Measurement and Verification Report for I&T Trial Project (Full)

Green/ Sustainable Indoor Positioning System Using luXbeacon Technology

I&T Project No. : P-0020 (Part 2)
I&T Wish No. : W-0081
I&T Solution No. : S-0051

E&M InnoPortal

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Purpose of the Project and Target Deliverable

This project is aimed to build a green/ sustainable IoT infrastructure for a batteryless Indoor Position System using luXbeacon from HKUST Social Media Lab (http://smedia.ust.hk/luxbeacon/), Jeon et al. (2019). luXbeacon is a batteryless Bluetooth Low Energy (BLE) Beacon technology, which enables a BLE Beacon to operate by harvesting energy even from the 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 IPS application by Liu et al. (2019). However, the reported system only consists of only 4 beacon devices, and has not been tested in real-world situation. Also, due to the high energy consumption induced by the requirement of short advertisement interval, frequent and periodic battery replacement will be required, which is very resource consuming. In the research experiment conducted by Faragher et al., the beacons are configured to advertise at 50Hz and 0 dBm transmit power, which consumes much energy to keep a relatively high accuracy.

In our previous project, we have deployed around 90 luXbeacons on 6/F & 7/F of EMSD headquarters to provide IPS application. During this project, we have observed that certain deployment locations do not have enough lighting availability in terms of duration to make IPS more reliable. At deployment locations such as near windows have sufficient light intensity, but due to the limited capacity of the energy storage, the operation lifetime of the luXbeacon was limited after sunset. To address this issue, in our current project, we propose a novel dual-supercapacitor design of luXbeacon, named luXb-d. Based on our experience, we extend the luXbeacon coverage zone to 4/F along with the IPS services. We will present our newly deployed luXbeacon infrastructure and related processes and finally evaluate it with well established methods introduced in Jeon *et al.* (2020)

Technology Adopted

luXbeacon is a ground-breaking hardware and firmware co-designed BLE technology for green and robust IoT infrastructure, which is invented by researches from HKUST Social Media Lab, and supported by EMSD Innovation funding along with other academic and industry sponsors. 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, 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.

Target Deliverables

The target deliverables are listed as below:

1. Dual super-capacitor luXbeacon design and development;
2. luXbeacon-based IPS for Innozone on EMSD 4/F;
3. Smart Demo Introduction System;

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

Phase 1 - On-site survey (1 week): Under 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 at the ceiling of the lobby, with the low light environment area (50 lux in some areas), batteries are embedded.

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. 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 demo of IPS (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.

Deliverable 1: Dual supercapacitor luXbeacon (luXb-d)

In this section, the key technology or technical tools, processes and results of deliverable #2 are summarized

I. Designing and manufacturing dual supercapcitor luXbeacon, luXb-d

In the previous design of luXbeacon, we realized that having one supercapacitor may have several drawbacks.

1. Limited capacity of supercapacitor may not be sufficient for high energy consuming application such as IPS, which may result in power failure very soon in the absence of light energy source. In case of luXbeacons deployed in 6/F & 7/F, the beacons could last around 2-3 hours in absence of light.
2. Having one supercapacitor may serve as a single point of failure. By having redundancy of supercapacitor, we can reduce the possibility of failures.

To address this issue, we have revised the design of the luXbeacon to accommodate up to 2 supercapacitors, therefore ensuring longer lifetime when supporting high energy consuming applications and more robust against hardware failures. To achieve this, we connect the two supercapacitors to the PMIC through load switches (TPS22917) which can help to control the flow of current to each supercapacitor. These load switches are controlled by the GPIO outputs of the Bluetooth IC (nRF52832). The block diagram is shown in Fig. 1.

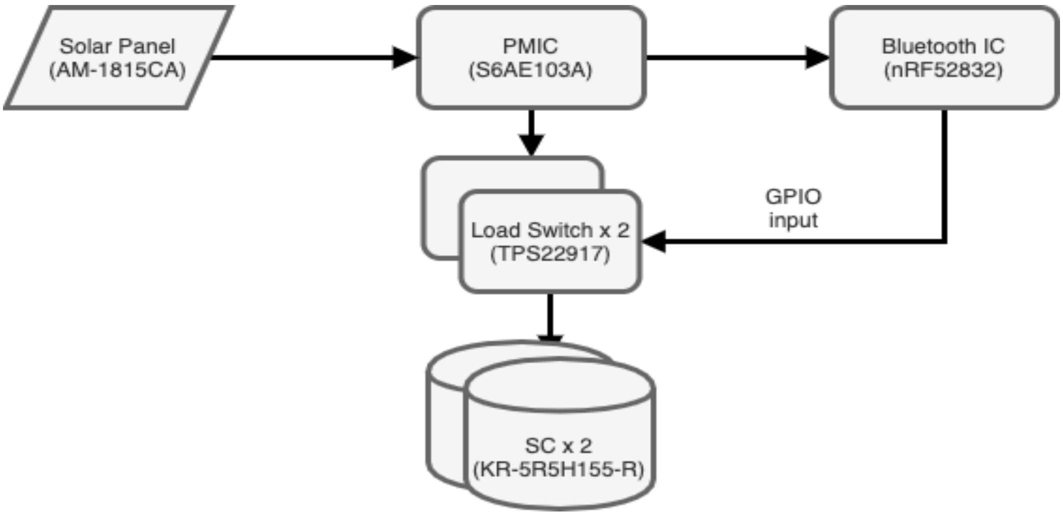

Fig. 1. Block diagram presenting the design of luXb-d.

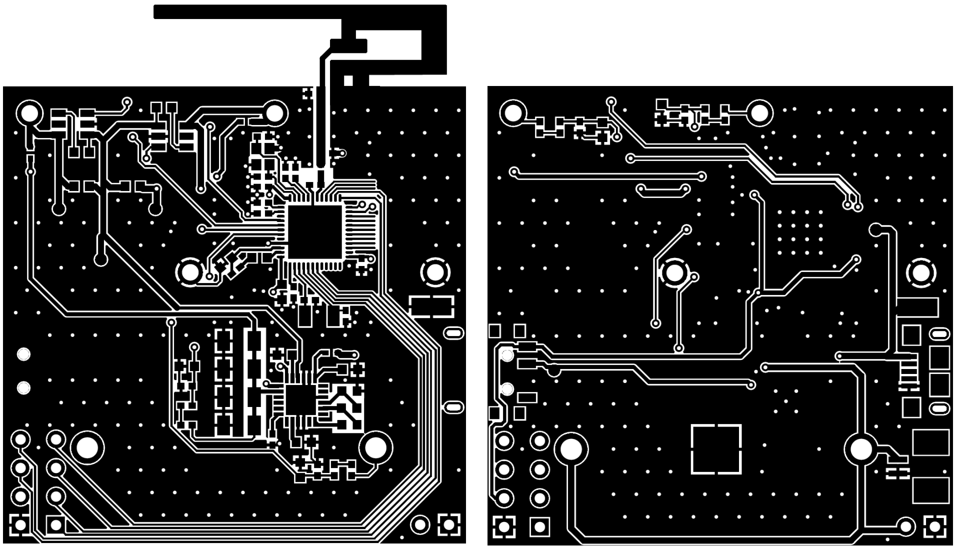

Fig. 2. PCB layout of luXb-d.

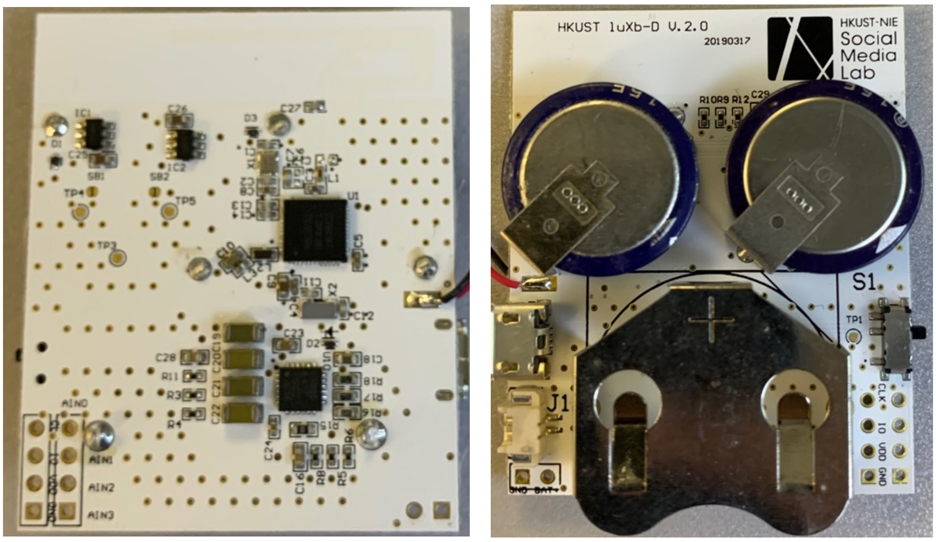

Fig. 3. Manufactured PCB board of luXb-d.

Fig. 2 and 3 shows the PCB design of luXb-d and the final manufactured PCB board. Table 3 reports the major components used in the design.

	Part name	# of units
1. Bluetooth IC	nRF52832	1
2. Power management IC	S6AE103A	1
3. Energy harvesting unit	AM-1815CA	1
4. Supercapacitor	KR-5R5H155-R (1.5F)	2
5. Load switch	TPS22917	2

II. Performance evaluation of luXb-d

To evaluate the performance of luXb-d, we conduct following two experiments:

1. Charging time of the supercapacitors;
2. Discharging time (lifetime) of the supercapacitors.

We conduct the above two experiments on both luXb-d and luXbeacons deployed on 6/F & 7/F to demonstrate the benefits and improvement on luXb-d. The procedures of the two experiments are shown in Table 2 & 3 respectively.

Step	Instruction	Condition
1	Fully discharge the luXbeacon	Supercapacitor voltage is below 2.2V
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 to track the changes is supercapacitor voltage	N/A
4	Wait until the supercapacitor is fully charged	Supercapacitor voltage is above 3.4V

Table. 2. Procedures for charging time experiment

Step	Instruction	Condition
1	Fully charge the luXbeacon	Supercapacitor voltage is above 3.4V
2	Place the luXbeacon in complete darkness	Lux level < 10 lux
3	Record the luXbeacon packet 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

The experimental results are shown in Fig. 4 & 5. Fig. 4 presents the experimental results from the charging time experiment. It can be seen that under the same lighting condition, charging time of luXb-d is double of that of luXbeacon @ 6/F & 7/F, due to its larger capacity. However, in certain environment where the light source is abundant, luXb-d will harvest and stock more energy, whereas luXbeacon @ 6/F & 7/F will be limited by its supercapacitor capacity.

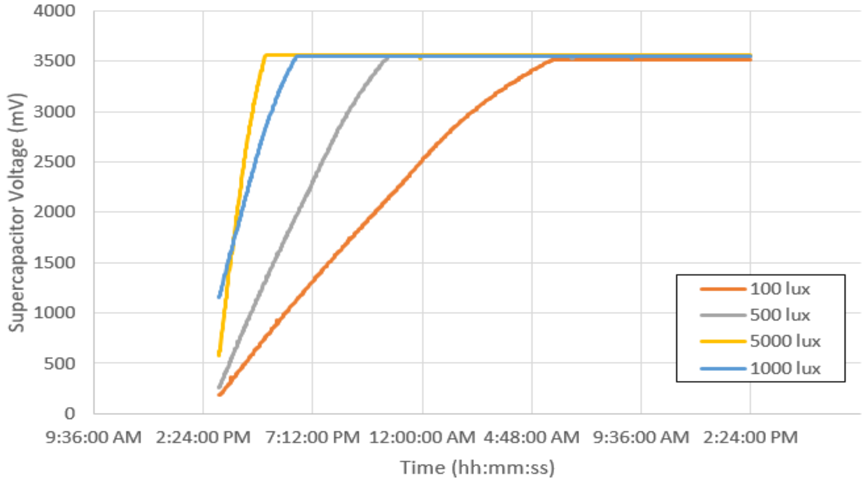

Fig. 4. Charging time comparison of luXb-d and luXbeacon @ 6/F & 7/F.

Fig. 5 presents the experimental results from the discharging time (lifetime) experiment. It can be observed that luXb-d will have double the lifetime of luXbeacon at 6/F & 7/F. Due to this extension in lifetime, luXb-d may be able to sustain its operation even in some unfavorable locations where the lighting source is often unavailable, such as deployment location near windows where luXbeacons mostly rely on sunlight. Although sunlight is very strong, it is not readily available as indoor lighting. Therefore, luXb-d will greatly benefit those deployment locations on 6/F & 7/F near the windows.

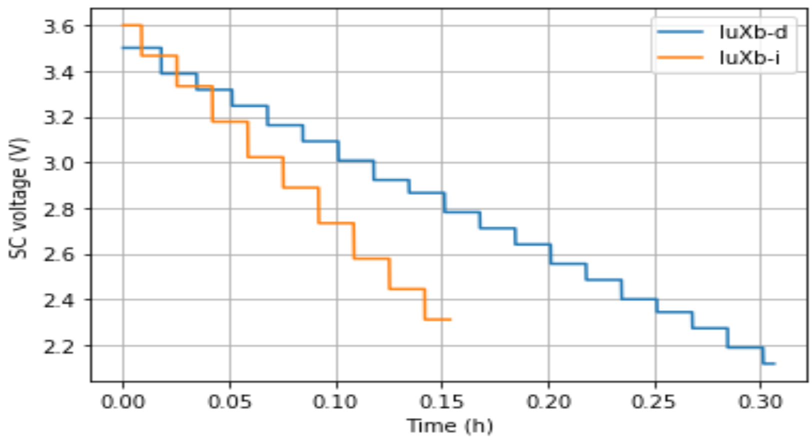

Fig. 5. Discharging time comparison of luXb-d and luXbeacon @ 6/F & 7/F.

III. Deployment of luXb-d on 7/F of EMSD HQ

In order to evaluate the effectiveness of the newly proposed design, we have deployed 2 luXb-d on EMSD 7/F HQ such as to compare their performance with its predecessors. To facilitate this, we have identified some challenging deployment locations on EMSD 7/F HQ as shown in Fig. 6. These locations had scarce light energy (<100 lux), and therefore luXbeacons had to be equipped with backup battery in order to ensure a reliable operation.

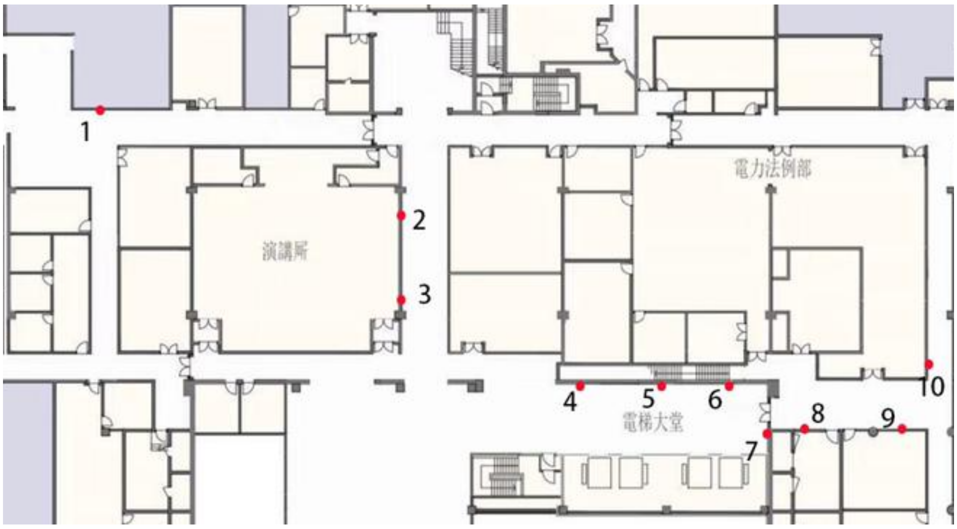

Fig. 6. Challenging deployment locations on 7/F.

However, from the preliminary experiments conducted at HKUST Lab. environment, it was observed that the proposed luXb-d design would not be effective in areas with low light intensity with long lighting availability. On the other hand, luXb-d would be effective in those locations that have high light intensity but for a short amount of time. The experimental results showing the charging time of the luXb-d under different light intensity is shown in Table 4. Therefore, it is important to choose those locations that can successfully charge the luXb-d according to the light intensity and charging time conditions.

Light intensity (lux)	Charging time
200 lux	Not chargeable
500 lux	16 hours
1000 lux	8 hours
2000 lux	4 hours

Table. 5. Conditions and definitions of challenging deployment locations.

Whereas in the previous luXbeacon design, the capacity of the energy storage bottle necked some locations to harvest enough energy to operate for extended amount of time in the absence of ambient lighting. luXb-d could alleviate such

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issues and extend the lifetime or even enable batteryless operation in two of the deployment locations on 7/F. These different types of challenging deployment locations are classified and described in detail in Table 5. Finally, the two proposed deployment locations of luXb-d are shown in Fig. 7.

	Lighting Conditions	Lighting Availability
Initial deployment location	< 200 lux	<12 hours
New deployment location	> 1000 lux	<12 hours

Table. 5. Conditions and definitions of challenging deployment locations.

Fig. 7. Final deployment locations on 7/F shown in red dots.

Deliverable 2: luXbeacon-based IPS for Innozone on 4/F

luXbeacons are deployed in the Innozone on the 4/F in EMSD Headquarter (HQ), and their hardware information, settings and location information are being tracked and managed by CyPhy CP Cloud System as shown in Fig. 10. These luXbeacons were configured with 100ms advertising interval and -16dBm transmit power to ensure reliable operation of the IPS. Fig. 9 shows the floorplan of the deployment area on 4/F in EMSD Headquarter, which the circle with numbers are luXbeacons for IPS and the blue squares are the asset trackers.

Fig. 8. luXbeacons deployment locations with varying lighting conditions on 4/F

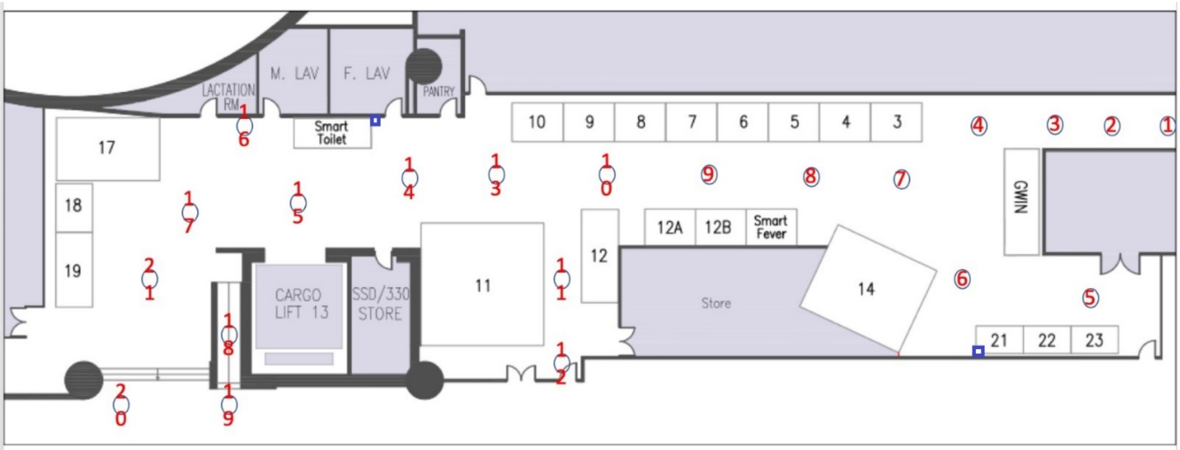

Fig. 9 Deployment plan of luXbeacon and Asset Tracker on EMSD 4/F

In total, 42 luXbeacons are deployed and 2 asset trackers are deployed. All luXbeacons are installed with a backup battery (i.e., CR2477) for each due to the poor lighting conditions. Table 5 summarizes the numbers of luXbeacons with their average lighting conditions in terms of lux level. Installation with low lighting conditions are shown in Fig.8.

Remark #1:

The luXbeacons were originally deployed equipped in a resin casing printed by SLA 3D printer. However, we noticed that this type of material was easily deformed and could potentially cause safety issues when installed on the ceiling. To address this issue, all of the top lids of the casings were replaced with ABS and PLA materials. Bottom casings were not replaced as the structure and thickness of the bottom casing helped to prevent any deformation.

	luXbeacon w/ Backup Battery
Units of luXbeacon	42
Avg. lifetime extended in poor light condition (≤ 50 lux)	5%

Table. 5. Number of luXbeacons at locations with certain conditions of average lux levels

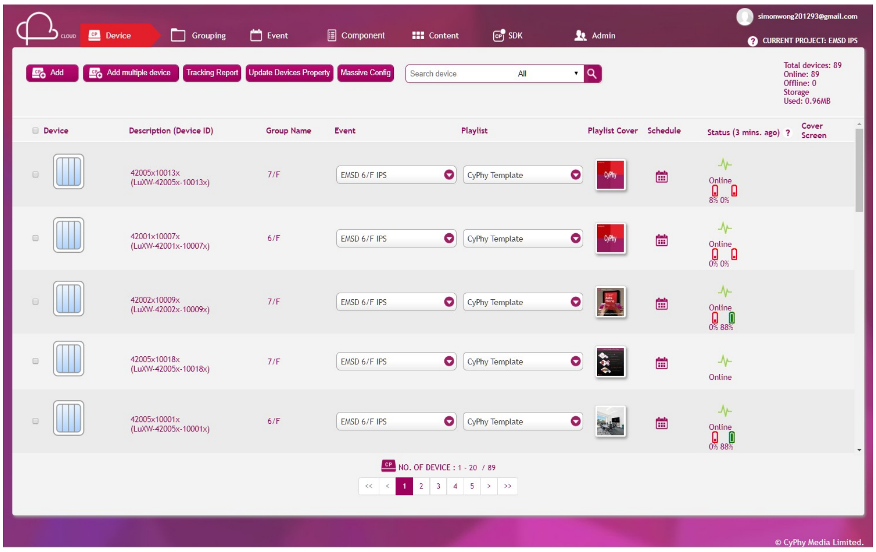

Fig. 10. luXbeacons are being tracked and managed by CyPhy CP Cloud

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

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. 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. 5. It shows that once the lighting condition is larger than the 1200 lux, the luXbeacon will be completely self-sustainable and support battery-less 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. 6. Lifetime of luXbeacon under varying lighting conditions.

I. Performance evaluation and demo of IPS on 4/F

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. Results from the test, as shown in Table. 8, shows a promising performance of the IPS system using luXbeacon. Mean of the estimated distance error for the IPS is presented to show an unbiased error for the IPS. Median of the estimated distance error is presented to show the mean is within ±10% of the actual median. Both mean and median represents the overall IPS distance error.

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. 7. Procedures for IPS accuracy measurement experiment

	Mean Error	Median Error	75th	90th	95th	Max Error
4/F (30 test locations)	2.5	2.4	3.6	4.7	5.7	6.6

Table. 8. IPS accuracy test results in meters

On 4/F, the average IPS accuracy was found to be around ±5.5m. The results show that the luXbeacon infrastructure can support energy-demanding IPS applications with good enough accuracy to support indoor wayfinding application even in poor lighting condition. The major factors that causes the performance difference between our system and the that of Faragher are the protocol implemented: Faragher et al. deployed 1 beacon per 30 m^2 whereas in our setup 4/F has deployed 1 beacon per 30m^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 even in poor lighting environment, can successfully support IPS application reliably.

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

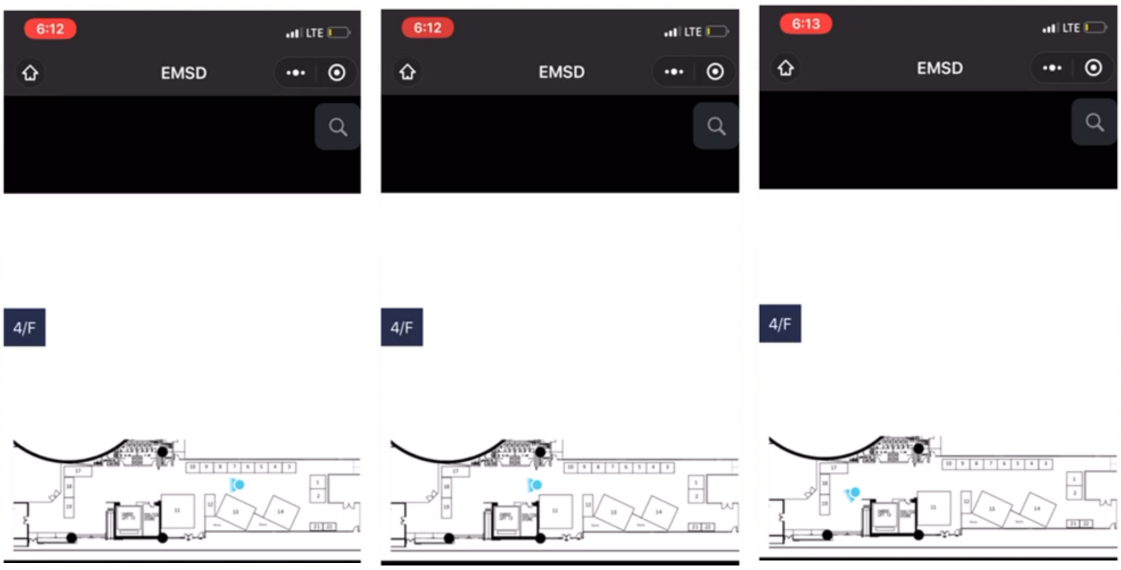

Fig. 11. Demo Video of the presented IPS

Remark #2:

a. One of the issues that we found was that the predicted location of the user may sometimes move around within 3-5 dot distance, even though the user was standing in the same location. This issue was only present in Android devices.

b. Although the IPS in previous project seems to have smaller latency, the mobile app could not be accessible from some widely downloaded app (like WeChat app), and suffered from a larger accuracy error. Due to the limitations of WeChat layer and the Android OS, the current Android version IPS application has a slightly slower user responses, but with high accessibility through WeChat and a higher location accuracy.

Fig. 12. Asset location report in the CP cloud

Besides the IPS, we have deployed an asset-tracking system as shown in Fig. 13. In this system, the position and condition of each asset can be remotely monitored in cloud like Fig. 12, both stationary and mobile components can be represented as

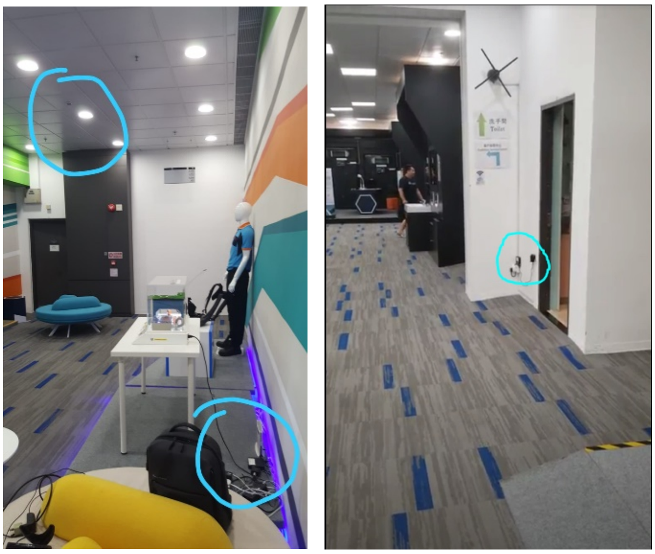

Fig. 13. Installation position of asset tracker

assets. The asset trackers are constantly scanning for the luXbeacons registered on CP Cloud and reports its existence within the coverage zone to the cloud every 5 minutes. In our project, asset trackers are deployed in 4/F to monitor our assets, the luXbeacon deployed at the ceiling of 4/F, by their advertisement signal. All existence and location of luXbeacons can be monitored in the cloud to ensure the setting of IPS is not affected.

To put our asset tracking feature into practice, we have deployed two luXbeacons on robots that are being demonstrated on 4/F. The luXbeacons are deployed on top of each robot and can be tracked by the two asset trackers as show in Fig 14. After the deployment, the current location of the two robots can be remotely checked through CP Cloud platform. The platform can tell whether the robots are currently located on 4/F and their closeness to the two asset trackers. The locations of the assets are updated in the cloud every 4-6 minutes. However, this update frequency can be configured accordingly to cater the need of the application at a cost of increased server loading and network traffic.

Fig. 14. Two robots on 4/F deployed with luXbeacon

The demonstrated asset tracking system can help to manage those mobile assets that could be hard to locate/keep track due to frequent usage from different groups of users. Furthermore, thanks to the luXbeacon's energy harvesting capability and its sustainable operation in the absence of battery sources, the asset can be reliably tracked without having to worry about its power failure. Furthermore, the asset's historical record can be logged and inquired on the cloud to check its previous or last seen locations.

To prove the functionality of the presented system, we have conducted a few experiments with the two robots. Our experiments consist of three steps. Firstly, a robot is moved into the asset tracker's coverage zone. Second, the robot is moved from one tracker's zone to the other. Lastly, the robot is removed from both of the trackers' zone. The experiment steps are summarized in Table 9.

Steps	Descriptions	Expected Outcome
1	Move the robot into the tracker 1 coverage zone.	The robot detected by tracker 1
2	Move the robot from tracker1 coverage zone to tracker 2	The robot detected by tracker 2
3	Remove the robot from tracker 2 coverage zone	The robot not detected

Table. 9. Experiment procedures for asset trackers

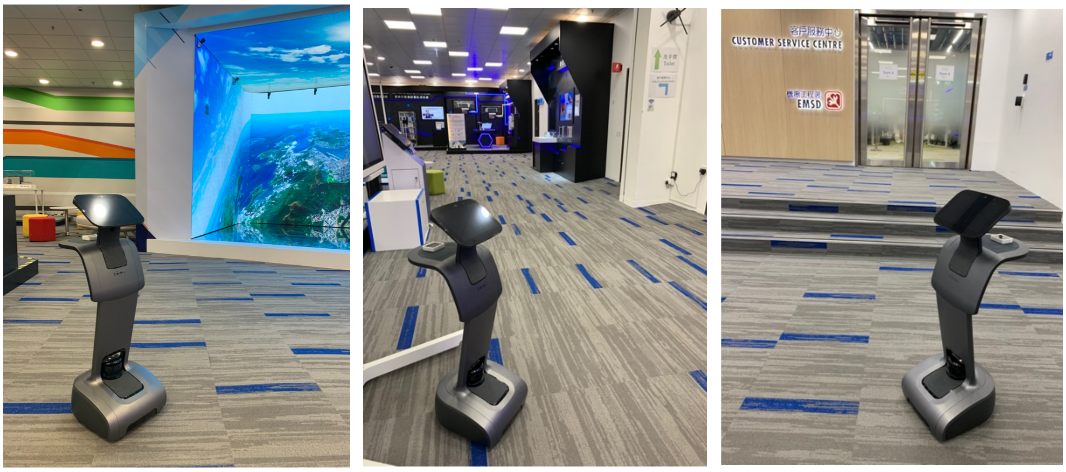

Fig. 15. Photos of different locations used for the experiment

Based on the above procedures, we have conducted two trials of the experiments. Fig. 15 shows the locations we have used in the experiment for each step. The results are shown in Table 10. We could successfully detect the existence of two different robots by the 2 asset trackers deployed on 4/F. Fig. 16 shows the report from the CP Cloud during the experiment.

Steps	Trial 1 Results	Trial 2 Results
1	The robot 1 detected by tracker 1	The robot 2 detected by tracker 1
2	The robot 1 detected by tracker 2	The robot 2 detected by tracker 2
3	The robot 1 not detected	The robot 2 not detected

Table. 10. Experimental results

Step 1

Detector	Detected Assets
BLE Detector 2 (EMSD)	20201x20204x, 20202x20204x, 20205x20203x
BLE Detector 1 (EMSD)	Robot1, 20202x20203x, 20203x20209x, 20205x20201x

Step 2

Detector	Detected Assets
BLE Detector 2 (EMSD)	20201x20204x, Robot1, 20202x20204x, 20205x20203x
BLE Detector 1 (EMSD)	20202x20203x, 20203x20209x, 20205x20201x

Step 3

Detector	Detected Assets
BLE Detector 2 (EMSD)	20201x20204x, 20202x20204x, 20205x20203x
BLE Detector 1 (EMSD)	20202x20203x, 20203x20209x, 20205x20201x

Fig. 16. CP Cloud reporting asset location during the experiment

In the future, we plan to improve our asset tracking system with following features: 1) visual interface for the users to locate the assets quickly; and 2) deployment of multiple asset trackers to enable high resolution localization of the asset. Since our current system, as shown in Fig. 16, displays the location of the assets mainly through text, the user interface may not be user friendly and difficult to use when multiple assets are located across a large area. By mediating this issue with much more user-friendly graphic interface, we aim to make the asset tracking system much easier to use and at the same time to support wider range of applications. Furthermore, we plan to extend the proposed system that includes more number of asset trackers to support finer resolution asset tracking.

Deliverable 3: Smart Demo Introduction System

A smart demo introduction system that can send push message to user app is designed and setup on the 4/F in EMSD Headquarter (HQ). A mobile application, called CPPush and shown in Fig. 17, is developed to receive customized messages from luXbeacons deployed in 4/F. When we launch the app and come close to the beacon, a message will be pushed to the phone. Furthermore, a content management system (CMS), called CPCloud, is developed to allow change of luXbeacons messages. Using the CPCloud allow the management of devices and push messages. Users can simply change another message on CPCloud and the set message will be pushed to the user phone when they repeat the action (come close to the beacons).

Fig. 17. CPPush App in App store

In the demonstration, users receive customized push messages (video/images/text) from CPPush app when they approach the inno-zone area. Push messages can be received are changed after the content of luXbeacon is changed in the CMS shown in Fig. 18.

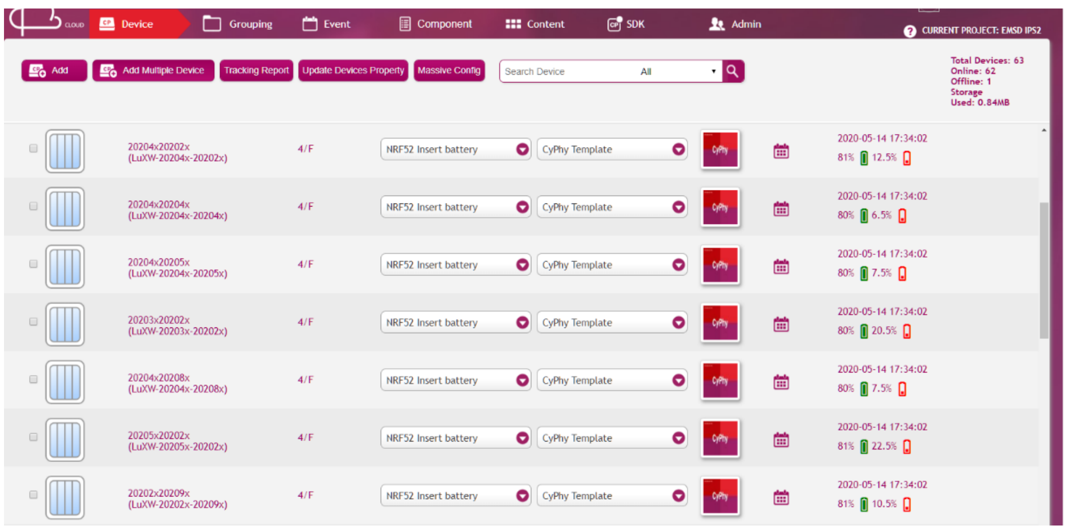

Fig. 18. Smart video introduction system CMS

Conclusion and Way Forward

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. We showed that all locations can operate well with luXbeacon even in poor light condition while supporting the IPS application on par with battery-powered infrastructure and with high accuracy of on average ±5.5m Furthermore, all the beacons equipped with backup battery enjoyed around 2 month of battery lifetime extension thanks to the luXbeacon technology. For future works, we will 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.

In order to address the issues that we have observed with limited energy storage capacity with luXbeacons deployed on 6/F & 7/F, we have proposed and manufactured a novel dual supercapacitor luXbeacon, named luXb-d, which allows to extend the operation lifetime of the luXbeacon nearly 185%.

To complement to the luXbeacon-based IPS coverage established in last EMSD project (S-0051), this project has also extended luXbeacon-based IPS coverage in the InnoZone at 4/F. The positioning performance could reach +/- 5.5 meter between the actual position and indicated position in the mobile application. Another mobile application is developed to provide the positioning and navigation services. It proved that the luXbeacon hardware (with and without batteryless) is effective to offer the batteryless or green IoT infrastructure for such performance demanded application (i.e., the beacon devices are operating at 100ms with -8dBm to -12dBm) like IPS.

Besides from IPS, luXbeacons have been used in an asset tracking system to track the 2 robots provided by EMSD. Two asset trackers are deployed on 4/F to trace the locations of both luXbeacon attached robots. In the demonstration, the remote monitoring system can react to the change of asset location within around 5 minutes and show a correct position of the updatest location of robots.

A luXbeacon-based proximity notification system is also setup and developed, which serves a smart demo introduction system to notify nearby visitors about the demo available in 4/F InnoZone area. A visitor will can receive some pushed messages about a demo with some briefing video or other multimedia information as well as the direction to approach the demo booth from his location.

Acknowledgement

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[Name of Divisions or SBUs]

Electrical and Mechanical Services Department

[Date of Report]

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