Energy Efficiency and Accuracy of Solar Powered BLE Beacons

Petros Spachos[a,*], Andrew Mackey[a]

[a] School of Engineering, University of Guelph, Guelph, Ontario, N1G 2W1, Canada

Abstract

In the last decade, there has been an exponential growth in the numbers of wireless devices which connect to the Internet. At the same time, the networks size have grown larger than ever before. Bluetooth Low Energy (BLE) beacons are an attractive solution for a plethora of Internet of Things (IoT) applications, from micro localization to advertisement and transportation. BLE beacons are small, low cost devices that are capable of providing contextual and locational information to the users. In the firth generation (5G) ecosystem, many BLE beacons are expected to be deployed among other devices. In 5G wireless networks era, sustainable and energy aware networks are vital to usability and performance. An appealing solution for energy efficiency is energy harvesting for wireless devices. To reduce the maintenance and increase the lifespan of networks that include such devices, solar powered beacons can be used. In this paper, the performance of solar powered BLE beacons is examined in terms of energy efficiency and accuracy. A comparison between the solar powered BLE beacon and battery powered beacon is also discussed. Experimental results shown that solar powered BLE beacon is a promising solution with minimum energy requirements and high accuracy.

Keywords: Solar powered BLE Beacons, Energy efficiency, Accuracy, Internet of Things

1. Introduction

The substantial growth in the Internet of Things (IoT) over the last few years has resulted in the development and popularity of many new wireless devices. One device in particular that has grown in popularity is the Bluetooth Low Energy (BLE) beacon. BLE beacons are small, low cost, low power consuming, and configurable devices. Many of the applications best suited for these beacon devices is indoor localization, using Received Signal Strength Indicator (RSSI) techniques [1, 2, 3]. They operate by simply broadcasting identifiers at a specified transmit power and interval. However, as wireless technology improves and hardware decreases in price, more and more devices continue to add to the density of all wireless networks, both indoors and outdoors. As the added devices take up more resources there is a lack of available bandwidth.

The issues regarding resource limitations and available bandwidth leads to the continuous development of mobile network standards and thus, the fifth generation (5G) is the next mobile wireless system to emerge. 5G aims to support more users, increase capacity, and lower latency and power consumption to better accommodate developments within the IoT. Specifically, energy consumption, is a vital aspect to the 5G ecosystem. The large density of devices and high throughput, relies on sustainable and energy aware design. If devices are unable to keep up with the power demands of the network, loss of service, network degradation, or even failure could occur. Current technological advancements have been made specifically with energy consumption in mind, both in software and hardware.

A common example of hardware energy-aware design is energy harvesting using solar power [4, 5, 6, 7]. Solar powered devices rely, to varying degrees, on sunlight energy as a power source rather than conventional battery or wired technology. To their advantage, they do not require power maintenance in the form of replacement or recharging, common to most wireless devices. Once deployed, the average solar cell has a lifespan of 20 years while maintaining 80% rated power production [8]. This in turn increases the lifespan of the wireless network substantially, although solar power may only be suitable in applications where sufficient light is available.

Bluetooth Low Energy (BLE) is an example of

*Corresponding author
Email address: petros@uoguelph.ca (Petros Spachos)

energy-aware design that leans more towards software [9]. BLE is a wireless standard developed by Bluetooth Special Interest Group for the purposes of low power consumption. It operates on the 2.4GHz band and maintains a range of approximately 100 m, similar to that of standard Bluetooth profiles. The drawback is that BLE sacrifices throughput for energy efficiency [10]. This makes BLE suitable for devices that do not transmit large amounts of data. Common applications for BLE include smart office energy management, museums, and attendance management. Frequently these applications are implemented with beacons [11, 12, 13]. With the fifth generation of wireless systems soon to deploy, a mix of energy aware technologies are being implemented into devices to meet the energy requirements of various networks. A great example of this is solar powered BLE beacons. These beacons can be used for indoor location services, among many other beacon applications that are able to provide sufficient light energy.

This paper focuses on the feasibility of utilizing solar powered BLE beacons. It evaluates the energy efficiency and accuracy of a solar powered beacon and compares it to a battery powered competitor.

The main contributions of this paper are:

- Experimentation and comparison of a solar powered BLE Beacon and a battery powered BLE Beacon in terms of energy consumption and localization accuracy. Two levels of transmission power were examined for each beacon.
- Design and implementation of a simple Android application to collect the Received Signal Strength Indicator (RSSI) of each beacon.
- Through comprehensive performance evaluation, the efficiency of each beacon at a complex indoor environment is demonstrated.

The rest of this paper is organized as follows; In Section 2, an overview of the background and related works regarding BLE devices is discussed. Section 3 introduces the experimental setup for the energy efficiency and accuracy measurements followed by Section 4 with the experimental results and analysis. Finally, the conclusion is in Section 5.

2. Background and Related Works

In this section, the related work in the area regarding BLE beacons is reviewed, followed by a brief description of the iBeacon protocol.

2.1. Related Work

There are a multitude of BLE beacon hardware devices and manufacturers. The Estimote [14], Gimbal Series 10 [15], Glimworm [16], and Kontakt.io [17] are among the wide variety of beacons available on the market [18]. These devices, and many like them, tend to implement Apple's iBeacon protocol [19] and/or Google' Eddystone protocol [20]. These beacons are fully wireless and operate on coin cell batteries, or in some cases even solar power. BLE Beacons are a popular solution for indoor location [21, 22, 23], tracking [24].

In [23], the authors focused on achieving unambiguous user positioning using practical BLE beacons with multiple discrete power levels. A novel denoising autoencoder-based BLE indoor localization (DABIL) method is proposed in [22], to provide high-performance 3-D positioning in large indoor places. A detailed study of BLE fingerprinting is provided in [21]. BLE beacons for indoor localization was also examined in [25, 26].

BLE beacons have limited energy resource, hence energy harvesting approaches should also be examined [27, 28, 29]. The literature on the topic of solar powered BLE beacons is limited. Much of it may have to do with the lack of solar powered beacons available on the market. In [30], the authors attempt to determine the feasibility of solar powered beacons. In their experiment, they modify a *Yunzi* BLE beacon to utilize a third party solar panel as a power source. The experiments determined that with a transmission power of 0dBm and an advertising interval of 800ms, the *Yunzi* beacon can be powered by a $300cm^2$ solar panel. The work presented in [31] outlines the development of an inkjet printed solar powered beacon device. Although it is not a BLE beacon that operates on the 2.4GHz bandwidth, the ideas and concepts in this research are still relevant. The end device is a flexible, low cost wireless beacon that operates on solar power and transmits packets at 800MHz.

The fifth generation of communications is emerging in the near future. New challenges and characteristics of such networks will have to be understood and overcome. Specifically, the density of devices in a 5G wireless network will be very high. The work presented by [32] investigate beacon collisions and avoidance mechanisms in dense Wi-Fi networks. The research considers both the 2.4GHz band as well as 5GHz, making the findings relevant for current networks and future 5G developments.

Figure 1: Cyalkit-E02 BLE Beacon [33].

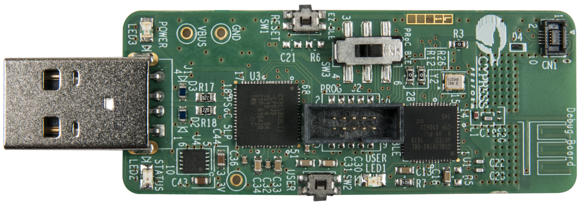


Figure 2: Cyalkit-E02 Debug Board [33].

2.2. *iBeacon Technology*

iBeacon is a packet layout format designed specifically for BLE beacons [19]. It was first introduced by Apple in 2013. The packet information was designed in such a way to make geofencing and regioning simple.

There are three distinct fields defined in the iBeacon packet format:

- A Universally Unique Identifier (UUID), which is a unique identifier for a proximity region (16 bytes), for instance the beacons that are used in a specific building.
- A Major value (2 bytes), helps to differentiate beacons of a specific brand ‘X’ present in a location such as a city ‘Y’.
- A Minor value (2 bytes), helps to identify the beacon of any brand ‘X’, in city ‘Y’ and department ‘Z’

These three fields are configurable by the application developer, and are generally used to region, and subregion areas with BLE beacon devices. User devices that are BLE enabled and running either iOS 7.0+ or Android 4.3+ operating systems can be used for beacon related services [19].

3. Experimental Setup

In this section, we initialize experiments on the energy consumption and the accuracy of the solar beacons and compare the results with a popular battery powered beacon.

Figure 3: Gimbal Series 10 BLE Beacon [15].

3.1. *Equipment*

Although there is a multitude of BLE beacon devices, there are limited choices of solar powered beacons in comparison. For the following experiments, the Cyalkit-E02 solar powered BLE sensor, developed by Cypress is used, shown in Fig. 1. The price of Cyalkit-E02 BLE beacon is competitive with some of the higher end beacon devices on the market, such as the Estimote BLE beacons [14].

The E02 BLE beacon is able to operate on any light source greater than 100 lux. It is small in size at only 25mm in diameter, and the included solar cell on the beacon measures at 15mm x 15mm. The E02 also includes two sensors: temperature and humidity. The beacon is fairly configurable, though unlike many of the battery powered beacons that configure wirelessly, it must be configured via the debug board, shown in Fig. 2. A full guide for beacon configuration and setup can be seen in [34].

An important insight when working with the E02 is that one field in particular, the transmission interval, cannot be configured. This is because an on-board power management chip governs the transmission interval based on the available light energy. At most, it will transmit every 3 seconds. Hence, this is a limitation when it comes to comparison with other beacons.

The transmit power however is configurable, and is capable of transmitting up to +3dBm. The full Power Management Integrated Circuit (PMIC) specifications can be referenced in [35].

For the battery powered beacon, the Gimbal Series 10 beacon was selected, shown in Fig. 3. The Gimbal Series 10 beacon, like the Cyalkit-E02, is a very small device, coming in at only 40 mm x 28 mm x 5.5 mm and 6.52 grams, including the battery. The gimbal beacon is by far one of the cheapest BLE beacons available on the market. However, it only includes a limited amount of telemetry data/ sensors, providing only temperature, ranging from -20 °C to 60 °C, and battery level of the device. In its default configuration it is only expected to last approximately 3-4 months. The output transmis-

Figure 4: Monsoon Power Monitor [37].

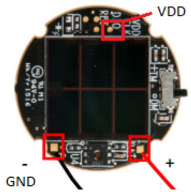


Figure 5: Cyalkit-E02 BLE Beacon: Out of Shell-Top View [33].

Figure 6: Gimbal BLE Beacon: Inside View [15].

sion power configurations range from -23dBm to a maximum of 0dBm. Depending on the application, the limited battery life and limited sensors may be an important consideration. The full Gimbal Series 10 manual can be referenced in [36].

3.1.1. Experimental Procedure

To measure the average power and current draw of each beacon device, a Monsoon Power Monitor, shown in Fig. 4 is used. Monsoon is capable of measuring and plotting power consumption and current draw, among many other parameters. It does this in real time at a sample rate of 5000 times/ second. Each iteration of the experiment measures the desired parameters over 4 minutes.

To measure the power consumption and average current in an equivalent scenario where the E02 beacon is under ideal lighting conditions (i.e. greater than 1000 lux) the Monsoon Power Monitor is connected to the + and - test pads as shown in Fig. 5, and is also configured to provide a 3.0V power source. This was done to ensure the Cyalkit-E02 beacon would transmit every 3 seconds, similar to the Gimbal configuration. The experiment was conducted in a room that provided approximately 500-600 lux to the solar panel for charging.

Figure 7: Android Application: Beacon Scanner.

To take the measurements of the Gimbal BLE beacon, it is disassembled and connected to the terminals as shown in Fig. 6. Once again, the Monsoon Power Monitor is set to provide the 3.0V power source, the same as its required CR2032 battery.

For the accuracy measurements, the beacon is placed at the end of a table in the middle of the room, while the receiving device, a Google Nexus 5 running Android 6.0.1, is moved along the table at 14 defined positions; 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0, 1.5, 2.0, 2.5, and 3.0 meters. The open sourced Android Application *Beacon Scanner* [38] is used to read in the RSSI values of the beacons. Minor modifications to the logic and UI allow for the raw data to be recorded, rather than the default smoothed values. The *AltBeacon* Android library [39] supports the receiving of iBeacon packets from the BLE beacons, as well as calculates the distance from the received RSSI values, using a best curve fit algorithm for the receiving device. A picture of the UI can be seen in Fig. 7.

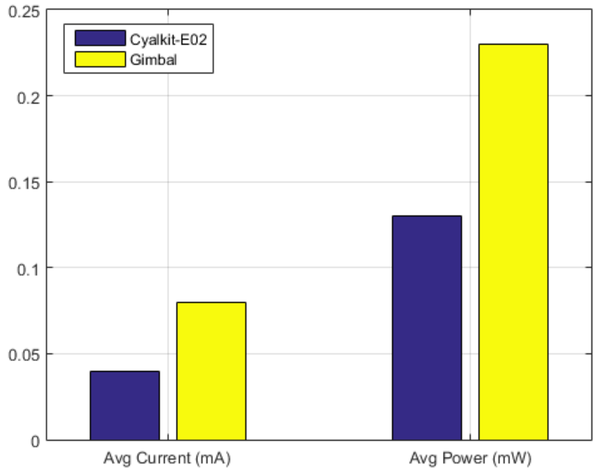


Figure 8: Power and Current Comparison, T_x = -12dBm.

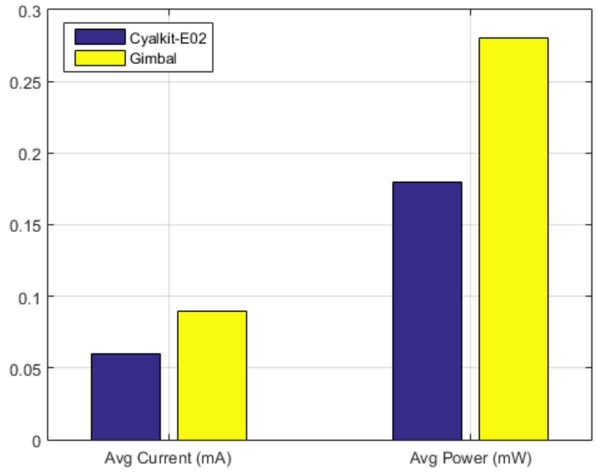


Figure 9: Power and Current Comparison, T_x = 0dBm.

4. Experimental Results and Analysis

In this section, the experimental results on energy efficiency and accuracy are presented followed by a brief discussion.

4.1. Energy Efficiency

The energy efficiency experiment attempts to measure and compare the average current draw and power consumption of the Cyalkit-E02 BLE beacon and Gimbal Series 10 beacons. Operation on solar energy in an indoor environment vs operation on an external battery source, mimicking a common 3.0V button cell, is compared.

There are two set of energy experiments. At first, each beacon is set to have a transmission power of $T_x = -12dBm$. This values is chosen as the -12dBm tends to be a standard/default transmission power for the majority of beacon devices, adequate for most room sizes. In the second set of experiments the transmit power was T_x = 0dBm. The 0dBm transmission power is chosen to obtain the energy consumption characteristics of the BLE beacon devices at the top end of their transmission power range. In an attempt at keeping all parameters the same, note that the Gimbal beacon is set to have a transmit interval of 3 seconds, matching the best case scenario of the Cyalkit-E02 under ideal lighting conditions.

The current and power characteristics of the two beacons under both configurations, -12dBm and 0dBm, are shown in Figs. 8 and 9, respectively.

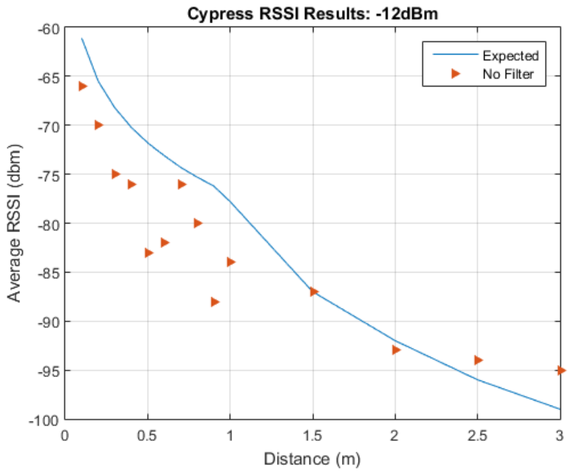
The solar powered E02 beacon is more energy efficient than the battery powered Gimbal beacon in both scenarios. Under the -12dBm configuration, it achieves an average current draw of 0.04mA and average power consumption of 0.13mW, whereas the Gimbal draws 0.07mA and 0.23mW on average.

Under the 0dBm configuration, both beacons increase in power consumption as expected. The energy consumption increases with an increase of transmission power. The E02 beacon achieves an average current draw of 0.06mA and an average power consumption of 0.17mW, whereas the Gimbal draws 0.09mA and 0.28mW respectively. Although the increase in current draw and power consumption may seem minimal given the large increase in transmission power, the beacons broadcast continuously and often, considerably increasing the impact of the power consumption on the overall lifespan of the beacon.

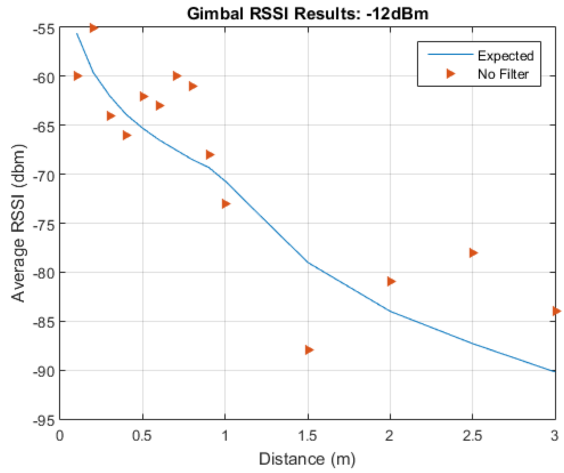
These results are a reflection of the fact that the Cyalkit-E02 is able to charge its battery during operation and directly power the beacon itself, meaning that it does not have the same power requirements of a strictly battery powered BLE beacon. During the measurements, the E02 solar beacon was in fact charging, although it was subject to indoor lighting of approximately 500-600 lux, and not charged under direct sunlight. If the solar beacon energy characteristics were to be measured under direct sunlight, the average power consumption may be expected to decrease due to the increase in energy harvesting potential. To improve the energy efficiency of either beacon more advancements in hardware design, or in the case of the Cyalkit-E02, energy harvesting, would be required.

4.2. Accuracy

The accuracy experiment compares the indoor proximity accuracy of the Cyalkit-E02 BLE beacon to that

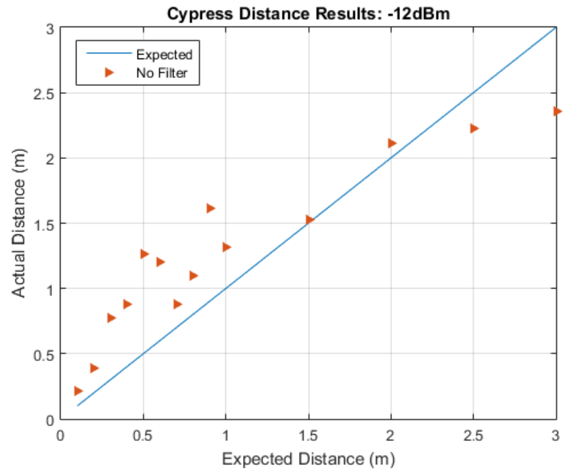


(a) Cyalkit-E02.

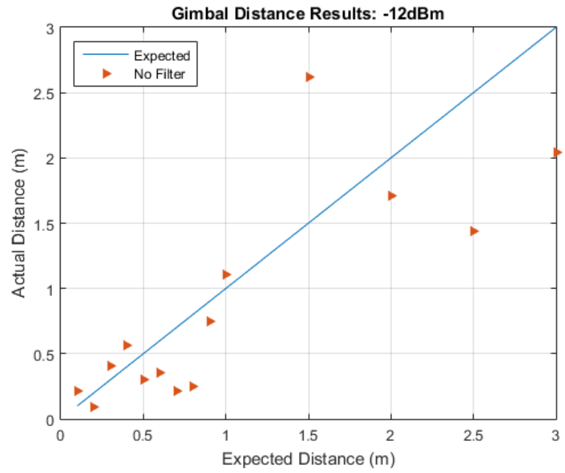


(b) Gimbal Series 10.

Figure 10: Raw RSSI values of the BLE beacons, T_x = -12dBm



(a) Cyalkit-E02.



(b) Gimbal Series 10.

Figure 11: Raw Distance values of the BLE beacons, T_x = -12dBm.

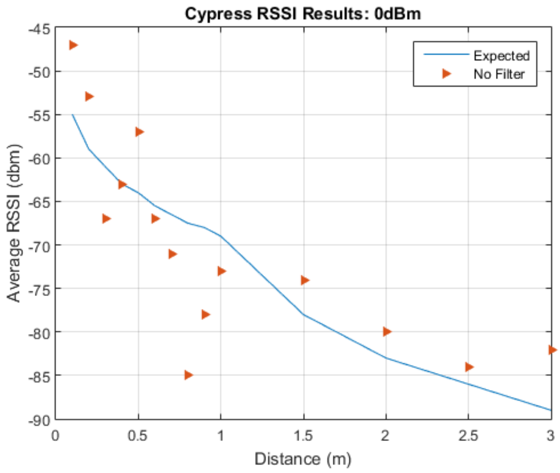
of a competitive battery powered beacon, specifically the Gimbal series 10. The test environment is a small meeting room of size 6m x 4m. The room is laid out with a set of chairs and tables, common to any meeting room.

The RSSI values are used to approximate the distance, and no filters are used in this comparison. As in the previous experiment, two variations of the experiment are conducted under the transmission power configurations of -12dBm and 0dBm. Each beacon also transmits a calibrated RSSI value at 1 meter. This value is used on the receiving end, and is used as an indication as to what signal strength should be seen at 1 meter away from the beacon. It is also a required parameter in the distance calculations. The E02 beacon is configured to have a calibrated RSSI value of -77dBm and -69dBm for the -12dBm and 0dBm configurations respectively, while the Gimbal is preconfigured with a default calibrated RSSI of -70dBm in both cases, thus the expected RSSI values for each beacon will differ from each other.

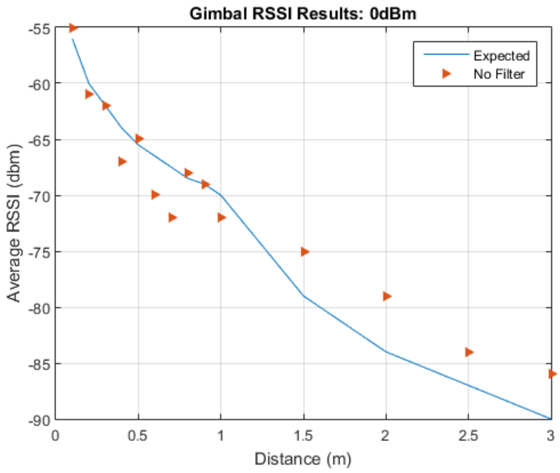
	Distance (m)	RSSI (dBm)
Cyalkit-E02	0.38	4.66
Gimbal	0.53	5.24

Table 1: Standard Deviation, T_x = -12dBm.

The accuracy results are shown in Figs. 10, 11, 12, 13. In each graph there is a line that represents the expected values, RSSI, and distance, at each defined point in the experiment. In the case of the RSSI plots, the

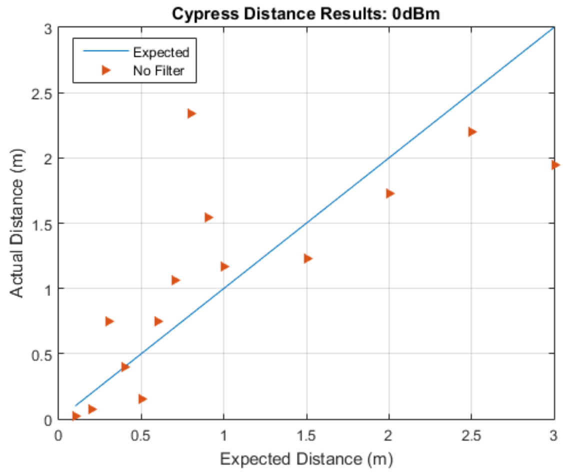


(a) Cyalkit-E02.

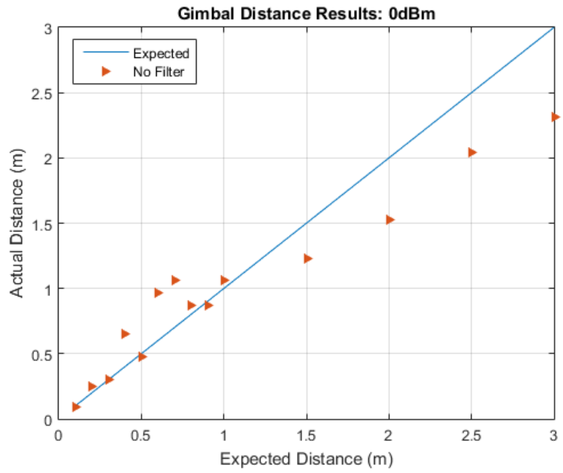


(b) Gimbal Series 10.

Figure 12: Raw RSSI values of the BLE beacons, T_x = 0dBm



(a) Cyalkit-E02.



(b) Gimbal Series 10.

Figure 13: Raw Distance values of the BLE beacons, T_x = 0dBm.

calibrated RSSI is plugged into the distance calculation, and at each defined expected distance the corresponding RSSI value is extracted. In the case of the distance plots, the expected distance line is just the set of 14 defined distance points used in the experimental procedure. In this particular environment the solar powered beacon is significantly more accurate off the shelf than the competing battery powered Gimbal Beacon, when configured with a transmission power of -12dBm, shown in Fig. 10 and Fig. 11. Fig. 11 clearly shows that the solar beacon achieves more consistent accuracy versus the Gimbal beacon in this case. The error standard deviation for these experiments, is shown in Table 1.

However, the opposite is true in the second experiment where the transmission powers of each beacon are increased to 0dBm, shown in Fig. 12 and Fig. 13. As seen in Fig. 13, the Gimbal beacon proximity accuracy improves over the previous experiment, while the solar beacon performs considerably worse. The error standard deviation for these experiments, is shown in Table 2.

	Distance (m)	RSSI (dBm)
Cyalkit-E02	0.59	7.36
Gimbal	0.31	2.95

Table 2: Standard Deviation, T_x = 0dBm.

There are a number of explanations as to why this may be. First, there may have been some unknown change in signal noise in the environment. The location in which the experiments took place, there was no possible way to control external signals such as Wi-Fi channels and nearby Bluetooth devices that may increase contention in the environment. Second, each beacon's hardware is designed differently, and so, the antennas on each device may behave differently under different configurations. This reinforces the point that BLE beacons are very sensitive to their environment, and reinforces the necessity to test and compare different beacon devices.

The results are interesting because the battery powered beacons are ensured to receive a consistent power source, assuming the battery is fully charged, while the E02 must have a dependable light source to provide a consistent source of power to the transmitter. When configured with a transmission power of -12dBm, the Cyalkit-E02 achieves a proximity accuracy improvement of 39% over the Gimbal series 10. This is likely due to differences in antenna hardware and extra configuration capabilities. The E02 beacon allows the calibrated RSSI at 1m value to be changed. This allowed it to be set to a value that was optimal for the test environment, whereas the Gimbal beacon has a preset calibrated RSSI value that cannot be configured. Under the 0dBm configuration, the Gimbal beacon was able to improve its accuracy by 41.5% when compared to its previous configuration, achieving a standard deviation of only 31cm, as shown in Table 2. The solar beacon however got worse, going from a standard deviation of 38cm to 59cm.

5. Conclusion

Beacons have many important applications in the 5G ecosystem, from monitoring and tracking to indoor localization and micro localization. This work focuses on the feasibility of utilizing solar powered beacons for smart cities applications. Multiple experiments were conducted in terms of energy efficiency and proximity accuracy. According to experimental results, the chosen solar powered beacon is more energy efficient than the battery powered beacons we used for comparison. It was also shown that the configuration of the beacon itself is vital to its performance, and that not every beacon can be treated the same. It is critical to test and configure the beacon according to its environment to ensure ideal performance. Under the correct configurations, the solar beacon is able to achieve considerably accurate results. Therefore, solar powered beacons can be thought of as a good candidate for indoor location based systems in a 5G environment.

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