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User Existence-aware BLE Beacon Firmware for Extended Battery Lifetime

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***Abstract*—Bluetooth Low Energy (BLE) beacon networks are one common infrastructure for IoT and smart city applications because of their scalability and affordability, as well as the proliferation of Bluetooth-enabled devices. However, BLE beacon networks suffer from short battery lifetime, which induces additional maintenance costs. In this paper, we propose a novel user existence-aware BLE beacon firmware, USTEA, that extends BLE beacon lifetime by changing its operating configuration. Leveraging scan response and request features of Bluetooth Core Specifications, a mechanism for the detection of nearby user smartphones is proposed. Furthermore, we present an energy consumption model of the proposed firmware, along with an optimization problem for finding the optimal configuration that minimizes the overall energy consumption and overhead induced by switching delay. Last but not least, we introduce a prototype of the USTEA firmware and demonstrate experiments. Through the experiments, we prove that the USTEA firmware can extend a beacon's lifetime up to 250% under low user-existence frequency and high energy demand application conditions.**

I. INTRODUCTION

With the Internet of Things leading trend globally, numerous wireless communication technologies have been investigated to bridge the virtual world with the physical one, thereby enabling various location-/context-aware services at the touch of a finger. Among these, Bluetooth Low Energy (BLE) beacons have drawn much attention from both the research and industrial communities as a key-enabler of this new paradigm [1]–[4]. A BLE beacon is a power-constrained Bluetooth device that broadcasts locational/contextual information to nearby user smartphones, enabling human-environment/-thing interactions in a plethora of applications [5]–[7]. Due to the pervasiveness of Bluetooth-enabled devices in modern society, a rapidly increasing number of BLE beacon networks are being adopted on a commercial scale, e.g., Hong Kong International Airport [8], Facebook [9], Apple [10] and Google [11] etc.

A drawback of BLE beacons, similar to battery-powered nodes in wireless sensor networks (WSNs), is that they suffer from short battery lifetime, which induces additional maintenance costs and operations. For energy-demanding applications, such as indoor navigation, the battery lifetime of a beacon may be as short as two months. In WSNs, such shortcomings were compensated for by energy harvesting systems [12], [13] and network lifetime maximization techniques [14], such as cross-layer design, routing/clustering [15], etc. However, such techniques have yet to be investigated to accommodate the unique attributes of BLE beacon devices. To address this issue, this paper proposes a novel user existence-aware BLE beacon firmware, *USTEA*, which detects the existence of nearby user smartphones, and duty cycle its operation, leveraging this information to extend the beacon's battery life.

The proposed approach is similar to that of sleep-wake scheduling techniques used to maximize network lifetime in WSNs, where minimizing packet delay [16], balancing teletraffic load [17], and maximizing throughput [18] have been used as the constraints to their optimization problems. However, since BLE beacon networks have different topologies and serve a different purpose, namely broadcasting information to nearby users, a firmware design and optimization problem tailored for BLE beacons needs to be investigated. The proposed firmware is highly practical, as the duration of beacon infrastructure usage vary greatly depending on the deployment environment, as shown in Fig. 1. Furthermore, since both the user existence frequency and application requirements for beacon infrastructures varies greatly, the proposed optimization method considers these two conditions to maximize the BLE beacon lifetime. In this paper, locations where users exist for less than 12 hours are classified as a low user-existence frequency environment and the others as high user-existence frequency. Similarly, applications that require advertising interval less than 1000 ms are classified as high demand applications and others as low demand applications.

To the best of our knowledge, this is the first attempt to propose user existence-aware BLE beacon firmware to maximize its battery lifetime. The contributions of this paper are as follows:

1) a novel dual-state firmware for BLE beacons, called USTEA, that detects and leverages user existence;
2) an optimization problem and its solution for the optimal beacon operation configuration considering varying usage conditions, namely, user existence frequency and application requirements;
3) experimental results to prove the practicality of the proposed system.

The rest of this paper is organized as follows. Section II presents a primer on BLE beacons. Section III proposes and models user-aware BLE beacon firmware. Section IV formulates the optimization problem. Section V presents experimental results with a working prototype to validate the proposed firmware. Finally, Section VI concludes the paper.

Fig. 1: User existence at locations in Hong Kong at different operation hours (data from Google Locations).

II. The Basics of BLE Beacons

The following section summarizes the basic knowledge of the BLE specifications and beacons required to understand the proposed firmware. Configurable operation parameters and energy consumption profiles of a beacon, along with scan request and response features of Bluetooth specifications are presented respectively. A detailed review on operating principles of BLE beacons can be found in [2].

A. Operation Parameters

A BLE beacon is a Bluetooth device that broadcasts configurable advertisement packets up to 31 bytes to its nearby surroundings. A beacon can also be configured with different advertising intervals and transmit power. The advertising interval, T, determines the time interval between each broadcast. A short advertising interval increases the reliability of the beacon signal and enables more accurate distance estimation and indoor localization. However, advertising intervals significantly influence the overall energy consumption of the beacon and therefore its lifetime. The transmit power determines the strength of the broadcasted beacon signal or its coverage range. However, a theoretical estimation of the coverage range for a given transmit power is difficult as it is affected by multiple factors, such as antenna design, the structure of the deployment environment (multi-path fading effect) etc. Because of the complicated nature of predicting and controlling the coverage range, this paper only considers the advertising interval as a configurable operation parameter and assumes that the transmit power is predetermined by some application requirement.

B. Energy Profiles

A BLE beacon's operation behavior is shown in Fig. 2. The beacon wakes up every advertising interval, T, to broadcast its advertisement packet and spends the rest of the time idle to minimize power consumption. Knowing this behavior, the power consumption of a beacon, P, can be modeled as follows:

$$P(T) = \frac{P_i(T - t_p) + P_p t_p}{T}, \qquad (1)$$

where P_i is the power consumption for the idle state, P_p is the power consumption and t_p is the time duration of the advertisement event. P_p and t_p vary depending on the beacon's mode (e.g., broadcast or connectable) and transmit power. With this knowledge, a beacon's lifetime, t_l, can be calculated given its energy storage capacity, E_g: $t_l = E_g / P(T)$.

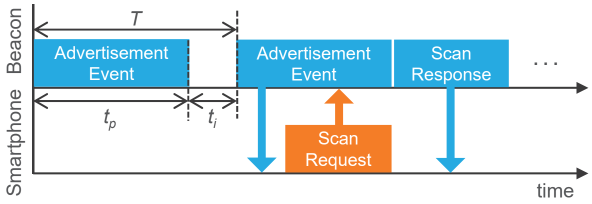

Fig. 2: Operation behavior of a BLE beacon.

C. Scan Request and Response

The scan request and response are features natively supported since Bluetooth Core Specification 4.0 [19]. This feature allows a BLE beacon to piggyback an additional 31 bytes to its advertisement packet if it is scanned by a user smartphone, as shown in Fig. 2. In order to leverage this feature, two conditions must be satisfied on both the beacon and the mobile phone. Firstly, the BLE beacon must be in connectable mode. A beacon in this mode will not only transmit its advertisement packet, but also scan for a scan/connection request from a smartphone after each transmission. However, because of this, the connectable mode consumes more energy (i.e., P_p and t_p in (1) will be larger) than broadcast mode, where a beacon only transmits. Secondly, the mobile phone must be in active scanning mode. Active scanning mode, in contrast to the passive one, allows a smartphone to send a scan request to BLE beacons at the cost of higher energy use. The proposed USTEA firmware makes use of these features to detect the existence of user smartphones and thereby operates in two different states that can either save energy or serve the application purpose.

III. USTEA BLE Beacon Firmware Architecture

The following section presents the design of the USTEA firmware. Details of the firmware, corresponding energy consumption model, normal state duration, and overhead due to switching delay are presented respectively.

A. Architecture Overview

The intuition behind the USTEA firmware is to detect the existence of user smartphones and switch between two states of operation, namely *saving state* and *normal state*, to either meet the application needs or conserve energy. Such an architecture brings great benefit to those beacons deployed in environments where opening or operation hours are short.

- *Saving state*: the beacon is configured to trigger a scan request from the central devices and reduce its power consumption when users are not within its coverage zone. Therefore, $P_s < P_n$, where P_s is the power consumption of the saving state and P_n is the power consumption of the normal state. The beacon must be operating in either connectable or scannable mode.
- *Normal state*: the beacon is configured to serve the application needs. Normal state is only activated when a scan request from a central device is received during the saving state. The beacon can be operating in either connectable or broadcast mode.

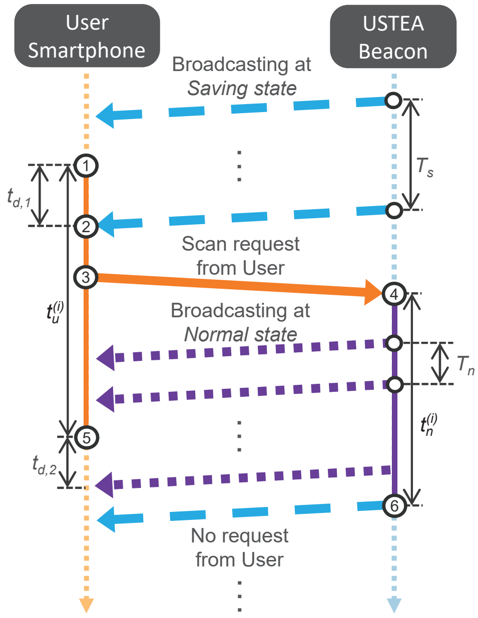

Fig. 3: Time diagram between a USTEA beacon and a user smartphone, where a USTEA beacon is initially operating at saving state.

Interaction between a USTEA beacon and a user mobile phone is shown in Fig. 3: 1) the user enters the USTEA beacon coverage zone; 2) the user receives a saving state advertising packet; 3) the user sends a scan request packet; 4) the beacon receives the request and operates in normal state; 5) the user exits the beacon coverage zone; and 6) the beacon operates in saving state after t_n, which is a multiple of T_s, and since it receives no scan request from the user, the beacon stays operating in saving state. In Fig. 3, T_s is the advertising interval of the saving state, T_n is the advertising interval of the normal state, $t_{d,1}$ and $t_{d,2}$ are delays that occur when the USTEA beacon is changing between states, hence referred to in this paper as switching delays, $t_u^{(i)}$ is the duration of the user existence for some instance i, and $t_n^{(i)}$ is the duration of the normal state for some instance i. The sum of $t_n^{(i)}$ $\forall i$ gives the total duration of the normal state, t_n, over some time period (i.e., $t_n = \sum_{\forall i} t_n^{(i)}$).

B. Energy Consumption Model and Analysis

Based on the operation mechanism of the USTEA firmware, the energy consumed over a duration t_o can be found as shown in Fig. 4:

$$E_u = P_n t_n + P_s t_o, \tag{2}$$

where t_n is the time that the beacon spends in normal state with advertising interval T_n. On the other hand, the energy consumption of a conventional BLE beacon with advertising interval T_n, E_c, is given by $P_n t_o$ (or $E_c = P_c t_o$, where $P_c = P_n$ is the power consumption for the conventional beacon). To ensure that the USTEA architecture is more energy saving than the conventional one, the following requirement must be satisfied, $E_u < E_c$. This expression can be simplified to yield two other important constraints using (2): 1) the maximum value of t_n; and 2) maximum value of P_s. Simplifying the constraint above yields the range of t_n where the USTEA beacon outperforms the conventional one:

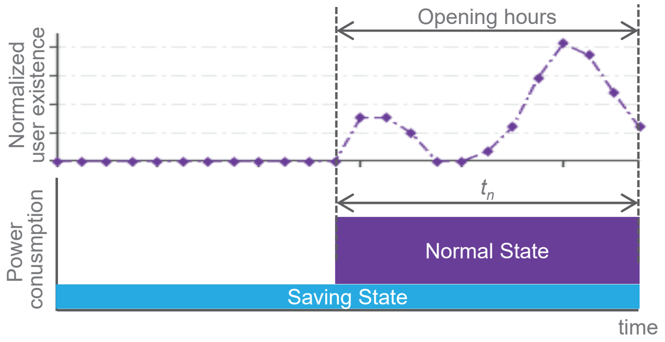

Fig. 4: Power consumption of a USTEA beacon against varying user existence frequency at different operating hours.

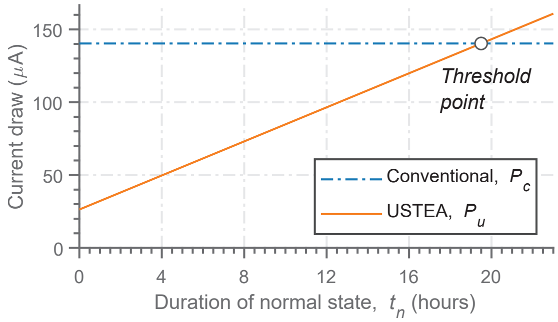

Fig. 5: Energy consumption of USTEA beacon against conventional beacon for a fixed T_s and varying t_n.

$$t_n < \frac{(P_n - P_s^{max})t_o}{P_n}, \tag{3}$$

where $t_n \geq 0$ and P_s^{max} is the power consumption in the saving state with the largest possible advertising interval according to the Bluetooth standard, 10240 ms. Similarly, the region of P_s where the USTEA beacon will outperform the conventional one, as shown in Fig. 5, can be found as:

$$P_s < P_n - \frac{P_n t_n}{t_o}, \tag{4}$$

where $P_s \geq 0$. The above two equations will be used in the next section, where the optimal value of T_s for a given environment and constraints is examined.

C. Modeling Duration of Normal State, t_n

In order to calculate E_u, it is imperative to know t_n. Therefore, this section presents a simple model to derive t_n based on a assumption that the time difference between each occurrence of user existence follows a Poisson distribution. Given the average duration of user existence, $\bar{t}_u$, and number of user existence occurrences over some time, N_u, t_n is given as follows:

$$\begin{aligned} t_n = &\Bigg[\left(1 - \frac{\mathrm{mod}(\bar{t}_u, T_s)}{T_s}\right)\left\lfloor \frac{\bar{t}_u}{T_s} \right\rfloor \\ &+ \left(\frac{\mathrm{mod}(\bar{t}_u, T_s)}{T_s}\right)\left\lceil \frac{\bar{t}_u}{T_s} \right\rceil\Bigg] T_s N_u \\ = &\ \bar{t}_u N_u. \end{aligned} \tag{5}$$

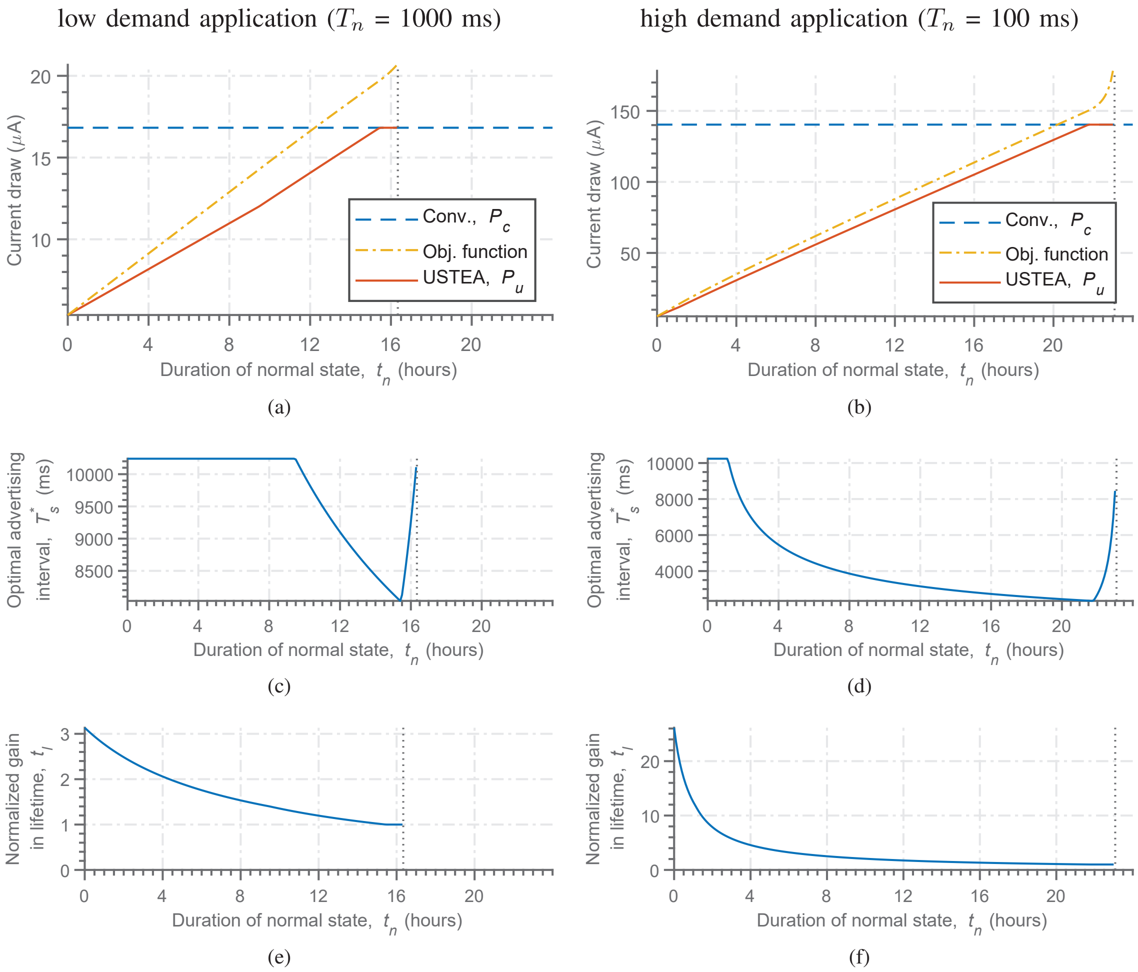

Fig. 6: Optimized saving state advertising interval under varying application scenarios and time duration in normal state.

From the above formulation, it can be observed that t_n and T_s are independent. Therefore, one can estimate t_n using the average duration of user existence and number of user existence occurrences.

D. Modeling Overhead from Switching Delay

The switching delays, $t_{d,1}$ and $t_{d,2}$, not only cause a delayed user experience, but also induces inefficient use of energy. It can be observed from Fig. 3, that $t_{d,1}$ refers to the delay experienced by the user smartphone in receiving a beacon packet, while $t_{d,2}$ refers to the duration of normal state operation when there is no user nearby, leading to inefficient energy use. Hence, this section investigates the impact of $t_{d,2}$ on a USTEA beacon's energy consumption. To this end, the relationship between $t_{d,2}$ and T_s is first studied. It is easy to see that $t_{d,2}$ is upper bounded by T_s. Since it is assumed in the previous section that the time between each occurrence of user existence follows a Poisson distribution, the distribution of the switching delay should also follow a uniform one. Therefore, the expected value of $t_{d,2}$ can be given by

$$\mathbb{E}(t_{d,2}) = \frac{T_s}{t_{d,2}}. \quad (6)$$

Note that switching delays exist for every user existence occurrence. Therefore, the total duration of switching delay $t_{d,2}$ can be calculated by $N_u T_s/2$. With these insights, the energy overhead for normal state operation during $t_{d,2}$ can be computed with the following function:

$$g(T_s) = \frac{N_u T_s P_n}{2}. \quad (7)$$

This overhead is minimized when a small T_s is selected. However, according to (2), smaller values of T_s will result in higher overall energy consumption. Such opposing goals emphasize the need for an optimization problem to find the right balance between minimizing the overall energy consumption and minimizing the overhead. Therefore, in the following section, an optimization problem and a solution for finding T_s that balances these two goals are presented.

IV. OPTIMIZING SAVING STATE ADVERTISING INTERVAL

The following section presents the optimization problem for finding the optimal T_s that extends beacon lifetime by minimizing the power consumption of a USTEA beacon, P_u. As shown in (2), as the saving state advertising interval decreases, the overall energy consumption of the system is also reduced. However, there will be switching delays, namely, a time delay in beacon detection on the user side and inefficient use of energy on the beacon side. Hence, an optimization problem is formulated to find the optimal saving state advertising interval that minimizes the USTEA beacon's energy consumption and the switching delay. Therefore the optimization problem is formulated as follows:

$$\begin{aligned} \min_{T_s} \quad & P_n t_n + P(T_s) t_o + g(T_s) \\ \text{s.t.} \quad & P(T_s) < P_n - \frac{P_n t_n}{t_o} \\ & t_n < \frac{(P_n - P_s^{max}) t_o}{P_n} \\ & T_s^{min} \leq T_s \leq T_s^{max}, \end{aligned} \tag{8}$$

where the optimization variable is the saving state advertising interval, T_s, the first constraint is from (3), the second constraint is from (4), the third constraint ensures the search region for T_s is compliant with the Bluetooth standard, and T_s^{min} is the smallest advertising interval allowed for BLE beacons in connectable mode (20 ms) while T_s^{max} the largest (10240 ms).

It can be easily seen that the optimization problem is a convex one: the objective function is the sum of a convex function and a linear one, with the first constraint a convex function and the third a linear one. Therefore a numerical solver can be used to solve this optimization problem. During the computations $\bar{t}_u$ was assumed to be 30 seconds. The optimal values for the objective function and the saving state advertising interval were computed, and are shown in Fig. 6 for low demand and high demand application cases. Fig. 6 (a) and (b) show the value of the objective function, the power consumption of a USTEA beacon, and that of a conventional one; (c) and (d) show the optimal saving state advertising interval, T_s^*, corresponding to the values of t_n; (e) and (f) show the normalized gain in lifetime from using a USTEA beacon when compared to a conventional beacon. In the figure, the vertical black dotted lines represent the upper bound for t_n in (4), which ensures the USTEA beacon saves more energy than the conventional beacon. It is interesting to note that there is a sharp increase in T_s^* in both Fig. 6 (c) and (d) when it approaches the upper bound of t_n. This is because (3) takes effect when t_n approaches its upper bound.

TABLE I: Experiment conditions.

low user existence frequency	t_n = 8 hours
high user existence frequency	t_n = 16 hours
low demand application	T_n = 1000 ms
high demand application	T_n = 100 ms

TABLE II shows the exact values of T_s^* and P_u^* acquired from solving the optimization problem under four different cases. For these cases, parameters t_n and T_n were varied, as shown in TABLE I. It can be seen that for low user existence frequency cases, the USTEA beacon will extend the lifetime from 1.5 to 2.5 times. This shows the effectiveness of the proposed firmware under low user existence frequency settings. Although the benefit for high user existence frequency cases are not as significant, lifetime can still be extended up to 1.3 times for high demand applications.


(a) (b)

Fig. 7: Experimental setup: (a) user-aware beacon deployment environment; (b) debugger and beacon used during the experiment.

TABLE II: Theoretical values of saving state advertising interval, power consumption of USTEA beacon, and normalized gain in lifetime.

User existence frequency	Application demand	T_s^* (ms)	P_u^* (μA)	Normalized gain in t_l
high	low	9262	16.82	1
high	high	2729	105.2	1.33
low	low	10240	10.98	**1.53**
low	high	3859	55.9	**2.51**

V. PROTOTYPE AND EXPERIMENTS

This section demonstrates two experiments to prove and evaluate the functionalities of the USTEA firmware. The first experiment demonstrates that the proposed firmware can detect mobile users and enable normal state operation for seamless service. The second experiment demonstrates the amount of energy that can be saved under different user existence frequency and application scenarios. The USTEA firmware was implemented on an off-the-shelf BLE beacon employing nRF51822 as its BLE SoC through the software development kit version 12 provided by Nordic Semiconductors.

A. *Experiment with a Mobile User*

To test the functionality of the USTEA beacon with mobile users, a beacon was installed in a corridor, as shown in Fig. 7. A single user with a smartphone walked down the corridor with his smartphone in active scanning mode. The goal of the experiment was to see if the mobile user could trigger the USTEA beacon to enter normal state. The BLE beacon and the debugger used in the experiment are also shown in Fig. 7. The result is show in Fig. 8, where the RSS signal of the USTEA beacon is plotted against time. Using the debugger, the time at which the USTEA beacon started to operate in normal state could be recorded. Once the RSS began to be measured from the mobile phone, which is plotted in blue dots, and the time that the USTEA beacon started to operate in normal state as reported by the debugger, which is plotted in black dotted line, match nearly perfectly, which means that the USTEA beacon could detect the incoming user and change from idle state to normal state.

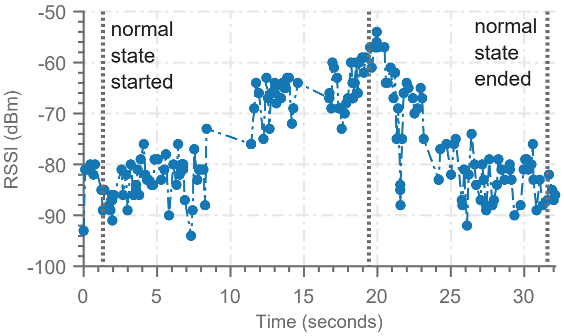

Fig. 8: Experiment showing the reaction of USTEA beacon when a user is approaching its coverage zone and leaving it.

B. Energy Consumption Comparison

To prove the effectiveness of the USTEA firmware, its energy consumption is compared with that of a conventional beacon for different values of t_n and P_n. Four different scenarios, as shown in TABLE I, are considered. Based on the above scenarios, the average current draw of a conventional and a USTEA beacon was measured over 24 hours. User existence was mimicked and reproduced by a smartphone that was programmed to be in active scanning mode for a given period of time, i.e., the t_n value. The measured average current draw and expected lifetime gain are shown in TABLE III.

TABLE III: Empirical values of power consumption of USTEA beacon and normalized gain in lifetime.

User existence frequency	Application demand	P_u (μA)	Normalized gain in t_l
high	low	17.32	0.98
high	high	107.64	1.32
low	low	11.38	**1.49**
low	high	57.40	**2.48**

It can be seen that empirical results of P_u do not deviate significantly from the theoretical results shown in TABLE II, which shows that the proposed energy model is practical. Moreover, the practicality of the USTEA firmware for extending battery life is proven through real-life experiments.

VI. CONCLUSION

This paper proposes a novel BLE beacon firmware to address limited battery capacity issues. The proposed architecture leverages the scan response and request features of Bluetooth Core Specifications to detect the existence of user smartphones and reduces beacons' overall power consumption by switching between two states: saving state and normal state. The energy consumption model for the architecture and the overhead from the switching delay, $t_{d,1}$ and $t_{d,2}$, were investigated and formulated. Based on these insights, an optimization was proposed to find the optimal saving state advertising interval, T_s, that minimizes the power consumption of a USTEA beacon and the overhead from the switching delays. The problem was numerically solved and optimal solutions for two different cases were presented. Lastly, the proposed architecture was implemented on an nRF51822 BLE SoC platform to prove its practicality. It is shown empirically that, for high energy demand applications with low user existence frequency, the lifetime can be extended by up to 250%.

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