Preliminary Design for Sustainable BLE Beacons Powered by Solar Panels

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***Abstract*—In the coming age of Internet of Things, the underlying infrastructure that supports IoT applications will play a pivotal role. Bluetooth Low Energy Beacons, small radio frequency broadcasters that advertise their unique identification, have been highlighted for their possible usage in the IoT infrastructure, as a sensor network of BLE Beacons is capable of providing contextual and locational information to the users. However, as the size of the wireless sensor network has grown, finite battery capacity has proven to be a major challenge. Due to the limited battery capacity, Beacons require periodic maintenance and battery replacement, which results in increased beacon management cost and complexity. This paper attempts to remedy this problem through the integration of an energy harvesting mechanism with BLE Beacons, and explore the possibilities of using solar power to operate these devices. Experimental results for BLE Beacon power consumption and solar panel power output characteristics are presented, and therefore baseline parameters of the power requirements for sustainable BLE Beacons are established. Furthermore, a preliminary design of a solar-powered BLE Beacon is presented. It has been shown that a typical BLE Beacon with a transmission power of 0 dbm and advertising interval of 800 ms can be powered by a solar panel with surface area of 300 cm^2, and a lithium ion rechargeable coin cell battery, LIR2450, with a nominal voltage of 3.6 V can be recharged by a solar panel with a surface area of 88 cm^2.**

***Index Terms*—Bluetooth Low Energy, BLE Beacons, Energy Harvesting, Solar Power**

I. INTRODUCTION

With the advancements in sensor and communication technologies, Internet of Things (IoT), a new paradigm for digital communication and networking, has emerged. Leveraging on Machine-to-Machine (M2M) communication, IoT expands the Internet network to common electronic appliances and physical objects, thereby transforming the ordinary physical environment into a smart cyber-physical space. IoT therefore requires infrastructure that will allow identification and tracking of physical objects in cyber space [2] [3]. Consequently, a localization infrastructure is required. An overview of the IoT architecture is shown in Fig. 1.

In light of this recent trend, Bluetooth Low Energy (BLE) protocol has become a popular research topic from both an academic and industrial point of view. Unlike its predecessor, now known as Bluetooth Classic, which was designed for efficient audio and data streaming applications consisting of large data transmission, BLE was designed for small data transmission. Consequently, BLE devices operate on very low power, making them a suitable communication module for power constrained wireless sensor nodes. Furthermore, as Dementyev et al. [1] have concluded, BLE protocol consumes less power than its competitors, ZigBee and ANT protocol, establishing a solid foothold as the leading candidate for the next-gen M2M communication protocol [4].

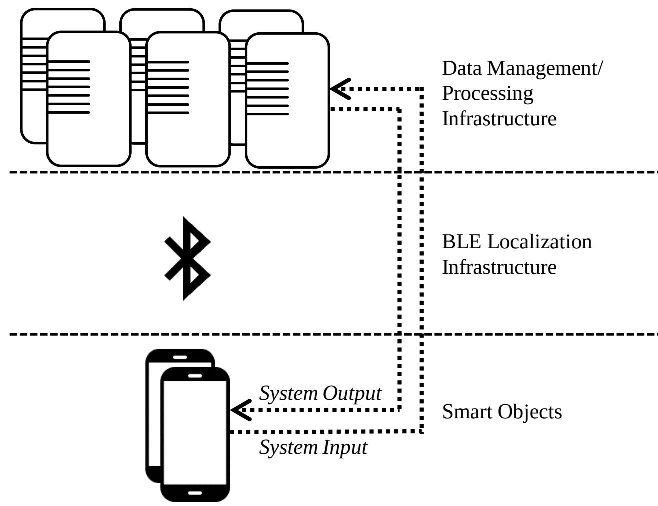

Fig. 1. Overview of IoT Architecture with BLE Localization Infrastructure

BLE has been particularly popular with many industries, because of such features. The most well-known industrial application of this novel technology is iBeacon. iBeacon, introduced by Apple inc. in 2013, is a technology standard that allows BLE enabled devices, also known as BLE Beacons, to broadcast their unique identifiers to their nearby surroundings, thereby providing Location-Based Services (LBS) for smart mobile devices. For this reason, iBeacon compatible BLE Beacons are actively deployed in retail stores, restaurants, shopping malls and museums. As a matter of fact, Sensoro, a BLE Beacon manufacturing company, recently distributed over 110,000 BLE Beacons across China. In addition, Stroer, an Out-of-Home advertising provider, plans to deploy 50,000 BLE Beacons in Germany in 2016.

However, as the number of sensor nodes increases in the BLE Beacon network, the infrastructure is expected to be more susceptible to errors and inaccuracies. Although wireless

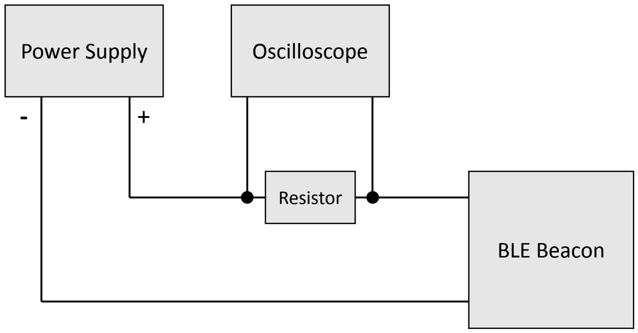

Fig. 2. Experimental setup for the current draw measurement

sensors, such as BLE Beacons, are popular due to their scalability and convenient deployment, they are limited by their finite battery capacity. This is one of the major drawbacks of untethered sensors, as use of batteries requires frequent maintenance. Consequently, as the BLE Beacon infrastructure expands its coverage, the maintenance cost will increase proportionally. Furthermore, the infrastructure will be prone to more errors and irregularities as some sensors may cease to operate before periodic maintenance due to the unpredictable rate of energy consumption that varies for every device.

The conventional approach to this problem is protocol optimization for better energy efficiency. The BLE protocol provides a number of user configurable parameters such as advertising interval and transmission power. However such a method achieves energy efficiency at the expense of responsiveness and accuracy. Siekkinen et al. [5] have claimed that energy efficiency of the BLE protocol can be further improved by adapting Adaptive Frequency Hopping to prevent frequent re-transmission caused by interference from other radio frequency signals. More studies conducted on protocol optimization for better energy usage for wireless sensor networks can be found in [6]. Although such an approach reduces unnecessary energy usage and prolongs the battery life, it does not change the fact that battery capacity is still limited and will eventually run out.

An ultimate solution for this problem would be achieved through the integration of energy harvesting technologies with BLE Beacons. It is most desirable to design a sustainable beacon that generates energy from its nearby resources, such as light, heat, kinetic movement, and radio frequency signal [6]. In order to design such a system, it is crucial to understand and predict following characteristics.

- *Power Consumption Characteristics of Typical BLE Beacons*: In order to choose a suitable energy harvesting mechanism, the power requirements and characteristics of BLE Beacons must be known.
- *Power Output Characteristics of Energy Harvesting Mechanism*: Because the energy harvesting mechanism's voltage and current output varies with different environments (e.g., solar panels provide higher voltage under lights with higher intensity), these characteristics of the mechanism must be known in order to design an efficient system.

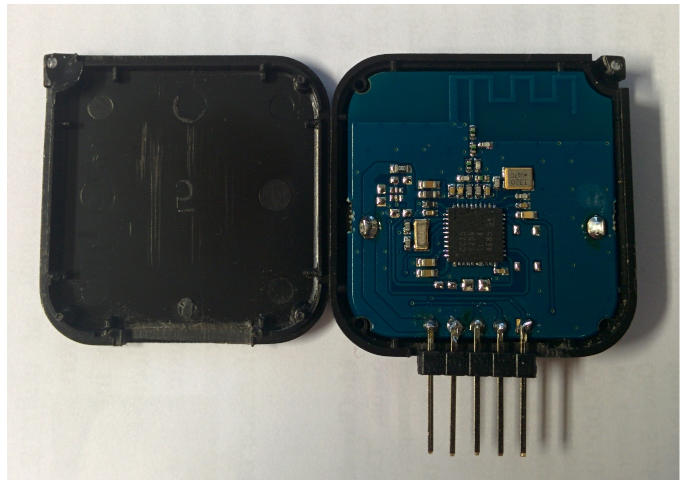

Fig. 3. Photo of the BLE Beacon used in the experiment with additional pins manually soldered to allow connection to an external power supply

In this paper, power consumption characteristics of a typical BLE Beacon are presented, and the baseline for power requirements of BLE Beacons is established. Power output characteristics for solar panels of different sizes are presented. A preliminary implementation of a solar powered BLE Beacon device is also presented.

II. Power Consumption Characterization of Standard BLE Beacons

Typical BLE Beacons are small sensors that broadcast a specific data packet at a user configurable advertising interval and transmission power. Due to their small size, they are usually equipped with a single coin cell battery. Although traditional BLE Beacons were equipped with BLE modules only, more recent trends show that some BLE Beacons are equipped with additional sensors such as accelerometers, ambient light sensors, and temperature sensors. The Yunzi Beacon, developed by Sensoro, is an example of the previously mentioned next-gen BLE Beacons. The Yunzi Beacon uses an ambient light sensor to automatically turn itself off when it is in a dark environment. Also, this BLE Beacon is equipped with 2 AA batteries that have a capacity of 5000 mAh in total (the capacity of a typical coin cell battery, CR2302, is 230 mAh). Due to the upgrade in battery capacity, the Yunzi can operate from 2 to 5 years without any battery replacement. However, the efficiency and usefulness of this upgraded hardware in forming an IoT infrastructure is yet to be seen. Therefore, the following experiment focuses on the power consumption of a BLE Beacon equipped with nothing more than a BLE module.

A. Experimental Setup

In this experiment, a BLE Beacon produced by a company named Ghostyu was used (shown in Fig. 3). The BLE Beacon was originally equipped with a CR2450 coin cell battery, and its recommended input voltage was 3V. However, during the

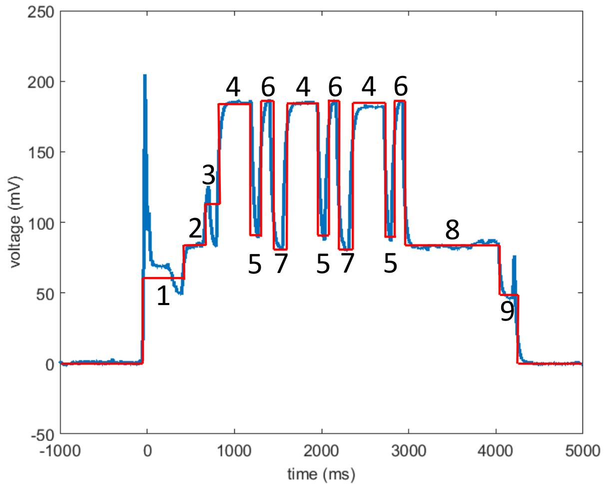

Fig. 4. Blue line shows voltage measurements across the 10 ohm resistor, and red line shows the 9 states of the BLE Beacon during a connection event

experiment, the CR2450 battery was replaced by an external power supply. The Beacon was employing a BLE MCU CC2541 developed by Texas Instruments. The BLE Beacon was configured to broadcast with an advertising interval of 800 ms and transmission power of 0 dbm. To measure the current draw of this device, a 10 ohm resistor was installed, as shown in Fig. 2. A resistance value of 10 ohms was chosen because the value was too small to affect the circuitry but large enough to measure the voltage level and therefore the current flow across the resistor. An oscilloscope equipped with voltage probe was used to measure the voltage across the 10 ohm resistor. The model name of the oscilloscope used in this experiment was DSO-X 2024A, and the device was manufactured by Agilent Technologies. Methods used in this experiments are referred from [7].

TABLE I
VOLTAGE AND CURRENT CONSUMPTION, AND TIME DURATION MEASUREMENTS DURING CONNECTION EVENT STATES

State Number	Description	t (μs) [1]	V (mV) [2]	I (mA) [3]
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

[1]time duration of the state
[2]voltage measurement across the 10 ohm resistor
[3]current draw of the BLE Beacon

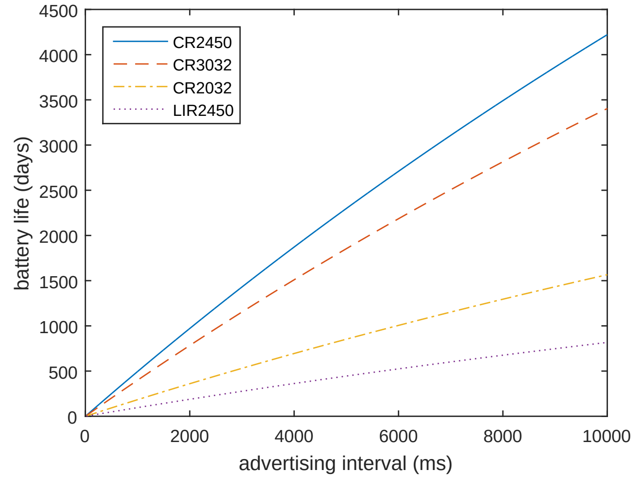

Fig. 5. Battery life of different coin cell batteries plotted versus advertising interval starting from 5 ms to 10000 ms

B. Results

Fig. 4 shows the change in voltage across the resistor during a connection event. These measurements can be divided into several different states for a clearer presentation and easier calculation. Each state is described in details in Table I. From these measurements, the average current draw, $I_{A_{conn}}$, during a connection event can be calculated by taking a weighted sum of the current with respect to time.

$$I_{A_{conn}} = \frac{\sum_{k=1}^{n} I_k t_k}{\sum_{k=1}^{n} t_k}, \tag{1}$$

where n is the total number of states, I_k is the current draw measured during state k, and t_k is the time duration of state k.

Using the Eq. 1, the average current draw during a connection event can be calculated as 11.95 mA. The average current draw during the idle state, $I_{A_{idle}}$, was measured to be around 0.001 mA. Knowing the advertising interval, t_i, the average current draw, I_{Avg}, for the BLE Beacon can be calculated:

$$I_{Avg} = \frac{I_{A_{idle}}(t_i - \sum_{k=1}^{n} t_k) + I_{A_{conn}} \sum_{k=1}^{n} t_k}{t_i}. \tag{2}$$

Eq. 2 yields an average current draw of 0.065 mA. Knowing that the voltage output of the power supply was 3.0 V, the power consumption, P, of the device can be calculated:

$$P = 3.0V \times 0.065mA = 0.195mW. \tag{3}$$

Knowing that a non-rechargeable battery equipped in the BLE Beacon, a CR2450, has a capacity of 620 mAh, an approximate estimation of the battery life can be made. With an average current draw of 0.065 mA, the BLE Beacon is expected to last 9538 hours, or around 397 days. However it must be noted that this is an over-estimation, because the calculation assumes that the BLE Beacon is in its advertising mode throughout its entire life cycle. In reality, BLE Beacons connect and communicate with master devices and consume more battery power.

In comparison with the result from TI's investigation [7], although TI's average current consumption was much lower (0.0247 mA)–this is because they made a modification in the firmware, where they had only 1 Tx and Rx section–than that presented in this paper (0.065 mA), TI's BLE Beacon was calculated to last a shorter length of time because of the battery they employed, a CR2032. A CR2032 is the most frequently used coin cell battery and has a nominal capacity of 230 mAh. If a CR2032 was equipped in the standard BLE Beacon, it would only last 147 days.

TABLE II
COMMONLY USED COIN CELL BATTERY SPECIFICATION

Battery Part Number	**Capacity** (mAh)	**Size**[1]
CR2450 (non-rechargeable)	620	24.0 mm x 5.0 mm
CR3032 (non-rechargeable)	500	30.0 mm x 3.2 mm
CR2032 (non-rechargeable)	230	20.0 mm x 3.2 mm
LIR2450 (rechargeable)	120	24.0 mm x 5.0 mm

In cases where a small coin cell battery is used as a power source, the battery should be replaced at around every 6 months or less. As mentioned previously, such a practice is expensive, time-consuming and complicated. Fig. 5 plots the battery life of commonly used coin cell batteries against a user-configured advertising interval of typical BLE Beacons. Specifications of the batteries are shown in Table II. Ranges of values between 5 ms to 4000 ms were chosen for the advertising interval, because the BLE protocol allows a minimum advertising interval of 10 ms and maximum of 10000 ms; however different BLE modules may support different ranges (e.g., TI allows a maximum advertising interval of 4000 ms). As shown in the figure, although some batteries might last more than several years at a longer advertising interval, the responsiveness of the system will decrease significantly. [10] shows significant decrease in accuracy with an increasing advertising interval. From their results, it seems the optimal advertising interval should be less than 1000 ms.

Because BLE Beacons require a short advertising interval in order to function properly as an IoT infrastructure, it is clear that a current coin cell batteries may not have sufficient capacity for prolonged usage of BLE Beacons.

III. POWER OUTPUT CHARACTERIZATION OF COMMERCIALLY AVAILABLE SOLAR PANELS

Energy Harvesting is one option that may solve this battery problem with low-powered wireless sensors. Energy harvesting refers to the practice of utilizing different types of energies from different sources to derive useful electrical energy to power a desired system load. Energy harvesting sources can be divided into two main types: controllable and non-controllable energy sources.

[1]diameter by height

Fig. 6. 3 types of solar panels used in the experiment, Panel A, B and C are shown from left to right respectively

- *Controllable energy sources* refers to energy sources that can provide power on demand. Examples of such types of energy sources include human finger motion [11] and footfalls. For example, Shenck et al. [12] has demonstrated a shoe-powered radio frequency tag system, where the circuitry of the RF tag was powered by the energy generated by human footfalls.
- *Non-controllable energy sources* refer to energy sources that are provided at an uncontrolled rate. Examples of these kind of sources include solar, wind, vibration, thermal and radio frequency energy.

In the case of a BLE Beacon, a non-controllable but predictable energy source is preferred. Because IoT infrastructure must be able to operate without any human intervention, controllable energy sources, which are largely generated from human activity, are not suitable for this application. Table III presents the power generation capability of some non-controllable energy sources.

TABLE III
POWER DENSITY OF COMMONLY USED NON-CONTROLLABLE ENERGY SOURCES [6], [13], [14]

Energy Source	**Power Density**
Solar	15 mW/cm^2
Vibration	0.2 mW/cm^2
Thermoelectric	40 $\mu W/cm^2$
Radio Frequency	3 $\mu W/cm^2$

From Table III, it is obvious that solar panel can provide more than a few hundred times higher power density than the other sources. Furthermore, solar panel technology maturity, cost, ease to use, and availability are much more favorable than those sources. Therefore, in this experiment, a solar panel's power output will be characterized.

TABLE IV
VOLTAGE AND CURRENT OUTPUT AT DIFFERENT LIGHT INTENSITIES

	Panel A				**Panel B**				**Panel C**			
L (Lux)	**V** (V)	**I** (mA)	**P** (mW)	**P/cm^2** (mW/cm^2)	**V** (V)	**I** (mA)	**P** (mW)	**P/cm^2** (mW/cm^2)	**V** (V)	**I** (mA)	**P** (mW)	**P/cm^2** (mW/cm^2)
1500	5.207	10.2	53.11	0.177	3.908	2.34	9.14	0.104	2.365	1.88	4.45	0.095
1300	5.207	9.4	48.95	0.163	3.859	2.14	8.26	0.094	2.325	1.71	3.98	0.085
1000	5.208	7.09	36.92	0.123	3.707	1.6	5.93	0.067	2.203	1.28	2.82	0.06
800	5.21	4.58	23.86	0.08	3.455	1.02	3.52	0.04	2.014	0.82	1.65	0.035
600	5.215	3.63	18.93	0.063	3.31	0.79	2.61	0.03	1.897	0.64	1.21	0.026
400	5.229	3.22	16.84	0.056	3.226	0.7	2.26	0.026	1.836	0.55	1.01	0.022
200	3.77	2.59	9.76	0.033	3.077	0.54	1.66	0.019	1.73	0.44	0.76	0.016
room light	1.295	1.41	1.83	0.006	2.615	0.28	0.73	0.008	1.407	0.22	0.31	0.007

A. Experimental Setup

In this experiment, the current and voltage output of 3 mono-crystalline silicon solar panels of different sizes are investigated. As shown in Fig. 6, Panel A had the dimensions of 15 x 20 cm (300 cm^2), panel B 8 x 11 cm (88 cm^2), and C 8.5 x 5.5 cm (46.75 cm^2). These panels were tested under an LED light source separated by 30 cm. The LED light source supported a brightness control mechanism that ranged from 1500 to 200 lux. An indoor lighting source was used instead of outdoor sunlight, because most BLE Beacons are placed indoors.

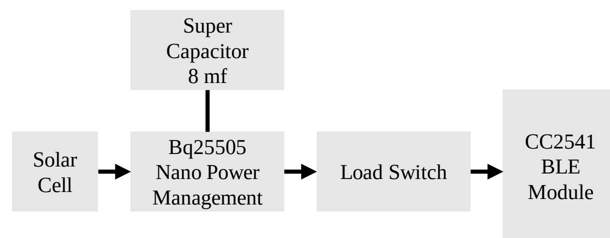

Fig. 7. Block Diagram of TI Indoor Light Harvesting BLE Circuit [15]

B. Results

From Table IV, it is observed that Panel A increases in voltage with decreasing light intensity. This is because Panel A came with a built in regulator that regulates the voltage output to around 5 V. However the trend of power output that increases with increasing intensity seems more reasonable. It is important that the voltage output from the energy harvesting system is regulated because this will help protect the BLE Beacon's circuitry from damage due to over-voltage.

It is observed that the power densities measured in Table IV and Table III are significantly different. This is because the results attained in Table III used sunlight as the light source, therefore the power output is much higher than that acquired with an LED light source. Also, low price solar panels were used in this experiment, and consequently the efficiency of the energy harvesting modules are not formidable.

The power output characterization plays a pivotal role in establishing the baseline design of a BLE Beacon energy harvesting system using a solar panel technology. Given that the power requirements of the sensor node and the environmental elements are known (e.g., light intensity), a better estimation of the size of the required solar panel can be made.

IV. PROPOSED DESIGN FOR SUSTAINABLE BLE BEACON USING SOLAR POWER

By considering the results acquired for the power consumption characteristics of the sensor node and the power output characteristics of the energy harvesting mechanism, efficient and cost saving designs can be derived. In the following section, some existing designs of BLE Beacons with energy harvesting capabilities and the experimental results from previous sections will be examined to derive some design considerations.

TI Inc. previously designed and implemented a solar energy harvesting BLE Beacon [15]. As can be seen in Fig. 7, TI's design of a sustainable BLE Beacon employs a harvest-use design, which means that it has no energy storage but uses energy from the harvesting module to power the load directly. Although such an approach maybe cost saving, this means that the sensor node will be inoperable when an energy source is absent. Therefore, in order to ensure stable and continuous performance of the sensor node, it is preferable to include a rechargeable battery in the design.

Although TI's design considered using only the solar panel as the energy harvesting mechanism, it would be much more beneficial to consider other energy harvesting mechanisms, such that multiple mechanisms are used in combination to provide power at more stable rate. Such a system must be equipped with an interface that will allow multiple energy harvesting modules to provide a single power output to the system [16].

From Section III, it has been shown that each solar panel provided different voltages at different intensities, therefore a voltage regulator is required to prevent the circuitry from any potential damage. Also, if a rechargeable battery is used in the system, then the power manager may require two different regulators as the charging voltage of the rechargeable

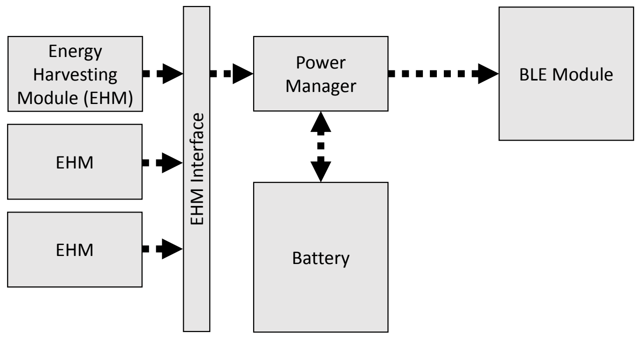

Fig. 8. Overall Architecture of Sustainable BLE Beacon

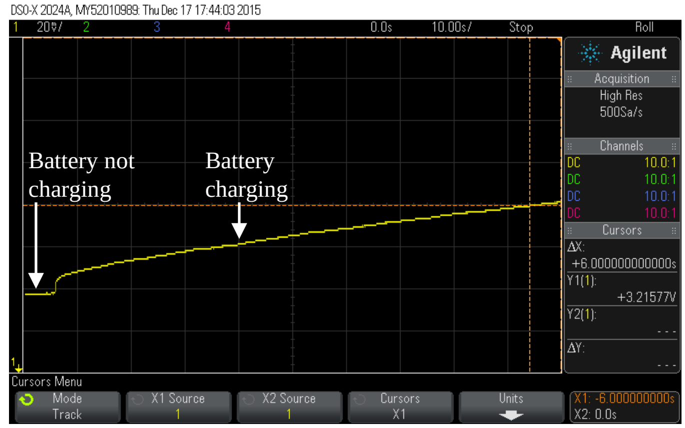

Fig. 9. Solar Powered LIR2450 Battery Charging

battery may be different from the operating voltage of the BLE circuitry.

Furthermore, because the system will be employing two different power sources, the energy harvesting module and rechargeable battery, the system will require a power path manager that will route the power from the energy harvesting module to the system. If the power output meets the power requirement, the excess energy will be rerouted to the rechargeable battery for recharging. When the power output from the energy harvesting module does not meet the requirement, some power will be drawn from the battery.

With regards to the design consideration mentioned above, the system architecture of a sustainable BLE Beacon can be divided into the following components.

- *Energy Harvesting Module (EHM)* refers to the energy harvesting devices that leverages on any kind of energy harvesting mechanism: solar, vibration, thermal, radio frequency, piezoelectric etc.
- *EHM Interface* refers to the interface that will be used to connect multiple EHMs to the power manager.
- *Battery* is used to store any excess energy provided by the EHMs. This stored energy is later used when the energy harvested from the EHMs is not sufficient to drive the system.
- *BLE Module* is a device used to transmit data packets according to the BLE protocol.
- *Power Manager* includes two regulators that will provide adequate voltage to either the BLE module or the rechargeable battery, and also a chipset that will route the energy from the EHM.

Additional experiments were carried out to justify the feasibility of the system. Firstly, solar panel A from Section III was connected to a standard BLE Beacon device from Section II, in parallel with some capacitors. Once the values of the capacitance of the capacitors were large enough, the Beacon successfully operated. However the same could not be done with panel B. Although panel B provided enough power to operate the BLE Beacon, its current output was too small. In order to operate the BLE Beacon with panel B and C, a super capacitor was required. However because a super capacitor was not available at the time, this could not be tested.

Another experiment was carried out to examine if the solar panels were capable of recharging a rechargeable coin cell battery, an LIR2450. The LIR2450 was discharged until the voltage dropped to around 3.1 V and then was connected to Panel B. As shown in Fig. 9, the voltage level of the battery slowly increased from 3.17 V, indicating that the battery was recharging. Panel C was incapable of recharging the battery because it's voltage output was too small. However, if multiple devices such as panel C are connected through the EHM interface, it will be able to provide enough power to recharge the battery.

V. Conclusion

This paper has presented several experimental results that explores the possibilities of solar powered sustainable BLE Beacons. Through BLE Beacon power consumption characterization, the power requirement and maximum current draw of the BLE module has been identified. Through solar panel power output characterization, solar panels could be examined to see if they satisfy the power requirements established in the previous experiment. Through a preliminary solar powered BLE Beacon design, the paper has shown that a solar panel with a surface area of 300 cm^2 powered by an LED light source can operate a BLE Beacon configured with an advertising interval of 800 ms and transmission power of 0 dbm. Furthermore, the solar panel has proven to be able to charge a rechargeable lithium ion battery, LIR2450, with a nominal voltage of 3.6 V and capacity of 120 mAh. Although a completed circuitry of a sustainable BLE Beacon will consume more power than a conventional BLE Beacon module, powering a BLE Beacon, or at least prolonging its battery life through the use of a solar panel seems feasible in light of these experimental results.

For future study, it would be interesting to utilize other energy harvesting sources, such as vibration, thermo-electrical, and radio frequency, to power the BLE Beacon. Because BLE Beacons are deployed in various environments, some energy harvesting methods may perform better in certain locations. For example, in a vehicular environment, where energy generated from vibration and heat is much larger than that in a static environment, a vibration and thermo-electrical energy harvesting mechanism would perform more efficiently. Furthermore, multiple energy harvesting mechanisms may be used in combination to meet the power requirement of the sensor node. Ultimately, it would be desirable to develop a sustainable BLE Beacon that can be equipped with multiple energy harvesting mechanisms on demand.

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