JETIR.ORG ISSN: 2349-5162 | ESTD Year : 2014 | Monthly Issue
JOURNAL OF EMERGING TECHNOLOGIES AND INNOVATIVE RESEARCH (JETIR)
An International Scholarly Open Access, Peer-reviewed, Refereed Journal

SEAMLESS INTEGRATION OF BLUETOOTH BEACONS FOR MULTI-CHANNEL SHOPPING EXPERIENCE

1. Kalaimathi R
Assistant Professor
rkalaimathirajendiran@gmail.com

3. Vishwajith M
vishwabhai0410@gmail.com

5.Manikandan R
manikandanrangan18@gmail.com

2. Nihal Ahmed N
n.nihalahmed1@gmail.com

4. ManojKumar V
pmt03102002@gmail.com

Department *of Electronics and Communication Engineering*
Velammal Engineering College
Chennai, India

***Abstract*— In the ever-changing retail landscape, where physical and digital merge, a seamless shopping experience spanning stores and online platforms is essential. This project leverages Bluetooth beacon tech to effortlessly unite these realms, creating personalized shopping. It involves physical stores, a mobile app, and an online platform, all linked by strategically placed Bluetooth beacons. The goal is to enhance customer engagement, simplify navigation, and enrich interaction. The mobile app serves as the core, bridging shoppers to the in-store world. As customers enter, beacons trigger tailored notifications, real-time promotions, and recommendations. It also guides in-store navigation via beacons. Seamless app-online integration ensures a consistent cart. Shoppers easily switch between online and in-store shopping, even using beacons for click-and-collect. Data analytic track user interactions, refining marketing and hyper-personalizing promotions. User feedback drives continual enhancements. This project re-imagines retail with a unified, adaptive, and context-aware shopping experience, driven by Bluetooth beacons, setting new standards in convenience and engagement.**

Keywords*— Bluetooth Beacon, mobile app, shopping mall, navigation, notification, promotions, recommendations

I. Introduction

In the rapidly evolving landscape of retail, providing customers with a seamless and personalized shopping experience across various channels has become a paramount objective for businesses seeking to stay competitive. One innovative solution that has gained significant traction is the integration of Bluetooth beacon technology. By leveraging the capabilities of these small, wireless devices, retailers have the potential to revolutionize how customers engage with their physical and digital storefronts.

This report delves into the intricacies of integrating Bluetooth beacons into the retail environment, aiming to elucidate the process and benefits associated with this technological advancement. From the selection of appropriate hardware to the development of a user-friendly mobile application, each step is meticulously considered to ensure a cohesive and immersive shopping experience. Furthermore, this report addresses the critical elements necessary for the successful implementation of this technology, including beacon infrastructure placement, region definition, and the incorporation of location-based services (LBS).

The overarching goal of this endeavor is to create a dynamic shopping environment where customers seamlessly transition between in-store, online, and mobile experiences, guided by real-time, context-aware interactions facilitated by Bluetooth beacon technology. By harmonizing the physical and digital realms, businesses stand to not only enhance customer satisfaction but also gain invaluable insights into consumer behavior.

Throughout the following sections, we will explore the key components of this integration, providing a comprehensive guide for retailers looking to elevate their multi-channel shopping experience through the strategic adoption of Bluetooth beacon technology.

II. Ease of Use

1. Intuitive User Interface: The mobile application should feature an intuitive and user-friendly interface, allowing customers to easily navigate and interact with beacon-triggered content or services.

2. Automated Connectivity: Ensure that the app can swiftly and automatically connect with nearby Bluetooth beacons, minimizing any manual intervention required from the user.

3. Clear Onboarding Process: Provide a clear and concise onboarding process within the app that guides users on how to enable Bluetooth, grant necessary permissions, and understand the benefits of beacon interactions.

4. Contextual Prompts : Implement contextual prompts or notifications that inform users about available beacon-triggered content or services when they are in proximity to a relevant beacon.

5. Transparent Privacy Settings : Clearly communicate and allow users to customize their privacy settings related to beacon interactions, ensuring compliance with data protection regulations.

6. Consistent Experience Across Channels : Strive for uniformity in user experience across in-store, online, and mobile channels. This includes maintaining similar navigation patterns and content presentation.

7. Efficient Content Delivery : Ensure that content delivered via beacon interactions is concise, relevant, and easily digestible, enhancing the overall user experience.

8. Personalization and Relevance : Leverage user data and preferences to personalize beacon-triggered content, offering products or services tailored to individual preferences.

9. Opt-out Options : Provide users with the ability to easily opt-out of beacon interactions if they choose to do so, respecting their preferences and privacy.

10. Accessibility Considerations : Design the app and beacon interactions with accessibility features in mind, ensuring that all users, including those with disabilities, can fully engage with the technology.

11. Feedback Mechanism : Implement a feedback mechanism within the app to gather user input and address any concerns or suggestions related to beacon interactions.

By prioritizing ease of use in the integration of Bluetooth beacons, businesses can create a seamless and intuitive shopping experience that empowers customers to effortlessly navigate between physical and digital channels, ultimately driving higher levels of engagement and satisfaction.

III. BLE BEACON APPLICATIONS

BLE beacons have seen widespread adoption in recent years, with major players like Google, Apple, Facebook, and LINE championing new standards and hardware. This has made BLE beacon-based services more accessible to both the public and developers than ever before. This surge of interest has led to the proposal of various intriguing applications in both academic and industrial sectors. These applications encompass indoor localization, proximity detection, and activity sensing.

A. Localization

Indoor localization stands out as a crucial potential application for BLE beacons. While GPS revolutionized outdoor localization, it falters in indoor environments and city streets due to signal attenuation and multi-path fading. Wi-Fi-based solutions have limitations in terms of access point availability and deployment flexibility. RFID, ultra-wideband, and infrared technologies have been used, but they require dedicated readers, making them less user-friendly. BLE beacon-based solutions hold a distinct advantage due to their low production cost, easy deployment, and user accessibility. Studies have shown impressive results, with < 2.6m error achieved 95% of the time in office setups using 19 beacons. This outperforms existing Wi-Fi networks, which achieve < 8.5m error. Additionally, stigmergic approaches leveraging RSSI information from static anchor nodes have been successful in crowded areas, aiding visually impaired individuals and facilitating navigation in places like museums and airports.

B. Proximity Detection and Interaction

BLE beacons not only provide locational information but also convey contextual data by measuring proximity to objects or areas. This distinction between location and proximity is crucial. While QR codes and NFC offer similar functionality, they have limitations such as size requirements and short interaction distances. BLE beacons address these concerns effectively. Deployed systems have demonstrated effective notifications based on proximity, enhancing user context and location. Examples include systems for tourist navigation, interactive art galleries, and detailed artwork information in museums. Industry giants like Google, Apple, Facebook, and LINE have introduced proximity-based applications, enabling seamless interaction with physical objects.

C. Activity Sensing

BLE beacons can also be leveraged to identify user activities by using the information they convey in reverse. For instance, gesture detection technology in smart wearables, combined with fine-grained location data from BLE beacons, helps narrow down possible user actions, leading to significant reductions in sensing time. Similarly, systems have been implemented to monitor the activity of senior citizens using accelerometer-equipped BLE beacon tags.

D. Future Applications

While most examples involve static deployments of BLE beacons, exploring their applications on moving objects like cars, trains, bicycles, and humans presents an intriguing area for future study. This would require investigating the reliability of BLE beacons for mobile objects and further research in activity sensing. Additionally, with the growing prominence of machine learning, gathering user information becomes paramount. Incorporating contextual and locational data through both localization and proximity detection opens up new avenues for machine learning to enhance user engagement and services.

IV. BLE PROTOCOL AND RF SIGNAL CHARACTERISTICS

This section provides a comprehensive understanding of BLE (Bluetooth Low Energy) beacons and their significance in the context of the Internet of Things (IoT). It begins by offering an overview of the historical development of Bluetooth technology and its associated protocol. Subsequently, it introduces two prominent BLE beacon profiles prevalent in the market, namely iBeacon and Eddystone. The section also delves into the specifics of Bluetooth signals, with a particular focus on Received Signal Strength (RSS) and its measurement using any Bluetooth-compatible receiver. Furthermore, it examines the behavior of these signals in environments where multiple beacons coexist.

A. Transition from Bluetooth Classic to Bluetooth Low Energy (BLE)

Bluetooth technology, overseen by the Bluetooth Special Interest Group (SIG), has established itself as a well-defined wireless standard for short-range communication for over a decade. Initially conceived as a wireless alternative to tethered device connections, Bluetooth aimed to enhance mobility within the communication range defined by its signal. For instance, it facilitated the replacement of wired mice with wireless Bluetooth mice. During this period, the primary success factor for Bluetooth was its reliability in ensuring seamless communication between devices, with power efficiency being of secondary importance.

However, the landscape changed with the emergence of IoT devices that demanded improved, energy-efficient communication technologies. This shift in requirements led to the development of low-power communication technologies such as RFID and ZigBee, as previously discussed. Concurrently, Bluetooth SIG introduced BLE as its first low-power iteration of Bluetooth. Notably, BLE is not backward compatible with Bluetooth Classic and is purposefully designed with IoT devices in mind, prioritizing energy efficiency over the high-speed, high-data-rate features of Bluetooth Classic. Table I summarizes the key distinctions between Bluetooth Classic and BLE. Despite these differences, both technologies operate within the same license-free 2.4 GHz ISM spectrum band, and the maximum range of their signals is determined by their transmit power.

The primary differences between classic Bluetooth and BLE can be summarized as follows:

- The two protocols cater to distinct purposes and applications, with Bluetooth Classic tailored for multimedia streaming and BLE targeting IoT applications where short bursts of sensor data require frequent broadcast.

- Bluetooth Classic relies on pairing between central and peripheral devices for streaming, while BLE obviates the need for such pairing.

- Bluetooth Classic facilitates one-to-one communication, while BLE enables one-to-many communication, with the "one" being a BLE beacon device.

To ensure the coexistence of both technologies, Bluetooth SIG introduced Bluetooth Smart Ready, capable of supporting both Bluetooth types simultaneously. Bluetooth Smart Ready is commonly found in devices with enhanced computational capabilities, such as smartphones and computers. As this paper centers on BLE beacons and their promising implications for IoT development, readers seeking detailed information about Bluetooth Smart Ready and other roles of BLE (e.g., peripheral, central, and observer modes)

TABLE I
CLASSIC BLUETOOTH VERSUS BLE

Feature	Classic Bluetooth	BLE
Symbol rate	1-3 Mbps	1 Mbps
Power consumption	1 (normalized)	0.01 - 0.5
Throughput	0.7-2.1 Mbps	305 kbps
Connection Latency	100+ ms	<6 ms
Channels	79	40
Channel Bandwidth	1 MHz	2 MHz
Peak Current	<30 mA	<15 mA

(a) Adv PDU				Payload defined by iBeacon Standard				
1 byte	4 bytes	2 bytes	6 bytes	9 bytes	16 bytes	2 bytes	2 bytes	1 byte
Preamble	Access Address	Header	MAC	iBeacon Prefix	Universally Unique Identifier (UUID)	Major	Minor	Tx Power

(b) Adv PDU				Payload defined by Eddystone Standard						
1 byte	4 bytes	2 bytes	6 bytes	UID	1 byte	1 byte	16 bytes	2 bytes		
Preamble	Access Address	Header	MAC		Frame Type	Ranging	UID	Reserve		
				URL	1 byte	1 byte	18 bytes			
					Frame Type	Ranging	URL			
				TLM	1 byte	1 byte	2 bytes	2 bytes	4 bytes	4 bytes
					Frame Type	TLM Version	Battery Level	Temperature	ADV_CNT	SEC_CNT

Fig. 2. Advertising PDU of (a) iBeacon and (b) Eddystone.

B. BLE Protocol and Beacon Profiles

As indicated in Table I, BLE allocates its 2.4 GHz ISM spectrum into 40 channels, with three channels (namely, Channel 37 at 2.42 GHz, Channel 38 at 2.426 GHz, and Channel 39 at 2.48 GHz) exclusively designated for advertisement purposes, while the remaining channels are reserved for data exchange. The significant spacing between the advertisement channels serves to minimize interference with Wi-Fi signals operating in the same ISM band. BLE devices responsible for advertising via Channels 37–39 are commonly referred to as beacons. These beacon devices are connectionless and periodically broadcast their signals. An advantage of this mechanism is that it eliminates the need for device pairing to receive the signals broadcasted by the beacon. Typically, the advertising signals contain a compact data payload, often referred to as an advertising protocol data unit (PDU). This payload may encompass packet header information, the MAC address, the device's unique identifier, and a limited space for manufacturer-specific data. Notably, both Apple and Google have harnessed this small payload encapsulated within the advertising PDU to introduce their respective popular beacon profiles: iBeacon and Eddyston.

1) iBeacon by Apple: iBeacon is a widely recognized BLE profile introduced by Apple Inc. during their annual Apple Worldwide Developers Conference (WWDC) in 2013. Apple's unveiling of iBeacon garnered significant attention from both industry players and academia. It was particularly notable for its claim to operate on a coin-cell battery for months or even years, thanks to its low power consumption, made possible by the small size of the advertising PDU. Figure 2(a) illustrates the iBeacon advertising PDU, which spans a total length of 46 bytes. This packet structure not only facilitates the convenient identification of individual beacon devices but also establishes a universal standard for application development within the industry. Subsequently, iBeacon has spurred the development of various location-based and proximity-based applications.

2) Eddystone by Google: Google introduced its open-source BLE profile, Eddystone, as a competitive response to Apple's iBeacon standard. The launch of Eddystone had a profound impact on IoT development, notably with the introduction of the Physical Web. Differing from the proprietary nature of iBeacon, Eddystone enables seamless interaction with the existing Chrome browser on any operating system. This flexibility in contextual content development obviates the need for creating a completely independent mobile application to interact with deployed beacons. For a comprehensive comparison between iBeacon and Eddystone, readers are encouraged to refer to the summary provided in . In general, Eddystone allows developers to switch between URL and TLM frames, as illustrated in Figure 2(b). The URL frame's working principle resembles that of a conventional QR code, while the TLM frame permits developers to convey additional data regarding the deployed beacon. Detailed technical information on the Eddystone protocol is available on Google's GitHub.

3) Manufacturer-Specific Custom Profiles: Beyond iBeacon and Eddystone, the BLE protocol exhibits flexibility in allowing manufacturers to configure customized BLE profiles tailored to specific use cases. Manufacturers can incorporate additional information into the beacons or modify the byte offsets for storing particular data, such as battery voltage level measurements for efficient management, sensor measurements for data collection, and authentication keys for enhanced security measures. However, the application side must be re-engineered to retrieve the correct data from these customized beacon packets. Furthermore, these custom profiles may evolve over time, potentially incorporating dynamic packet structures and information. Such designs have the potential to offer more sophisticated services, opening up new avenues for research.

C. Received Signal Strength and Coverage Distance

One critical parameter of interest from any beacon, regardless of its BLE profile, is Received Signal Strength (RSS). RSS is measured in dBm and describes the power received at the receiving end relative to the transmit power. For Bluetooth 4.0, the maximum range of a beacon signal is known to be approximately 150 meters. However, this level of coverage is achieved only in open environments with an unobstructed line of sight between the transmitter and receiver. In reality, the signal strength decreases along its propagation path, following the inverse square law. The received signal power (Pr) is inversely proportional to the square of the distance (d), denoted as Pr ∝ d^(-1/2). In practice, the signal often attenuates more rapidly due to various environmental factors. To account for these loss factors, the relationship between received signal power and distance can be further defined as Pr ∝ d^(-α), where α represents the loss exponent. RSS is typically measured on a dBm scale (i.e., RSS = 10 log(Pr/1 mW)), and the relationship between RSS and distance can be expressed as RSS ∝ -α log(d). In logarithmic terms, the linear relationship between RSS and distance can be formulated as

$$RSS = -\alpha \log(d) + K,$$

where -α represents the loss exponent, K is the offset constant, and d represents the distance in meters. It's worth noting that this equation represents a general path loss model applicable to various scenarios, each with its unique loss exponent.

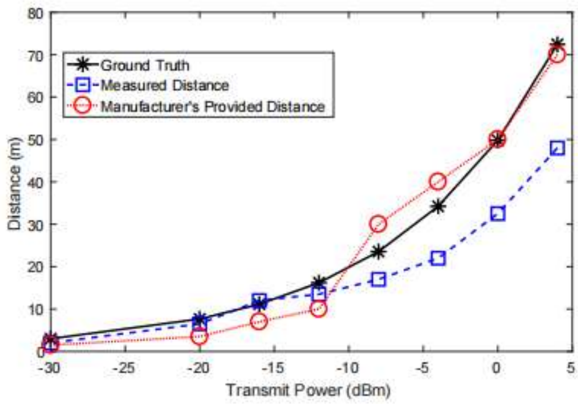

Fig. 3. Distance versus transmit power.

In practice, the signal coverage of Bluetooth Classic and BLE is identical if both are configured with the same transmit power. Figure 3 compares the theoretical and measured distances for a beacon with varying transmit powers ranging from -30 dBm to 4 dBm. The theoretical distances were provided by the beacon's manufacturer, Estimote, while the measured distances were collected using a commercially available Android smartphone. The graph demonstrates that weaker transmit power reduces the range of signal coverage. Additionally, it shows discrepancies between the measured and theoretical distances. Signal fluctuations introduce errors in the theoretical distance estimation, which relies solely on the RSS value. Previous research has also concluded that distance estimation based on RSS is unreliable. This unreliability is exacerbated in environments with multiple beacons in close proximity. Therefore, the subsequent subsection explores signal behavior in dense environments.

D. Beacon Signals in Dense Environments

Although BLE reduces the number of channels to 40 (from the total 79 channels in Bluetooth Classic), with each channel equally spaced at 2 MHz, in scenarios with ten randomly placed beacons, a smartphone may not detect all beacon signals within a brief scanning period. The scanning period refers to the time during which the smartphone listens for nearby BLE signals.

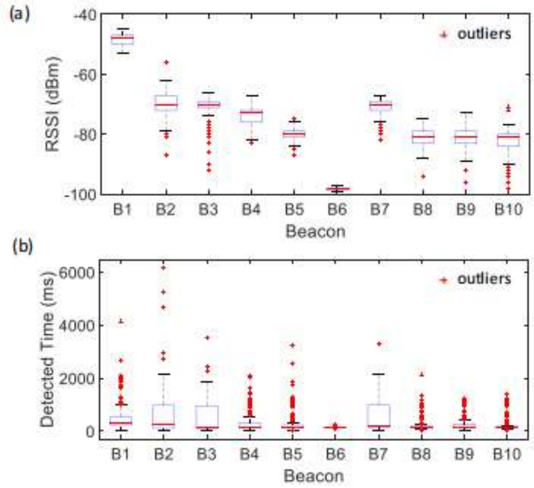

Fig. 4. Variation in BLE beacon signal characteristics in a dense environment: (a) the RSS; (b) the time interval to detect a beacon signal.

Figure 4(a) illustrates the variation in RSS from each of the ten beacons. It's observed that the RSS levels fluctuate over time, even when the beacons remain stationary during the experiment. Figure 4(b) depicts the time taken for each beacon to be detected. Under optimal conditions, each beacon requires less than 1 second to be detected. However, under suboptimal conditions, the detection time can exceed 5 seconds. The variation in RSS and detection time can be attributed to signal propagation effects (e.g., multipath fading, shadowing, etc.) and environmental factors (e.g., movement of people in the vicinity and fluctuations in room temperatures). Beacon B2, in particular, exhibits significant RSS variation. Among a total of 751 scans conducted, 12 scans failed to detect any signals, while only one scan successfully captured all ten signals. These observations highlight the challenges posed by signal fluctuations in RSS and detection times, especially in environments with multiple beacons.

V. BLE BEACON HARDWARE

A thorough understanding of the hardware components within a BLE (Bluetooth Low Energy) beacon is essential for building a robust physical layer that can deliver dependable and scalable services. Figure 5 presents an illustration of these components. We conduct an extensive examination of the hardware choices available for a BLE chipset, energy storage solutions, and casing. Additionally, we delve into the advantages and disadvantages of these options to offer deeper insights into their selection and implementation.

A: Power Consumption Characteristics of BLE Beacons

When it comes to designing a BLE (Bluetooth Low Energy) beacon, two primary objectives are of utmost importance: maximizing its battery life and accurately predicting that lifespan. Extending battery life is crucial for making the infrastructure more manageable and cost-effective, while precise battery life estimation ensures timely battery replacement, thus optimizing the utilization of available energy resources. To achieve these goals, a thorough analysis of the power consumption characteristics of BLE beacons is indispensable. In this subsection, we meticulously examine the power usage of an off-the-shelf BLE beacon, with some results sourced from our previous research. For this study, we used a reference Bluetooth chipset, the CC2451 from Texas Instruments Inc., selected because it is one of the most widely adopted BLE ICs, as evidenced by its market share in Figure 9.

Fig. 5. An illustration of generic hardware components of BLE beacon.

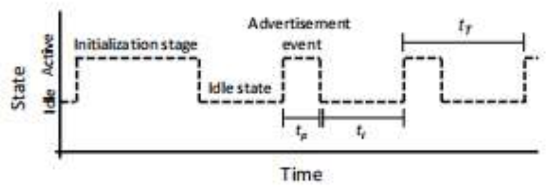

Fig. 6. Electrical characteristics of BLE beacon including initialization state.

Figure 6 provides an illustration of the different operational states of a beacon device. Here, "tT" represents the advertising interval of the beacon, "tp" signifies the time during which the beacon actively broadcasts its advertisement packet, and "ti" denotes the time between each advertising event when the beacon remains idle to conserve energy. The diagram also includes the initialization stage, which consumes a significant amount of energy. It's important to note that this initialization stage occurs only once during the system's boot-up, unless there is a fatal error. Figure 7 offers a more detailed breakdown of current consumption during advertising events. An advertising event typically consists of three different states, and more specifically, we consider nine distinct states. These states and their corresponding current draws are outlined in Table II. Since the device maintains a constant current draw during the idle state, and the initialization stage is a one-time occurrence, our primary focus is on scrutinizing the current consumption characteristics observed during advertising events.

To calculate the average current draw during an advertising event, denoted as "Ip," we calculate the average across the different states over the duration of the advertising event. Determining the average current consumption during the idle state, denoted as "Ii," is straightforward and involves direct measurement with an ammeter, as it exhibits a consistent current draw. Armed with these two parameters, we can compute the average current draw, accounting for the advertising interval, using the following formula:

$$I(t_T|t_p, I_p, I_i) = \frac{t_p I_p + t_i I_i}{t_T},$$

Here, "I" represents the average current draw at an advertising interval "tT," with "tp" indicating the advertising event duration, "Ip" representing the average current during the event, and "Ii" reflecting the current drawn during the idle state.

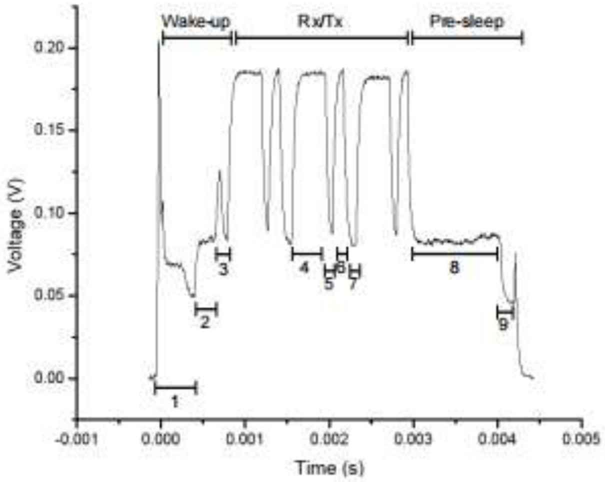

Fig. 7. Current draw of BLE beacon during advertisement event.

TABLE II
ELECTRICAL CHARACTERISTICS OF BLE BEACON DURING BROADCASTING EVENT DIVIDED INTO DIFFERENT STATES.

State Number	Description	t (μs)	V (mV)	I (mA)
State 1	Wake-up	480	69.12	6.91
State 2	Pre-processing	225	85.04	8.50
State 3	Pre-Rx	160	114.20	11.42
State 4	Rx	395	184.80	18.48
State 5	Rx-to-Tx	90	89.49	8.95
State 6	Tx	130	187.60	18.76
State 7	Tx-to-Rx	155	80.96	8.10
State 8	Post-processing	1070	85.03	8.50
State 9	Pre-sleep	195	47.08	4.71

This average current draw serves as a valuable metric for estimating the battery life of a beacon at a given advertising interval, a critical parameter for deployment and management considerations. It's important to acknowledge that while this method is commonly used for its simplicity, it assumes a constant current draw, despite the actual pulsed nature of the draw.

For more precise predictions, battery models that account for the battery recovery effect may become necessary.

B: BLE Chipset Options

Bluetooth chipsets are currently manufactured by several prominent companies, including Texas Instruments, Nordic Semiconductors, Dialog Semiconductors, and Cypress. Each of these companies offers unique advantages and features for BLE chipset options:

1. Texas Instruments (TI): TI is known for providing excellent reference designs and sample codes, which greatly assist developers in initiating their projects. Their BLE chipsets are well-regarded for their reliability and ease of integration.

2. Nordic Semiconductors: Nordic Semiconductors is recognized for producing highly energy-efficient chipsets, which can significantly extend the battery life of BLE devices. Their chipsets are particularly suitable for applications requiring low power consumption.

3. Dialog Semiconductors: Dialog Semiconductors is another key player in designing integrated chipsets for low-powered devices. They offer a range of power management ICs that operate with ultra-low current consumption, often in the range of picoamperes.

4. Cypress: Cypress specializes in integrated chipsets for low-power devices and offers numerous power management ICs. Their solutions are known for their efficiency and can operate at very low currents, often in the range of a few hundred picoamperes.

When selecting a BLE IC, it's essential to consider four major aspects:

a. Power Consumption: Evaluating the power consumption of a BLE chipset is crucial, as it directly impacts the device's battery life. Lower power consumption is particularly vital for devices that need to operate for extended periods without frequent battery replacements.

b. Flash Capacity: Flash storage capacity is essential for storing firmware and data on the BLE beacon. The choice of flash capacity depends on the complexity of the application and the need for additional storage space, such as for firmware updates or logging purposes.

c. RAM Capacity: RAM capacity is important for storing and processing data during device operation. While larger RAM can be beneficial in some cases, it's primarily determined by the specific requirements of the application.

d. Internal Voltage Regulator: Many BLE beacons come equipped with an internal voltage regulator. While this offers convenience by accommodating a wide range of input voltages and reducing the need for additional components, it may not always be the most energy-efficient option.

It's worth noting that higher voltages typically result in lower current draw, but this isn't always the case. Some BLE chipset designs employ low-dropout regulators, which can be inefficient at high voltages. In contrast, certain chipsets from Nordic Semiconductors feature a DC-DC regulator designed to reduce current draw at higher voltages. However, this feature has been associated with stability issues in some hardware revisions. Consequently, developers may opt to include an external voltage regulator in their designs to optimize battery life and avoid potential complications.

In summary, the choice of a BLE chipset involves careful consideration of power consumption, storage capacities, and voltage regulation options to align with the specific requirements and objectives of the project. Each chipset option offers unique advantages and trade-offs, allowing developers to select the most suitable solution for their BLE beacon applications.

TABLE III
A COMPARISON OF REPRESENTATIVE BLE CHIPSETS FROM LEADING MANUFACTURERS

BLE Chipset	Supported Version	Current
CC2541	Single Mode BLE v4.0	18.2 - 14.3 mA
nRF51822	Single Mode BLE v4.1	9.7 mA
PSoC 4 BLE	Single Mode BLE v4.1	15.6 mA

C: Energy Storage Options

Various methods of energy storage are available for BLE beacons, including disposable batteries, rechargeable batteries, and supercapacitors. Many beacons currently on the market use disposable lithium-ion batteries, such as Estimote and Kontakt.io beacons. These batteries are favored for their affordability, thermal stability, and non-toxic properties. In this section, we will delve into the different means of energy storage for BLE beacons and explore their advantages and limitations.

BLE beacon devices often employ coin-cell batteries due to their low-profile form factor and ability to provide sufficient power. Nearly all major beacon manufacturers utilize lithium coin-cell batteries, denoted by CR or BR. However, both practical experience and theoretical calculations have shown that these coin-cell batteries typically have a relatively short lifespan, necessitating frequent replacements. Table IV demonstrates the theoretical lifespan of a beacon with an 800 ms advertising interval, a common interval used by BLE beacon manufacturers.

To extend the lifespan of beacon devices, some manufacturers have opted for larger alkaline batteries like AA or AAA. These larger batteries indeed offer a longer operational lifespan, but they come at the cost of increased casing size and weight. For instance, Sensoro Pro beacons use four AA batteries and claim to last 5–6 times longer than regular beacons equipped with a CR2477 battery with a capacity of 1000 mAh. Similarly, TheBeacons use 2 AA alkaline batteries with a capacity of 2600 mAh. However, the increased size and weight of beacons equipped with larger batteries can undermine one of the core advantages of BLE beacons—ease of deployment. Traditional BLE beacons typically weigh around 20–30 grams, making them easy to attach to surfaces using simple adhesive tape.

BLE beacons are highly scalable, owing to their minimalist protocol and user-friendly deployment. Their lightweight nature, typically 20–30 grams, facilitates convenient placement using adhesive tape, which is readily available at hardware stores. However, the use of larger batteries can compromise this unique advantage.

TABLE IV
THEORETICAL BATTERY LIFE CALCULATION

Model	Capacity (mAh)	Size (mm x mm)	Life Time (days)
CR2477	1000	24 x 7.7	640
CR2450	620	24 x 5.0	397
CR3032	500	30 x 3.2	320
CR2032	320	20 x 3.2	205

D: Energy Harvesting Capability for BLE Beacons

To address the battery-related challenges of BLE beacons, some manufacturers have introduced energy harvesting BLE beacons equipped with solar panels. The concept of energy harvesting wireless sensor nodes has been a prominent research area, with extensive studies aimed at optimizing energy harvesting hardware in terms of mechanisms, storage sources, and charging circuitry. This trend in energy harvesting untethered devices has had a significant impact on the development of IoT devices.

Previous works have explored various energy harvesting methods, such as kinetic energy harvesting from human movement, light harvesting from ambient sources, and combinations of RF and light harvesting. These endeavors have led to the creation of BLE beacon systems powered by energy harvesting. However, it's essential to note that the energy harvesting capabilities of these devices often fall short of supporting the required advertising frequency of 1 Hz or may have limitations in terms of energy storage capacity for sustained operation when ambient energy is unavailable.

The earlier investigations into energy harvesting wireless sensors were primarily focused on outdoor deployment scenarios. However, many BLE beacon applications occur indoors, where certain energy sources may be absent or too scarce to provide sufficient energy for perpetual operation. Consequently, there is a growing need to explore indoor energy harvesting solutions to design energy-neutral BLE beacon devices. Recent research has begun to investigate indoor lighting and photovoltaic cells as potential energy sources for wireless sensors. These efforts have resulted in prototypes designed to operate for extended periods without maintenance.

E: Casing for Aesthetics and Protection

When it comes to BLE beacon casings, two primary concerns are aesthetics and protection. The choice of casing design can have a significant impact on a beacon's visual appeal and its ability to blend into its environment or stand out as a decoration. For example, Estimote beacons are known for their aesthetically pleasing design, making them suitable for deployment in venues like retail shops. In contrast, some beacons, like Gimbal's S21 beacons, are designed to be inconspicuous and blend seamlessly with their surroundings.

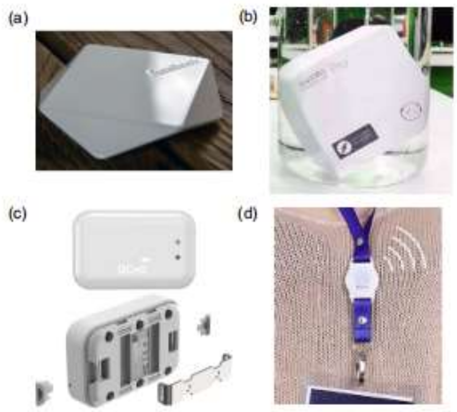

Fig. 8. Different features of beacon casings: (a) aesthetic design, Facebook beacon; (b) water-resistance, Sensoro Pro beacon ; (c) installation brackets, GCell G300 Universal iBeacon; (d) neck lanyard and a card holder design, Bright Beacon.

Ensuring the long-term reliability of BLE beacons requires protecting their internal circuits from environmental factors such as water, dust, and potential physical impacts. To meet these demands, modern beacon casings often adhere to water and dust resistance standards, such as the International Electrotechnical Commission's (IEC) Ingress Protection (IP) Code. However, it's essential to note that many off-the-shelf BLE beacons may not provide long-lasting protection. For example, while Estimote's beacon can withstand high water pressure, the casing must be cut open to replace the battery, resulting in the loss of its water-resistant feature after the first maintenance. This is a common issue with many protective casings currently available in the market.

F: Casing for Installation and Deployment

Often overlooked, the design of installation casings plays a crucial role in the effective deployment and maintenance of BLE beacons. These casings offer distinct advantages over conventional installation methods, such as the use of double-sided adhesive tape. They serve as a critical element in securely anchoring the beacon in place and may include mechanisms for the convenient removal of the BLE beacon from its casing, typically for battery replacement. For example, the GCell beacon utilizes installation brackets designed for secure attachment to a wall, ensuring a robust installation. On the other hand, Kontakt's Beacon Pro incorporates a mounting clip at the back, facilitating both deployment and disassembly.

Nevertheless, it's imperative to consider potential drawbacks associated with certain types of installation casings, particularly when they have the potential to cause damage to the installation location. Casings that involve drilling or other intrusive methods can compromise the integrity of the deployment surface, which may not be desirable. To achieve a dependable installation without compromising the condition of the deployment site, innovative approaches are warranted.

The design of installation casings should also take into account the material and orientation of the surfaces where they will be deployed. In various real-world deployment scenarios, such as those observed at the Hong Kong University of Science and Technology (HKUST), newsstands across Hong Kong, and BTS Skytrain stations in Bangkok, the choice of installation surface material and orientation can significantly influence beacon placement.

For example, vertical surfaces were predominantly chosen for deployment in Bangkok and Hong Kong, whereas HKUST necessitated horizontal placement to conceal the beacons from direct line of sight, such as positioning them under tables. However, horizontal deployment may negatively impact signal propagation, as BLE signals are prone to attenuation. Obstructions, particularly metal surfaces, can severely degrade the performance of BLE beacon signals. To optimize signal performance, it is advisable to install beacons at heights that ensure unobstructed line-of-sight visibility while shielding them from physical interference. Furthermore, elevated installation locations can mitigate signal attenuation caused by the presence of human bodies, particularly in densely populated areas.

The selection of installation surface material should also guide the choice of installation method. Surfaces like wood or plastic may not be compatible with double-sided adhesive tape, necessitating alternative methods tailored to the specific surface type. Given that metal surfaces are frequently encountered in beacon deployments, there exists potential for installation casings designed to leverage magnets and high-friction materials, such as rubber pads, which can securely adhere to metal surfaces. However, it is essential to study the impact of magnets on BLE signal performance more comprehensively.

While the shape and dimensions of the casing may have limited effects on BLE signals, the choice of casing material holds promise for potentially enhancing signal propagation and safeguarding internal components from environmental factors such as water and dust. Investigating casing materials and their potential influence on beacon performance and protection represents a valuable avenue for further exploration.

TABLE V
REVIEW OF COMMERCIALLY AVAILABLE ENERGY HARVESTING BLE BEACONS

Parameters \ Model Name	GCell Solar iBeacon	TheBeacon iBeacon Solar	Cypress SolarBeacon	TIDA Indoor Light Harvesting Beacon	HKUST SolarBeacon X1
					
Size	123 x 61 x 25 mm	54 x 54 x 20 mm	25mm diameter x 5.5 mm	86.36 x 60.96 mm	12 x 28 x 36 mm
BLE Chipset	TI CC2541 (TI)	Unknown	Cypress CYBLE-022001-00	TI CC2541 (TI)	Nordic nRF51822 (ND)
Rechargeable energy storage	2 mF capacitor	120 mAh Li-ion battery	0.2 F supercapacitor	8 mF supercapacitor	17mAh Li-ion battery
Disposable energy storage	AA battery x 2	N/A	N/A	N/A	N/A
Minimum operating light intensity (l_m)	N/A	Unknown	100 Lux	250 Lux	250 Lux
Minimum advertising interval @ l_m	N/A	Unknown	45 s	1 s	1 s
Operation lifetime at full charge	N/A	90 days	Unknown	< 30 mins	100 hours
Remarks	Cannot operate without disposable battery	Very slow recharge under indoor lighting	Very low advertising frequency	Very small energy storage	Difficult to recharge in indoor settings

TABLE VI
CYPHY BEACONS PLANES IN THREE LOCATIONS

Locations	Vertical	Horizontal	Slope	Total
HKUST	29 (36%)	45 (56%)	6 (8%)	80
News-stands, HK	101 (94%)	7 (6%)	0	108
BTS Skytrain, BKK	217 (100%)	0	0	217

VI. Software and System for BLE Beacon

While BLE beacons have significantly advanced IoT applications and services, they do possess inherent architectural limitations, primarily stemming from their variability in Received Signal Strength (RSS) and finite battery capacity. These shortcomings can complicate the implementation and management of beacon infrastructures. To address these challenges, software-driven solutions, leveraging big data and advanced signal processing techniques, have emerged as powerful tools. This section delves into the software and system aspects of BLE beacon infrastructure, encompassing battery monitoring, distance estimation, security features, and server scalability.

Fig. 9. Review of commercially available BLE beacons categorized by casing, power source and chipset.

TABLE VII
MATERIALS OF DEPLOYMENT SURFACES IN THREE LOCATIONS

Locations	Metal	Wood	Plastic	Others
HKUST	32 (40%)	15 (19%)	15 (19%)	18 (22%)
News-stands, Hong Kong	61 (56%)	20 (19%)	26 (24%)	1 (1%)
BTS Skytrain, Bangkok	217 (100%)	0	0	0

A. Battery Monitoring

Effective battery monitoring is crucial for managing deployed BLE beacon infrastructures. Eddystone-TLM, as shown in Fig. 2 (b), incorporates battery voltage information within its advertising packet, making it accessible to smart devices interacting with the beacon. In contrast, iBeacon's standard advertising packet, as illustrated in Fig. 2 (a), lacks built-in battery level information. Manufacturers can address this limitation by adding an extra packet or configuring unused bytes to store battery data in iBeacon-compatible BLE beacons. Kontakt.io, for instance, utilizes this approach, storing battery level information in 23 bytes presented in decimal format. Many beacon-related software development kits (SDKs) and libraries, such as Estimote and AltBeacon, offer functions to collect battery levels from their beacons.

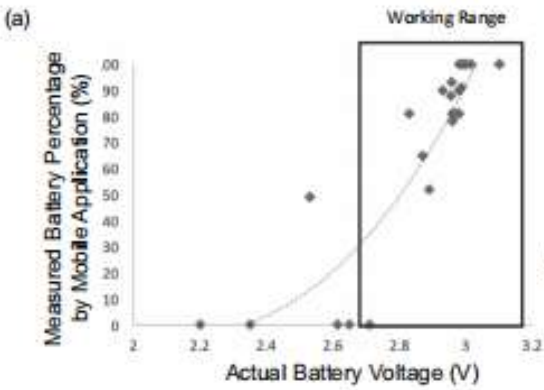

Fig. 11. Comparison of beacon's battery levels measured by mobile application and actual value: (a) full voltage range; (b) working voltage range.

To validate the accuracy of battery monitoring, an experiment was conducted, comparing measured battery levels with actual battery voltage levels. The results, as depicted in Fig. 11 (a), indicate that the measured battery percentage aligns with the theoretical working voltage range (2 - 3.6 V) for the tested CR2450 battery model with a nominal voltage of 3 V. It's noteworthy that the measured battery level appears to drop when the voltage falls below 2.7 V. This phenomenon may be attributed to the beacon's inability to operate under 2.7 V or the smartphone's inability to detect the beacon's RSS. This experiment's working range closely resembles the voltage characteristics of the CR2450 battery, underscoring the method's utility in providing approximate battery level information when the smartphone detects the beacon's signal.

B. Distance Estimation

Distance estimation is pivotal for numerous IoT applications, yet it is challenged by the fluctuating nature of RSS. For instance, Apple provides a distance estimation algorithm within its CoreLocation framework for iBeacon-related development.

An experiment utilizing this framework was conducted to measure distances, with results illustrated in Fig. 12. Evidently, estimation errors increase with greater distances, with reliable estimations limited to approximately the first 0.5 meters. It is important to note that distance estimation accuracy heavily relies on obtaining reliable RSS measurements. Some studies have proposed improvements, such as optimizing RSS thresholds and advanced localization algorithms.

Third-party beacon SDKs often employ their own algorithms to provide distance estimation capabilities tailored to specific user requirements.

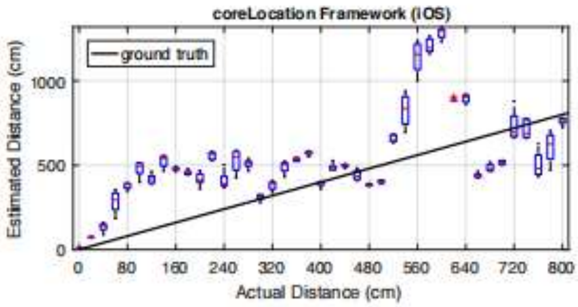

Fig. 12. Comparison between estimated distance from RSS measurements and actual distance.

C. Security Features

BLE beacon infrastructures, despite their scalability and simplicity, are vulnerable to various unauthorized activities, including physical attacks, cyber-attacks, and exploitation. These threats encompass beacon spoofing, packet injection, beacon hijacking, denial of service attacks, battery drainage attacks, and selective frequency jamming. Solutions to secure beacon infrastructures have been introduced by the industry, including geolocation validation and cloud-based token authentication. Geolocation validation requires pre-registering geolocational information for individual beacons on an online server, ensuring that users' physical presence aligns with detected beacons. However, this method is resource-intensive and impractical for indoor environments due to unreliable GPS readings. Cloud-based token authentication entails beacons generating unique IDs based on token values decipherable only by a cloud server. Yet, this approach may be vulnerable if the algorithm generating the IDs is discovered by attackers. Additionally, updating firmware for existing infrastructures can be challenging.

D. System Scalability

Scalability is crucial in beacon systems, as they involve interactions between beacons and edge devices like smartphones and wearables, along with network requests to cloud servers. After detecting a new beacon, edge devices send the unique beacon identifier to servers via HTTP requests to retrieve relevant information. Scalability considerations are vital in optimizing system performance and handling increased loads as the number of users and beacons grows. Tools like Amazon Elastic Compute Cloud (Amazon EC2) are favored choices for scalability, offering robust performance and scalability services. Scalable servers must maintain a successful connection rate as request volume and packet size increase. Tools like Jmeter facilitate testing server scalability by simulating real network requests.

In essence, software-driven solutions have the potential to mitigate the limitations of BLE beacon infrastructures, enabling more reliable and secure IoT applications and services.

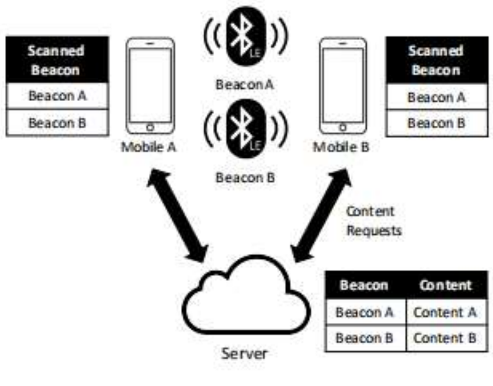

Fig. 13. Interaction between beacons, mobile devices and server.

VII. Research Challenges and Opportunities

Upon close examination of BLE beacon technology, its feasibility and suitability for IoT infrastructure are evident. The flexibility of the BLE protocol offers developers significant freedom, while the affordability and scalability of low-cost hardware ease deployment. However, inherent design limitations of BLE beacons give rise to certain drawbacks, including a lack of interoperability between different BLE profiles, short battery life, and security concerns. In this section, we delve into these limitations and suggest future research directions.

A. Challenges of the Protocols:

Within the context of BLE beacons, BLE profiles define the format of the advertising PDU (Protocol Data Unit). One prominent interoperability challenge arises between two major profiles: iBeacon and Eddystone. Notably, iBeacon and Eddystone are incompatible, and while some manufacturers have created beacons that can support both protocols, they can only do so one at a time. This forces developers or users to manually switch between the protocols. At present, no beacons on the market can simultaneously support both iBeacon and Eddystone. This issue stems from the limited space available within the advertising PDU for customization, making it challenging to load both protocols. A standardized protocol supporting both iBeacon and Eddystone simultaneously or a seamless switching technique that doesn't require human intervention is essential to ensure widespread adoption.

In an IoT era characterized by many-to-many interactions and the deployment of multiple beacons within the same region, interference becomes a significant concern. In dense environments, closely spaced beacons are prone to interference, impacting the reliability of interactions. Most beacon interactions rely on the RSS-comparison approach, where the strongest signal is processed. However, this approach can fail in crowded environments. The absence of standardized interaction interfaces poses challenges for applications involving diverse connected things using different technologies.

B. Challenges of the Hardware:

Several IoT-related challenges are related to the energy efficiency of BLE beacons and constraints associated with their deployment, particularly regarding the battery, casing design, and installation. A major limitation of BLE beacons is their reliance on limited power sources. For instance, BLE beacons powered by a commonly used coin-cell CR2032 battery have a lifespan of less than a year, necessitating regular battery replacement and maintenance.

While energy harvesting devices have been explored in wireless sensor networks, similar research is needed for BLE beacons, especially in indoor environments. Additionally, hardware specifications of energy harvesting and storage devices must be optimized for beacon applications.

Energy sources like ambient light have been explored for energy harvesting, but other sources such as thermoelectric, wind, acoustic, vibration, and RF require further investigation. Deployment procedures for energy harvesting devices, especially those relying on less common sources like thermoelectric and vibration, need to be streamlined.

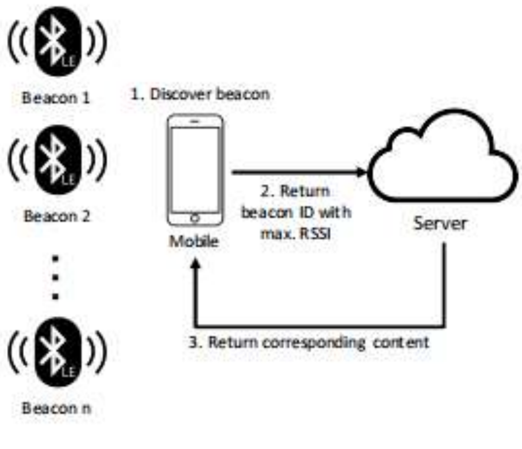

Fig. 14. An illustration of RSS comparison approach for a BLE beacon-based interaction system.

Casing design is another challenge, as it must comply with protection standards while allowing for easy battery replacement. Material selection and form factor design are crucial for minimizing signal attenuation. Innovative casing designs can enhance energy harvesting efficiency, such as incorporating photovoltaic modules in three-dimensional configurations.

Installation methods should be convenient, protective, and easy to replace. Design considerations should align with deployment surfaces, incorporating features like synthetic setae for adhesive-free attachment.

C. Challenges of the Software and System:

Battery monitoring for BLE beacons presents challenges in terms of monitoring frequency and data extraction. Monitoring frequency is constrained by the need for beacon-user interactions, which can be infrequent in low-traffic areas. Additionally, variability in battery information packet offset and presentation methods complicates reliable battery level monitoring.

Distance estimation faces challenges due to the unstable nature of BLE signals in dense environments. Stability of RSS values is crucial to reducing measurement errors, and research is needed to improve algorithms.

System scalability is vital as beacon applications connect to servers and generate numerous network requests. Efficient management of these requests is necessary, especially when multiple beacons are involved, each interacting with multiple users. Minimizing server requests and applying controls can enhance server performance.

Security measures for BLE beacon networks are still in the early stages. Existing systems provide precautions against abuses but lack robust security features. Developing scalable and computationally efficient attack detection methods and security protocols for network control is essential for beacon infrastructure security.

VIII. Conclusion

In conclusion, the seamless integration of Bluetooth beacons for a multi-channel shopping experience holds significant promise in enhancing the retail landscape. This technology offers an innovative solution to bridge the gap between the physical and digital realms, providing retailers with new opportunities to engage customers and optimize their shopping journeys.

By leveraging Bluetooth beacons, retailers can deliver personalized and context-aware content to shoppers' smartphones, enriching their in-store experiences. The ability to send location-based promotions, product recommendations, and real-time information enables retailers to create a more immersive and convenient shopping environment.

Furthermore, Bluetooth beacons empower retailers with valuable data insights into customer behavior and preferences. This data-driven approach allows for more informed decision-making, enabling retailers to tailor their offerings and marketing strategies to better meet customer needs.

However, it's essential to address certain challenges, such as privacy concerns and the need for robust security measures, when implementing Bluetooth beacons in a retail setting. Shoppers must have confidence that their data is handled responsibly and that their privacy is respected.

In summary, the seamless integration of Bluetooth beacons has the potential to revolutionize the shopping experience by providing customers with a more personalized and convenient journey while enabling retailers to optimize their operations and drive sales. As technology continues to advance, retailers who embrace these innovations are likely to stay at the forefront of the evolving retail landscape.

Acknowledgment

I would like to express my heartfelt gratitude to Mrs. kalaimathi , professor for their invaluable guidance, support, and mentorship throughout the duration of this project. Their expertise and insightful feedback were instrumental in shaping the outcome. I would also like to extend my thanks to velammal engineering college for their assistance and contributions. Their input greatly enriched the content and quality of this project. Lastly, I am grateful to my family and friends for their unwavering encouragement and belief in my abilities. Their support provided the motivation needed to see this project through to completion.

References

[1] K. Ashton, "That 'internet of things' thing," *RFiD J.*, vol. 22, no. 7, pp. 97–114, 2009.

[2] L. Atzori, A. Iera, and G. Morabito, "The internet of things: A survey," *Comput. Netw.*, vol. 54, no. 15, pp. 2787–2805, 2010.

[3] M. Friedewald and O. Raabe, "Ubiquitous computing: An overview of technology impacts," *Telematics Inform.*, vol. 28, no. 2, pp. 55–65, 2011.

[4] M. Weiser, "Ubiquitous computing," *Comput.*, no. 10, pp. 71–72, 1993.

[5] T. Sánchez López, D. Ranasinghe, M. Harrison, and D. McFarlane, "Adding sense to the internet of things-an architecture framework for smart object systems," *Pers. Ubiq. Comput.*, pp. 1–18, 2011.

[6] J. Cho, Y. Shim, T. Kwon, and Y. Choi, "Sarif: A novel framework for integrating wireless sensor and rfid networks," *IEEE Wireless Commun.*,vol. 14, no. 6, pp. 50–56, 2007.

[7] H. Liu, M. Bolic, A. Nayak, and I. Stojmenovic, "Taxonomy and challenges of the integration of rfid and wireless sensor networks," *IEEE Netw.*, vol. 22, no. 6, pp. 26–35, 2008.

[8] K. Gill, S.-H. Yang, F. Yao, and X. Lu, "A Zigbee-based home automation system," *IEEE Trans. Consum. Electron.*, vol. 55, no. 2, pp. 422–430,2009.

[9] C. Gomez and J. Paradells, "Wireless home automation networks: A survey of architectures and technologies," *IEEE Commun. Mag.*, vol. 48,no. 6, pp. 92–101, 2010.

[10] A. Wheeler, "Commercial applications of wireless sensor networks using Zigbee," *IEEE Commun. Mag.*, vol. 45, no. 4, pp. 70–77, 2007.

[11] J. Gubbi, R. Buyya, S. Marusic, and M. Palaniswami, "Internet of things (IoT): A vision, architectural elements, and future directions," *Future Generation Comput. Syst.*, vol. 29, no. 7, pp. 1645–1660, 2013.

[12] D. Miorandi, S. Sicari, F. De Pellegrini, and I. Chlamtac, “Internet of things: Vision, applications and research challenges,” *Ad Hoc Netw.*, vol. 10, no. 7, pp. 1497–1516, 2012.

[13] S. Agrawal and M. L. Das, “Internet of things: A paradigm shift of future internet applications,” in *Nirma University Int. Conf. Eng. (NUiCONE)*, 2011, pp. 1–7.

[14] D. Zaim and M. Bellafkih, “Bluetooth Low Energy (BLE) based geomarketing system,” in *11th Int. Conf. Intell. Syst.: Theories Appl. (SITA)*, Oct 2016, pp. 1–6.

[15] S. Alletto, R. Cucchiara, G. D. Fiore, L. Mainetti, V. Mighali, L. Patrono, and G. Serra, “An indoor location-aware system for an IoT-based smart museum,” *IEEE Internet Things J.*, vol. 3, no. 2, pp. 244–253, April 2016.

[16] M. S. Gast, *Building Applications with iBeacon: Proximity and Location Services with Bluetooth Low Energy*. O’Reilly Media, 2014.

[17] S. A. Cheraghi, V. Namboodiri, and L. Walker, “Guidebeacon: Beacon based indoor wayfinding for the blind, visually impaired, and disoriented,” in *2017 IEEE Int. Conf. Pervasive Comput. Commun. (PerCom)*, 2017, pp. 121–130.

[18] D. Kendrick, “Lowviz guide: Indoor navigation for people who are blind or visually impaired,” 2015.

[19] A. J. Ruffa, A. Stevens, N. Woodward, and T. Zonfrelli, “Assessing iBeacons as an assistive tool for blind people in Denmark,” *Worcester Polytechnic Institute, Interactive Qualifying Project E-project-050115- 131140*, 2015.

[20] H. J. Tay, J. Tan, and P. Narasimhan, “A survey of security vulnerabilities in Bluetooth Low Energy beacons,” 2016.

[21] M. Choi, W.-K. Park, and I. Lee, “Smart office energy management system using Bluetooth Low Energy based beacons and a mobile app,” in *2015 IEEE Int. Conf. Consum Electron. (ICCE)*, 2015, pp. 501–502.

[22] A. Akinsiku and D. Jadav, “Beasmart: A beacon enabled smarter workplace,” in *IEEE/IFIP Netw. Operations Manage. Symp. (NOMS)*, 2016, pp. 1269–1272.

[23] M. Collotta and G. Pau, “A novel energy management approach for smart homes using Bluetooth Low Energy,” *IEEE J. Select. Areas Commun.*, vol. 33, no. 12, pp. 2988–2996, Dec 2015.

[24] Z. Zhao, J. Fang, G. Q. Huang, and M. Zhang, “iBeacon enabled indoor positioning for warehouse management,” in *4th Int. Symp. Comput. Bus.*