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Perpetual Bluetooth Communications for the IoT

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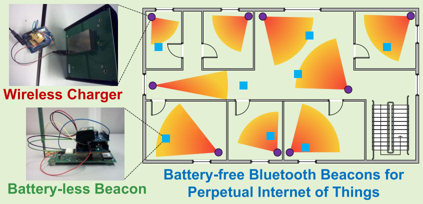
***Abstract*—Battery-powered beacon devices introduce high maintenance costs due to the finite operation time dictated by the fixed capacity of their batteries. To tackle this problem we propose FreeBLE: an indoor beacon system aimed at operating perpetually without batteries. We propose three methods to increase the utilization efficiency of harvested Radio Frequency (RF) energy in the beacon system, by which the energy consumption level becomes low enough to fit within the energy harvesting budget. We implement FreeBLE using off-the-shelf Bluetooth Low Energy (BLE) and RF energy harvesting devices, and test FreeBLE in a laboratory environment. Our results show that FreeBLE enables perpetual operation in an indoor deployment of RF-powered BLE beacon devices.**



***Index Terms*—Bluetooth, energy harvesting, Internet of Things, radio frequency.**

I. INTRODUCTION

BEACON communication is widely adopted as one of the key technologies for the Internet of Things (IoT) applications requiring low energy consumption and low data rate. Among various beacon schemes, Bluetooth Low Energy (BLE) beacon is one of the most promising systems, in particular for indoor applications due to its low power consumption and simplicity. Integrating BLE beacon into IoT devices promotes various applications, including localization [6], activity sensing [7], smart office [8], etc. However, maintaining a battery-powered beacon system is difficult when large-scale deployments are considered—e.g. the cost of replacing the batteries of a thousand beacon nodes is too high and unmanageable [9].

Various energy harvesting techniques; e.g. solar [10] and radio frequency (RF) energy harvesting [11], are integrated with IoT devices in order to eliminate batteries and provide sustainable systems. Among the existing energy harvesting solutions, RF energy harvesting is the most promising one for battery-free BLE beacon operation since it can power indoor BLE devices continuously without interrupting the users. However, building a battery-free BLE beacon system relying only on RF energy harvesting is not trivial since RF-powered beacon devices should operate by using the marginal amount of harvested RF energy. The harvested energy must be effectively used to sustain the operation of these devices.

Prior studies in the literature that proposed battery-free BLE systems [12]–[14] mainly focused on the hardware design optimizations. In this article, in contrast to these studies, we focus on the software aspects of BLE and on the design of an efficient communication protocol for battery-free BLE systems. In particular, battery-free BLE systems require an efficient communication scheme that should meet the following goals *G1–G3*:

- *G1* minimize the duration of beacon communication and in turn the overall power consumption;
- *G2* prevent idle listening of beacon devices to save energy;
- *G3* enable only relevant nodes to perform communication so that unnecessary beacon operations are avoided.

In this paper, we design and implement a novel indoor RF-powered batteryless BLE beacon system named **FreeBLE** that meets these goals. In FreeBLE, battery-free beacon devices utilize RF energy effectively; harvested from dedicated RF energy sources, by optimizing their energy consumption requirements to fit within their energy budget. This is enabled by three innovations in our system design. First, we propose a *collision-based beacon* approach, based on capture effect and orthogonal codes, that minimizes the duration of beacon communication and in turn the overall power

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consumption—meeting G1. Second, we introduce a *passive wake-up* technique to prevent idle listening of beacon devices to save extra energy—meeting G2. For further proceeding towards the target of decreasing energy requirements, we propose a *proximity range estimation* solution so that only nearby nodes perform communication and unnecessary beacon operations are avoided—meeting G3. We implement FreeBLE based on the off-the-shelf BLE module [15], RF energy transmitters and harvesters [16] and perform real-world experiments in an office environment to systematically evaluate our system implementation. Our experimental results indicate that FreeBLE achieves perpetual beacon communication efficiently with high packet reception rates by relying only on harvested RF energy. As a consequence, FreeBLE provides the necessary underlying communication infrastructure that can transmit any kind of sensor data for battery-free BLE sensing applications.

The rest of the paper is organized as follows. The main motivation and incentives of the proposed FreeBLE system is presented in Section II. The FreeBLE system design details are presented in Section III and its experimental evaluation is presented in Section IV. Finally, we present the future work in Section V and our conclusions in Section VI.

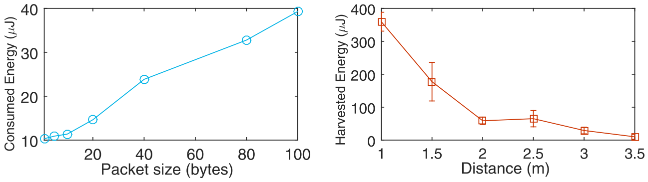
II. FREEBLE MOTIVATION AND DESIGN INCENTIVES

There are studies that employ energy harvesting to support resource constrained embedded devices [13], [17]. Due to their low power requirements [9] BLE systems have potential to exploit energy harvesting for their sustainable operation. Among the research work that targets battery-free BLE beacon systems running entirely using harvested energy, a hardware design that operates entirely on harvested energy from dual ISM-band RF sources and partially on photovoltaic energy harvesting is proposed in [12]. BLE beacon systems that use ambient light energy are presented in [13], [14].

A. Design Incentives

As compared to these studies, we propose a BLE beacon system design that operates by relying only on RF energy harvesting from dedicated energy sources. Since dedicated RF energy transmitters are deployed at specific positions and they continuously radiate radio energy to the RF energy receiver devices, we have the following advantages:

- Without dedicated energy transmitters, the harvested energy depends on the unpredictable environmental ambient energy. This might prevent sustainable system operation.
- The transmission power of dedicated RF sources can be adjusted based on the energy requirements of the receiver BLE beacons.
- As compared to solar energy harvesting, the size of the RF energy harvesting device is smaller so that it can easily be attached on the BLE beacons.
- The harvested energy can also be estimated based on the distance between RF energy transmitters and harvesters on the receiver devices.
- Distance estimation can be performed based on the harvested energy between energy transmitter and receiver—that can be leveraged to reduce the energy requirements of beacon communication as we present in the next sections.



(a) Energy consumption (b) Harvested energy

Fig. 1. Energy consumption of BLE Mote nRF51822 [18] during transmission and reception of packet of different sizes (left) and harvested RF energy within 100 ms from Powercast P2110 [19] at different distances to the energy transmitter (right).

B. Preliminary Experiments

In order to see if RF energy harvesting will be sufficient to power BLE beacon devices, we performed preliminary measurements. We used Monsoon power meter to measure the power consumption of BLE beacons and the time it takes to send and receive packets. We set up an auxiliary BLE device that listens the communication channel. Upon receiving a packet, it sends back a packet of the same size. We set up another BLE device for measurement purposes. This device wakes up from sleeping mode and sends a packet, then listens the communication channel and waits for receiving a packet from the auxiliary device. After receiving the packet, it returns to sleep mode. During our experiments, we placed these devices one meter above the floor, line-of-sight from each other. Fig. 1(a) shows the energy consumption of the measuring BLE device with respect to various packet sizes. In order to assess the energy harvesting performance, we measured the harvested energy using off-the-shelf RF-based wireless power transmitter Powercast [16] that has an Effective Isotropic Radiated Power (EIRP) of 3 W and operates at a center frequency of 915 MHz. We measured the harvested power using a Powercast P2110 receiver [19] with a 0.5 kΩ load at various distances.[1] Fig. 1(b) shows the total harvested energy in 100 ms.

C. Observations

We observed that the energy required to send and receive packets of sizes from 10 to 100 bytes is no more than 40 μJ. On the other hand, at 1 m distance from the RF energy transmitter, more than 350 μJ of energy can be harvested within 100 ms—sufficient for the operation of BLE beacons. For further distances, such as at distance 3.5 m to the energy transmitter, the harvested energy within 100 ms is not enough for transmitting and receiving BLE packets—more time is needed in order to harvest sufficient energy.

D. Conclusions

Based on the preliminary observations above, we conclude that if the harvested RF energy is used efficiently, it is enough to support the power consumption of BLE beacon applications.

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[1] The typical output voltage of the P2110B Power harvester receiver [19] is 1.2 V. The receiver has the highest harvesting efficiency when the input power is 3 mW. To evaluate the device with the highest efficiency, the resistance load is calculated by $(1.2\,\mathrm{V})^2/3\,\mathrm{mW} = 0.48\,\mathrm{k}\Omega$, which is rounded to $0.5\mathrm{k}\,\Omega$.

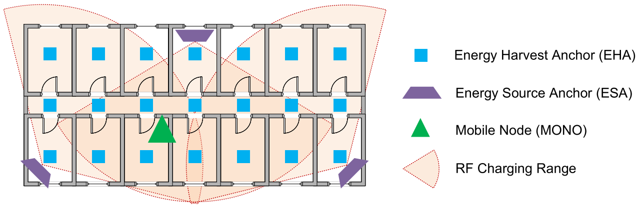

Fig. 2. A representative indoor FreeBLE deployment with energy harvesting anchors (EHAs) whose position is fixed, a mobile node (MONO) that communicates with EHAs to receive useful information and energy source anchors (ESAs) that power EHAs and MONOs.

In order to use harvested energy in an efficient way, the power consumption of the beacon devices can be decreased via a duty-cycled operation so that their radio should be kept in idle listening mode as short as possible. Moreover, the beacon request rate must be carefully selected so that the beacon nodes have enough harvested energy to finish the sending and receiving beacon messages.

III. FREEBLE SYSTEM DESIGN

The main design objective of FreeBLE is to decrease the power consumption of beacon communication and increase the efficiency of utilizing harvested energy by:

- including reducing time length of receiving messages by collision based beacon communication;
- reducing idle listening time length by passive wake-up;
- reducing unnecessary beacons by range estimation.

Before going into the system details, we introduce three types of nodes forming FreeBLE system—an example deployment scenario is shown in Fig. 2. *Energy Source Anchors* (**ESAs**) are tethered to power supply and statically deployed to emit energy continuously to nearby devices. Each ESA consists of an *ESA-Transmitter* and *ESA-Controller*. ESA-Transmitter is the dedicated RF energy source that uses a fixed frequency and transmission power. ESA-Controller is a BLE beacon device attached to ESA-Transmitter for controlling its operation (e.g. turning energy transmission on/off).

*Energy Harvesting Anchors (**EHAs**)* are BLE beacon devices with RF energy harvester. EHAs are stationary and they are uniformly deployed in the center of equally partitioned square cells of the deployment area. With this deployment strategy, the unique ID of each EHA can be used to locate the square cell where the EHA is. It is worth mentioning that EHAs do not accumulate the harvested RF energy in a battery—they directly utilize the harvested energy for beacon operations. We also assume that, each ESA is pre-programmed with a table that is used to map the ID of each EHA to its position. The static deployment of EHAs as well as the pre-programmed position table at ESAs will be exploited to eliminate energy consuming operations for ranging that will be defined in the following subsections. *Mobile Nodes* (**MONOs**) have the same hardware as EHA but they are attached to mobile users. They also do not have batteries and use the harvested energy from nearby ESAs for beacon operations.

A. A Summary of FreeBLE Operation

FreeBLE is designed to provide beacon communication by using only harvested RF energy. The aforementioned nodes operate in the following manner: (i) ESAs emit RF energy to the nearby space continuously so that MONOs and EHAs harvest sufficient energy for their operation; (ii) each MONO broadcasts beacon request to request beacon services; (iii) each ESA that receives beacon request wakes up the EHAs that are nearby the corresponding MONO; (iv) EHAs receive the wake-up signal from ESA and wait for beacon request from MONO; (v) if they receive nothing in a predefined amount of waiting time they sleep again; (vi) when MONO sends beacon request within the waiting time, EHAs send beacon reply back to the corresponding MONO; and (vii) MONO decodes the content of beacon packet from the nearest EHA, and receives the contextual information.

B. Collision-Based Beacon Communication

We first focus on the (iv)–(vi) steps of the FreeBLE operation. When several EHAs need to send beacon reply packets to MONO, there might be packet collisions. Existing communication schemes avoid packet collisions among packets via employing techniques such as CSMA/CA and frequency hopping [20]. Although these approaches are quite effective, they demand non-negligible energy for coordinating transmission timing and frequency selection—harvested RF energy is quite limited to enable these operations. Moreover, receiving separate packets from multiple EHAs increases the duration of communication for MONO—not suitable since harvested energy allows communication for a very short amount of time. Considering these issues, we leverage packet collisions in order to decrease the duration of communication: all EHAs send their packets at the same time and the receiver MONO exploits the *capture effect* [21] to decode the strongest signal. The key advantage of this method is its energy efficiency since MONO only needs to be active for a single time slot for packet reception. The detailed procedure is given as follows.

1) Transmission Synchronization: To achieve simultaneous transmission by EHAs, the MONO broadcasts a beacon request packet that can be seen as a synchronization signal. Upon receiving this signal, all receiving EHAs send beacon-reply with their ID encoded in the payload simultaneously. It should be noted that in order to leverage the capture effect, the packets from multiple EHAs should arrive at MONO within each other's preamble. This gives us much space to synchronize the beacons from EHAs.

2) Orthogonal Spreading Code: In order to utilize the capture effect, the strongest received signal needs a certain minimum signal-to-interference-plus-noise ratio (SINR) [22]. If this requirement is not satisfied, packets will collide and the content will not be retrieved. To overcome this limitation the packet payload is encoded with an orthogonal code to increase inter-packet distinction. In our design, each EHA ID corresponds a unique orthogonal code. In the encoding process, each bit of the EHA ID is multiplied by an orthogonal code unique for this EHA. The encoded EHA ID is then sent in the payload of a packet. The decoding process at MONO is an XOR operation between the payload of received packet with a list of orthogonal codes. Any method can be used as long as the codes all have zero cross-correlation with each other.

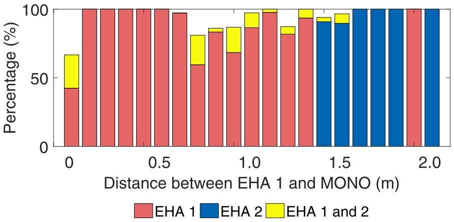

Fig. 3. The percentage of the received packets by MONO where it is placed between the two static EHAs that are placed two meters apart from each other. The MONO is placed at points that are a multiple of 10 cm on the line connecting these two EHAs.

In this paper a Hadamard matrix of size k is used to generate the codes, i.e., $H_{2^k} = \begin{bmatrix} H_{2^{k-1}} & H_{2^{k-1}} \\ H_{2^{k-1}} & -H_{2^{k-1}} \end{bmatrix} = H_2 \otimes H_{2^{k-1}}$, where $H_2 = \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$, $2 \leq k \in \mathbb{N}$ and $\otimes$ is the Kronecker product.

3) Forward Error Correcting Code:

To further increase the success rate of packet decoding, the EHA ID is first encoded with a Forward Error Correction (FEC) code before it is multiplied by the orthogonal codes. The FEC is constructed by maximum minimum-distance Hamming codes [23] i.e. codes having equal Hamming distance to each other.

4) Encoding Process:

Every EHA ID is FEC encoded by replacing ID with an unique FEC code from the array of Hamming codes. The orthogonal code matrix is generated by replacing each -1 symbol with a 0 so that each row of the matrix represents a binary spreading code. Finally, every bit of the FEC code is represented by an unique orthogonal code in the orthogonal code matrix.

5) Decoding Process:

Each MONO holds an array of all the orthogonal and FEC codes used by the EHAs. Upon receiving a packet, MONO decodes the packet for every entry in the orthogonal code array. Then, the ID field in each decoded packet is compared to the correlating FEC codes. If the Hamming distance of these values is smaller than that of the FEC codes, then the correct ID is found.

In order to verify that collision based beacon works, we present some initial results collected during the following experiment—the details hardware setup is described in Section IV. We placed two EHAs two meters apart from each other. Moreover, a MONO is placed at several points on a straight line between the EHAs. We set the transmission power of the EHAs to 0 dBm. The MONO stays at each measuring (10 cm intervals) point for 30 s and sends beacon-request every second. The two EHAs send their beacon-reply message back immediately after receiving the beacon-request. The percentage of the received packets by MONO from the two EHAs are shown in Fig. 3. It can be concluded that with the proposed approach, MONO is able to decode packets from EHAs successfully. The yellow bars in Fig. 3 show the percentage of simultaneously received packets that MONO decoded successfully. When MONO receives a packet, it decodes the payload using the orthogonal codes dedicated to EHA 1 and EHA 2, one by one. If the decoded payload, with these codes, corresponds to 1 and 2, this means MONO decoded simultaneously received packets.

C. EHA Wake-up Procedure

The collision based beacon protocol requires EHAs to continuously listen the channel to catch the synchronization signal as harvested energy is not sufficient for this operation. To overcome this limitation, we propose a *semi*-passive wake-up approach that triggers EHAs only when the MONO sends a beacon request. Since existing BLE beacon devices do not have passive wake-up function, we implement our approach as follows. The harvested energy is very sensitive to the variations in the RF energy—therefore, EHAs can detect ON/OFF states of ESA-Transmitters by measuring the harvested power. This can be used as a wake up signal: (i) an ESA can be switched off and then on shortly for sending passive wake-up signal; (ii) EHAs can periodically wake-up from sleeping mode to measure the harvested energy and detect the energy change—a middle-ground approach between a real passive wake-up and a duty-cycling operation.

In our passive wake-up procedure, when a MONO broadcasts a wake up-request message, the ESA-Controller, which is continuously on, sends a wake up-reply message back immediately—used to notify the MONO that EHAs will be waking up from listening mode soon. Then, the ESA sends passive wake up signals to all the neighbor EHAs by switching off and then on the ESA-Transmitter. Each EHA—sampling the harvested energy periodically in a duty-cycled manner—detects the decrease in the harvested power and wakes up from sleeping mode to start listening.[2] After waiting twice the sampling period to guarantee that all EHAs woke-up, the MONO broadcasts a beacon-request. Each EHA receiving this packet sends beacon-reply to MONO simultaneously. Then, the MONO decodes the packet by collision-based beacon approach described previously.

D. EHA Selection Based on Range Estimation

Passive wake-up approach activates all the EHAs near the ESA. As the number of EHAs that send collision based beacon increases, the decoding error might also increase, as scalability decreases due to radio interference. Moreover, it is more energy efficient to wake-up only the EHAs which are close to the requesting MONO, as the received information from the nearest EHA is sufficient for MONO. In order to restrict the number of EHAs used for beaconing, we propose to use the harvested RF energy from ESA for estimating the range of MONO without requiring any additional components or communication. This range information is used to select the nearby EHAs to MONO for sending collision based beacons.

Being inspired by [24], we exploit harvested power rather than RSS (Received Signal Strength) values, to estimate the range of MONO. The range estimation using RSS of the BLE beacon requires the devices to collect several RSS measurements and in turn to perform several communication rounds. Obviously, these operations require extra energy consumption which is undesired for the devices using harvested energy. On the contrary, the received power can be easily measured by the MONOs without requiring extra communication.

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[2] EHAs detect the passive wake-up signal via their ADC voltage measurements. In our hardware platform, we selected 5.9mV as a threshold value to detect power on and off states of ESAs.

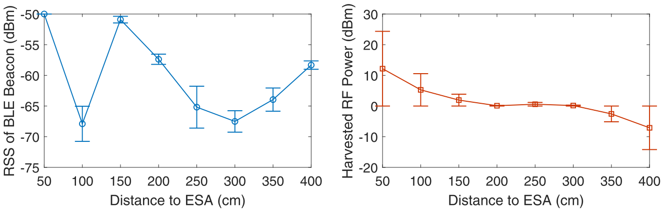

Fig. 4. The signal strength versus harvested RF-energy with respect to the different distances between ESA and MONO.

Furthermore, the received power by RF energy harvester is much higher than the power received by the transceiver circuit. Thus the harvested power is more robust to the interference from the other wireless communication signals. To further support this, we measured the harvested power and the RSS of BLE packets at various distances. For each testing position we recorded 100 measurement results. The measurement results, shown in Fig. 4, indicate that range estimation using the harvested power is superior over that with RSS in our case.

The range estimation procedure starts with step (ii) as indicated in Section III-A. In order to request beacon services, the MONO broadcasts beacon-request with its measured power value. Since ESA knows the harvested power as well as the pre-programmed table that holds the positions of each EHA, it can decide which EHAs' harvested power value are closer to the MONO's, so that they can perform communication. Suppose the EHAs are categorized to cells based on their positions. ESA categorizes the cells into two classes: (i) the cell in which the average harvested power of EHAs is closer to the MONO's and (ii) far-away to the MONO's. ESA wakes up the closer EHAs via the passive wake-up procedure; thereafter it sends a sleep message to the far-away EHAs to prevent their involvement in beacon communication.

E. Multiple ESAs and MONOs

Suppose that multiple ESAs receive the beacon request from the same MONO. Upon receiving this request, each ESA will use the passive wake-up technique to wake-up the EHAs that are closer to the corresponding MONO. Since EHAs sample the harvested power periodically, no matter which ESAs send the wake-up signal first, each EHA can detect the variation in the harvested power and in turn the wake-up signal. The EHAs that do not receive the sleep messages keep their operation and employ the collision-based beacon communication with MONO. Another issue is that, ESA can only process one MONO request at a time (the collision-based beacon communication can only send a message to a single MONO at a time). Therefore, if multiple MONOs send beacon requests at the same time, only the first beacon request can be processed. If a MONO sends a request and does not receive any message, it performs a back-off operation, which is widely used in protocols such as CSMA/CA.

IV. SYSTEM IMPLEMENTATION AND EXPERIMENTS

In this section, we present in depth evaluation of the FreeBLE[3] system by demonstrating several experiments. Before presenting our results, we provide the hardware setup used to implement ESA, EHA, and MONO nodes.

A. Hardware Setup

For ESA-Transmitter, we used Powercast TX91501 [16] that has an EIRP of 3 W and operates at a center frequency of 915 MHz. We used nRF51822 SoC Smart Beacon Kit [25] with integrated PCB antenna for ESA-Controller. A transistor is added to the power line of the ESA-Transmitter, to let the nRF51822 switch the power on or off to implement passive wake-up signal. We set the transmission power of ESA-Controller to 4 dBm. EHA and MONO are implemented using almost the same hardware: the only difference is that EHA is equipped with nRF51822 chip meanwhile the BLE development board of MONO is equipped with nRF51822 nRFgo PCA10005 [18] that has an ARM Cortex M0 CPU with a helical monopole SMA-connected antenna and has increased signal sensitivity. For both nodes, we used Powercast P2110B power harvester [16] to harvest energy. The harvester antenna is a vertical polarized patch antenna with a 6.1 dBi gain. To keep the power consumption at a minimum, the transmission power of EHA is set to −20 dBm, and all the peripherals of the BLE mote are turned off except for one hardware timer which is set to generate an interrupt periodically. The transmission power of MONO is set to 4 dBm. EHA and MONO nodes receive power from a dedicated pin of the harvester: they monitor this pin for a wake-up signal, once a voltage drop is being observed the nRF51822 wakes up from sleeping mode and starts listening incoming radio packets until a valid packet is received, upon a timeout the nRF51822 goes back to sleep mode. We fixed the payload of the beacon packets to 30 bytes: they contain the ID value of the node in the first two bytes of the payload which is enough for several kinds of sensing tasks, such as temperature measurement.

B. Impact of Passive Wake-up During Beacon Operation

To evaluate the performance of FreeBLE, it is necessary to know whether the implemented FreeBLE system is able to harvest enough energy for beacon communication from the RF energy transmitter. In order to explore if our passive wake-up based approach works well in that sense, we measure the length of the time that EHA needs to harvest RF energy for a beacon communication with passive wake-up.

1) Experiment Setup: One EHA is used to send beacon messages. We deployed one ESA and one EHA by placing them at several distances from 0.5 m to 3.5 m apart using 0.5 m step sizes. We modified MONO so that it is connected to a personal computer, i.e. the harvester is removed while all the power is supported by the USB port of the PC. This modification is needed to keep the MONO in listening mode continuously. The EHA, ESA, and MONO are deployed in the communication range of each other. At each testing position, MONO performs 100 wakeup-request with a fixed request period. We chose several fixed period value starting from 500 ms and increasing this value by 100 ms. Upon receiving the wakeup-request from MONO, ESA activates EHA from sleeping mode by sending a passive wakeup signal. EHA sends

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[3] We invite the reader to explore the source, documentation, and resources: https://github.com/TUDSSL/freeble

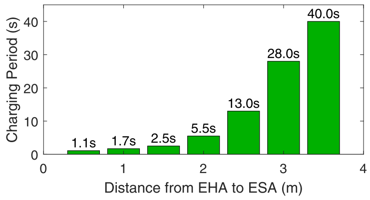


Fig. 5. Distance (to ESA) versus charging time of EHA.

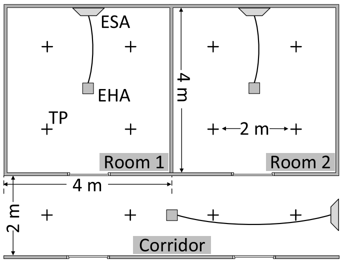


Fig. 6. Top view of FreeBLE deployment in the office environment. EHA has wired power supply connected to ESA-Transmitter. The places marked as “+” are the testing positions of MONO.

TABLE I
EXPERIMENT RESULT OF COLLISION BASED BEACONS

Position of EHAs	PRR (%)	PDA (%)	LE (m)
Room 1 and 2	95.5	99.3	0.03
Room 1, 2 and Corridor	84.7	89.6	0.25

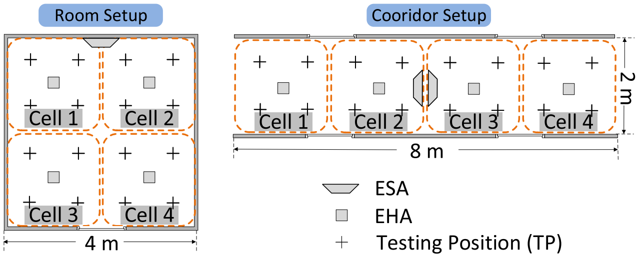


Fig. 7. Experiment setup of the office and the corridor for cell-level testing of FreeBLE using range estimation.

a beacon-reply immediately after receiving the beacon-request. The beacon-reply packets are captured by the modified MONO so that we were able to measure the PRR (packet reception rate). We assumed that the current energy charging period is long enough for the EHA to finish a round of beacon operation at this particular distance if the PRR is more than 95%.

2) Results: Our results are presented in Fig. 5. We observed that FreeBLE allows perpetual batteryless beacon using RF based energy harvesting, reaching a beacon period of 40 s at a 3.5 m distance between ESA and EHA. During our experiments, the duration of turning off the charger was only around 40 ms, and the energy lost due to this off time depends on the distance between ESA and EHA. As an example, according to Fig. 5, it requires around 5.5 seconds to harvest enough energy for beacon communication at a distance of 2 meters between ESA and EHA. In this case, the energy that could not be harvested is just 40 ms/5.5 s = 0.7%—this amount of energy loss does not have an observable effect on system performance. Therefore, as compared to time-to-charge that requires several seconds, the energy lost in passive wake-up is negligible.

C. Evaluation of Collision-Based Beaconing

We simplified the workflow of FreeBLE so that we focus on collision beacons as follows. We disabled the passive wake up procedure, removed the RF harvester of EHA and tethered it to a power supply, so that it listens the communication channel continuously. The MONO, operating in a batteryless manner by relying only on harvested RF energy, periodically wakes up from sleep mode to broadcast beacon-request, and then waits for packet reception. Upon receiving this request, EHA transmits a beacon-reply packet. MONO receives and decodes this message and goes back to sleep mode.

1) Experiment Setup: The deployment of ESA, EHA and MONO is shown in Fig. 6. The room and corridor are divided into four cells of 2 m×2 m respectively. The center of each cell is the test position of the MONO. Three EHAs are deployed in the center of room 1, room 2 and corridor, respectively. The MONO is placed at every testing position. Every device is placed 1.0 m above the floor and they are all in line-of-sight from each other. We used a BLE USB dongle as a sniffer to sniff and aggregate the testing results. This sniffer monitors all the packets sent by the MONO. In our experiment, the result of every beacon round is attached in the beacon-request packet of the next beacon round. The sniffer receives the data and saves it for further data processing.

2) Results: In the first round of experiment, we deployed two EHAs in room 1 and 2. In the second round of experiment, we deployed all the three EHAs in the rooms and the corridor. At every test position, 50 beacon rounds were performed. For each test position, PRR (packet reception rate), PDA (proximity detection accuracy) and LE (localization error) are computed and averaged. The results are shown in Table I. We observed that the PRR and PDA decrease as the number of deployed EHAs increases. This is due to the fact of the increased number of packets collisions. We conclude that beacon communication can be effectively implemented if the number of EHAs involved is limited via range-based selection.

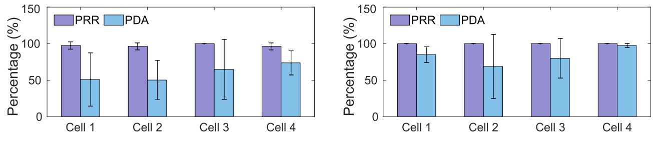
D. Evaluation of FreeBLE With Range Estimation

In this experiment, we evaluate the performance of FreeBLE in a real office area illustrated in Fig. 7.

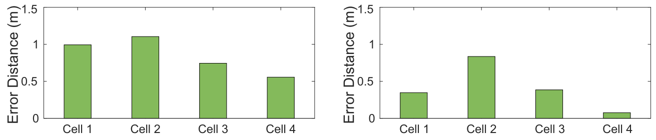
1) Experiment Setup: The experiments are performed in a room and a corridor, respectively. Four EHAs are deployed in each scenario. As the length of the corridor is longer than the effective energy transmitting range from ESA to EHA, we deployed two ESAs back-to-back in the middle of the corridor pointing to the begin and the end of the corridor, respectively. Each ESA in the corridor is responsible for waking up and controlling two EHAs. We use the pre-measured harvested power value 3.7 dBm at the geographic middle position of the deployment area of EHAs as the threshold value to categorize the two ranges. The MONO sends 20 beacon requests at each testing position. As used in the previous subsection, an BLE packet sniffer was used for result data collection. The decoding of the beacon packet is done by the MONO, so only the decoding result is transmitted to the sniffer.

TABLE II
EXPERIMENT RESULTS OF FREEBLE USING RANGE ESTIMATION

Location	PRR (%)	PDA (%)	LE (m)
Room	97.5	59.9	0.85
Corridor	100	82.2	0.41



(a) PRR/PDA (room) (b) PRR/PDA (corridor)



(c) Localization error (room) (d) Localization error (corridor)

Fig. 8. PRR, PDA and LE in each cell of the room and the corridor.

2) Results: The average values of the experiment results in the room and corridor are shown in Table II, and the results in each cell are shown in Fig. 8. Compared with the FreeBLE room-level experiment results as shown in Table I, the average PRR increases. This is because of the range estimation component, which selects only part of the EHAs to send beacon signals in a beacon round. The cell-level accuracy of FreeBLE is lower than the room-level accuracy. We find that the cell-level accuracy at some cell positions is much lower than the others as shown in Fig. 8. This is due to two reasons. First, the deployed cell area of each EHA is only $4\,\mathrm{m}^2$ in this experiment, which is much smaller than the $16\,\mathrm{m}^2$ deployed room area in presented in the previously. The received beacon packets from EHAs by the MONO only have small difference in terms of harvested power. This could cause error for decoding the packet from the closest EHA. Second, the radio pattern of ESA-Transmitter has only 60° coverage in width and height, therefore some testing positions at the border of the room are not effectively covered. The MONO at these positions can not harvest enough energy.

The LE value in Table I is smaller than that in Table II due to two main reasons. First, in the deployment depicted in Fig. 6, there were only one EHA and one ESA in a room. In this setup, the EHAs are far away from each other (around 4 meters with a wall between), so the radio interference between EHAs is weak. On the contrary, in the deployment depicted in Fig. 7 there are 4 EHAs in one room that leads to a more dense deployment. Second, in Fig. 6, each EHA in the room is powered by a fixed power supply. Only the MONO harvests energy from the chargers. Therefore, the EHA nodes always have enough energy for beacon communication, which further decreases the beacon error caused by low power due to harvested energy. On the contrary, in Fig. 7 all EHAs and MONO use harvested RF energy. There are two ways to effectively increase the proximity accuracy of FreeBLE without changing its design. First, the average value of LE in multiple beacon rounds can be used to calculate PDA. Second, the size of the cell area for proximity detection can be increased—the accuracy with the large cell area is much higher than the small cell area. As a final remark, at points where the harvested energy is low (due to reflective and destructive radio propagation [26]), MONO cannot estimate range correctly, and ask the charger to wake up the nearby EHAs. This scenario is more likely to happen in a corridor and this is the reason for different PDA, e.g. in cell 2 and 3 of the corridor.

V. DISCUSSION

A. Sensors and Sensing

With FreeBLE, EHA beacons can actually transmit any kind of sensor data to MONO devices. This fits perfectly with, in particular, IoT data collection applications. Within this work, we did not incorporate sensing energy overhead to our measurements since: (i) energy consumption due to sensing is sensor/application specific; (ii) many sensing operations, e.g. temperature measurement using our prototype, consumes much less energy as compared to that of communication; (iii) sensing and communication are separate tasks where the harvested energy can be first consumed to sense and then it can be used to communicate using our energy-optimized communication scheme.

B. Environmental Dynamics

The FreeBLE system design assumes the devices are deployed in line-of-sight of each other. This issue might effect the range estimation performance if the harvested energy is fragile due to environmental conditions.

C. Multiple ESAs

Future work can target performance evaluation when multiple ESAs are deployed. Firstly, the destructive radio from multiple RF energy transmitters might decrease the harvested energy of EHAs and MONOs [27]. Secondly, the passive wake up signal from multiple ESAs might trigger unnecessary wake up of EHAs. Future work can target eliminating these effects and coordinate the operation of ESAs.

D. Efficient Codes

More efficient encoding and decoding techniques are required to reduce interference [28]. In our approach, MONO needs to try all the orthogonal codes to decode the beacon message, which is energy-consuming. As the number of EHA increases, the power consumption on decoding the orthogonal codes will become considerable. A strategy that reduces the list of orthogonal codes is required.

VI. CONCLUSION

We presented an indoor BLE beacon system, **FreeBLE**, powered by RF energy harvesting. Key innovations of FreeBLE are: (i) leveraging collisions-based beacons to decrease energy used for receiving BLE packets; (ii) use of passive wake-up based on RF-energy harvesting to decrease idle listening; and (iii) waking up only the energy harvesting anchors near the BLE mobile node to send beacon messages by estimating the general range of the mobile node. We implemented FreeBLE with using off-the-shelf BLE motes and RF harvesting devices. Experimentally we show that FreeBLE provides continuous beacon services to mobile nodes by using only harvested energy from dedicated RF transmitters.

VII. ACKNOWLEDGMENT

This research was performed while Q. Liu was a Ph.D. student, and W. IJntema and A. Drif were M.Sc. students—all at TU Delft, The Netherlands. This paper is based on the MSc graduation theses [4], [5] and PhD thesis [3] of the authors. This paper is also available in two earlier versions containing more information on the system design, i.e. as [2] (this paper version focuses on the implementation of RF-based wireless power transfer) and as [1] (this paper version focuses on the implementation of IoT communication protocol and the system-level design).

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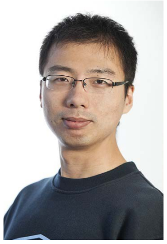

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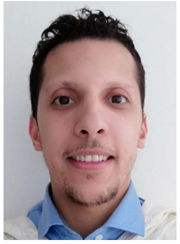

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