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

Kang Eun Jeon, James She, Perm Soonsawad, and Pai Chet Ng

***Abstract*—While the Internet of Things (IoT) is driving a transformation of current society towards a smarter one, new areas of challenges and opportunities have also arisen to accommodate the increasing demands of the IoT developments. Low power wireless devices, undoubtedly, are the viable solution for diverse IoT use cases. Among them, Bluetooth Low Energy (BLE) beacon has emerged as one of the most promising candidates due to the ubiquitous use of Bluetooth-compatible devices, such as Androids and iPhones. However, for BLE beacons to continue penetrating the IoT ecosystem from a holistic manner, a seamless integration in interdisciplinary research is needed. This paper consolidates state-of-the-art BLE beacon starting from its application and deployment cases, hardware requirements, casing designs to software and protocol design and delivers a timely review regarding related research challenges in BLE beacons. In particular, the latest developments of cutting-edge applications, the interoperability between its protocol, the reliability of signal detection and distance estimation methods, the sustainability of its low energy, the deployment constraint are discussed to identify related research opportunities and directions.**

***Index Terms*—Bluetooth Low Energy, BLE Beacons, Internet of Things (IoT).**

## I. Introduction

THE integration of recently emerging technologies, namely, 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 Mark 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 [5] encapsulation of RFID, embedded sensing system, and ad-hoc networking for a large-scale network of smart objects for the IoT [6], [7]. ZigBee, on the other hand, has been widely used for wireless home automation network [8], [9], and commercial applications development [10]. Among them, this paper focuses on surveying the latest development of BLE and its corresponding influence on development of IoT technologies and applications.

As a successor to its previous version – Bluetooth Classic, where its primary aim is in providing effective high data rate for audio and data streaming applications, BLE, on the other hand, evolved to be an energy efficient low data rate device suitable for power constrained IoT applications [11], [12]. Since BLE unifies the advantages of both unmanned power constrained IoT applications and Bluetooth-enabled smart devices, it is witnessing an increasing number of adoption; BLE beacon is one of its most promising subset. The ease of integration between off-the-shelf BLE beacons and smartphone particularly, has empowered diverse IoT use cases especially in the emerging unmanned IoT applications, creating less efforts for human to do any task [2], [13]. The reinforcement of BLE beacon infrastructure with priority on IoT development has gained much research interests from both academia and industrial sectors, leading to limitless possibilities for IoT innovation to accommodate the needs of heterogeneous ecosystem. BLE


Fig. 1. Real-life use cases of BLE beacons in IoT applications: (a) interactive exhibition in Guggen-heim museum, New York; (b) interactive content distribution system by CyPhy Media Ltd., Hong Kong; (c) vending machine with location-based digital payment service by LINE Corp., Japan; (d) pull-notification based advertisement in a retail store by LINE Corp. at Uniqlo, Japan; (e) pull-notification based advertisement and promotion by LINE Corp. at BTS station, Thailand; (f) indoor navigation system with augmented reality in Gatwick Airport, England.

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beacons has been employed in a wide range of emerging IoT innovations. namely, improving shopping experience of users [14], guiding in museums [15], indoor localization and tracking [16], helping blind or vulnerabilities people [17]–[20], saving energy for smart office [21], [22], managing smart home [23] and warehouse [24], locating BLE devices with beacons using fingerprinting [25] and so on. Furthermore, increasing number of BLE beacon infrastructures are being deployed for commercial uses; some of these real-life deployment examples are shown in Fig. 1. [26] provided a forecast of a deployment of 19 billion Bluetooth devices over the next three years. Unquestionably, the adoption of BLE beacons in the IoT ecosystem will soon embark enormous research opportunities with its low power operation capabilities [27].

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

1) an overview of BLE protocol and beacons, its applications, and related hardware and software issues;
2) a survey of state-of-the art research on BLE beacons;
3) a review of limitations of BLE beacons and suggestion of future research directions, challenges and opportunities;

To the best of our knowledge, this article is the first attempt from academia to present a holistic overview of BLE beacon for IoT solution, considering every aspects of beacons from BLE protocol and applications to hardware design conditioned for practicality and real-life deployment.

The rest of the paper is organized as follows. Section II presents an overview of latest developments of different application leveraging BLE beacon infrastructure and further hints its possibilities and drawbacks. Section III reviews the BLE beacons in connection to its beaconing protocols and received signal strength. Section IV presents the beacon hardware from inside out, from its chipset, energy storage to its casing. Section V studies the enabling software and systems for BLE beacon and such as battery monitoring techniques, distance estimation, security features and server scalability. Section VI identifies the research challenges with respect to the three sections discussed above and Section VII concludes the paper.

## II. BLE Beacon Applications

BLE beacons have been adopted and deployed 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 the public and developers than ever before. Riding with 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. Following section reviews the state-of-the-art applications empowered by BLE beacons from both of the sectors and also shares our visions on potential creative applications.

### *A. Localization*

Localization is one of the most prospected application of BLE beacons. Global positioning system (GPS) that has revolutionized outdoor localization has proven to be ineffective in indoor environment and city streets due to severe attenuation and multi-path fading effects. Wi-Fi access point based solutions has limitations due to limited number of APs and their flexibility in deployment. Namely, Wi-Fi APs are installed for signal coverage and not for localization. Other technologies such as RFID, ultra-wideband and infrared have been emplyoed. However, these devices require a dedicated reader inorder to operate. Therefore, it is hard for general public to fully utilize such service. BLE beacon-based solution have a decided advantage over currently existing solution due to its low-production cost, easy to deploy, and easily accessible by the users. Feasibility of BLE beacon based indoor localization system has been extensively investigated [25]. In their investigation, authors discuss the accuracy that can be achieved with given configuration for deployment and operation parameter, namely denseness of deployment, advertising interval, transmission power etc. In their investigation, they had setup 19 beacons in an office area and have achieved $< 2.6$ m error 95% of the time when 1 beacon was deployed every 30 $m^2$, out-performing $<$ 8.5 m error when using existing Wi-Fi network.

[28] presents a stigmergic approach for indoor localization that strongly leverages RSSI information provided by static anchor nodes. Such method alleviates severe attenuation that any BLE signal may suffer in crowded areas. Recently such systems have been deployed for all sorts of different environments, namely museums, airports, and to help visually impaired to navigate indoor facilities. From real-life cases, Hong Kong international airport [29], Hamad international airport [30], Gatwick international airport [31], Dallas and Houston international airport [32] have deployed beacons to aid the passengers in navigating usually unfamiliar grounds. Among them, Gatwick international airport is an interesting example as they are combining augmented reality technology with BLE beacon-based localization system.

### *B. Proximity Detection and Interaction*

Besides providing users with locational information, BLE beacons can also convey contextual information by proximity measurement to an object or area. The difference between location and proximity is often blurred and therefore confusing. In this article proximity refers to relative distance to an object where as location refers to absolute position within a given environment. This means a beacon may be attached to non-stationary objects as well. The proximity information may trigger some event allowing seamless interaction between a user and an object. Technologies that achieves similar purpose, such as QR code and NFC exists. However, QR code needs to be installed or printed largely to reach larger number of audiences; however, design of QR code is not the most aesthetic. NFC has very short interaction distance 10 - 20 cm, which requires users to approach the media before interacting. On the other hand, BLE beacon can address both of these concerns.

BLE beacon-based proximity detection systems have already been deployed and demonstrated in real life to send effective notifications that strongly leverages on user context/location. [33] has implemented proximity detection based tour and navigation system. The system provided time table of nearby bus stop and distance to nearby subway station to the tourists. [34] has demonstrated the interactive system for art galleries, which has outperformed the conventional QR code's engagement conversion rate and time. Similarly, Estimote has implemented a BLE-beacon based system in a museum to provide detailed information about an artwork to nearby users [35]. The system employs a pull mechanism, where the information is only provided at an request. On the other hand, [36] demonstrates use case of push promotion and location advertising. In this example, beacon network consisting 1000 nodes was deployed across Hong Kong.

From the industrial parties, the Physical Web, introduced by Google Inc., provided an open way to interact smoothly and rapidly with physical objects without installing any mobile application by embedding compressed URLs in the advertisement packets. These objects are enabled with this feature by deploying Eddystone protocol employing beacon near them. When a user pass within the distance range of beacons, the services on the device including nearby notifications or Google Chrome will receive signals and transmit to the proxy before receiving URLs back and show on user smart phone/device [37]. There are three main benefits of using Physical Web with beacons. Firstly, mobile users can interact with everything around easily and quickly without downloading any mobile application at first. Secondly, they can see what is advantageous around by viewing webpages linked with the space surrounding them. Thirdly, when everything in the vicinity can transmit data and advantages, a whole new experience will occur [38].

Apple, leveraging on its iBeacon standard, has been implementing proximity based services such as continuity features [39]. 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 introduced their own lineup of beacons to further enhance locality features to the users. Similar technology has been adopted by the automobile industry. [40] demonstrated installation of iBeacon system on a car for automatic transaction at toll booths, parking meters, gas station and more.

LINE corp. has also incorporated LINE beacon services in their mobile applications. Fully utilizing its messenger platform, LINE has integrated BLE beacon's ability to convey contextual information with chatbot services. This allows users to engage in short dialogues to retrieve desired information. For example, LINE beacon service deployed in a Japanese clothing brand, Uniqlo, allows users to receive information regarding nearby garments through its LINE messenger applications. More interestingly, LINE has collaborated with LG to create a new application, HomeChat [41] that integrates BLE beacon, chatbot and home automation technologies. This service allows user to receive status notification of their home appliances and also make simple commands such as to change the mode of their air conditioner.

### C. Activity Sensing

In previous examples BLE beacons have been mainly used to provide more user-aware services by knowing their location and context through beacons. However, in the examples shown below, the information conveyed by the beacons were reversely used to help better identify the activities of the users. [42] has used BLE beacons to detect fine-grained location and movement to better identify the activity of the users with help of gesture detection technology of smart wearable devices. Knowing the user's micro-location helps to narrow down the list of possible gestures/ actions users may take. Consequently, the authors claim they have significantly reduced active sensing time up to 92.9%. Similarly, [43] has implemented a system to help to keep track of senior citizen's activity information. The system requires senior citizens to wear BLE beacon tag equipped with an accelerometer. BLE beacon signals scanned by pre-deployed fixed scanners helps to identify micro-location of the user, whereas built-in accelerometer helps to identify simple activities such as sit, stand and walk.

### D. Future Applications

The section has reviewed three very distinct use cases of BLE beacons: localization, proximity detection and activity sensing. In most of the examples BLE beacons were deployed in static location. 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 reliability of BLE beacons for mobile objects and also more study related to activity sensing. On the other hand, with machine learning on the rise, collecting user information is of paramount importance. Inspired by the use of chatbot, we believe providing contextual and locational information of the user through both localization and proximity detection open up a new paradigm of study, where machine learning will incorporate user information to make better engagements and therefore a better service.

## III. BLE Protocol and RF Signal Characteristics

In order to understand BLE beacon and their role in IoT thoroughly, this section first provides an overview on the development of Bluetooth technology, and then introduces two popular BLE beacon profiles on the market. BLE protocol is a foundation upon from which these low power wireless devices are built upon. Therefore, this section elaborates on the building block of BLE particularly the protocol related to BLE beacon and its signal characteristics. Firstly, 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 received signal strength (RSS), which can be measured by any Bluetooth-compatible receivers are investigated, especially their behaviors in a dense beacon environment.

### A. From Classic Bluetooth 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 such that to provide greater mobility for the devices' communication within the range defined by the Bluetooth signal. For example, replacing the wired mouse with Bluetooth mouse. Obviously, the determinant factor which guarantee the past success of Bluetooth is its reliability in providing hassles-free communication between two devices, and the power feature is not the top consideration for Bluetooth technology. The story changes when the IoT devices are knocking on the door, demanding for a better and lower power communication technology to empower 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, such trends also drove Bluetooth SIG to invent their first low power version of Bluetooth, known as BLE. Note that BLE is backward incompatible with classic Bluetooth, and it is designed for IoT devices in mind rather than for short-range devices' communication. Having said that, BLE trade-off the high speed and high data rate features in classic Bluetooth to minimize the power consumption. Table. I summarizes the key differences between classic Bluetooth and BLE. Apart from these differences, both technologies are operating 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. To ensure the coexistence of both technologies, Bluetooth SIG has introduced Bluetooth Smart Ready which is able to support both type of Bluetooth simultaneously. Bluetooth Smart Ready is normally found in the devices with higher computational capabilities such as smartphone and desktop. The main focus of this survey paper is BLE beacon and its promising features for IoT development, for the detail descriptions about Bluetooth Smart Ready and other roles of BLE (i.e., peripheral, central, er and observer), one can always refer to [44], [45]. The main differences between classic Bluetooth and BLE can be summarized:

- Two protocols serve different purposes and applications. Classic Bluetooth is tailored for multimedia streaming application. Whereas BLE is aiming for IoT applications where short sensor data need to be broadcast frequently.
- Two protocols leverage different wireless communication methods. As mentioned previously, Classic Bluetooth is for streaming, consequently requiring pairing between central and peripheral devices. In BLE, such operation is not necessary.
- Following the previous point, classic Bluetooth is a one-to-one communication and BLE is one-to-many communication, where the one is a BLE beacon device.

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 3 channels (i.e., Channel 37 (2.42 GHz), 38 (2.426 GHz) and 39 (2.48 GHz)) dedicated for advertisement purpose and the rest for data exchange. The wide spacing of the advertisement channels minimize the WiFi signals operated on the same ISM band. BLE device which only responsible for advertising via Channel 37-39 is commonly known as beacon. Beacon is connectionless and only uses advertisement channels to broadcast their signals periodically. The beauty of this mechanism is that no device pairing is required to receive the signals advertised by the beacon. This advertising signal generally contains a small data payload (known as advertising Protocol data Unit (PDU) most of the time) which may include the packet header, MAC address, device's unique identifier, and a small headroom for manufacturer specific data. Both Apple and Google manipulate this small chunk encapsulated in the advertising PDU and introduce their popular beacon profiles, iBeacon [46] and Eddystone [47], 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 (WWDC) [48]. Such movement of Apple has drawn a lot of attentions from both industrial and academia players, particularly regarding the possible applications that they can 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 feature is enabled with the small data size of the advertising PDU. Fig. 2 (a) shows the advertising PDU of iBeacon, which take up total 46 bytes in length [49]. Such packet structure not only enabled convenient identification of individual beacon devices, but also provided the industry with a universal standard for application development. Moreover, ever since then, many interesting location-based and proximity-based applications have been developed [16].

*2) Eddystone by Google:* On the other hand, Google launched their open source BLE profile, Eddystone [50], to compete with Apple's proximity marketing campaign. The launching of Eddystone has further impact the development of IoT especially with the introduction of Physical Web [51]. Different from the proprietary iBeacon, Eddystone allows seamless interaction with existing Chrome browser installed in any operating system. That is to say, that Eddystone allows more flexibility in contextual content development rather than

<table>
<tr><td colspan="4">(a) Adv PDU</td><td colspan="5">Payload defined by iBeacon Standard</td></tr>
<tr><td>1 byte</td><td>4 bytes</td><td>2 bytes</td><td>6 bytes</td><td>9 bytes</td><td>16 bytes</td><td>2 bytes</td><td>2 bytes</td><td>1 byte</td></tr>
<tr><td>Preamble</td><td>Access Address</td><td>Header</td><td>MAC</td><td>iBeacon Prefix</td><td>Universally Unique Identifier (UUID)</td><td>Major</td><td>Minor</td><td>Tx Power</td></tr>
</table>

<table>
<tr><td colspan="4">(b) Adv PDU</td><td colspan="7">Payload defined by Eddystone Standard</td></tr>
<tr><td>1 byte</td><td>4 bytes</td><td>2 bytes</td><td>6 bytes</td><td rowspan="2">UID</td><td>1 byte</td><td>1 byte</td><td colspan="2">16 bytes</td><td colspan="2">2 bytes</td></tr>
<tr><td rowspan="5">Preamble</td><td rowspan="5">Access Address</td><td rowspan="5">Header</td><td rowspan="5">MAC</td><td>Frame Type</td><td>Ranging</td><td colspan="2">UID</td><td colspan="2">Reserve</td></tr>
<tr><td rowspan="2">URL</td><td>1 byte</td><td>1 byte</td><td colspan="4">18 bytes</td></tr>
<tr><td>Frame Type</td><td>Ranging</td><td colspan="4">URL</td></tr>
<tr><td rowspan="2">TLM</td><td>1 byte</td><td>1 byte</td><td>2 bytes</td><td>2 bytes</td><td>4 bytes</td><td>4 bytes</td></tr>
<tr><td>Frame Type</td><td>TLM Version</td><td>Battery Level</td><td>Temperature</td><td>ADV_CNT</td><td>SEC_CNT</td></tr>
</table>

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

to build a completely independent mobile application to interact with the deployed beacon. For further comparison between iBeacon and Eddystone, one can refer to the summary provided by [52]. In general, Eddystone allows developers to switch between URL and TLM frame, as shown in Fig. 2 (b). The working principle of a URL frame is similar to the conventional QR code, whereas TLM frame allows developer to provide additional data regarding the deployed beacon. All the technical details regarding Eddystone protocol is available in Google GitHub [53].

*3) Manufacturer specific custom profiles:* Beside iBeacon and Eddystone, BLE protocol is flexible enough to allow manufacturers to configure customized BLE profiles for specific usage. Manufactures can add extra information they need to the beacons or change the offset of bytes for storing 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 re-designed for retrieving the correct data from the customized beacon packets. Furthermore, these profiles may evolve to become a profile by incorporating dynamic packet structure and information. Such design 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 their BLE profile, is RSS [54], [55], 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., $P_r \propto \frac{1}{d^2}$. 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 $P_r \propto \frac{1}{d^\alpha}$, where $\alpha$ is the loss exponent. Typically, RSS is measured in dBm scale (i.e., $RSS = 10\log(\frac{P_r}{1mW})$). The relationship between the RSS and distance is hence $RSS \propto -\alpha\log(d)$. That is, in logarithmic scale, the linear relationship between RSS and distance can be formulated as below,

$$RSS = -\alpha\log(d) + K \quad (1)$$

where $-\alpha$ is the loss exponent, $K$ is the constant that intersect at RSS axis, and $d$ is the distance measured in meter. Note that the above equation is a general path loss model which can be applied for different scenarios, in which each scenario has their own loss exponent. [56] provides a list of possible loss exponent for different scenarios.

In fact, there are no differences regarding the signal coverage of classic Bluetooth and BLE if both are configured to have same transmit power. Fig. 3 compares theoretical distance and measured distance for a beacon with different transmit power ranging from -30 dBm to 4 dBm. Theoretical distance was provided by the manufacturer, Estimote [57], 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 theoretical range. The signal fluctuation has resulted error in theoretical distance

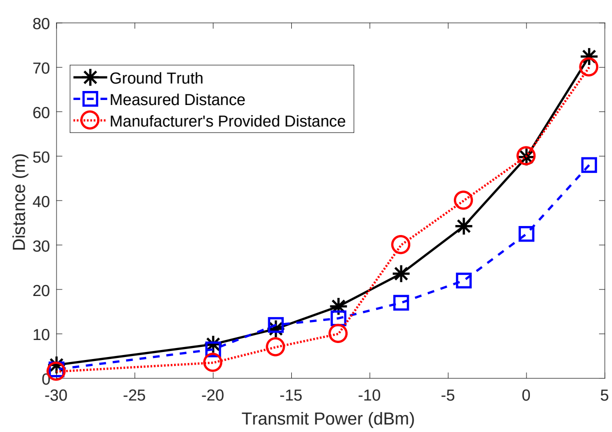



Fig. 3. Distance versus transmit power.

estimation that is purely based on RSS value. Prior research also had concluded that the distance estimation based on RSS is unreliable [58], [59]. Such situation gets even severe when multiple beacons are present within a small area. Following the above observation, the next subsection examines the signals behaviors in a dense environment.

### *D. Beacon Signals in Dense Environment*

Since BLE has reduced the number of channels (total 79 channels in classic Bluetooth) to 40 and each channels are equally spaced at 2 MHz [60], such strategical arrangement in the 2.4 GHz ISM band has prevented it from overlapping with the common Wi-Fi channel. However, consider an environment with 10 beacons placed randomly, smartphone might unable to see all the beacons' signals within a short scanning period, a time window during which the smartphone listens to BLE signal nearby. Fig. 4 (a) shows the RSS variation from each of the 10 beacons, it is observed that the RSS detected are varied across time even though each of the beacons are placed in a fixed location (i.e. the beacons are static and never move during the time of experiment). While Fig. 4 (b) shows each of the beacons required less than 1s to be detected under good condition, however, under worst condition the detection time can take more than 5s. 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 for the phenomenon of high RSS variation and detection time variation observed above, namely from beacon B2. Out of the total 751 scans, there were 12 scans that detected 0 signal, and only 1 scan was able to capture all the 10 signals.

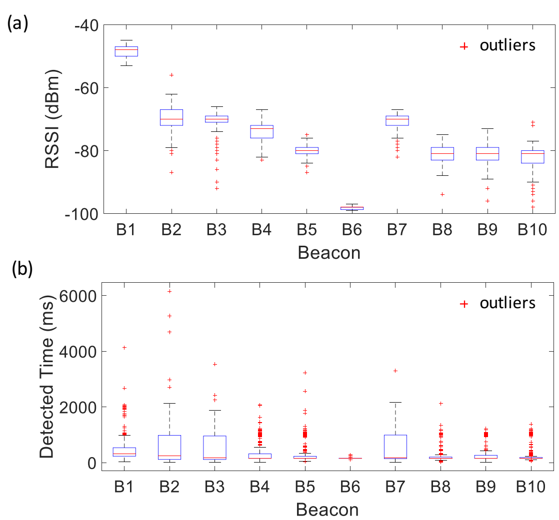



Fig. 4. Variation in BLE Beacon signal characteristics in a dense environment: (a) the RSS; (b) the time to detect beacon signal.

## IV. BLE Beacon Hardware

In-depth knowledge of different hardware components of a BLE beacon is crucial in 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 BLE chipset, energy storages, and casings are made. Furthermore, strengths and drawbacks of the options are discussed to provide better insights.

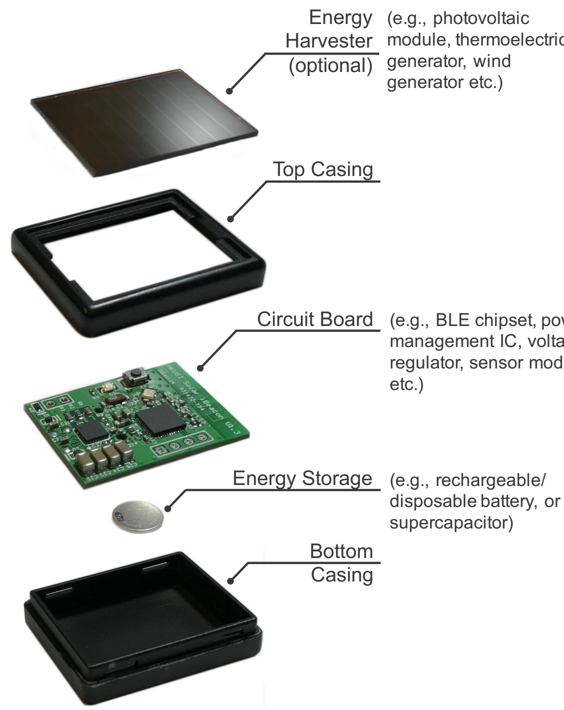



Fig. 5. An illustration of generic hardware components of BLE beacon.

### *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. On the other hand, precise estimation of the battery life will allow timely battery replacement of beacons, utilizing the available energy resources to their limits. In order to achieve this, detailed study on beacon's power consumption characteristics is required. In this subsection, the power usage of a off-the-shelf BLE beacon is carefully analyzed. The results presented in this section is referred from the studies conducted by the authors previously [61]. During their study, CC2451, Bluetooth chipset manufactured by Texas Instruments Inc. is used. This specific chipset is chosen as a reference as it is one of the most popular BLE ICs; market share of this chipset can be seen in the later subsection, 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 wakes up 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 rebooted itself due to some fatal error. Fig. 7 presents current consumption during advertising event in more detail. An advertising event is largely divided into three different states and more specifically nine states. These states and corresponding

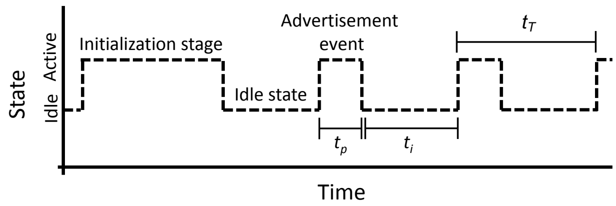



Fig. 6. Electrical characteristics of BLE beacon including initialization state.

current draw is shown in Table II. Since during the idle state, the device draws constant current, and initialization stage in only executed once, we are more interested in studying the current consumption characteristics exhibited in advertising event.

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. 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, one can calculate average current draw by taking the weighted sum with respect to the advertising interval as shown below:

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

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 idle state, $I_i$. The average current draw can help us to estimate battery life of a beacon at given advertising interval, which is a crucial parameter to consider during deployment and management. Although this method has been used in industries due to its simplicity, this method assumes constant current draw even though it is a pulse draw. In order to make a better prediction, it may be required to consider different battery models that takes battery recovery effect into consideration [62], [63].

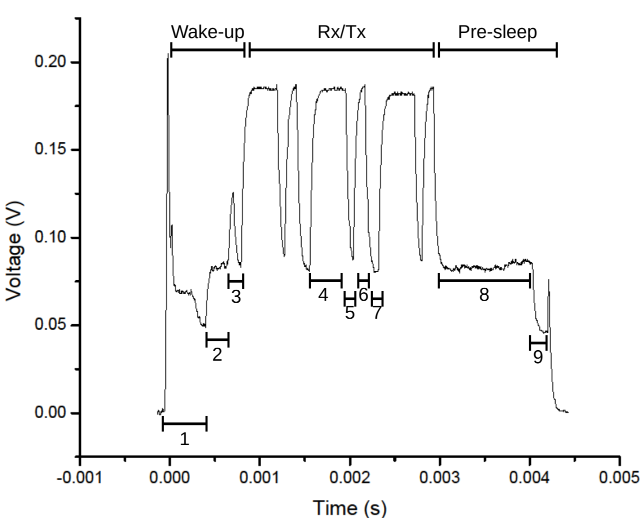



Fig. 7. Current draw of BLE beacon during advertisement event.

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

| State Number | Description | t ($\mu$s) | 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 |

### B. Options for BLE Chipset

Bluetooth chipsets are currently produced by a number of different companies, namely Texas Instruments, Nordic Semiconductors, 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 project, whereas Nordic Semiconductors have very energy efficient chipsets that will help to prolong the battery life. Cypress, on the other hand, is a leading company in designing integrated chipset for low powered devices, providing many power management ICs that can operate at a cost of few hundred pico current. When choosing a processor one may inspect in terms of 4 major aspects: power consumption, flash and RAM capacity, and internal voltage regulator. Computational ability has been 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 its current draw and Bluetooth version. In many cases, current draw from the radio is considered most important as CPU intensive operation is barely found in a BLE chipset. The current draw values can be mainly found on in its 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 nRF51 series from Nordic Semiconductors, flash storage usually comes in 2 variants: 128 and 256 KB. Generally, 128 KB is sufficient to implement basic functionalities of BLE beacon and simple features. However, if the device is running more complicated codes and calculation or require extra storage space for logging purposes, one may find 128 KB too small. Especially if one wants to develop Device Firmware Update (DFU), where a firmware of a beacon is programmed over the air with only a smartphone and mobile application, a larger flash storage is a must. Regarding RAM capacity, we have not faced much problems and have been contempt with 16 KB variants. Unless one is attempting to implement RAM retention technique for slightly better power consumption, larger RAM does not help the development or performance from our experience.

Most beacons are equipped with internal voltage regulator, so as to allow wide range of input voltage and reduce the number of extra components required for circuit manufacturing. However, its convenience may come at a cost of its efficiency. It is a general knowledge that at higher voltage the current draw will be less. However, this is not always true as many of the beacon chipsets employ low-dropout voltage for its simplicity which is energy inefficient at high voltages. To mitigate this, some of the chipsets from Nordic semiconductors have DC-DC regulator that helps to reduce current draw at higher voltage. However, this feature has known to cause instability in the chipset in 2$^{nd}$ revision hardware. Such incidents may motivate the developers to dedicate an efficient voltage regulator to extend battery life and avoid complications.

TABLE III
A COMPARISON OF REPRESENTATIVE BLE CHIPSETS FROM AFOREMENTIONED MANUFACTURERS

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

### C. Energy Storage

There are various means to store energy, namely, disposable batteries, rechargeable batteries and supercapacitors. Many of the beacons currently available in the market employs a type of disposable lithium ion batteries; Estimote and Kontakt.io beacons both employ lithium manganese dioxide batteries for their affordable price, thermal stability, and non-toxic properties. In the following section, different means of energy storages that could be used for beacons will be reviewed and discussed.

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

Consequently, some manufacturers have employed a larger size alkaline battery, such AA or AAA batteries to extend the life span of the beacon device. However, such life span comes at a cost of larger casing footprint and heavy weight. For example, Sensoro Pro beacons from Sensoro are equipped with four AA batteries and claims to last 5-6 times longer than ordinary beacons equipped with CR2477, which has capacity of 1000 mAh. Beacons from TheBeacons uses 2 AA alkaline batteries with capacity of 2600 mAh. However, such increase in size and weight of a beacon ultimately undermines the very advantage of BLE beacon devices, convenience of deployment. BLE beacon is considered very scalable not only due to its minimalistic protocol but also because it is very easy to deploy and use. Conventional beacon usually weights around 20 - 30 g, making the deployment procedure as easy as just attaching the beacon on a wall with a simple sticky tape available in any hardware store. However, use of larger batteries usually undermines this unique advantage.

TABLE IV
THEORETICAL BATTERY LIFE CALCULATION

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

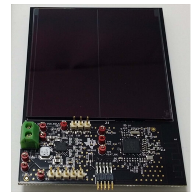
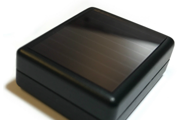
### D. Energy Harvesting Capability for BLE Beacons

To mitigate the battery issue of BLE beacon, some manufacturers have attempted to design an energy harvesting BLE beacons equipped with solar panels to sustain itself.Energy harvesting wireless sensor nodes has been a popular research topic [64]. Many researches were conducted to optimize energy harvesting hardware in terms of energy energy harvesting mechanisms, storage source, and charging circuitry. Such trend in energy harvesting untethered devices have affected the developments of IoT devices. [65] used kinetic energy harvesting method to harvesting energy from human movement and power a sensor node measuring human motion. [66] presented wireless sensor node system equipped with light harvesting capability with extremely small form factor of few millimeters. In addition, [67] used combination of RF and light harvesting to operate BLE beacon system with very long advertising interval of 45 s. Number of industries attempted to prototype similar device relying on ambient light harvesting methods. These products are reviewed in detail in Table V. However, energy harvesting capabilities of these devices are too low to support required advertising frequency of 1 Hz or storage capacity of the devices will forbid them from long-term operation in absence of ambient energy. Previous works on energy harvesting wireless sensor shown above focus mostly on outdoor deployments. However, many BLE beacon applications take place indoor. Hence, some of the previously mentioned energy sources may be absent or too scarce to harvest enough energy for perpetual operation of the untethered device. Therefore study of indoor energy harvesting is necessary in order to design energy-neutral BLE beacon device. Only recently, investigations on use of indoor lighting and photovoltaic cell for wireless sensor were carried out. [68] have provided comprehensive design consideration for indoor light energy harvesting wireless sensor system that employs MPPT technique and rechargeable battery. They claim that their prototype is expected to operate for 10 to 20 years without maintenance. [69] have presented different models of indoor energy harvesting sensors utilizing combination of capacitors and batteries. Based on previous works, generic system architecture of solar powered BLE beacon will consist of three main components: a photovoltaic energy harvesting module, power management unit, and BLE unit.

### E. Casing for Look and Protection

Two major concerns for BLE Beacon casing are looks and protection. Fig. 9 summarizes main stream BLE beacons with respect to different casing designs, power sources and chipset manufacturers. A casing may have an aesthetically pleasing

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 |

design that may even serve as a decoration. Such designs encourage venues, such as retail shops, to deploying these devices. Estimote beacon is a good example. On the other hand, the casing may be designed to be homogeneous and with the environment, making the device less noticeable. For instance, Gimbal's S21 beacons were made in white color and invisible brand name to achieve this purpose. In order to provide reliable and long-lasting service, it is vital to protect its inner circuit from water, dust and impact from potential abuses. To meet these demands, latest beacon casing designs often follow water/dust resistant standards such as the International Electrotechnical Commission's (IEC) Ingress Protection (IP) 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 inside. Consequently, the beacon will no longer have the water-resistant feature after its first maintenance. This is a common issue for most of the protective casings currently available in the market.

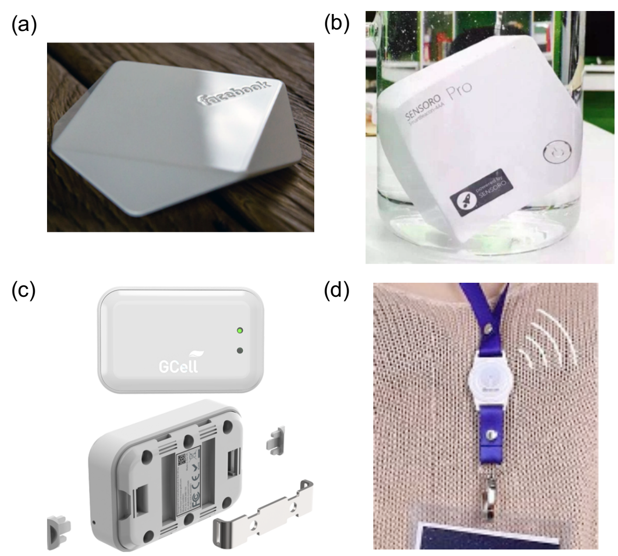



Fig. 8. Different features of beacon casings: (a) aesthetic design, Facebook beacon; (b) water-resistance, Sensoro Pro beacon ; (c) installation brackets, GCell G300 Universal iBeacon; (d) neck lanyard and a card holder design, Bright Beacon.

### *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 a double-sided adhesive tape was used to install beacon, installation case can fix the beacon much more securely; 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). This GCell beacon has an installation case with an installation brackets, which is meant to be drilled to a wall. Kontakt has also designed Beacon Pro with a mounting clip at the back to deploy and dismount this beacon. However, it is not easy to used these type of installation casings as they will damage the deployment location. Clearly, to achieve both solid installation without damaging the deployment facilities, an approach from a new angle is imperative.


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


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

Design of installation casing may also be influenced by material and orientation of installation surface. For real-life deployment locations, CyPhy Media beacons were deployed in 3 major locations: Hong Kong University of Science and Technology (HKUST), various news-stands across Hong Kong and BTS Skytrain stations in Bangkok as shown in shown in Fig. 10. From Table VI, beacons were deployed on vertical surfaces more than horizontal ones in BKK and HK. However, in HKUST, beacons were deployed horizontally more than vertically because they may need to be hidden from line of sight, for example under a table for some furnitures. However, such method of deployment is not ideal in signal propagation as BLE signals are extremely easy to attenuate. When we were deploying beacons in Fig. 10 (c), we have attempted to install the beacon inside the aluminum column to protect it from weather and people. However, due to severe attenuation from the aluminum plates, BLE beacon signal could barely be detected. To avoid such degradation in performance, it is highly recommended to ensure nothing obstructs 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 BLE beacons signal attenuates with human body, as it is composed mainly of water, BLE beacon signal will attenuate more in crowded area. Placing beacons in higher location alleviates such attenuation effect.

Table VII shows materials of three major deployment locations are mostly made of metal. In Hong Kong, wood and plastic share similar number of deployed beacons after metal, and beacons were only deployed on aluminum advertising sign at BTS Skytrain columns in Bangkok. We have found that double-sided adhesive tapes are not suitable for surfaces like wood, therefore different installation method may be employed depending on deployment surfaces. Noting that, metal is the most popular deployment surface material, the potential for installation casing leveraging on magnets can be envisioned. Since beacons are very light-weighted, use of magnets and high-friction material, such as rubber pads, may work well on any metal surfaces. However, a study on performance of BLE signals near magnets need 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. Deployment environment can influence BLE signal due to refraction and obscuration. For example, beacons deployed hidden from line of sight to avoid vandalism and theft may affect the signal propagation and therefore its coverage. However, it is worth to investigate whether what type of case materials can enhance the propagation of BLE signal and protection of circuit components from external factors such as water and dust.

TABLE VI
CyPhy beacons planes in 3 major 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 locations in 3 major 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 protocol and hardware developments of BLE beacon has laid a strong foundation upon which IoT applications and services can be implemented on, BLE beacon has drawbacks that arises from its inherent architecture, namely, large fluctuation in RSS and finite battery capacity. Such weaknesses makes beacon infrastructure difficult to implement and manage. Leveraging on power of big data and advanced signal processing techniques, aforementioned shortcomings can be overcomes thorough softwarization. Software and system for BLE beacon infrastructure includes battery measurement, distance estimatoin, security features and scalable server architecture and algorithms. In this section, current state of aforementioned developments are reviewed and discussed in detail.

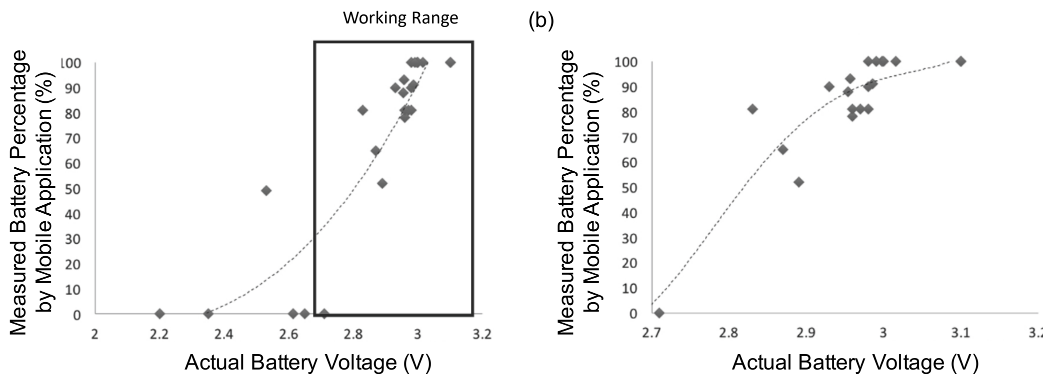



Fig. 11. Comparison of beacons battery level measured by mobile application and actual value: (a) full voltage range; (b) working voltage range.

### A. Battery Monitoring

After deploying a BLE beacon infrastructure, monitoring the battery levels and replace 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 Eddystore-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 extra packet or configure unused bytes for BLE beacons to store battery information when they are being produced [70]. Therefore, a smart device can request the packet storing battery information when the beacons broadcast signal to smart devices. Kontakt.io provides beacon with iBeacon protocol and supports battery level monitoring. They are also using this method by storing the battery level information in 23 bytes. The information is presented in decimal number and need 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 them, especially for iBeacon protocol. Most of the beacon related SDKs and libraries also include function to collect their beacon's battery level such as Estimote, AltBeacon, etc.

To verify the accuracy of battery monitoring, an experiment on comparing the measured battery level and the actual battery voltage level, the results is shown in Fig. 11 (a). The beacon's battery model is CR2450 with nominal voltage of 3 V. The graph shows the measured battery percentage by mobile app in between the theoretical working voltage level (2 - 3.6 V). Battery level was measured using a mobile application installed on iOS device provided by CyPhy Media. The result shows that the measured battery level starts getting zero value when the voltage drop to under 2.7 V. Possible reasons are the beacon cannot work under 2.7 V or the RSS from the beacon cannot be detected by the smartphone. By studying the working range in this experiment showing in Fig. 11 (b), which is very similar to CR2450 voltage characteristic [71] showing that the battery monitoring method is able to provide approximate battery level information for user to reference if the beacon signal can be detected by the smartphone based on this experiment.

### B. Distance Estimation

Distance estimation is a key-enabler to many IoT applications. While RSS is the cost-efficient method for distance computation, the fluctuation of RSS affects the reliability of the final estimation result. Let's take a look at the distance estimation algorithm provided by Apple; this algorithm 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 samples were taken for each 0.2 meter. The result is 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 meters.

Several studies have indicated that the distance estimation can be improved by first obtaining a reliable RSS measurement. [72] introduced a RSS threshold optimization method to improve RSS for estimating distance for indoor application. [73] also concluded that the error rate of distance measurement is even higher than RSS measurement based on the experiment result. Therefore providing accurate distance information is very important for developing IoT applications. An improvement on traditional centroid localization algorithm has been made and given a significant accuracy improvement at 63% [74]. The algorithm in measures three intersecting point of the beacons region and calculates the beacon position. Another approach is to calculate a path loss index by comparing the RSS in 1 m and the target distance [75]. The algorithm gives an average of 0.4 m error for experiment within 3.5 m. Based on the discussion here, various estimation method can be used based on users' need. Therefore, third-party beacon SDK like AltBeacon, Estimote who support distance estimation use their own algorithm to measure 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

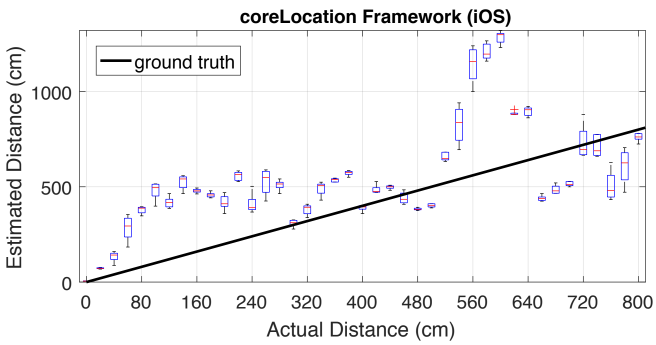



Fig. 12. Comparison between estimated distance from RSS measurements and actual distance.

as piggybacking, device spoofing, packet injection, beacon hijacking, denial of service attack, battery drainage attack, and selective frequency jamming. Piggybacking is a kind of an 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 scavenger hunt at CES 2014 [76], 2016 [77], beacon spoofing is undesired. Packet injection is very similar to beacon spoofing, but instead of placing cloned beacon outside the service area, it is placed among the original network, disturbing its normal operation. Therefore, packet injection is considered as a type of an attack. In case of localization services, such attack may lead to critical system malfunction. Potential damages of this type of attack is well illustrated in [78]. Battery drainage attack on a single beacon, rendering it inoperable, was also demonstrated in [79].

Currently, most solutions to securing beacon infrastructure is proposed by the industries, namely geolocation validation and cloud-based token authentication. In geolocation validation approach, geolocational information of individual beacons are pre-registered on an online server. On the user mobile side, location information provided by GPS module is transmitted to the server along with detected beacon signals, thereby ensuring physical presence of the user near the detected beacons. This approach can secure beacon infrastructure from beacon spoofing attacks. However, such security framework has many loop holes. Firstly, the operation of pre-registering every beacon's geolocation information on online server is tedious and resource consuming, therefore reducing the scalability of the approach. Furthermore, since GPS readings in indoor environment in unreliable, geolocation validation would be restricted for outdoor use only. Another approach is cloud-based token authentication method. In this approach, beacons are provided with an algorithm to generate beacon ID based on some 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, once the algorithm generating the beacon ID is discovered by the attacker, the system can be abused. Secondly, such framework is difficult to deploy onto already existing infrastructure, as it requires individual beacon's firmware.

### D. System Scalability

BLE beacons are normally used on the applications interacting between beacons and the edges (e.g., smartphone, smart wearable, etc.). These applications are not just measuring RSS or estimating distance, they also involve network requests 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 application. After ranging a new beacon, the edges will send the unique beacon's identifier to servers using HTTP requests for getting related information. For example, 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) [80]. The network requests can use both POST or GET methods, depends the application needs [81]. POST method are usually used for updating content on the server side, it will not include the request information in the URL body so it can provide a better security level. GET does not involve write-in process to the database, can reduce the loading on the server side but the request information needs to be added to the URL body means that it will cause security issue while sending some credentials.

Considering there are $n$ beacons interacting with one user at the same time, there will be $n$ requests sent by the user to the server for getting information. If there are $m$ users interacting the $n$ beacons at the same times, there will be $m \times n$ requests being sent to the server, and certain amount of responses will be sent back. Fig.13 shows an example of a server interacts with a beacon network with 2 beacons and there are 2 users in the region interacting with both two beacons, a total of 4 requests and responses will be generated normally in the case. When the scale of the beacon network increase, more users will interact with more beacons and the requests will increase accordingly. Therefore, deployment of server is important for beacon application systems. Amazon Elastic Compute Cloud (Amazon EC2) [82] is one of the possible choice providing good scalability and performance service that many companies such as Netflix, Adobe, etc. are using [83]. Tools like Jmeter [84] can simulate real network requests to server for testing the scalability of a server. A scalable server is expected to able to maintain good successful connection rate when requests number and packet size increase.

## VI. Research Challenges and Opportunities

At close inspection of BLE beacon technology, there is no doubt on its feasibility and suitability as IoT infrastructure: flexibility in BLE protocol allows 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 its inherent design, such as interoperability between different BLE profiles, short battery life, security issue and so on. In this

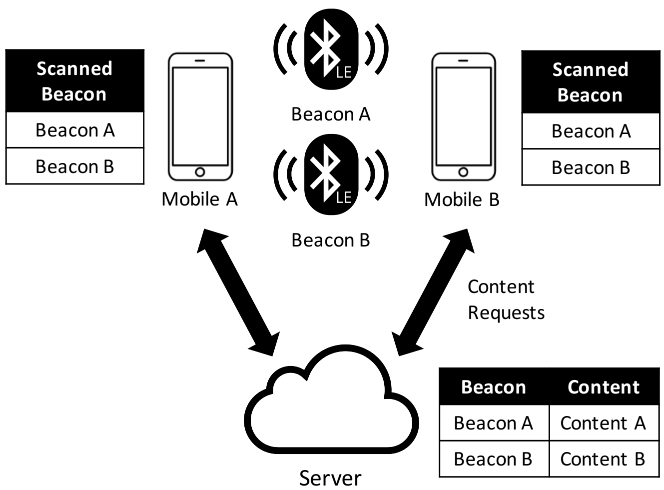



Fig. 13. Interaction between beacons, edges and server

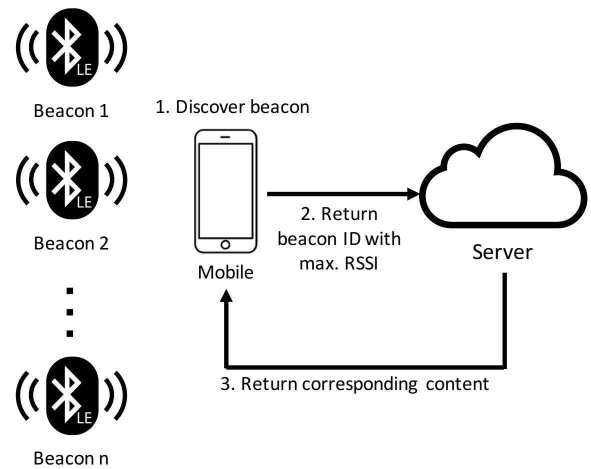



Fig. 14. An illustration on RSS comparison approach for BLE beacon-based interaction system.

section, such demerits of BLE beacon are discussed and future research directions are suggested accordingly.

### *A. Challenges about the Protocols*

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

The most challenging issue to deal with is BLE beacons only allocate a small chunk to customize their advertising PDU. It is, if impossible, quite hard to load both protocols within this short advertising PDU. Consider the market with diverse smartphones or BLE-enabled receivers. Failing to incorporate either one of the protocols might possibly mean that service providers will fail to reach to the other half or more of the users. Hence, to ensure a wide penetration, it is an urge to have 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.

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 during the interaction process is an issue affecting smooth and interruption-free interaction in an environment with dense beacons deployment. In such an environment, chances are these beacons will interfere with one another if they are closely spaced [85]. As illustrated in Fig. 14, most interactions with beacons are based on the RSS-comparison approach [85], 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 create a challenge for the connected-things to participate in the interaction activities when incorrect RSS is processed. Furthermore, as different connected-things might use different technologies, this poses an application development challenge, as there are non-standardize interaction interface.

### *B. Challenges about the Hardware*

The following section identify the IoT-related challenges in connection to energy efficiency of BLE beacons and the possible deployment constraint. In particular, three related issues are identified, that is battery, casing design and fixing. One of the major drawbacks of BLE beacons is rooted in its limited power source. As mentioned in previous section, battery life of BLE beacon powered by coin cell battery CR2032, most commonly used battery, will last less than a year. Such short life span of beacons requires periodic operations that replace and maintain the already deployed beacons. Although energy-harvesting devices are well studied in fields of wireless sensor network, study of similar nature is deemed necessary also in the field of BLE beacons for several reasons. Firstly, wireless sensor network focused their research on energy harvesting in outdoor environment. However, BLE beacons are used widely in both indoor and outdoor environment, therefore study on energy harvesting devices in indoor setting is required. Furthermore, a robust design that considers several different deployment environment is strongly desired to enhance the scalability of the devices. Secondly, electrical characteristics of BLE beacon devices are quite different from those of wireless sensor devices. Therefore, different chipsets and hardware specifications of energy harvesting devices and storage devices are not optimal for beacon devices and should be tailored for this application. Consequently, the new research field comes down to studying hardware specifications and optimizing it to application specific requirements.

With respect to energy harvesting BLE beacons, ambient light energy harvesting beacons have been investigated and prototyped by number of groups. However, in terms of other energy sources such as, thermoelectric, wind, acoustic, vibration, RF has not been fully explored. [67] has explored use of RF harvesting to power beacon and their energy neutral beacon could broadcast every 45 seconds at input power of 15 dBm at frequency bands between 2.4 GHz and 5 GHz. However, input power of 15 dBm is usually not feasible considering that most Wi-Fi router's transmission power is limited around 20 dBm. Furthermore, advertising interval of 45 seconds makes 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 complicated deployment procedure. Thermoelectric generators requires 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, energy harvesting device must be attached to vibrating object and stationary object, so as to generate alternating current using the principles of electromagnetism. Such deployment procedure is quite complicated and painstaking. Such needs may connect to research on casing design that may help to facilitate these needs.

First challenge for beacon casing is to design a case according to the IEC standard 60529 or standard 250-2003 [86] that can retain its protection feature even after battery replacement. Since BLE beacons may require frequent battery replacement, it is important to research on devising a casing structure that can facilitate convenient battery replacement and still can effectively protect the inner circuitries from water and dust. In addition, attenuation caused by the casing should be kept minimal. If the case were made of metal, it would block the signal. Furthermore, it should still achieve small form factor by using different materials such as hydrophobic nanomaterial for better water-resistance [87]. Second challenge is to investigate cases that can increase efficiency for energy harvesting. Recently, there are ongoing investigation on photovoltaic modules assembled three-dimensional. Inspired by photosynthesizing plants, [88] has studied placement of photovoltaic module in a tree-shape following the Fibonacci number. [89] has demonstrated a 3D structure that uses photovoltaic modules as both reflector and absorber to enhance the efficiency. Such designs can be incorporated in to the casing to facilitate perpetual operation of light harvesting beacon in scarce ambient light environment. Third challenge, unique installation techniques and cases that are convenient to install, strong in protection and easy to replace. Furthermore, the design may incorporate the knowledge of deployment surface and employ adequate installation methods accordingly. Furthermore, recent advancement in synthetic setae [90] with the help of nanotechnology, may be incorporated to the casing design to replace adhesive-tape method.

### *C. Challenges about the Software and System*

Since beacons are battery-powered device, it is hence important to have a software program that is able to accurate monitor the battery locally and remotely. Another challenge arises with application development is to deal with the unreliability of RSS to achieve a 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 user's smart devices. The battery information is collected by user smartphones and sent to the cloud server so that other infrastructure managers can access them. However, BLE technology requires user presence in close proximity of the monitored beacon. This means the battery information cannot be updated frequently if there are small user traffic near deployed infrastructure. Since most of the beacons are built with limited power source, monitoring the battery level frequently is a serious challenge in this stage. Beacon's battery information can be configured into the different bytes of the advertising packet. It may occur error when retrieving the battery level because the battery information packet offset may be different for each beacon, developers may not able to get beacon A's battery level by using the same method for getting beacon B's. Moreover, the presentation method of the battery information in the packet may also be different such as it can be presented as battery percentage, voltage level, etc. Therefore, developers should aware the information extracting method of every beacons so that the correct battery level can be obtained.

*2) Distance Estimation:* Considering the studies previously reviewed on distance estimation, accurate distance estimation is difficult to achieve due to unstable BLE signals. BLE beacon needs to work in an environment with multiple signal emitter for some special purpose such as indoor location service. Before, the closest signal source of most of the wireless communication technology can be identified easily as the signal source are not that close to each other like beacon infrastructure. Hence, measuring an accurate RSS to identify different beacons in dense environment is a new challenge on developing beacon related applications to make sure correct information is collected by smart devices. The future works need to stabilize the RSS so that the calculated distance will not fluctuate too much and cause measurement error. Some works have been done on the research area such as self-correction beacons [91] by comparing the RSS measured in 1 meter to obtain a more actuate value. People also proposed 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 researches and studies need to be done in the future to improve the algorithm to achieve accurate distance estimation.

*3) System Scalability:* System scalability is important to study as most of the beacon applications will connect to server and can generate lots of network requests that need to be managed properly. In some condition, 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 by using 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 beacon before sending the requests to server. For example, they can group all the requests together for certain period of time instead of requesting the server once they meet a beacon if the application does not request that frequently update.

*4) Security Issue:* In terms of security measures for BLE beacon network, previously introduced systems, such as cloud-based token authentication or geo-location validation systems, are more of precautionary systems rather than security systems, as it is capable of preventing any abuses, but fails to counteract or even detect any potential attacks. To remedy those drawbacks there has been a study on detection of physical attacks on beacons [92]. In their work, hidden Markov model (HMM) was used to estimate the probability of a beacon device being physical removed, relocated, and being cloned. With false-alarm rate of 5%, they have been able to achieve a promising results where removed/stolen beacons could be detected perfectly, and relocated or cloned beacons could be detected with around 70% accuracy. However, it is well known that HMM are computationally demanding, and therefore lays doubt on the practicality of the proposed system as real beacon infrastructure involves few hundreds or even thousands of beacon devices; in their work only 11 beacon devices were used in their experiments. Security features of BLE beacon infrastructure is in its infant stage and there are only handful of researches done in this field. At current stage, detection system using HMM and precautionary systems with beacon ID shuffling method are 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

Internet of Things has tremendous potential to change the modern lifestyle as the Internet has done in the past; and BLE beacons are prospected to play a pivotal part in realization of this new paradigm. Recognizing such potential in BLE beacon, this article reviews different aspects of BLE beacon for its usage in IoT application. Firstly, different applications leveraging BLE beacon infrastructure were introduced: localization, proximity detection and interaction, and activity sensing. After that, to form a good understanding of BLE beacon, BLE protocol and its signal characteristics, which is common to all BLE devices, were first reviewed. After that BLE beacon hardware was inspected regarding 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 internal voltage regulator were discussed. Different casings to protect and install beacons were also reviewed in detail. Software and system for BLE beacons with respect to battery measurement, distance estimation, security features, and server scalability reviewed in-depth

Based on the survey done on aforementioned topics, limitations of BLE beacons are identified and future research direction on individual topics were discussed. Interoperability between different BLE beacon devices and operation in dense BLE beacon environment are obstacles that must be overcame in order to make the infrastructure more robust. Study on sustainability issue and casings of beacon is necessary in order to make infrastructure management less resource consuming. In terms of 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 is still in its infancy; studies regarding its casings, deployment methods, security issue, and server scalability has been barely studied. However, its scalability that arises from small form factor and affordable hardware price and flexibility in protocol that can host numerous types of application, outweighs its current underdevelopment and makes it worthwhile to further investigate and research.

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