesian filtering. IEEE Internet Things J. **7**(4), 3160–3169 (2020)
8. Nikodem, M., Szelinski, P.: Channel diversity for indoor localization using bluetooth low energy and extended advertisements. IEEE Access (2021)
9. Nikoukar, A., Abboud, M., Samadi, B., Günes, M., Dezfouli, B.: Empirical analysis and modeling of bluetooth low-energy (BLE) advertisement channels. In: 17th Annual Mediterranean Ad Hoc Networking Workshop (Med-Hoc-Net) (2018)

10. Obeidat, H., Shuaieb, W., Obeidat, O., Abd-Alhameed, R.: A review of indoor localization techniques and wireless technologies. Wireless Pers. Commun. **119**, 289–327 (2021)
11. Pakanon, N., Chamchoy, M., Supanakoon, P.: Study on accuracy of trilateration method for indoor positioning with BLE beacons. In: 2020 6th International Conference on Engineering, Applied Sciences and Technology (ICEAST), pp. 1–4. IEEE (2020)
12. Spachos, P., Plataniotis, K.N.: BLE beacons for indoor positioning at an interactive IoT-based smart museum. IEEE Syst. J. **14**(3), 3483–3493 (2020)
13. Yang, J., Poellabauer, C., Mitra, P., Neubecker, C.: Beyond beaconing: Emerging applications and challenges of BLE. Ad Hoc Netw. **97**, 102015 (2020)