Final Measurement and Verification Report for I&T Trial Project

Green/ Sustainable Indoor Positioning System Using luXbeacon Technology

I&T Project No. : P-0020
I&T Wish No. : W-0081
I&T Solution No. : S-0051

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Purpose of the Project and Target Deliverables

This project aimed to build a green/ sustainable Internet of things (IoT) infrastructure for a batteryless Indoor Position System using luXbeacon from Hong Kong University of Science and Technology (HKUST) Social Media Lab (http://smedia.ust.hk/luxbeacon/). luXbeacon is a batteryless Bluetooth Low Energy (BLE) Beacon technology, which enables a BLE Beacon to operate by harvesting energy even from indoor lightings. Simply due to the use of batteries in regular BLE beacons, many large-scale BLE-based IoT applications are suffering from the issues of demanding manpower maintenance, massive battery consumptions and unpredicted services disruption. This project is the world-first attempt to create a batteryless BLE-based Indoor Positioning System to overcome these common issues by using luXbeacon. Although BLE beacons are commonly used in indoor positioning system as used by Faragher *et al.* (2015), Zhuang *et al.* (2016), and Xiao *et al.* (2017), only recently, there have been an attempt to form a batteryless infrastructure to support Indoor Positioning System (IPS) application by Liu *et al.* (2019). However, the reported system only consists of 4 beacon devices, and has not been tested in real-world situation. The report presented the real-world deployment of around 90 luXbeacons in the Electrical and Mechanical Services Department (EMSD) headquarters. The function compatibility and performance comparison of luXbeacon will also be evaluated and compared with regular BLE beacon for the demanding BLE-based application IPS.

Target Deliverables:

a) Setup of a BLE beacon network in the EMSD Headquarters (HQ) using luXbeacon;
b) Performance evaluation of luXbeacon at locations with various lighting conditions for supporting the required IPS system;
c) Development of IPS mobile app and measurement apps;
d) Performance evaluation and demos of IPS system using luXbeacon-based infrastructure and follow-up action plan.

Project Description

This project is a collaborative research between the EMSD and the HKUST to seek synergism in facilitating the development of IoT Infrastructure and Applications for the EMSD Operations and Facilities. The HKUST-NIE Social Media Lab applied its expertise in developing the BLE beacons for indoor navigation. The design included photo-voltaic (PV) panels to eliminate the need for extra electric wires and periodic battery replacement inside buildings.

Trial Site

The trial venue of this project is at the EMSD HQ located in Kowloon Bay. The 6th and 7th floor office area was dedicated as trial site to evaluate the project in practical settings.

Type of Equipment/ Installation/ Technology Adopted

luXbeacon is a solution to green and robust IoT infrastructure. Unlike the regular battery powered BLE beacons, luXbeacon harvests ambient energy from its photovoltaic panel. The hardware design of the luXbeacon maximizes its energy harvesting capability while its firmware design minimizes its energy usage. Therefore, luXbeacon technology is capable of energy neutral operation even in low-light environment, such as indoor office environment.
In the meantime, an IoT device management platform, CyPhy CP Cloud, is used to track and manage the information, settings and locations of luXbeacon.
In addition, Blue-Pin IPS software, is adopted to make use the luXbeacon hardware to provide the BLE-based indoor position services.

Trial Timeframe

The project was divided into 4 phases with the time spent along with key focuses below:

Phase 1 - On-site survey (1 week): Under the EMSD environment and maximize use of batteryless luXbeacons, an 8m separation between beacons were used for the IPS system. luXbeacon is installed in a position closest to the near light source in order to obtain energy.

Phase 2 - Installation (2 weeks): Most of the luXbeacons are installed within the lightbox of the corridor, therefore no battery was needed for those beacons.

Phase 3 - Fine tuning of luXbeacons and mobile apps (2-3 weeks): This phase is mainly used to relocate the positions of some luXbeacon hardware, so that more batteryless luXbeacon could be used. Whereas, some setting of broadcast intervals and transmit power of luXbeacon are required to adjusted to support the accuracy of the IPS.

Phase 4 - Performance evaluation and IPS demonstration (1 week): Lastly, the IPS application was tested and demonstrated with the deployed luXbeacon infrastructure to prove its capability to support high-energy demanding applications.

Name and Background of I&T Solution Provider

The HKUST-NIE Social Media Lab was first established in 2012. The lab focuses on researching big data system and analytics, cyber-physical interactive media system, and Internet of Things (IoT) systems and infrastructure for smart cities. BLE beacons have recently been highlighted as potential building block for IoT infrastructure. However, due to their limited power source, periodic battery replacement operation proved to be tedious and exhaustive. Therefore, HKUST NIE Social Media Lab created luXbeacon, the first open hardware sustainable IoT to address the issue.

Details of Implemented Trials

In this section, the key technology or technical tool, process and results of each target deliverable are summarized as follow.

I. Methodology and Applicable Standards

Setup of a BLE beacon network in the EMSD HQ using luXbeacon. luXbeacons are deployed in the 6/F and 7/F of the EMSD HQ, and their hardware information, settings and location information are being tracked and managed by CyPhy CP Cloud System as shown in Fig. 1. These luXbeacons were configured with 100ms advertising interval and -8dBm transmit power to ensure reliable operation of the IPS. Fig. 2 shows the deployment locations of the luXbeacons on 6/F and 7/F with orange markers.

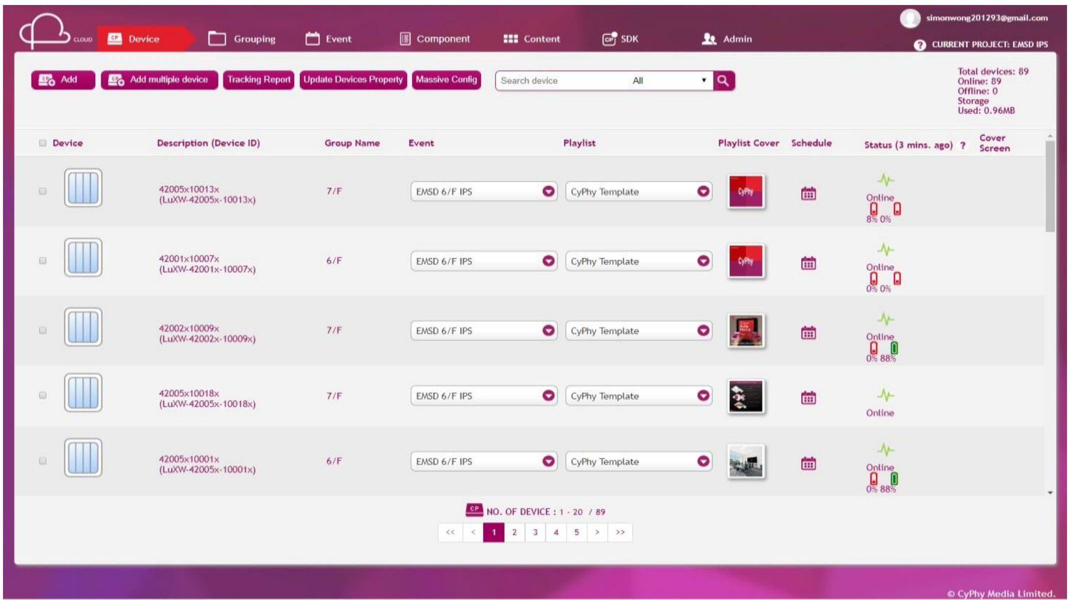

Fig 1. luXbeacons are being tracked and managed by CyPhy CP Cloud System.

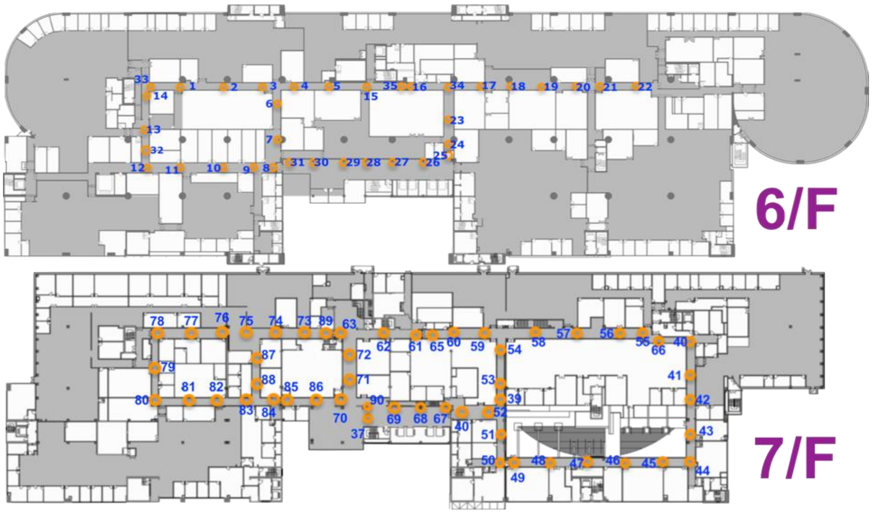

Fig 2. Floor plan of 6/F & 7/F of EMSD HQ with luXbeacon locations.

In total, 88 luXbeacons are deployed in the 2 floors. However, 29 units of the luXbeacons are installed with a backup battery (i.e., CR2477) due to the poor lighting conditions. Table 1 summarizes the numbers and types of luXbeacons at the two major locations with their average lighting conditions in terms of lux level. Some of these locations with varying lighting conditions are shown in Fig 3.

	luXbeacon batteryless	luXbeacon w/ Backup Battery
Units of luXbeacon	59	29
Avg. lux level of deployed locations	> 1200 lux	< 1200 lux

Table 1. Number and types of luXbeacons at locations with certain conditions of average lux levels

Fig 3. luXbeacons deployment locations with varying lighting conditions on 6/F and 7/F of the EMSD HQ.

luXbeacons are tested in regard to charging and discharging performance under different lighting conditions.

II. Measurement and Verification Activity Details

Performance of luXbeacon charging time in varying lighting conditions:

First, an experiment to investigate the relationship between environment light intensity and charging time of the supercapacitor is conducted. The luXbeacon was left under an LED light source that can vary its light intensity. The voltage of the supercapacitor was then measured by the Bluetooth chipset, nRF51822, and reported to the mobile phone. During this experiment, iPhone 6 equipped with Beacon360 was used to collect the experimental data.

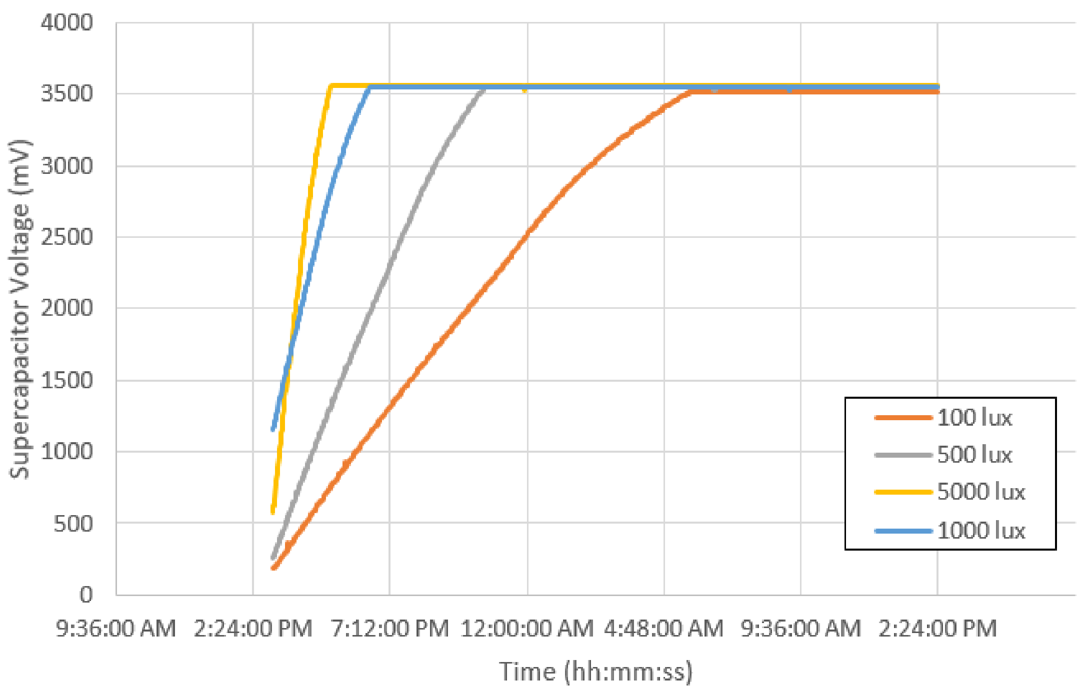

Fig 4. Charging time of luXbeacon under varying lighting condition

Fig 4 shows the experimental result of the charging time of the luXbeacon under different light intensity environment. It is proved that luXbeacon only takes less than 15 hours to be fully charged at about 100 lux (a poor indoor environment) and 2.5 hours at 5000 lux (an ideal outdoor environment). Since the lighting conditions of most of the EMSD locations were found to be above 1200 lux, the luXbeacons is fully charged within a few hours in general. Such fast charging time allows the luXbeacons deployed in such locations to support batteryless operations while supporting the IPS application reliably.

To find the discharging time of the luXbeacon, a fully charged luXbeacon was left in complete darkness until it stopped broadcasting any signal. It was found that a fully charged luXbeacon with 100ms advertising interval and -8dBm transmit power will take approximately 2 to 2.5 hours to completely discharge. Experimental procedures are shown in Table 2 and 3.

Step	Instruction	Condition
1	Fully discharge the luXbeacon	Supercapacitor voltage is below 0.5V
2	Leave the luXbeacon under the light source and measure the light intensity at the center of the solar panel	N/A
3	Record the luXbeacon packet broadcasted to track the changes is supercapacitor voltage	N/A
4	Wait until the supercapacitor is fully charged	Supercapacitor voltage is above 3.5V

Table. 2. Procedures for charging time experiment

Step	Instruction	Condition
1	Fully charge the luXbeacon	N/A
2	Place the luXbeacon in complete darkness	N/A
3	Record the luXbeacon packet broadcasted to track the changes is supercapacitor voltage	N/A
4	Wait until the luXbeacon stops broadcasting	Supercapacitor voltage is below 2.2V

Table. 3. Procedures for discharging time experiment

Interim Review on Performance and Outcomes

As shown above, depending on the lighting conditions, the charging time of the luXbeacon will be different. Therefore, luXbeacons deployed at locations with poor lighting condition, as shown in Fig 3, requires a backup battery to ensure reliable operation. However, even under such poor lighting condition, luXbeacon technology can still harvest some energy and therefore extend the battery lifetime. Without the luXbeacon technology, the battery lifetime of the beacon would be around 6 months. On the other hand, luXbeacon harvesting around 200 lux lighting for 8 hours a day, which is a common lighting condition in office environment, would allow to extend the lifetime for extra 2 months, which is around 33% longer than the original battery lifetime.

More detailed lifetime calculation is shown in Table 4. It can be seen that once the lighting condition is larger than the 1200 lux, the luXbeacon will be completely self-sustainable and support batteryless operation.

Lighting condition	luXbeacon lifetime
No light	6 months (0%)
200 lux	8 months (+33%)
600 lux	12 months (+100%)
1200 lux	Self-sustainable

Table 4. Lifetime of luXbeacon under varying lighting conditions.

Summary Results and Analysis

I. Pre and Post-installation Comparison – luXbeacon Navigation

BLE Beacons were deployed at corridors of the venue and visitors to the EMSD HQ can navigate to designated meeting rooms.

Beacon360, a luXbeacon monitoring app was developed to record and analyze the performance of the deployed luXbeacons as shown in Fig 5. Beacon360 can be downloaded on both iOS and Android platforms through the links below:

- iOS: https://itunes.apple.com/us/app/beacon360/id1337607447?mt=8
- Android: https://play.google.com/store/apps/details?id=hkust.SML.locatebeacon.beacon360

IPS mobile app was developed as shown in Fig. 6 that uses the RSS measurements from nearby luXbeacons to estimate the current location of the user mobile phone.

During the development of this mobile applications, SDK from BluePin and CyPhy was used.

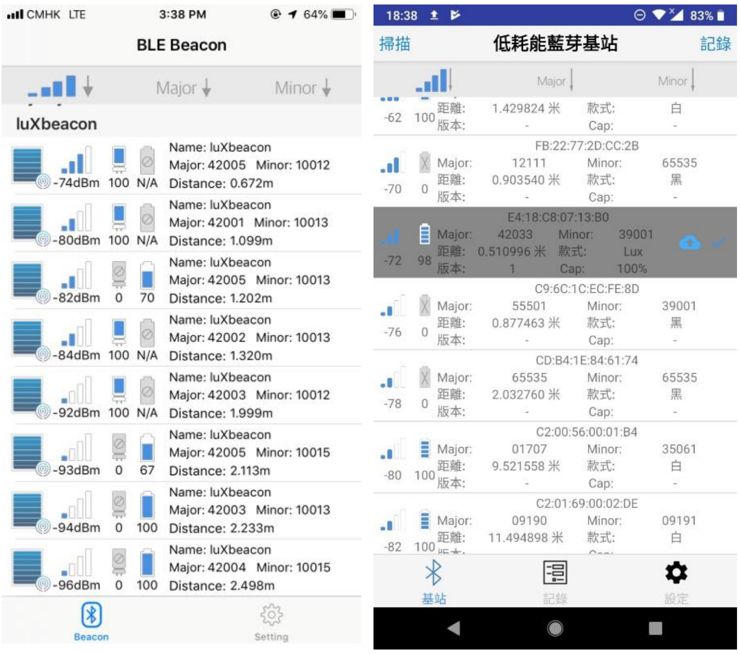

Fig 5. Mobile app to monitor luXbeacon status

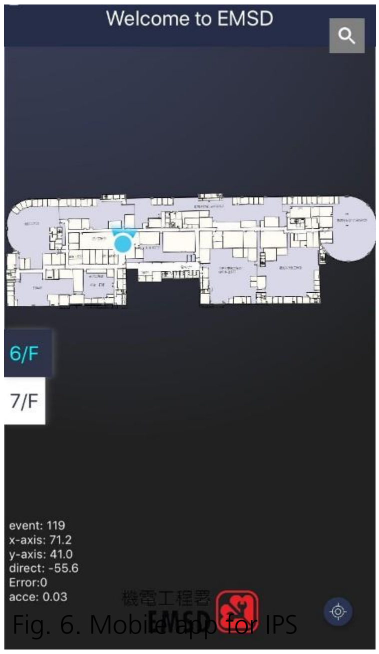

Fig. 6. Mobile app for IPS

II. Key Statistics, Figures, Infographics to Support the Results – Accuracy of Positioning

To prove the effectiveness of the presented luXbeacon-based IPS applications, IPS accuracy test was measured. The accuracy test was conducted by measuring the average difference of the prediction made by the IPS mobile app and the true positions of tester, using the formulas:

$$e(l) = \sqrt{(x - \hat{x})^2 + (y - \hat{y})^2}$$

$$a = \frac{\sum_{i=1}^{N} e(l^{(i)})}{N}$$

.IPS coordinate was recorded by taking log from IPS backend, and true coordinate of tester was calculated by taking tester’s walking speed on a designed path. The procedures are shown in Table. 5 and the test routes are shown in Fig. 7. Results from the test, as shown in Table. 6, shows the performance of the IPS system using luXbeacon.

Step	Instruction	Condition
1	Design a testing path to test the accuracy of the IPS	N/A
2	Walk along the testing path and record the predicted coordinates from the IPS application	N/A
3	Compute the accuracy of the IPS based on the collected data	N/A

Table 5. Procedures for IPS accuracy measurement experiment

Fig. 7. Test routes for the IPS

	Mean Error	Median Error	75th	90th	**95th**	Max Error
6/F (147 test locations)	5.6	5.8	8.2	9.2	**10.4**	13.1
7/F (201 test locations)	5.4	5.0	7.5	10.1	**11.3**	24.0

Table 6. IPS accuracy test results in meters

III. Analysis of M&V Results to Address the Target Deliverables

The results show that the luXbeacon infrastructure, although it is batteryless, can support energy-demanding IPS applications with an accuracy to support indoor wayfinding application. The major factors that causes the performance difference between our system and the that of Faragher are

1. the beacon deployment density: Faragher et al. deployed 1 beacon per 30 m2 where as in our setup 6/F has deployed 1 beacon per 80m2, 7/F has deployed 1 beacon per 50m2.
2. the software solution: whereas Faragher et al. employed fingerprinting method our system employs triangulation method.

Given these differences, an eye-to-eye comparison between the presented system and that of prior arts is difficult. However, the proposed experimental result can demonstrate that luXbeacon infrastructure, where 67% of the devices are batteryless, can successfully support IPS application.

Demo Video

A demo video of the presented IPS application can be found in the link: http://smedia.ust.hk/luxbeacon/cases.html.

Following feedbacks were given after the demo session. These feedbacks will be carefully considered and reflected on the current luXbeacon infrastructure and the presented IPS application.

a) Reduce fluctuation in user position when the user is standing still or stationary
b) Prevent inaccurate user position prediction due to lost signal beacon
c) Develop an Admin APP to report "No Signal" Beacon
d) Implement way-finding features to find selected meeting rooms

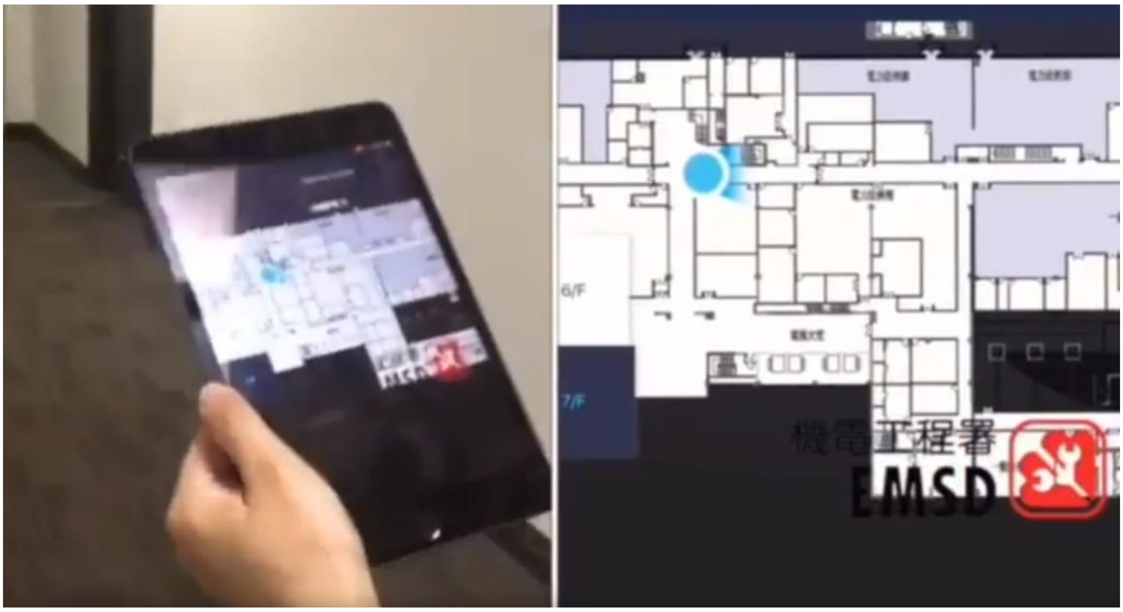

Fig 8. Demo Video of the presented IPS

Conclusion and Way Forward

Through this project, luXbeacon has demonstrated its ability to support energy-demanding beacon-based IoT applications like IPS, which requires 100ms advertising interval and -8dBm transmit power, with the energy harvested from the indoor environment.

Results showed that 59 out of 88 (67%) locations could operate batteryless while supporting the IPS application

Furthermore, those 29 locations equipped with backup battery enjoyed around 2 month of battery lifetime extension in adopting the luXbeacon technology. For future works, the research team may develop next-generation luXbeacon design to reduce its power consumption through circuit and firmware designs and increase its energy storage capacity through multi super-capacitor technology.

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Inno-Office

Electrical and Mechanical Services Department

21st January 2020

References

Faragher, R. and Harle, R., 2015. Location fingerprinting with bluetooth low energy beacons. IEEE journal on Selected Areas in Communications, 33(11), pp.2418-2428.

Liu, Q., IJntema, W., Drif, A., Pawełczak, P. and Zuniga, M., 2019. BEH: Indoor Batteryless BLE Beacons using RF Energy Harvesting for Internet of Things. arXiv preprint arXiv:1911.03381.

Xiao, C., Yang, D., Chen, Z. and Tan, G., 2017. 3-D BLE indoor localization based on denoising autoencoder. IEEE Access, 5, pp.12751-12760.

Zhuang, Y., Yang, J., Li, Y., Qi, L. and El-Sheimy, N., 2016. Smartphone-based indoor localization with bluetooth low energy beacons. Sensors, 16(5), p.596.