BLE Beacons for Internet of Things Applications: Survey, Challenges, and Opportunities

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***Abstract*—While the Internet of Things (IoT) is driving a transformation of current society toward a smarter one, new challenges and opportunities have arisen to accommodate the demands of IoT development. Low power wireless devices are, undoubtedly, the most viable solution for diverse IoT use cases. Among such devices, Bluetooth low energy (BLE) beacons have emerged as one of the most promising due to the ubiquity of Bluetooth-compatible devices, such as iPhones and Android smartphones. However, for BLE beacons to continue penetrating the IoT ecosystem in a holistic manner, interdisciplinary research is needed to ensure seamless integration. This paper consolidates the information on the state-of-the-art BLE beacon, from its application and deployment cases, hardware requirements, and casing design to its software and protocol design, and it delivers a timely review of the related research challenges. In particular, the BLE beacon's cutting-edge applications, the interoperability between packet profiles, the reliability of its signal detection and distance estimation methods, the sustainability of its low energy, and its deployment constraints are discussed to identify research opportunities and directions.**

***Index Terms*—Bluetooth low energy (BLE), BLE beacons, Internet of Things (IoT).**

I. Introduction

THE INTEGRATION of emerging low power wireless technology and mobile computing, has led to the development of the Internet of Things (IoT) [1], [2], which realizes the ubiquitous computing concept [3] laid down by the late Weiser [4]. Recent advancement of low power wireless technologies, such as radio-frequency identification (RFID), ZigBee, 6LoPan, Bluetooth low energy (BLE), etc., has revolutionized wireless communication between devices. Such technologies have removed the hassles caused by traditional wired communication and allowed dynamic data transmission between devices over the air. The maturity of RFID technology had inspired the encapsulation of RFID, embedded sensing systems, and ad-hoc networking to form large-scale networks of smart objects for IoT [5]–[7], while ZigBee has been widely used for wireless home automation networks [8], [9], and commercial application development [10]. Among them, this paper focuses on surveying the latest development of BLE and its corresponding influence on the development of IoT technologies and applications.

A successor to the previous Bluetooth Classic, whose primary aim was to provide an effective high data rate for audio and data streaming applications, BLE has evolved to be an energy efficient low data rate technology suitable for power constrained IoT applications [11], [12]. Since BLE unifies the advantages of unmanned power constrained IoT applications and Bluetooth-enabled smart devices, it is increasingly adopted, and BLE beacons one of its most promising applications. The ease of integration between off-the-shelf BLE beacons and smartphones in particular, has promoted diverse IoT use cases, especially among the emerging unmanned IoT applications, requiring less human efforts to do any task [2], [13]. The reinforcement of BLE beacon infrastructure with the focus on IoT development has gained much research interest from both academia and industry, leading to limitless possibilities for IoT innovation to accommodate the needs of heterogeneous ecosystems. BLE beacons have been employed in a wide range of IoT innovations, for example, improving shopper's experience [14], museum guiding [15], indoor localization and tracking [16], helping the blind or disabled [17]–[20], energy saving smart offices [21], [22], managing smart homes [23] and warehouses [24], locating BLE devices with beacons using fingerprinting [25], and so on. Fig. 1 shows some of these innovations. Reference [26] forecasts a deployment of 19 billion Bluetooth devices over the next three years. Unquestionably, the adoption of BLE beacons, with their low power operation capability, in the IoT ecosystem will soon spark enormous research opportunities [27].

Recognizing the promising features of BLE beacons for IoT development, this paper surveys the holistic development of BLE beacons for IoT applications. This paper is centered around presenting different applications and features of beacons including its protocol design, characteristics of the Bluetooth signal, hardware components, casing designs, and software developments for realizing an interoperable, easy-to-deploy and scalable beacon-based IoT solution. Referencing the key requirements of an IoT application, interoperability, detection accuracy, energy efficiency, deployment flexibility, application processing latency, and system scalability, this survey identifies the relevant issues in BLE beacons and reviews their current development. The main contributions of this paper are summarized as follows.

1) An overview of the BLE protocol and beacons, their applications, and related hardware and software issues.

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Fig. 1. Real-life use cases of BLE beacons in IoT applications. (a) Interactive exhibition in Guggenheim museum, New York, NY, USA. (b) Interactive content distribution system by CyPhy Media Ltd., Hong Kong. (c) Vending machine with location-based digital payment service by LINE Corporation, Japan. (d) Pull-notification-based advertisement in a retail store by LINE Corporation at Uniqlo, Japan. (e) Pull-notification-based advertisement and promotion by LINE Corporation at BTS station, Thailand. (f) Indoor navigation system with augmented reality in Gatwick Airport, U.K.

2) A survey of the state-of-the-art research on BLE beacons.
3) A review of limitations of BLE beacons and suggestions of future research directions, challenges and opportunities.

To the best of our knowledge, this paper is the first attempt from academia to present a holistic overview of BLE beacons for IoT solutions. We consider every aspect of beacons, from the BLE protocol and their applications to hardware design conditioned for practicality and real-life deployment.

The rest of this paper is organized as follows. Section II presents an overview of the latest applications leveraging BLE beacon infrastructure and highlights future opportunities and challenges. Section III reviews BLE beacons in connection to their beaconing protocols and received signal strength (RSS). Section IV presents the beacon hardware from inside out, from its chipset and energy storage to its casing. Section V studies the enabling software and systems of BLE beacons, such as battery monitoring techniques, distance estimation, security features, and server scalability. Section VI identifies the research challenges with respect to protocol, hardware, software, and systems of BLE beacons and Section VII concludes this paper.

II. BLE Beacon Applications

BLE beacons have been adopted frequently over the last few years. With big industrial players, such as Google, Apple, Facebook, and LINE, pushing for new standards and hardwares, BLE beacon-based services are now more accessible to both public and developers than ever before. Riding the tide, many interesting applications of BLE beacons have been proposed from both academic and industrial sectors. These applications include indoor localization, proximity detection and activity sensing. The following sections review the state-of-the-art applications made possible by BLE beacons and also shares our vision of potential creative applications.

A. Localization

Localization is one of the most important prospective applications of BLE beacons. GPS, which has revolutionized outdoor localization, has proven to be ineffective in indoor environments and on city streets due to severe attenuation and multipath fading effects. Wi-Fi access point-based solutions have limitations due to the limited number of APs and their inflexibility in deployment, namely, that Wi-Fi APs are installed for signal coverage and not for localization. Other technologies such as RFID, ultrawideband and infrared have been employed for localization. However, these technologies require a dedicated reader to operate. Therefore, it is hard for the general public to fully utilize such services.

BLE beacon-based solutions have a decided advantage over currently existing solutions due to BLE beacons' low-production cost, ease of deployment, and easy accessibility to users. The feasibility of BLE beacon-based indoor localization systems is extensively investigated in [25], where Faragher and Harle discussed the accuracy that can be achieved with given deployment configurations and operation parameters, such as the deployment density, advertising interval, transmission power, etc. In their investigation, they set up 19 beacons in an office area, and achieved <2.6 m error 95% of the time when one beacon was deployed every 30 m^2, out-performing the <8.5 m error achieved by existing Wi-Fi networks.

Palumbo *et al.* [28] presented a stigmergic approach for indoor localization that strongly leverages RSSI information provided by static anchor nodes. This method alleviates the severe attenuation that any BLE signal may suffer in crowded areas. Recently such systems have been deployed for instance, to help the visually impaired to navigate indoor facilities, and for diverse environments, such as museums and airports. For example, Hong Kong [29], Hamad [30], Gatwick [31], Dallas, and Houston International Airports [32] have deployed beacons to aid passengers in navigating unfamiliar ground. Among these, Gatwick International Airport's system is an interesting example as it combines augmented reality technology with a BLE beacon-based localization system.

B. Proximity Detection and Interaction

Besides providing users with locational information, BLE beacons can also convey contextual information by measuring proximity to an object or area. Note that the difference between location and proximity is often confused. In this paper, proximity refers to the relative distance to an object whereas location refers to the absolute position within a given environment. This means a beacon may be attached to non-stationary objects, and the proximity information may trigger an event, allowing seamless interaction between a user and the object. Technologies that achieves similar purpose, such as QR codes and near-field communication (NFC) exist. However, QR codes need to be installed or printed in a large size to reach a large audience. Furthermore, design of QR codes is not aesthetically pleasing. Meanwhile, NFC has a very short interaction distance of 10–20 cm, which requires users to approach media before interacting. BLE beacons can address both of these concerns.

BLE beacon-based proximity detection systems have already been deployed and demonstrated to send effective notifications that strongly leverage user context/location. Ito *et al.* [33] implemented a proximity detection-based tour and navigation system. The system provides the timetable of nearby bus stops and the distance to nearby subway stations to tourists. Ng *et al.* [34] demonstrated an interactive system for art galleries, which outperforms the conventional QR code's engagement conversion rate and time. Similarly, Estimote implements a BLE beacon-based system in a museum to provide detailed information about artworks to nearby users [35]. The system employs a pull mechanism, where information is only provided on user's request. On the other hand, Kang [36] demonstrated a use case of push promotion and location advertising. In this example, a beacon network consisting of 1000 nodes was deployed across Hong Kong.

Industry players Google, Apple, Facebook, and LINE have also introduced proximity-based applications. The Physical Web, introduced by Google Inc., provides an open way for mobile users to interact smoothly and rapidly with physical objects, without needing to install a mobile application, by embedding compressed URLs in advertisement packets. These objects are enabled with this feature by deploying beacons employing the Eddystone protocol near them. When a user passes within the distance range of beacons, the services on his or her device, such as Google Chrome, will receive signals and transmit to the proxy before receiving URLs back to show on the device [37]. There are three main benefits of using the Physical Web with beacons. First, mobile users can interact without downloading a mobile application first. Second, they can see what is available immediately around them by viewing webpages linked with that space. Third, when everything in the vicinity can transmit data a whole new experience will occur [38].

Similarly, Apple, leveraging its iBeacon standard, has been implementing proximity-based services such as continuity features [39]. The most well known and daily used feature is AirDrop. When an iOS device is looking for other devices, it is basically scanning for iBeacon signals from other iPhones and MacBooks. Facebook has also introduced its own lineup of beacons to enhance locality features for its users. Similar technology has been adopted by the automobile industry. Thompson [40] demonstrated installation of an iBeacon system on a car for automatic transactions at toll booths, parking meters, gas station, and more.

LINE has also incorporated LINE beacon services in their mobile applications. Fully utilizing its messenger platform, LINE has integrated BLE beacons' ability to convey contextual information with chatbot services. This allows users to engage in short dialogues to retrieve desired information. For example, a LINE beacon service deployed in Japanese clothing brand Uniqlo's stores allows users to receive information regarding nearby garments through its LINE messenger applications.

C. Activity Sensing

In the previous examples, BLE beacons are mainly used to provide user-aware services by recognizing a user's location and context. However, in the examples below, the information conveyed by beacons is reversely used to help better identify the activities of users. Vigneshwaran *et al.* [41] used BLE beacons to detect fine-grained location and movement to better identify the activities of users with the help of gesture detection technology in smart wearable devices. Knowing a user's micro-location helps to narrow down the list of possible gestures/actions users may take. Consequently, the authors claim to significantly reduce active sensing time up to 92.9%. Similarly, Kashimoto *et al.* [42] implemented a system to help to keep track of senior citizens' activity information. The system requires senior citizens to wear a BLE beacon tag equipped with an accelerometer. BLE beacon signals scanned by predeployed fixed scanners identify the micro-location of the user, while the built-in accelerometer identifies simple activities such as sitting, standing, and walking.

D. Future Applications

This section has reviewed three distinct use cases of BLE beacons: localization, proximity detection and activity sensing. In most of our examples BLE beacons are deployed in static locations. However, it would be interesting to see more application of BLE beacons on moving objects, such as cars, trains, bicycles, and humans. This may require a study on the reliability of BLE beacons for mobile objects and also more study related to activity sensing. Additionally, with machine learning on the rise, collecting user information is of paramount importance. Inspired by the use of chatbots, we believe providing contextual and locational information of the user through both localization and proximity detection opens up a new paradigm of study, where machine learning will incorporate user information to give better engagement and therefore better service.

III. BLE PROTOCOL AND RF SIGNAL CHARACTERISTICS

To give a thorough understanding of BLE beacons and their role in IoT, this section first provides an overview of the development of Bluetooth technology and protocol, and then introduces two popular BLE beacon profiles on the market. First, the BLE protocol design and its working mechanism are introduced, followed by currently existing industrial BLE profiles: iBeacon and Eddystone. The characteristics of Bluetooth signals, more specifically, the RSS, which can be measured by any Bluetooth-compatible receiver, are investigated, especially their behaviors in a dense beacon environment.

A. From Bluetooth Classic to Bluetooth Low Energy

Bluetooth technology, governed by Bluetooth SIG, has been a well-defined wireless standard for short-range communication for over a decade. Initially, Bluetooth was designed to be an alternative to wired communication between devices so as to provide greater mobility for the devices' communication within the range defined by the Bluetooth signal, for example, replacing a wired mouse with a Bluetooth mouse. For this purpose, the determinant factor which guarantees the past success of Bluetooth was its reliability in providing hassle-free communication between two devices, and the power feature was not a primary consideration. The story changes with IoT devices demanding a better and lower power communication technology to encourage their further development.

The demands of IoT devices have driven the design of low power communication technologies, such as RFID and ZigBee described previously. Similarly, this trend also drove Bluetooth SIG to invent BLE, their first low power version of Bluetooth. Note that BLE is backward incompatible with Bluetooth Classic, and is designed with IoT devices in mind rather than for short-range devices' communication. BLE trades off the high speed and high data rate features of Bluetooth Classic to minimize the power consumption. Table I summarizes the key differences between Bluetooth Classic and BLE. Apart from these, there are similarities. Both technologies operate on the same license-free 2.4-GHz ISM spectrum band, and the maximum range their signal can reach is determined by their transmit power. The main differences between classic Bluetooth and BLE can be summarized as follows.

1) The two protocols serve different purposes and applications. Bluetooth Classic is tailored for multimedia streaming applications, whereas BLE is aimed at IoT applications where short sensor data need to be broadcast frequently.
2) The two protocols leverage different wireless communication methods. As mentioned previously, Bluetooth Classic is for streaming, consequently requiring pairing between central and peripheral devices. In BLE, such operation is not necessary.
3) Bluetooth Classic is a one-to-one communication and BLE is one-to-many communication, where the one is a BLE beacon device.

To ensure the coexistence of both technologies, Bluetooth SIG has introduced Bluetooth Smart Ready, which is able to support both types of Bluetooth simultaneously and is normally found in devices with higher computational capabilities, such as smartphones and computers. As the focus of this paper is BLE beacons and their promising features for IoT development, interested readers should refer to [43] and [44] for a detailed description about Bluetooth Smart Ready and other roles of BLE (i.e., 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

B. BLE Protocol and Profiles

As shown in Table I, BLE divides its 2.4-GHz ISM spectrum band into 40 channels, with three channels [namely, channel 37 (2.42 GHz), 38 (2.426 GHz), and 39 (2.48 GHz)] dedicated to advertisement purposes and the rest for data exchange. The wide spacing of the advertisement channels minimizes the Wi-Fi signals operating on the same ISM band. BLE devices, only responsible for advertising via channels 37–39, are commonly known as beacons. These devices are connectionless and broadcast their signals periodically. The beauty of this mechanism is that no device pairing is required to receive the signals advertised by the beacon. The advertising signals generally contain a small data payload [generally known as an advertising protocol data unit (PDU)] which may include the packet header, MAC address, device's unique identifier, and a small headroom for manufacturer-specific data. Both Apple and Google have manipulated this small chunk of information encapsulated in the advertising PDU and introduced their own popular beacon profiles, iBeacon [45] and Eddystone [46], respectively.

1) iBeacon by Apple: iBeacon is a popular BLE profile that was introduced by Apple Inc. at their annual Apple Worldwide Developers Conference 2013 [47]. This movement of Apple's has drawn attention from both industry and academic players, particularly regarding the possible applications that they could develop on top of this small beacon, which claims to operate for months or even years on a coin-cell battery. Such low power consumption is enabled by the small data size of the advertising PDU. Fig. 2(a) shows the advertising PDU of iBeacon, which is a total 46 bytes in length [48]. This packet structure not only enables convenient identification of individual beacon devices, but also provides the industry with a universal standard for application development. Moreover, ever since iBeacon's development, many interesting location-based and proximity-based applications have been developed [16].

2) Eddystone by Google: Google launched their open source BLE profile, Eddystone [49], to compete with Apple's iBeacon standard. The launching of Eddystone has further impacted the development of IoT, especially with the introduction of the Physical Web [50]. Different from the proprietary iBeacon, Eddystone allows seamless interaction with existing Chrome browser installed on any operating system, which allows more flexibility in contextual content development as it does not require building a completely independent mobile application to interact with the deployed beacon. For further

(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	UID	Frame Type	Ranging	UID		Reserve	
				URL	1 byte	1 byte	18 bytes			
				URL	Frame Type	Ranging	URL			
				TLM	1 byte	1 byte	2 bytes	2 bytes	4 bytes	4 bytes
				TLM	Frame Type	TLM Version	Battery Level	Temperature	ADV_CNT	SEC_CNT

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

comparison between iBeacon and Eddystone, readers can refer to the summary provided in [51]. In general, Eddystone allows developers to switch between URL and TLM frames, as shown in Fig. 2(b). The working principle of a URL frame is similar to the conventional QR code, whereas a TLM frame allows developers to provide additional data regarding the deployed beacon. All the technical details regarding the Eddystone protocol are available on Google's GitHub [52].

3) Manufacturer-Specific Custom Profiles: Beyond iBeacon and Eddystone, the BLE protocol is flexible enough to allow manufacturers to configure customized BLE profiles for specific usage. Manufactures can add extra information to the beacons or change the offset of bytes for storing particular information, namely, battery voltage level measurements to facilitate timely management, sensor measurements for data collection, and authentication keys for better security measures. However, the application side needs to be redesigned for retrieving the correct data from the customized beacon packets. Furthermore, these profiles may evolve to become a profile by incorporating a dynamic packet structure and information. Such designs may be used to provide services that are more sophisticated and ultimately open up new research opportunities.

C. Received Signal Strength and Coverage Distance

One parameter of interest from a beacon, regardless of its BLE profile, is RSS [53], [54], a measurement in dBm that describes the power received at the receiving end with respect to the transmit power. The maximum range of a beacon signal of Bluetooth 4.0 is known to be 150 m; such coverage is only obtained in an open environment where line-of-sight between a transmitter and a receiver is unobstructed. Since the signal decays along its propagation path, according to the inverse square law, the received signal power P_r is inversely proportional to the square of the distance, i.e., $P_r \propto (1/d^2)$. In reality, the signal often decays much faster due to unavoidable environmental factors. To cater for the various loss factors, the relationship between the received signal power and the distance can be further defined to $P_r \propto (1/d^{\alpha})$, where α is the loss exponent. Typically, RSS is measured in dBm scale [i.e., $\mathrm{RSS} = 10\log(P_r/1mW)$]. The relationship between the RSS

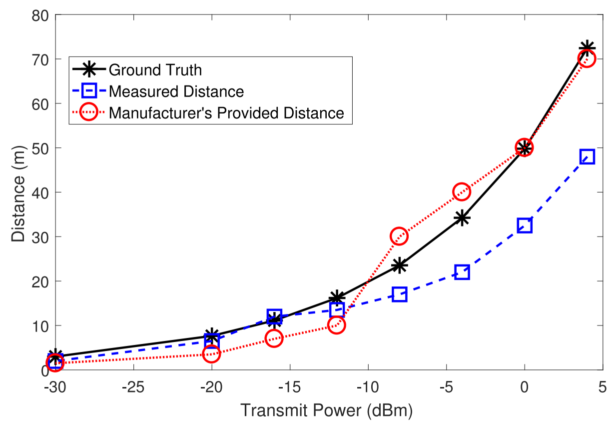


Fig. 3. Distance versus transmit power.

and distance is hence $\mathrm{RSS} \propto -\alpha\log(d)$. That is, in logarithmic scale, the linear relationship between RSS and distance can be formulated as

$$\mathrm{RSS} = -\alpha\log(d) + K \tag{1}$$

where $-\alpha$ is the loss exponent, K is the offset constant, and d is the distance measured in meters. Note that the above equation is a general path loss model which can be applied for different scenarios, in which each scenario has its own loss exponent. Rappaport [55] provided a list of possible loss exponents for different scenarios.

In fact, there are no differences in the signal coverage of Bluetooth Classic and BLE if both are configured to have the same transmit power. Fig. 3 compares the theoretical distance and measured distance for a beacon with different transmit powers ranging from -30 to 4 dBm. The theoretical distance was provided by the beacon's manufacturer, Estimote [56], and the measured distance was collected using an off-the-shelf Android smartphone. It can be observed that weaker transmit power reduces the range of signal coverage. In addition, it can be seen that the measured range deviates from the theoretical range. The signal fluctuation results in error in the theoretical distance estimation that is purely based on the RSS value. Prior research has also concluded that distance estimation based on RSS is unreliable [57], [58]. This situation gets

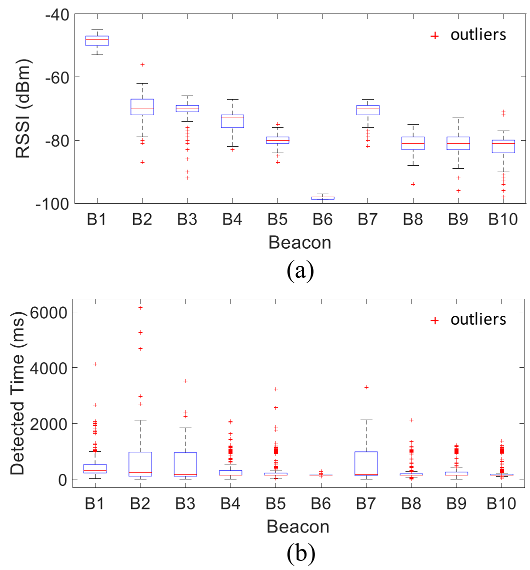


Fig. 4. Variation in BLE beacon signal characteristics in a dense environment. (a) RSS. (b) Time interval to detect a beacon signal.

even more severe when multiple beacons are present within a small area. So the next section examines signal behaviors in a dense environment.

D. Beacon Signals in Dense Environment

Since BLE reduces the number of channels to 40 (from the total 79 channels in Bluetooth Classic) and each channel is equally spaced at 2 MHz [59], this strategical arrangement in the 2.4-GHz ISM band prevents the BLE signals from overlapping with the common Wi-Fi channel. However, if we consider an environment with ten beacons placed randomly, a smartphone might be unable to see all the beacons' signals within a short scanning period, a time window during which the smartphone listens to BLE signals nearby. Fig. 4(a) shows the RSS variation from each of the ten beacons. It is observed that the RSS detected varies across time even though each of the beacons is placed in a fixed location (i.e., the beacons are static during the time of experiment). Fig. 4(b) shows each of the beacons requires less than 1 s to be detected under good conditions. However, under the worst condition the detection time can take more than 5 s. Signal propagation (e.g., multipath fading, shadowing, fading, etc.) and environmental factors (e.g., movement of people in the laboratory and room temperatures) are the causes of the phenomenon of high RSS variation and detection time variation observed, specifically from beacon B2. Out of the total 751 scans, there were 12 scans that detected no signals, and only one scan was able to capture all ten signals.

IV. BLE Beacon Hardware

In-depth knowledge of the hardware components of a BLE beacon is crucial to constructing a physical layer capable of providing reliable and scalable service. An illustration of the components is shown in Fig. 5. A comprehensive review of available hardware options for a BLE chipset, energy storage, and casing are made. Furthermore, the strengths and drawbacks of the options are discussed to provide better insight.

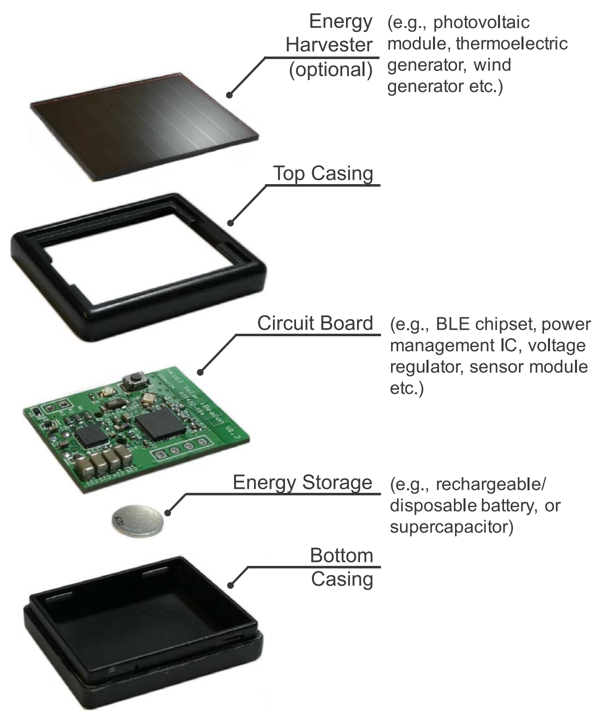


Fig. 5. Illustration of generic hardware components of BLE beacon.

A. Power Consumption Characteristics of BLE Beacon

In designing a BLE beacon, it is important to maximize and estimate its battery life. Maximizing the battery life will prolong the use of an infrastructure, making it more manageable and affordable, while precise estimation of the battery life will allow timely battery replacement, utilizing the available energy resources to their limits. To achieve this, detailed study of beacons' power consumption characteristics is required. In this section, the power usage of an off-the-shelf BLE beacon is carefully analyzed. The results presented in this section are partially taken from our previous studies [60]. For the study, a CC2451, Bluetooth chipset manufactured by Texas Instruments Inc. was used. This specific chipset is chosen as a reference as it is one of the most popular BLE ICs; the market share of this chipset can be seen in Fig. 9.

Fig. 6 shows the different states of a beacon device, where t_T is the advertising interval of the beacon, t_p is the time during which the beacon is awake to broadcast its advertisement packet, and t_i is the time between each advertising event, during which the beacon stays idle to save energy. Furthermore, the diagram includes the initialization stage, where a considerable amount of energy is drawn. This initialization stage only occurs once during the system boot up, unless the system reboots itself due to a fatal error. Fig. 7 presents current consumption during advertising events in more detail. An advertising event is generally divided into three different states and more specifically nine states. These states and their corresponding current draw are shown in Table II. Since during

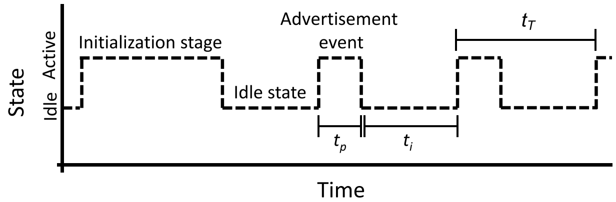


Fig. 6. Electrical characteristics of BLE beacon including initialization state.

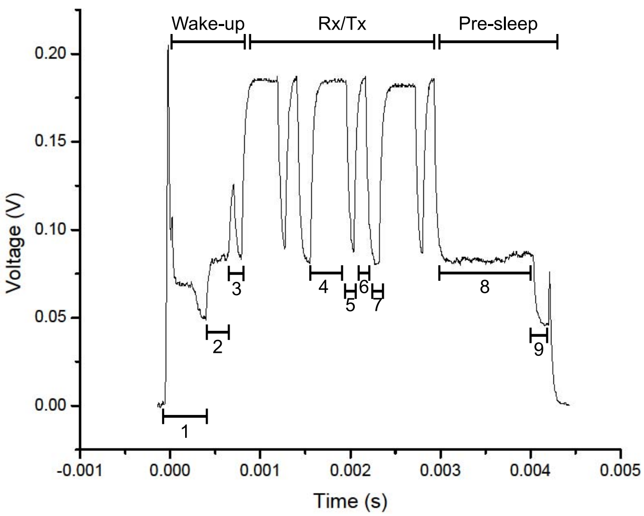


Fig. 7. Current draw of BLE beacon during advertisement event.

the idle state, the device draws constant current, and the initialization stage is only executed once, we are more interested in studying the current consumption characteristics exhibited in advertising events.

The average current draw during an advertising event, I_p, can be found by taking the average of different states over the time duration of advertising event. The average current consumption during an idle state can be found simply through measurement with an ammeter as it draws current steadily. By knowing these two parameters, we can calculate the average current draw by taking the weighted sum with respect to the advertising interval, as follows:

$$I\left(t_T|t_p, I_p, I_i\right) = \frac{t_p I_p + t_i I_i}{t_T} \quad (2)$$

where I is the average current draw at an advertising interval t_T, with advertising event duration t_p, average current drawn during the event I_p, and current drawn during the idle state I_i. The average current draw can help us to estimate the battery life of a beacon at a given advertising interval, which is a crucial parameter to consider during deployment and management. Although this method has been widely used due to its simplicity, it assumes constant current draw even though it is a pulse draw. To make a better prediction, battery models may be required to take the battery recovery effect into consideration [61], [62].

B. Options for BLE Chipset

Bluetooth chipsets are currently produced by the companies, such as Texas Instruments (TI), Nordic Semiconductors,

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

Dialog Semiconductors, and Cypress. It is commonly known that TI provides excellent reference designs and sample codes to aid developers in getting started with their projects, while Nordic Semiconductors have very energy efficient chipsets that will help to prolong the battery life. Cypress, meanwhile, is a leading company in designing integrated chipsets for low-powered devices, providing many power management ICs that can operate at a cost of a few hundred pico currents. When choosing a BLE IC, we should consider four major aspects: power consumption, flash capacity, RAM capacity, and the internal voltage regulator. Computational ability is excluded as most BLE chipsets have converged to the ARM Cotex M0 processor.

Table III shows a comparison of representative BLE chipsets from the aforementioned manufacturers with respect to their current draw and Bluetooth version. In many cases, current draw from the radio is considered the most important as CPU intensive operation is rarely found in a BLE chipset. The current draw values can usually be found on the datasheet. However, it is important to check the usage of a regulator, as this may reduce the current draw by a couple of milli amperes.

For the nRF51 series from Nordic Semiconductors, flash storage usually comes in two variants: 128 and 256 KB. Generally, 128 KB is sufficient to implement basic functionalities of the BLE beacon and simple features. However, if the device is running more complicated codes and calculation or requires extra storage space for logging purposes, 128 KB may be insufficient, especially if one wants to develop device firmware update, where the firmware of a beacon is programmed over the air with only a smartphone and mobile application, a larger flash storage is a must. In our experience, 16-KB variants are sufficient for RAM capacity. Unless one is attempting to implement a RAM retention technique for slightly better power consumption, larger RAM does not help the development or performance.

Most beacons are equipped with an internal voltage regulator, so as to allow a wide range of input voltages and reduce the number of extra components required for circuit manufacturing. However, its convenience may come at the cost of its efficiency. It is general knowledge that at higher voltages the current draw will be lower. However, this is not always true as many beacon chipsets employ a low-dropout regulator for its simplicity which is energy inefficient at high voltages. To mitigate this, some of the chipsets from Nordic Semiconductors

TABLE III
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

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

have a dc–dc regulator that helps to reduce current draw at higher voltages. However, this feature is known to cause instability in the chipset in the second revision hardware, which may motivate the developers to incorporate an external voltage regulator in their design to extend battery life and avoid complications.

C. Energy Storage

There are various means to store energy, such as disposable batteries, rechargeable batteries and supercapacitors. Many of the beacons currently available in the market employ a type of disposable lithium ion battery. Estimote and Kontakt.io beacons both employ lithium manganese dioxide batteries for their affordable price, thermal stability, and nontoxic properties. In the following section, the means of energy storage for beacons will be reviewed and discussed.

Many BLE beacon devices use coin-cell batteries due to their low-profile form factor while being able to deliver sufficient power. As a proof of this, almost all major beacon manufacturers use lithium coin-cell batteries, denoted by CR or BR. However, both empirically and theoretically, these coin-cell batteries have proven to last only a short period of time and thus require a frequent replacement. Table IV shows the theoretical life span of a beacon at a 800-ms advertising interval, an interval often used by BLE beacon manufacturers.

Some manufacturers have employed a larger size alkaline battery, such AA or AAA batteries, to extend the life span of beacon devices. However, this extended life span comes at the cost of a larger casing footprint and heavy weight. For example, Sensoro Pro beacons from Sensoro are equipped with four AA batteries and claim to last 5–6 times longer than ordinary beacons equipped with a CR2477, which has capacity of 1000 mAh. Beacons from TheBeacons use two AA alkaline batteries with capacity of 2600 mAh. However, such an increase in size and weight of a beacon ultimately undermines the very advantage of BLE beacon devices, convenience of deployment. BLE beacons are considered very scalable not only due to their minimalistic protocol but also because they are easy to deploy and use. Conventional beacons usually weights around 20–30 g, making the deployment procedure as easy as attaching the beacon to a wall with simple adhesive tape available at any hardware store. However, use of larger batteries usually undermines this unique advantage.

D. Energy Harvesting Capability for BLE Beacons

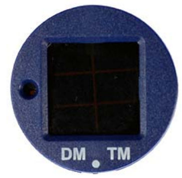
To mitigate the battery issue of BLE beacons, some manufacturers have designed energy harvesting BLE beacons equipped with solar panels. Energy harvesting wireless sensor nodes have been a popular research topic [63], with many studies conducted to optimize energy harvesting hardware in terms of energy harvesting mechanisms, storage sources, and charging circuitry. This trend of energy harvesting untethered devices has affected the development of IoT devices. Gorlatova *et al.* [64] used a kinetic energy harvesting method to harvest energy from human movement and power a sensor node measuring human motion. Chen *et al*. [65] presented wireless sensor node system equipped with light harvesting capability and with an extremely small form factor of a few millimeters. In addition, Shih *et al.* [66] used a combination of RF and light harvesting to operate a BLE beacon system with very long advertising interval of 45 s. A number of developers have prototyped similar devices relying on ambient light harvesting methods. These products are reviewed in detail in Table V. However, an energy harvesting capabilities of these devices are too low to support the required advertising frequency of 1 Hz or the storage capacity of the devices prevents long-term operation in the absence of ambient energy.

The previous works on energy harvesting wireless sensors shown above focus mainly on outdoor deployment. However, many BLE beacon applications take place indoors. Hence, some of the energy sources may be absent or too scarce to harvest enough energy for perpetual operation of untethered devices. Therefore the study of indoor energy harvesting is necessary in order to design an energy-neutral BLE beacon device. Only recently, investigations into the use of indoor lighting and photovoltaic cells for wireless sensors have been carried out. Wang *et al.* [67] provided comprehensive design considerations for indoor light energy harvesting wireless sensor system that employs the MPPT technique and rechargeable battery. The authors claim that their prototype should operate for 10 to 20 years without maintenance. Nasiri *et al.* [68] presented different models of indoor energy harvesting sensors utilizing a combination of capacitors and batteries. Based on these previous works, the generic system architecture of a ambient light powered BLE beacon will consist of three main components: 1) a photovoltaic energy harvesting module; 2) power management unit; and 3) BLE unit.

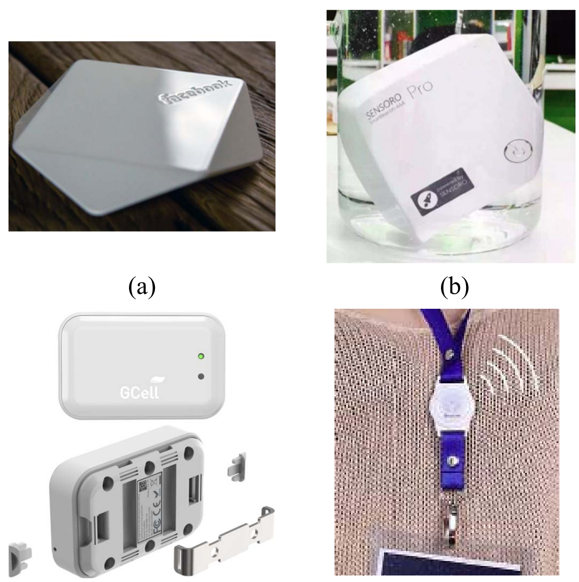
E. Casing for Looks and Protection

The two major concerns for BLE beacon casings are looks and protection. Fig. 9 summarizes the mainstream BLE beacons with respect to casing designs, power sources, and chipset manufacturers. A casing may have an aesthetically pleasing design and may even serve as a decoration. Such designs encourage venues, such as retail shops, to deploy

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

these devices. The Estimote beacon is a good example. On the other hand, the casing may be designed to be homogeneous and blend with the environment, making the device less noticeable. For instance, Gimbal's S21 beacons are white and brand name is invisible to achieve this purpose. In order to provide reliable and long-lasting service, it is vital to protect a beacon's inner circuit from water, dust and impact from potential abuses. To meet these demands, the latest beacon casing designs often follow water/dust resistant standards such as the International Electrotechnical Commission's (IEC) Ingress Protection Code. However, most of the off-the-shelf BLE beacons are not protected for long. Estimote's beacon is able to withstand high water pressure, but the case has to be cut to replace the battery. Consequently, the beacon will no longer have the water-resistant feature after its first maintenance. This is a common issue for most protective casings currently available in the market.



(a) (b) (c) (d)

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.

F. Casing for Installation and Deployment

The installation casings, which are often overlooked and not incorporated into the designs, play a pivotal role in deployment and maintenance procedures. Compared to the traditional method, where double-sided adhesive tape is used to install the beacon, an installation case can fix the beacon much more securely; for example, we have experienced that adhesive tapes can be very weak for materials such as wood. Furthermore, they can provide removal mechanism to easily detach BLE beacon from its installation casing for battery replacement, as shown in Fig. 8(c). The GCell beacon has an installation case with installation brackets, which are meant to be drilled in to a wall. Kontakt.io has also designed Beacon Pro with a mounting clip at the back to deploy and dismount the beacon. However, the drawbacks of these types of installation casings is that they will damage the deployment location. Clearly, to achieve solid installation without damaging the deployment facilities, a new approach is imperative.

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

The design of installation casings may also be influenced by the material and orientation of installation surfaces. We deployed CyPhy Media beacons in three real-life locations: 1) Hong Kong University of Science and Technology (HKUST); 2) various news-stands across Hong Kong; and 3) BTS Skytrain stations in Bangkok, as shown in Fig. 10. From Table VI, beacons were deployed on vertical surfaces more than horizontal ones in Bangkok and Hong Kong. However, in HKUST, beacons were deployed horizontally more than vertically because they needed to be hidden from

(a) (b) (c)

Fig. 10. Examples of beacon deployment locations. (a) HKUST campus, Hong Kong. (b) Outdoor news-stands, Hong Kong. (c) BTS Skytrain, Bangkok.

line-of-sight, for example under a table. However, this method of deployment is not ideal for signal propagation as BLE signals are easily attenuated. When we deployed beacon shown in Fig. 10(c), we attempted to install it inside the aluminum column to protect it from weather and people. However, due to severe attenuation from the aluminum plates, the BLE beacon signal could barely be detected. To avoid such degradation in performance, it is highly recommended to ensure nothing obstructs the beacon signal. Therefore, it is most appropriate to install beacons at a height, which will ensure line-of-sight in many cases and also protect it from physical attacks. Furthermore, since a BLE beacon's signal is also attenuated by the human body, it will attenuate more in crowded areas. Placing beacons in higher locations alleviates this attenuation effect as well.

Table VII shows the materials of the installation surfaces in the three deployment locations. In all three locations the beacons were mostly deployed on metal. In Hong Kong, wood and plastic share a similar number of deployed beacons after metal, and beacons were only deployed on aluminum on advertising signs on BTS Skytrain columns in Bangkok. We found that double-sided adhesive tape is not suitable for surfaces like wood, and therefore different installation methods should be employed depending on the deployment surface. Noting that metal is the most popular deployment surface material, there is potential for installation casings leveraging magnets. Since beacons are very light-weight, use of magnets and high-friction materials, such as rubber pads, may work well on metal surfaces. However, the performance of BLE signals near magnets needs to be studied.

Case shapes and sizes may have very little or no effects on BLE signals because they are mostly made of plastic or silicon-based rubber-like material. However, it would be worthwhile to investigate how casing material can enhance the propagation of the BLE signal and protection of circuit components from external factors such as water and dust.

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

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

V. Software and System for BLE Beacon

Although the protocol and hardware developments of BLE beacons have laid a strong foundation upon which IoT applications and services can be implemented, BLE beacons have drawbacks that arise from their inherent architecture, namely, a large fluctuation in RSS and finite battery capacity. Such weaknesses makes beacon infrastructure difficult to implement and manage. Leveraging the power of big data and advanced signal processing techniques, these shortcomings can be overcome thorough softwarization. The software and system for BLE beacon infrastructure includes battery measurement, distance estimation, security features, and a scalable server architecture and algorithms. In this section, the current state of development is reviewed and discussed in detail.

A. Battery Monitoring

After deploying a BLE beacon infrastructure, monitoring the battery levels and replacing the battery on time is necessary for management. According to the Eddystone-TLM advertising packet specification in Fig. 2(b), the battery voltage level is built inside the TLM frame, 2 and 3 bytes offset. When a smart device interacts with an Eddystone-TLM protocol BLE beacon, it can get the battery information together with the advertising packet and extract the battery level. However, iBeacon's battery level cannot be found inside its standard advertising packet Fig. 2(a). For iBeacon, manufacturers can add an extra packet or configure unused bytes

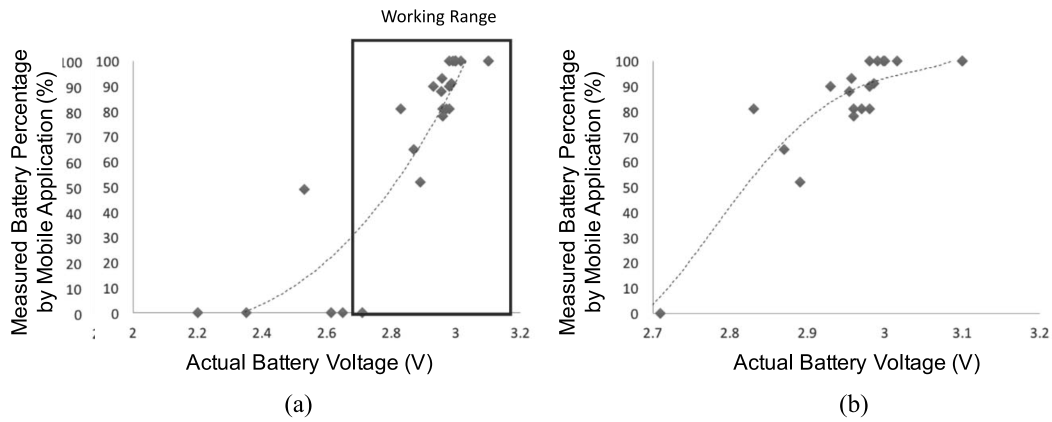


Fig. 11. Comparison of beacon's battery levels measured by mobile application and actual value. (a) Full voltage range. (b) Working voltage range.

for BLE beacons to store battery information when they are being produced [69]. Therefore, a smart device can request the packet storing battery information when the beacons broadcast signals to smart devices. Kontakt.io provides beacons with the iBeacon protocol and supports battery level monitoring. They also use this method, storing the battery level information in 23 bytes. The information is presented in decimals and needs to be rephrased on the application side. Based on the methods mentioned, BLE beacons provide flexibility for users to collect battery information by interacting with the beacons, especially for iBeacon protocol. Most of the beacon related SDKs and libraries, such as Estimote, AltBeacon, etc., also include function to collect their beacons' battery levels.

To verify the accuracy of battery monitoring, an experiment was conducted to compare the measured battery level and the actual battery voltage level. The results are shown in Fig. 11(a). The tested beacon's battery model is a CR2450 with a nominal voltage of 3 V. The graph shows the measured battery percentage is within the theoretical working voltage range (2–3.6 V). The battery level was measured using a mobile application installed on an iOS device provided by CyPhy Media. The result shows that the measured battery level reached value when the voltage drops to under 2.7 V. Possible reasons are that the beacon could not work under 2.7 V or that the RSS from the beacon could not be detected by the smartphone. The working range in this experiment as shown in Fig. 11(b), which is very similar to the CR2450 voltage characteristics [70], demonstrates that the battery monitoring method is able to provide the approximate battery level information for a user to reference if the beacon signal can be detected by the smartphone.

B. Distance Estimation

Distance estimation is a key enabler to many IoT applications. While RSS is a cost-efficient method for distance computation, the fluctuation of RSS affects the reliability of the final estimation result. For example, distance estimation algorithm provided by Apple is available with the CoreLocation framework for iBeacon related development. We implemented a simple app using their framework and conducted an experiment to measure the distance. A total of 60

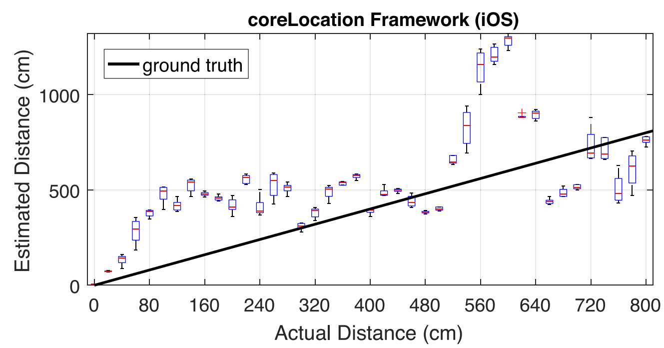


Fig. 12. Comparison between estimated distance from RSS measurements and actual distance.

samples were taken for each 0.2 m. The results are shown in Fig. 12. Obviously, the estimation error increases when the distance increases. In general, the estimation is reliable only up to the first 0.5 m.

Several studies have indicated that the distance estimation can be improved by first obtaining a reliable RSS measurement. Yin *et al.* [71] introduced an RSS threshold optimization method to improve RSS for estimating distance for indoor applications. Patwari and Hero [72] also concluded that the error rate of the distance measurement is even higher than the RSS measurement-based experimental results. Therefore, providing accurate distance information is very important for developing IoT applications. Shen *et al.* [73] improved on the traditional centroid localization algorithm, giving a significant accuracy improvement of 63%. The algorithm measures three intersecting points of beacons' regions and calculates the beacon's position. Another approach is to calculate a path loss index by comparing the RSS at 1 m and the target distance [74]. Under experiment conditions, the algorithm gives an average of 0.4-m error within 3.5 m. As various estimation methods can be used based on users' needs, third-party beacon SDKs which support distance estimation, use their own algorithms to measure the distance of their beacons.

C. Security Features

Although extremely scalable due to its simplistic broadcasting architecture, BLE beacon infrastructure can be easily abused and attacked by unauthorized parties. Such attacks include but are not limited to physical attacks, such as thievery and vandalism, but also cyber-attacks and sabotaging such as piggybacking, device spoofing, packet injection, beacon hijacking, denial of service attack, battery drainage attack, and selective frequency jamming. Piggybacking is a kind of abuse where an unauthorized party uses the beacon infrastructure without prior consent from the infrastructure owner. Such abuse can be done because beacon advertisement packets are static and therefore can be easily recorded and remapped to any content on a different online server. Beacon spoofing is an act where an advertisement packet of a beacon is cloned to a different beacon device, thereby impersonating or "spoofing" the original beacon. Such abuse can be problematic in some cases, as beacon spoofing enables beacon infrastructure service outside its service area; in some applications, such as the scavenger hunt at CES 2014 [75] and 2016 [76], beacon spoofing is undesired. Packet injection is very similar to beacon spoofing, but instead of placing a cloned beacon outside the service area, it is placed within the original network, disturbing its normal operation. In the case of localization services, such an attack may lead to critical system malfunction. The potential damage of this type of attack is well illustrated in [77]. The battery drainage attack on a single beacon, rendering it inoperable, is also demonstrated in [78].

Currently, most solutions to securing beacon infrastructure have been proposed industry, for example, geolocation validation and cloud-based token authentication. In the geolocation validation approach, geolocational information of individual beacons is preregistered on an online server. On the user mobile side, location information provided by a GPS module is transmitted to the server along with the detected beacon signals, thereby ensuring the physical presence of the user near the detected beacons. This approach can secure beacon infrastructure from beacon spoofing attacks. However, such a security framework has many loopholes. First, the operation of preregistering every beacon's geolocation information on an online server is tedious and resource consuming, therefore reducing the scalability of the approach. Furthermore, since GPS readings in indoor environments are unreliable, geolocation validation would be restricted to outdoor use only.

Another approach is the cloud-based token authentication method. In this approach, beacons are provided with an algorithm to generate a beacon ID based on a token value. This token value is the true ID of the beacon and can only be deciphered by the cloud server. However, this method is implemented at the firmware level of the device, which means that once the algorithm generating the beacon ID is discovered by the attacker, the system can be abused. Second, such a framework is difficult to deploy onto an already existing infrastructure, as it requires individual beacons' firmware updated.

D. System Scalability

BLE beacons are normally used on the applications interacting between beacons and the edges (e.g., smartphones, smart wearables, etc.). These applications do not just measure RSS or estimate distance, they also involve network requests made to corresponding cloud servers. Therefore, study of server scalability is necessary for developing a beacon system to help optimizing the loading and improve performance for beacon applications. After ranging a new beacon, the edges will send the unique beacon identifier to servers using HTTP requests to get related information. For example, in a smart shipping system in mall, users are able to purchase items or get store coupons when they are close to the shop's beacon(s) [79]. The network requests can use both POST or GET methods, depending on the application needs [80]. The POST method is usually used for updating content on the server side, and it will not include the request information in the URL body, so it can provide a better security level. The GET method does not involve a write-in process to the database. This reduce the loading on the server side, but the requested information needs to be added to the URL body, causing a security issue while sending some credentials.

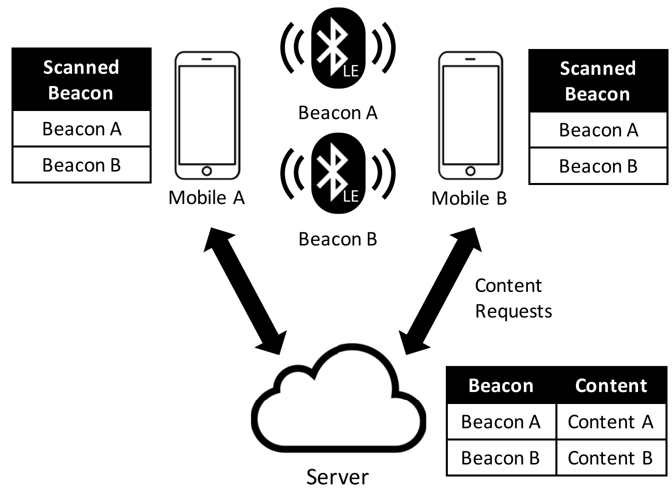


Fig. 13. Interaction between beacons, mobile devices, and server.

Considering n beacons interacting with one user at the same time, there will be n requests sent by the user to the server to get information. If there are m users interacting with the n beacons at the same time, there will be $m \times n$ requests being sent to the server, and a certain number of responses will be sent back. Fig. 13 shows an example of a server interacting with a beacon network with two beacons, and there are two users in the region interacting with both beacons. A total of four requests and responses will normally be generated in this case. When the scale of the beacon network increases, more users will interact with more beacons and the requests will increase accordingly. Therefore, deployment of the server is important for beacon application systems. Amazon Elastic Compute Cloud (Amazon EC2) [81] is one of the possible choices providing good scalability and performance services, and many companies such as Netflix, Adobe, etc. are using it [82]. Tools like JMeter [83] can simulate real network requests to the server for testing its scalability. A scalable server is expected to maintain a successful connection rate when the request number and packet size increases.

VI. Research Challenges and Opportunities

With close inspection of BLE beacon technology, there is no doubt of its feasibility and suitability for IoT infrastructure: flexibility in the BLE protocol allows a great degree of freedom for developers, low cost hardware, and ease of deployment makes the infrastructure more affordable and scalable. However, it is evident that there are still some drawbacks arising from BLE beacons' inherent design, such as lack of interoperability between different BLE profiles, short battery life, security issues, and so on. In this section, the demerits of BLE beacons are discussed and future research directions are suggested.

A. Challenges of the Protocols

In the BLE beacon context, the BLE profile simply defines the data structure or the format of the advertising PDU. This section discusses the interoperability challenge across two major profiles: 1) iBeacon and 2) Eddystone. Note that both iBeacon and Eddystone are incompatible. Even though some manufacturers have created beacons to support the above two protocols, they can only support one protocol at a time, and developers or users need to switch between the protocols manually. At the time of this survey, no beacons on the market can support both protocols running concurrently. While most manufacturers incorporate a switching mechanism to support both protocols, this switching needs to be performed during the development or configuration phase. Once the beacon is deployed with particular a protocol, it is very hard to change the protocol on the fly.

The most challenging issue is that BLE beacons only allocate a small chunk to customize their advertising PDU. It is quite hard, if not impossible, to load both protocols within this short advertising PDU. Consider the market with diverse smartphones and BLE-enabled receivers. Failing to incorporate either one of the protocols will mean that service providers fail to reach one half or more of users. To ensure a wide penetration, a standardized protocol that can support both iBeacon and Eddystone at the same time, or at least a technique that allows the beacon to switch between both protocols seamlessly without human intervention, is needed.

In the era of IoT, it is expected that there will be many-to-many interaction within the same given region along with the deployment of multiple beacons. However, interference is an issue affecting smooth and interruption-free interaction in an environment with dense beacon deployment. In such an environment, chances are beacons will interfere with one another if they are closely spaced [84]. As illustrated in Fig. 14, most interactions with beacons are based on the RSS-comparison approach [84], in which all RSS values are compared and only the strongest signal will be processed. However, this type of interaction only works sometimes. This undoubtedly creates a challenge for connected things to participate in interaction activities when the incorrect RSS is processed. Furthermore, as different connected things might use different technologies, the nonstandardized interaction interfaces pose an application development challenge.

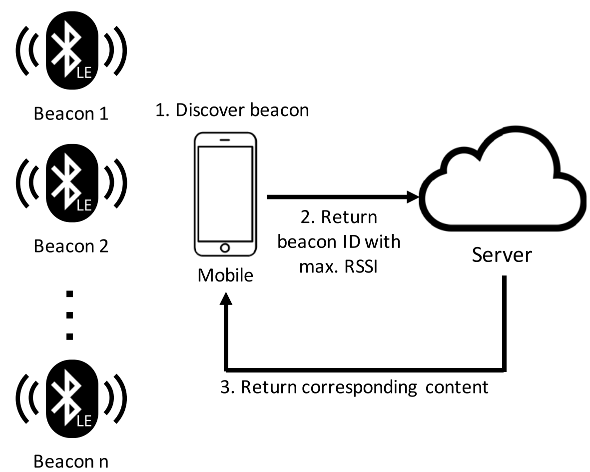


Fig. 14. Illustration of RSS comparison approach for a BLE beacon-based interaction system.

B. Challenges of the Hardware

The following section identifies the IoT-related challenges in connection with the energy efficiency of BLE beacons and the possible deployment constraint. In particular, three issues are identified, namely, the battery, casing design, and installation. One of the major drawbacks of BLE beacons is its limited power source. As mentioned in the previous section, the battery life of BLE beacon powered by a coin-cell CR2032, the most commonly used battery, is less than a year. Such a short life span requires periodic operations to replace and maintain deployed beacons.

Although energy-harvesting devices have been well studied in the field of wireless sensor networks, similar study is also necessary in the field of BLE beacons for two reasons. First, wireless sensor network research focused on energy harvesting in outdoor environments. However, BLE beacons are widely used in both indoor and outdoor environments. Therefore, study of energy harvesting devices in indoor settings is required. Furthermore, a robust design that considers several different deployment environments is strongly desired to enhance the scalability of the devices. Second, the electrical characteristics of BLE beacon devices are quite different from those of wireless sensor devices. Therefore, the chipsets and hardware specifications of energy harvesting and storage devices are not optimal for beacon devices and should be tailored for the application. Consequently, new research comes down to studying hardware specifications and optimizing them to application specific requirements.

For energy harvesting, ambient light energy harvesting beacons have been investigated and prototyped by a number of groups. However, other energy sources such as thermoelectric, wind, acoustic, vibration and RF have not been fully explored. Shih *et al.* [66] explored the use of RF harvesting, and their energy neutral beacon can broadcast every 45 s at an input power of 15 dBm at frequency bands between 2.4 and 5 GHz. However, an input power of 15 dBm is usually not feasible considering that most Wi-Fi routers' transmission power is limited to around 20 dBm. Furthermore, an advertising interval of 45 s makes the beacon device unsuitable to serve as proximity detection or localization infrastructure, but more like a sensor device. Other energy sources such as thermoelectric and kinetic energy from vibration may require a complicated deployment procedure. Thermoelectric generators require a heat source and a heat sink to create a thermal gradient. Furthermore, thermal pastes that facilitates heat transfer must be applied during deployment procedures. For vibration, an energy harvesting device must be attached to a vibrating object and a stationary object, so as to generate alternating current using the principle of electromagnetism. Such a deployment procedure is complicated and painstaking. These drawbacks may connect to research on casing design that may help to facilitate convenient installation for thermal or vibration energy harvesting devices.

The first challenge with the beacon casing is to design a case according to the IEC standard 60529 or standard 250-2003 [85] so that the beacon can retain its protection feature even after battery replacement. Since BLE beacons may require frequent battery replacement, it is important to research a casing structure that can facilitate convenient battery replacement and still effectively protect the inner circuitry from water and dust. In addition, attenuation caused by the casing should be kept minimal. If the case were made of metal, for example, it would block the signal. Furthermore, it should still achieve a small form factor by using different materials, such as a hydrophobic nanomaterial for better water-resistance [86]. The second challenge is to investigate increasing the efficiency for energy harvesting. Recently, there have been ongoing investigations of photovoltaic modules assembled in 3-D. Inspired by photosynthesizing plants, Yuji and Yachi [87] studied placement of a photovoltaic module in a tree-shape following the Fibonacci number, while Bernardi *et al.* [88] demonstrated a 3-D structure that uses photovoltaic modules as both reflector and absorber to enhance the efficiency. Such designs could be incorporated into the casing to facilitate perpetual operation of a light harvesting beacon in a scarce ambient light environment. The third challenge is unique installation techniques and cases that are convenient to install, strong in protection and easy to replace. The design may incorporate knowledge of the deployment surface and employ adequate installation methods accordingly. For example, recent advancement in synthetic setae [89] with the help of nanotechnology, could be incorporated into the casing design to replace adhesive tape.

C. Challenges of the Software and System

Since beacons are battery-powered devices, it is important to have a software program that is able to accurately monitor the battery locally and remotely. Another challenge arising with application development is to deal with the unreliability of RSS to achieve better distance estimation.

1) Battery Monitoring: The major challenges of monitoring battery level of BLE beacons is the monitoring frequency, as the battery information can only be retrieved when the beacons interact with users' smart devices. The battery information is collected by users' smartphones and sent to the cloud server so that other infrastructure managers can access it. However, BLE technology requires users to be in close proximity to the monitored beacon. This means the battery information cannot be updated frequently if there is low user traffic near the deployed infrastructure. Since most beacons are built with a limited power source, monitoring the battery level frequently is a serious challenge at this stage. A beacon's battery information can be configured into the different bytes of the advertising packet. Error may occur when retrieving the battery level because the battery information packet offset may be different for each beacon, and developers may not be able to get beacon A's battery level by using the same method as for beacon B. Moreover, the presentation method of the battery information in the packet may also be different, as it can be presented as a battery percentage, voltage level, etc. Therefore, developers should be aware of the information extracting method of every beacon so that the correct battery level can be obtained.

2) Distance Estimation: According to the previously reviewed studies, accurate distance estimation is difficult to achieve due to unstable BLE signals. BLE beacons need to work in an environment with multiple signal emitters for special purposes such as indoor location services. Before, the closest signal source of most wireless communication technologies could be identified easily, as the signal sources were not close to each other, unlike in a beacon infrastructure. Hence, measuring an accurate RSS to identify beacons in a dense environment is a new challenge in developing beacon related applications. In the future the RSS needs to be stabilized so that the calculated distance will not fluctuate too much and cause measurement error. Some work has been done in this research area, such as beacons that self-correct [90] by comparing the RSSs measured in 1 m to obtain a more actuate value. Researchers have also proposed to create different profiles on each device to achieve a better accuracy assumption as a beacon's RSS will vary for different devices. Since distance estimation is important for application development, more research needs to be done to improve the algorithm to achieve its accuracy.

3) System Scalability: System scalability is important to study as most beacon applications will connect to a server and can generate many network requests that need to be managed properly. Under some conditions, users may interact with more than one beacon at the same time. If there are n beacons, n requests and n responses will be generated using the normal approach. There are several ways to improve server performance by minimizing the server requests from the application. Developers may consider putting more controls on the network requests or filtering out only the useful beacons before sending requests to the server. For example, they could group all the requests for a certain period of time instead of requesting the server once a beacon is met if the application does not request frequent updates.

4) Security Issue: In terms of security measures for BLE beacon networks, previously introduced systems, such as cloud-based token authentication or geolocation validation systems, are more precautionary systems than security systems, as they are capable of preventing abuses, but fail to counteract or even detect potential attacks. To remedy this drawback there has been a study on the detection of physical attacks on beacons [91]. In their work, a hidden Markov model (HMM) was used to estimate the probability of a beacon device being physically removed, relocated, or cloned. With a false-alarm rate of 5%, removed/stolen beacons could be detected perfectly, and relocated and cloned beacons could be detected with around 70% accuracy. However, it is well known that HMM is computationally demanding, and this lays doubt on the practicality of the proposed system, as a real beacon infrastructure involves a few hundred or even thousands of beacon devices. In [91], only 11 beacon devices were used. Security features of BLE beacon infrastructure are in their infant stage, and there has been little research done in this field. At the current stage, a detection system using HMM and precautionary systems with a beacon ID shuffling method have been devised; however, they are not a perfect security system. A secure system must be able to detect potential threats and attacks and respond appropriately while being able to take some form of precautionary measures. Therefore, a more scalable and computationally less intensive method of detecting attacks must be devised, and a security protocol that allows full control over the network is desired.

VII. Conclusion

The IoT has the tremendous potential to change our modern lifestyle as the Internet did in the past; and BLE beacons are projected to play a pivotal part in realizing this new paradigm. Recognizing the potential in BLE beacons, this paper reviews different aspects of BLE beacons for their use in IoT applications. First, applications leveraging BLE beacon infrastructure were introduced: localization, proximity detection and interaction, and activity sensing. After that, to form a good understanding of BLE beacons, the BLE protocol and its signal characteristics, which are common to all BLE devices, were first reviewed, and then BLE beacon hardware was examined with regard to its generic electrical consumption characteristics. Furthermore, a model to estimate the current draw of a beacon with respect to its advertising interval was provided. Varying options available for chipsets, such as flash and RAM capacity, and an internal voltage regulator were discussed. Different casings to protect and install beacons were also reviewed in detail. The software and system for BLE beacons with respect to battery measurement, distance estimation, security features, and server scalability were reviewed in-depth.

Based on our survey, limitations of BLE beacons were identified and future research directions were discussed. Interoperability between different BLE beacon devices and operation in dense BLE beacon environments are obstacles that must be overcame to make the infrastructure more robust. Study of the sustainability and casings of beacons is necessary to make infrastructure management less resource consuming. In terms of the software and system, algorithms to measure battery level and distance with precision is strongly desired. From the server side, a scalable server infrastructure and security protocol needs to be developed. Indeed, BLE beacon related studies and technology are still in their infancy; studies regarding their casings, deployment methods, security issues, and server scalability have barely been studied. However, their scalability, which arises from their small form factor and affordable hardware, and their flexibility in protocol, hosting numerous types of applications, outweighs their current underdevelopment, and makes further investigation worthwhile.

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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," *Computer*, vol. 26, no. 10, pp. 71–72, 1993.

[5] T. S. López, D. C. Ranasinghe, M. Harrison, and D. McFarlane, "Adding sense to the Internet of Things—An architecture framework for smart object systems," *Pers. Ubiq. Comput.*, vol. 16, no. 3, pp. 291–308, 2011.

[6] J. Cho *et al.*, "SARIF: A novel framework for integrating wireless sensor and RFID networks," *IEEE Wireless Commun.*, vol. 14, no. 6, pp. 50–56, Dec. 2007.

[7] H. Liu, M. Bolic, A. Nayak, and I. Stojmenović, "Taxonomy and challenges of the integration of RFID and wireless sensor networks," *IEEE Netw.*, vol. 22, no. 6, pp. 26–35, Nov./Dec. 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, May 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, Jun. 2010.

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

[11] J. Gubbi, R. Buyya, S. Marusic, and M. Palaniswami, "Internet of Things (IoT): A vision, architectural elements, and future directions," *Future Gener. 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 *Proc. Nirma Univ. Int. Conf. Eng. (NUiCONE)*, Ahmedabad, India, 2011, pp. 1–7.

[14] D. Zaim and M. Bellafkih, "Bluetooth low energy (BLE) based geomarketing system," in *Proc. 11th Int. Conf. Intell. Syst. Theories Appl. (SITA)*, Mohammedia, Morocco, Oct. 2016, pp. 1–6.

[15] S. Alletto *et al.*, "An indoor location-aware system for an IoT-based smart museum," *IEEE Internet Things J.*, vol. 3, no. 2, pp. 244–253, Apr. 2016.

[16] M. S. Gast, *Building Applications With iBeacon: Proximity and Location Services With Bluetooth Low Energy*. Sebastopol, CA, USA: 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 *Proc. IEEE Int. Conf. Pervasive Comput. Commun. (PerCom)*, Kailua, HI, USA, 2017, pp. 121–130.

[18] Mdsupport.org. (2018). *MD Support—LowViz Guide*. Accessed: Jan. 15, 2018. [Online]. Available: http://www.mdsupport.org/audioguide/

[19] N. Woodward, T. Zonfrelli, A. J. Ruffa, and A. Stevens, "Assessing iBeacons as an assistive tool for blind people in Denmark," M.S. thesis, Worcester Polytech. Inst., Worcester, MA, USA, 2015.

[20] H. J. Tay, J. Tan, and P. Narasimhan, "A survey of security vulnerabilities in Bluetooth low energy beacons," Parallel Data Lab., Carnegie Mellon Univ., Pittsburgh, PA, USA, Rep. CMU-PDL-16-109, 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 *Proc. IEEE Int. Conf. Consum Electron. (ICCE)*, Las Vegas, NV, USA, 2015, pp. 501–502.

[22] A. Akinsiku and D. Jadav, "BeaSmart: A beacon enabled smarter workplace," in *Proc. IEEE/IFIP Netw. Oper. Manage. Symp. (NOMS)*, Istanbul, Turkey, 2016, pp. 1269–1272.

[23] M. Collotta and G. Pau, "A novel energy management approach for smart homes using Bluetooth low energy," *IEEE J. Sel. 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 *Proc. 4th Int. Symp. Comput. Bus. Intell. (ISCBI)*, Olten, Switzerland, 2016, pp. 21–26.

[25] R. Faragher and R. Harle, "Location fingerprinting with Bluetooth low energy beacons," *IEEE J. Sel. Areas Commun.*, vol. 33, no. 11, pp. 2418–2428, Nov. 2015.

[26] ABIResearch. (Dec. 2015). *ABI Research Predicts Wireless Connectivity Gap to Widen as Bluetooth Enabled Device Shipments Reach 19 Billion Over the Next Five Years*. [Online]. Available: https://www.abiresearch.com/press/abi-research-predicts-wireless-connectivity-gap-wi/

[27] M. Radhakrishnan, A. Misra, R. K. Balan, and Y. Lee, "Smartphones and BLE services: Empirical insights," in *Proc. IEEE 12th Int. Conf. Mobile Ad Hoc Sensor Syst. (MASS)*, Dallas, TX, USA, 2015, pp. 226–234.

[28] F. Palumbo, P. Barsocchi, S. Chessa, and J. C. Augusto, "A stigmergic approach to indoor localization using Bluetooth low energy beacons," in *Proc. 12th IEEE Int. Conf. Adv. Video Signal Based Surveillance (AVSS)*, Karlsruhe, Germany, Aug. 2015, pp. 1–6.

[29] A. Yu. (Jul. 2017). *Hong Kong Airport Set to Install 'Beacon' System to Aid Passengers*. [Online]. Available: http://www.scmp.com/news/hong-kong/article/1843845/hong-kong-airport-set-install-beacon-system-aid-passengers

[30] C. H. News. (Mar. 2016). *Hamad International Airport Launches Mobile App With iBeacon Capabilities*. [Online]. Available: https://dohahamadairport.com/media/hamad-international-airport-launches-mobile-app-ibeacon-capabilities

[31] N. Lomas. (May 2017). *Gatwick Airport Now Has 2,000 Beacons for Indoor Navigation*. [Online]. Available: https://techcrunch.com/2017/05/25/gatwick-airport-now-has-2000-beacons-for-indoor-navigation/

[32] M. Halper. (Oct. 2017). *Acuity Teams With Indoor Mapping Firm That Has Big Airport Presence*. [Online]. Available: http://www.ledsmagazine.com/articles/2017/10/acuity-teams-with-indoor-mapping-firm-that-has-big-airport-presence.html

[33] A. Ito *et al.*, "A trial of navigation system using BLE beacon for sightseeing in traditional area of Nikko," in *Proc. IEEE Int. Conf. Veh. Electron. Safety (ICVES)*, Yokohama, Japan, 2015, pp. 170–175.

[34] P. C. Ng, J. She, and S. Park, "Notify-and-interact: A beacon-smartphone interaction for user engagement in galleries," in *Proc. IEEE Int. Conf. Multimedia Expo (ICME)*, Hong Kong, Jul. 2017, pp. 1069–1074.

[35] J. Anderson. (Feb. 2017). *The Icon of Modern Art Puts Estimote Beacons on Display*. [Online]. Available: http://blog.estimote.com/post/157200820650/the-icon-of-modern-art-puts-estimote-beacons-on

[36] S. C. Kang. (Nov. 2017). *Apple Daily Launches In-App, Beacon-Based Targeting*. [Online]. Available: http://www.campaignasia.com/article/apple-daily-launches-in-app-beacon-based-targeting/441080

[37] M. Sneps-Sneppe and D. Namiot, "On physical Web models," in *Proc. IEEE Int. Siberian Conf. Control Commun. (SIBCON)*, Moscow, Russia, 2016, pp. 1–6.

[38] N. Allurwar, B. Nawale, and S. Patel, "Beacon for proximity target marketing," *Int. J. Eng. Comput. Sci*, vol. 15, no. 5, pp. 16359–16364, May 2016.

[39] A. Cunningham. (Jul. 2014). *Explaining Continuity: The Tech Tying iOS 8 and OS X Yosemite Together*. [Online]. Available: https://arstechnica.com/gadgets/2014/07/explaining-continuity-the-tech-tying-ios-8-and-os-x-yosemite-together/

[40] D. Thompson. (Feb. 2014). *iBeacon Auto: Your Car is a Beacon*. [Online]. Available: http://beekn.net/2014/02/ibeacon-auto/

[41] S. Vigneshwaran, S. Sen, A. Misra, S. Chakraborti, and R. K. Balan, "Using infrastructure-provided context filters for efficient fine-grained activity sensing," in *Proc. IEEE Int. Conf. Pervasive Comput. Commun. (PerCom)*, St. Louis, MO, USA, Mar. 2015, pp. 87–94.

[42] Y. Kashimoto *et al.*, "Sensing activities and locations of senior citizens toward automatic daycare report generation," in *Proc. IEEE 31st Int. Conf. Adv. Inf. Netw. Appl. (AINA)*, Taipei, Taiwan, Mar. 2017, pp. 174–181.

[43] J. DeCuir, "Introducing Bluetooth smart: Part 1: A look at both classic and new technologies," *IEEE Consum. Electron. Mag.*, vol. 3, no. 1, pp. 12–18, Jan. 2014.

[44] C. Gomez, J. Oller, and J. Paradells, "Overview and evaluation of Bluetooth low energy: An emerging low-power wireless technology," *Sensors*, vol. 12, no. 9, pp. 11734–11753, 2012. [Online]. Available: http://www.mdpi.com/1424-8220/12/9/11734

[45] Apple. (2017). *iBeacon*. [Online]. Available: https://developer.apple.com/ibeacon/

[46] Google. (Feb. 2017). *Mark Up the World Using Beacons*. [Online]. Available: https://developers.google.com/beacons/

[47] Apple. (2017). *WWDC2013 Videos*. [Online]. Available: https://developer.apple.com/videos/wwdc2013/

[48] N. Newman, "Apple iBeacon technology briefing," *J. Direct Data Digit. Market. Pract.*, vol. 15, no. 3, pp. 222–225, 2014.

[49] R. Amadeo. (Jul. 2015). *Meet Google's "Eddystone"—-A Flexible, Open Source iBeacon Fighter*. [Online]. Available: https://arstechnica.com/gadgets/2015/07/meet-googles-eddystone-a-flexible-open-source-ibeacon-fighter/

[50] D. Bhattacharya, M. Canul, and S. Knight, "Impact of the physical Web and BLE beacons," in *Proc. 5th ACM Annu. Conf. Research Inform. Technol.*, 2016, pp. 4262–4265.

[51] S. Mittal. (Jan. 2016). *iBeacon vs Eddystone: Which One Works Better for Your Pilot Project*. [Online]. Available: https://blog.beaconstac.com/2016/01/ibeacon-vs-eddystone/

[52] GitHub. (2017). *Specification for Eddystone, an Open Beacon Format Form Google*. [Online]. Available: https://github.com/google/Bluetoothmartone

[53] R.-H. Wu, Y.-H. Lee, H.-W. Tseng, Y.-G. Jan, and M.-H. Chuang, "Study of characteristics of RSSI signal," in *Proc. IEEE Int. Conf. Ind. Technol. (ICIT)*, Chengdu, China, 2008, pp. 1–3.

[54] S. Kajioka, T. Mori, T. Uchiya, I. Takumi, and H. Matsuo, "Experiment of indoor position presumption based on RSSI of Bluetooth LE beacon," in *Proc. IEEE 3rd Glob. Conf. Consum. Electron. (GCCE)*, 2014, pp. 337–339.

[55] T. S. Rappaport, *Wireless Communications: Principles and Practice*, vol. 2. Upper Saddle River, NJ, USA: Prentice-Hall, 1996.

[56] Estimote. (2014). *Beacon Tech Overview*. [Online]. Available: http://developer.estimote.com/

[57] Q. Dong and W. Dargie, "Evaluation of the reliability of RSSI for indoor localization," in *Proc. IEEE Int. Conf. Wireless Commun. Unusual Confined Areas (ICWCUCA)*, Clermont-Ferrand, France, 2012, pp. 1–6.

[58] R. Faragher and R. Harle, "An analysis of the accuracy of Bluetooth low energy for indoor positioning applications," in *Proc. 27th Int. Tech. Meeting Satellite Divis. Inst. Navig. ION+GNSS*, vol. 812. Tampa, FL, USA, 2014, p. 2.

[59] K.-H. Chang, "Bluetooth: A viable solution for IoT? [industry perspectives]," *IEEE Wireless Commun.*, vol. 21, no. 6, pp. 6–7, Dec. 2014.

[60] K. E. Jeon, T. Tong, and J. She, "Preliminary design for sustainable BLE beacons powered by solar panels," in *Proc. IEEE Conf. Comput. Commun. Workshops (INFOCOM WKSHPS)*, San Francisco, CA, USA, 2016, pp. 103–109.

[61] C. F. Chiasserini and R. R. Rao, "A model for battery pulsed discharge with recovery effect," in *Proc. IEEE Wireless Commun. Netw. Conf. (WCNC)*, vol. 2. New Orleans, LA, USA, 1999, pp. 636–639.

[62] C. K. Chau, F. Qin, S. Sayed, M. H. Wahab, and Y. Yang, "Harnessing battery recovery effect in wireless sensor networks: Experiments and analysis," *IEEE J. Sel. Areas Commun.*, vol. 28, no. 7, pp. 1222–1232, Sep. 2010.

[63] Y. Liu *et al.*, "Self-powered wearable sensor node: Challenges and opportunities," in *Proc. Int. Conf. Compilers Architect. Synthesis Embedded Syst. (CASES)*, Amsterdam, The Netherlands, 2015, p. 189.

[64] M. Gorlatova *et al.*, "Movers and shakers: Kinetic energy harvesting for the Internet of Things," *IEEE J. Sel. Areas Commun.*, vol. 33, no. 8, pp. 1624–1639, Aug. 2015.

[65] Y. Chen *et al.*, "Energy-autonomous wireless communication for millimeter-scale Internet-of-Things sensor nodes," *IEEE J. Sel. Areas Commun.*, vol. 34, no. 12, pp. 3962–3977, Dec. 2016.

[66] W.-C. Shih, P. H. Chou, and W.-T. Chen, "A batteryless beacon based on dual ISM-Band RF harvesting with solar-biasing current," in *Proc. 4th Int. Workshop Energy Harvest. Energy Neutral Sens. Syst. (ENSsys)*, Stanford, CA, USA, 2016, pp. 7–12. [Online]. Available: http://doi.acm.org/10.1145/2996884.2996886

[67] W. S. Wang *et al.*, "Design considerations of sub-mW indoor light energy harvesting for wireless sensor systems," *ACM J. Emerg. Technol. Comput. Syst.*, vol. 6, no. 2, 2010, Art. no. 6.

[68] A. Nasiri, S. A. Zabalawi, and G. Mandic, “Indoor power harvesting using photovoltaic cells for low-power applications,” *IEEE Trans. Ind. Electron.*, vol. 56, no. 11, pp. 4502–4509, Nov. 2009.

[69] S. Toulson. (2016). *Scan Response Packet Structure*. [Online]. Available: https://support.kontakt.io/hc/en-gb/articles/201492522/

[70] *Energizer CR2450*. Accessed: Nov. 15, 2017. [Online]. Available: http://data.energizer.com/pdfs/cr2450.pdf

[71] F. Yin, Y. Zhao, F. Gunnarsson, and F. Gustafsson, “Received-signal-strength threshold optimization using Gaussian processes,” *IEEE Trans. Signal Process.*, vol. 65, no. 8, pp. 2164–2177, Apr. 2017.

[72] N. Patwari and A. O. Hero, III, “Using proximity and quantized RSS for sensor localization in wireless networks,” in *Proc. 2nd ACM Int. Conf. Wireless Sensor Netw. Appl.*, San Diego, CA, USA, 2003, pp. 20–29.

[73] X. Shen, S. Yang, J. He, and Z. Huang, “Improved localization algorithm based on RSSI in low power Bluetooth network,” in *Proc. 2nd Int. Conf. Cloud Comput. Internet Things (CCIOT)*, Dalian, China, Oct. 2016, pp. 134–137.

[74] A. Thaljaoui, T. Val, N. Nasri, and D. Brulin, “BLE localization using RSSI measurements and iRingLa,” in *Proc. IEEE Int. Conf. Ind. Technol. (ICIT)*, Seville, Spain, Mar. 2015, pp. 2178–2183.

[75] A. Allan and S. Mistry. (Jan. 2014). *Hacking the CES Scavenger Hunt*. [Online]. Available: http://makezine.com/2014/01/03/hacking-the-ces-scavenger-hunt/

[76] A. Allan and S. Mistry. (Jan. 2016). *Hacking the CES Scavenger Hunt for a Second Time*. [Online]. Available: http://makezine.com/2016/01/07/hacking-ces-scavenger-hunt-second-time/

[77] P. Misra, S. Raza, V. Rajaraman, J. Warrior, and T. Voigt, “Poster abstract: Security challenges in indoor location sensing using Bluetooth LE broadcast,” in *Proc. 12th Eur. Conf. Wireless Sensor Netw. Poster Demo Session*, Porto, Portugal, 2015, pp. 11–12.

[78] C. Kolias, L. Copi, F. Zhang, and A. Stavrou, “Breaking BLE beacons for fun but mostly profit,” in *Proc. ACM 10th Eur. Workshop Syst. Security (EuroSec)*, Belgrade, Serbia, 2017, pp. 1–6.

[79] R. Pugaliya, J. Chabhadiya, N. Mistry, and A. Prajapati, “Smart shoppe using beacon,” in *Proc. IEEE Int. Conf. Smart Technol. Manag. Comput. Commun. Controls Energy Materials (ICSTM)*, Chennai, India, Aug. 2017, pp. 32–35.

[80] P. Shende, S. Mehendarge, S. Chougule, P. Kulkarni, and U. Hatwar, “Innovative ideas to improve shopping mall experience over e-commerce websites using beacon technology and data mining algorithms,” in *Proc. Int. Conf. Circuit Power Comput. Technol. (ICCPCT)*, Kollam, India, Apr. 2017, pp. 1–5.

[81] *Amazon EC2 Instance Types*. Accessed: Nov. 12, 2017. [Online]. Available: https://aws.amazon.com/ec2/instance-types/

[82] P. Somogyi, “Analysis of server-smartphone application communication patterns,” M.S. thesis, School Sci., Aalto Univ., Espoo, Finland, Jun. 2014.

[83] *Apache JMeter*. Accessed: Nov. 12, 2017. [Online]. Available: http://jmeter.apache.org

[84] I. Howitt, “Mutual interference between independent Bluetooth piconets,” *IEEE Trans. Veh. Technol.*, vol. 52, no. 3, pp. 708–718, May 2003.

[85] D. Jenkins and B. Morse, “Application considerations for LED light fixtures in process industry production environments,” in *Proc. IEEE IAS/PCA Cement Ind. Tech. Conf.*, Dallas, TX, USA, 2016, pp. 1–6.

[86] L. Feng *et al.*, “Super-hydrophobic surface of aligned polyacrylonitrile nanofibers,” *Angewandte Chemie*, vol. 41, no. 7, pp. 1221–1223, 2002.

[87] A. Yuji and T. Yachi, “A novel photovoltaic module assembled three-dimensional,” in *Proc. 35th IEEE Photovolt. Specialists Conf.*, Jun. 2010, Honolulu, HI, USA, pp. 002811–002816.

[88] M. Bernardi, N. Ferralis, J. H. Wan, R. Villalon, and J. C. Grossman, “Solar energy generation in three dimensions,” *Energy Environ. Sci.*, vol. 5, no. 5, pp. 6880–6884, 2012.

[89] K. Liu, J. Du, J. Wu, and L. Jiang, “Superhydrophobic gecko feet with high adhesive forces towards water and their bio-inspired materials,” *Nanoscale*, vol. 4, no. 3, pp. 768–772, 2012.

[90] H. Cho, J. Ji, Z. Chen, H. Park, and L. Wonsuk, “Accurate distance estimation between things: A self-correcting approach,” *Open J. Internet Things*, vol. 1, no. 2, pp. 19–27, 2015.

[91] C. Liu, P. Zhao, K. Bian, T. Zhao, and Y. Wei, “The detection of physical attacks against iBeacon transmitters,” in *Proc. IEEE/ACM 24th Int. Symp. Qual. Service (IWQoS)*, Beijing, China, 2016, pp. 1–10.

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