Attendance Tracking System using Many Battery-free Photovoltaic Bluetooth Beacon Badges

Chenyang Wu
School of Information Science and Technology, ShanghaiTech University
Shanghai, China
wuchy2022@shanghaitech.edu.cn

Lei Che
School of Information Science and Technology, ShanghaiTech University
Shanghai, China
chelei1@shanghaitech.edu.cn

Siyu Jin
School of Information Science and Technology, ShanghaiTech University
Shanghai, China
jinsy@shanghaitech.edu.cn

Cheng Tian
School of Information Science and Technology, ShanghaiTech University
Shanghai, China
tiancheng2022@shanghaitech.edu.cn

Gongwei Wang
School of Information Science and Technology, ShanghaiTech University
Shanghai, China
wanggw2022@shanghaitech.edu.cn

Siyang Liu
School of Information Science and Technology, ShanghaiTech University
Shanghai, China
liusy2022@shanghaitech.edu.cn

Xin Li
Guangzhou Research Institute, Xidian University
Guangzhou, China
lixin01@xidian.edu.cn

Guobiao Hu
IoT Thrust, Hong Kong University of Science and Technology (Guangzhou)
Guangzhou, China
guobiaohu@hkust-gz.edu.cn

Lihua Tang
Department of Mechanical and Mechatronics Engineering, the University of Auckland
Auckland, New Zealand
l.tang@auckland.ac.nz

Junrui Liang*
School of Information Science and Technology, ShanghaiTech University
Shanghai, China
liangjr@shanghaitech.edu.cn

Abstract

The concept of *ambient IoT* was introduced by 3GPP to describe low-cost, self-powered, or battery-free sensor nodes, which may reach up to 10 trillion units in the future. By replacing chemical batteries in many standalone IoT devices, we can achieve ubiquitous connectivity through environmentally friendly and maintenance-free solutions. This paper presents a systematic design of an attendance tracking system utilizing battery-free photovoltaic (PV) Bluetooth beacon badges, along with several stationary gateways. In particular, the experiences with real-world massive deployments of these battery-free Bluetooth badges are emphasized. Thanks to a customized power management design that experiences only nano-watt power leakage before activation, these beacon badges can operate in low-light environments by gradually accumulating energy from indoor lighting, functioning in conditions as low as 17 Lux. The design prioritizes cost-effectiveness, making these badges suitable for potential commercialization, with each compact badge measuring only 40 × 30 × 4 mm^3 and a bill of materials (BOM) costing less than \$1. In field tests, every attendee at an academic conference wore a souvenir battery-free PV badge, which broadcasted a packet once sufficient power was accumulated. Stationary gateways installed in various conference rooms collected attendance information, while a cloud-based program was developed to visualize the results.

Keywords

Attendance tracking, battery-free, ambient IoT, BLE beacon

ACM Reference Format:
Chenyang Wu, Lei Che, Siyu Jin, Cheng Tian, Gongwei Wang, Siyang Liu, Xin Li, Guobiao Hu, Lihua Tang, and Junrui Liang*. 2024. Attendance Tracking System using Many Battery-free Photovoltaic Bluetooth Beacon Badges. In *International Workshop on Energy Harvesting and Energy-Neutral Sensing Systems (ENSsys '24), November 4–7, 2024, Hangzhou, China.* ACM, New York, NY, USA, 6 pages. https://doi.org/10.1145/3698384.3699613

1 Introduction

With the rapid growth of the Internet of Things (IoT), the number of IoT end devices has surged, raising concerns about maintenance and environmental impact due to their reliance on chemical batteries. To address these challenges, ambient IoT systems have emerged, focusing on developing battery-free or self-powered devices that can operate sustainably by scavenging energy from their surroundings. Traditional indoor crowd monitoring methods have primarily

---

ENSsys '24, November 4–7, 2024, Hangzhou, China

ACM ISBN 979-8-4007-1296-8/24/11
https://doi.org/10.1145/3698384.3699613

relied on cameras for human detection or WiFi gateways to estimate the number of connected smart devices. However, these approaches can be costly and raise privacy concerns. Cameras, in particular, may expose excessive personal information. At the same time, WiFi-based methods overlook populations, such as school-aged teenagers, who may not consistently carry or be permitted to carry smart devices.

This paper presents a low-cost, maintenance-free indoor attendance tracking and monitoring system that eliminates the risk of privacy leakage. The system is designed for scenarios such as academic conferences or high school visits to universities on open days, where participants are equipped with identity badges. It consists of photovoltaic (PV)-powered Bluetooth name badges, signal receivers, and a cloud platform for visualization. The PV badges harvest indoor light energy to transmit Bluetooth packets, and the number of packets received by the signal receivers is used to estimate and track the number of attendees near each receiver.

We deployed this system in six rooms during the 5th International Conference on Vibration and Energy Harvesting Applications (VEH 2024), held on June 26–29, 2024, in Auckland, New Zealand. The experimental results demonstrated that the system can effectively monitor attendance trends throughout the events.

The main contributions of this paper are summarized as follows:

- **Customized Energy Management:** Thanks to a tailored energy management unit, this self-powered system operates effectively in very low-light environments, with a minimum lighting intensity threshold as low as 17 Lux. This feature makes the system suitable for various indoor applications.
- **Cost-Effective Solution:** We propose a reasonably cost-effective system for battery-free indoor attendance tracking, comprising numerous movable Bluetooth Low Energy (BLE) beacon badges, several receiving gateways, and a cloud platform for data visualization.

2 Related Work

In recent years, the rapid development of the IoT has led to a significant increase in the number of node devices used for data transmission, forming Wireless Sensor Networks (WSN). However, the proliferation of these energy-consuming devices presents several challenges. Notably, many of these devices rely on batteries for continuous operation and data transmission. As the number of IoT devices continues to grow, the costs associated with battery replacement and pollution management become increasingly burdensome. Harvesting energy from the ambient environment offers a viable solution to these issues. Consequently, a growing number of studies are focusing on ambient IoT systems, employing various energy-harvesting techniques to power end nodes. These techniques include solar energy [4], kinetic energy [3], thermal energy [13], and Radio Frequency (RF) energy [10], among others.

Among the various energy harvesting methods, solar energy remains the most popular and reliable solution. As urbanization progresses, people are spending increasing amounts of time indoors. Given that indoor lighting is typically sufficient when people are present, artificial light can also be harvested and utilized. Consequently, several studies have begun to explore the potential of harvesting indoor solar energy to power IoT devices [1, 2].

Many studies on crowd population monitoring have focused on two primary methodologies. The first involves using cameras and computer vision to detect individuals in a given environment. For instance, in [11], a low-memory model for crowd counting on embedded platforms was introduced, utilizing a custom lightweight version of YOLOv5 and an architecture based on ShuffleNetV2. Similarly, [5] proposed a real-time intelligent monitoring method based on deep learning and spatial division, achieving comprehensive and accurate real-time monitoring of evacuee distribution across indoor spaces.

The second approach leverages wireless communication technologies, such as Bluetooth or WiFi, to access signals from smart devices carried by individuals. This method exploits WiFi or Bluetooth probe packets sent by these devices. For example, [12] employed commercial WiFi scanners connected to edge devices and used virtual network functions to process data collected by an IoT platform, enabling accurate people counting and mobility detection. The system described in [7] localized users and detected crowd movement using probe counts with an average accuracy of 7.28 meters.

To address privacy concerns, [14] combined Bloom filters for set membership testing with homomorphic encryption, allowing secure and oblivious operations under encryption. While randomizing MAC addresses in passive probe sessions can protect user privacy, it complicates crowd tracking and behavioral analysis. Nonetheless, [6] achieved sufficient accuracy in tracking visitor movements in a multi-floor museum, even when devices used randomized MAC addresses. The latter approaches rely on WiFi-enabled smart devices, which do not account for situations where individuals either do not carry smart devices or have WiFi probing turned off, such as high school students visiting university labs.

Several studies have also focused on energy-harvesting beacons. For example, [9] introduced a beacon measuring $67 \times 57 \times 11$ mm^3, incorporating a 58.1×64.4 mm^2 solar panel and two integrated circuits (ICs): the S6AE103A for power management and the nRF51822 for Bluetooth Low Energy (BLE) functionality. This beacon can charge under light intensities as low as 40 Lux and broadcast packets at predetermined intervals. However, it has a relatively long charging time compared to its discharging time under low light conditions. Another study, [16], proposed a real-time indoor light illuminance evaluation system using photovoltaic beacons designed to grade light levels above 30 Lux, utilizing a three-transistor energy management (3T-EM) circuit for energy management and an nRF52832 for BLE broadcasting. Additionally, [8] implemented a photovoltaic beacon within the size of $66.4 \times 56.9 \times 18.5$ mm^3, integrating a 58×65 mm^2 solar panel and a 120-mAh backup battery. These beacons transmit sensor data, with solar energy harvesting extending battery life and a sensing interval of one sample per minute for greenhouse monitoring.

In summary, there is currently no battery-less device-based crowd-tracking system specifically designed for many battery-free end devices in indoor environments. Existing beacon systems for low-light indoor conditions cannot operate in environments with light intensity below 30 Lux, which is quite common in indoor conferences. We have carefully selected components optimized for indoor light energy harvesting, minimizing unnecessary energy

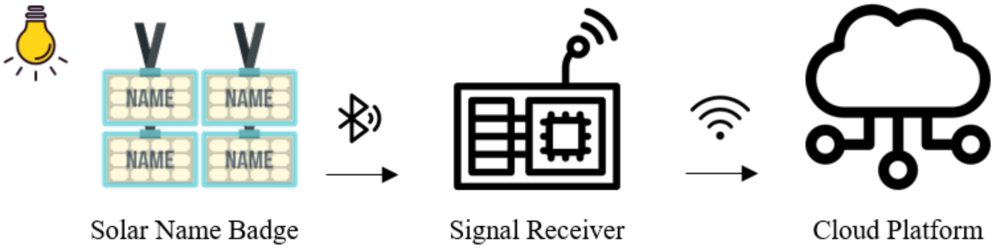


Figure 1: System architecture.

Figure 2: Prototype of a PV-powered Bluetooth badge.

consumption to ensure that the devices can function properly under the lowest possible light intensity.

3 Proposed System

The Bluetooth SIG has projected that the total addressable market for Ambient IoT will exceed 10 trillion devices across various sectors. As a result, very low-cost solutions are essential for the widespread adoption of these self-sustaining devices. In this section, we introduce a low-cost, battery-free, PV-powered Bluetooth badge designed for an attendance tracking system. This system enables the analysis of dynamic human movement in indoor environments, making it ideal for scenarios where participants move between multiple rooms while wearing identification badges. Such applications include academic conferences, product exhibitions, campus open days, and similar events.

3.1 System Architecture

The block diagram of the proposed indoor attendance tracking system is illustrated in Fig. 1. The system comprises several key components: multiple battery-free, PV-powered Bluetooth badges worn by attendees, signal-receiving gateways installed in various rooms, and a cloud platform equipped with a visualization program. Each badge features a PV panel and a printed circuit board assembly (PCBA) that contains an energy management circuit (EMC) and a Bluetooth Low Energy (BLE) system on chip (SoC). The PV panel harvests energy from indoor light sources, while the EMC stores the generated electrical current. Once sufficient energy is accumulated, it is released at a regulated voltage to power the BLE SoC, which broadcasts BLE data packets. Signal-receiving gateways in each room collect nearby data packets. After minimal processing, these gateways transmit the data to the cloud platform via WiFi for further analysis and visualization.

3.2 PV-powered Bluetooth badge

Fig. 2 shows the front and rear views of a PV-powered badge, as well as the attachment to the conference lanyard.

3.2.1 Photovoltaic Panel. To achieve a good compromise between low-cost design and effective performance under indoor lighting conditions, an off-the-shelf amorphous silicon solar cell (model SC-3722-9) has been selected for energy harvesting purposes. The panel consists of nine sub-cells stacked in series, providing an open-circuit voltage of 4.5 V and a short-circuit current of 10 μA under an illumination level of 200 Lux and a temperature of 25°C.

3.2.2 Energy Management Circuit (EMC). The selected energy management circuit, 3T-EM [15], employs just three transistors to perform all essential functions required in energy-harvesting (EH) powered IoT scenarios, including energy awareness, load switching, and voltage regulation. It can successfully start with an input current as low as 0.4 μA, making it highly suitable for indoor light energy harvesting tasks.

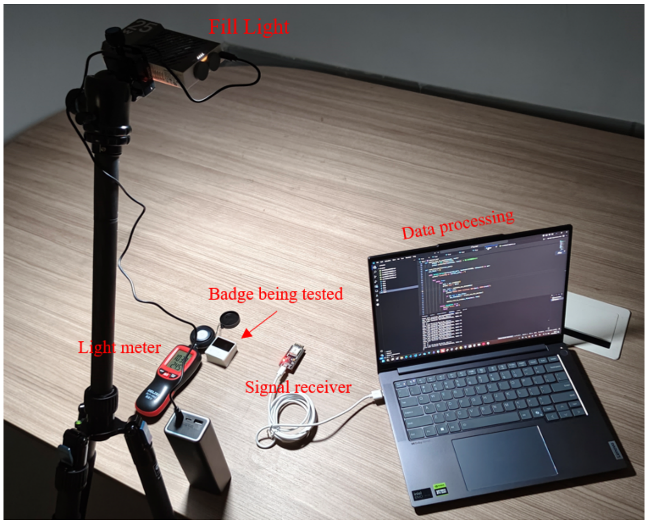


Figure 3: Experiment setup of single badge evaluation.

3.2.3 System on Chip (SoC). The selected System on Chip (SoC) is the NanoBeacon^{TM} IN100-D1-R-RC0I by Inplay Ltd., an ultra-low-power and low-cost Bluetooth sensor beacon SoC. The chip costs about \$0.4. It is the most expensive part of the bill of materials (BOM) (the whole assembly costs about \$1.0). The IN100 chip can be configured to automatically transmit Bluetooth Low Energy (BLE) advertising packets at a battery voltage as low as 1.1 V. Its compact size of 2.5 × 2.5 mm² makes it particularly suitable for this system. The packet structure is efficient, containing only essential information such as device names and MAC addresses. The chip supports a minimum advertising interval of 20 ms and a transmission power ranging from -54 to +5 dBm. It is important to note that while lower transmission power reduces power consumption, it also affects transmission coverage. To achieve adequate coverage for a conference hall, a transmission power of +2 dBm has been selected. Given the methodology of consuming power to broadcast Bluetooth signals as soon as sufficient energy is available, the minimum advertising interval is set to 1.0 second. This configuration effectively meets the requirements for most indoor conferences.

3.3 Signal Receiver

The selected signal receiver is an ESP32 module by Espressif Systems Ltd., which features both Bluetooth and WiFi communication capabilities. It serves as an important intermediary gateway by receiving local Bluetooth data packets and transmitting the data to the cloud platform via WiFi. Its working flow is illustrated in Fig. 4. Multiple signal receivers will be strategically placed throughout the indoor environment to ensure that their coverage areas encompass as much space as possible, while also preventing the same Bluetooth signal from being received by multiple receivers. Whenever a signal receiver captures a BLE packet containing a device's MAC address, it can be inferred that the device was present near that receiver's location during that period. The MAC address is then recorded in a list, where the length of the list represents the number of devices detected. By clearing this list at appropriate intervals, the number of people present within the corresponding period can be determined.

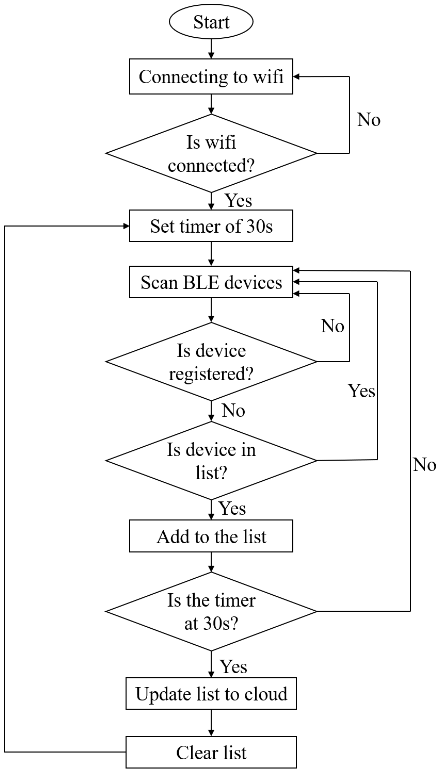


Figure 4: Flow chart of a signal receiver.

3.4 Cloud Platform

The cloud platform selected for online visualization and demonstration is OneNET by China Mobile Ltd. OneNET is an integrated platform that provides comprehensive IoT services. We primarily utilized its visualization interface to display the number of people in each indoor room in "real-time" at editable intervals, set to 30 seconds for this field test.

4 Experimental Evaluation

The experiment of the entire system can be divided into two parts. The first part is the evaluation of a single badge, which includes testing the operational light intensity of the badge and the successful reception rate of Bluetooth broadcast packets. The second part involves a field test of the whole system, where participants are provided with solar badges. Six signal receivers are strategically arranged in the indoor environment for crowd monitoring. The network environment is configured to upload data to the cloud in real-time for display.

4.1 Single-badge Evaluation

The single badge test is primarily conducted to assess the illumination range required for system operation, which helps determine the refresh interval for signal receivers. As shown in Fig. 3, a fill light

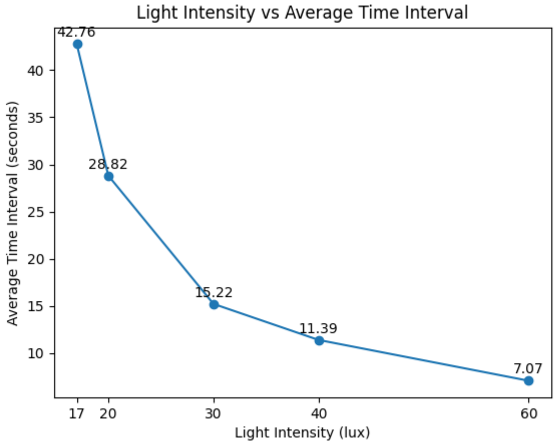


Figure 5: Result of single badge evaluation.

with multiple lamp beads is used as the sole light source in a completely dark environment. The badge being tested and a light meter are symmetrically positioned under the fill light, with the badge placed at the same height as the light probe. An ESP32, serving as a signal receiver, is placed nearby to collect the badge's packets, record timestamps, and calculate time intervals under different light intensities. The results are shown in Fig. 5; the beacon badge can broadcast once every 43 seconds at a light intensity as low as 17 Lux. Therefore, the refresh interval for visualization could be set at 30 seconds, corresponding to light intensities above 20 Lux, which is particularly common in the edges and corners of a conference room.

4.2 Field Test

This system was field-tested during the 5th International Conference on Vibration and Energy Harvesting Applications (VEH 2024), with data recorded over three days. Each participant was provided with a compact solar-powered Bluetooth badge displaying their name, as shown in Fig. 2. Six ESP32 devices were strategically placed in two main halls (Foyer and Lecture Theatre OGGB4) and four breakout rooms (Caseroom 1-4). The refresh interval was set to 30 seconds, and each ESP32 uploaded the list of nearby devices to the cloud to display the number of attendees in each room within 50 minutes, as illustrated in Fig. 6.

As shown in Fig. 7, the data collected reveals the trend of crowd population in Case Rooms 2 and 4 during the conference from 9:45 to 11:30 on June 27. The crowd data collected can be used for further analysis, such as comparing the popularity of presentations on different topics or simply confirming whether the activity has started normally. Additionally, if the displayed number of attendees is abnormal, staff can be dispatched to investigate promptly.

5 Conclusion and Future Works

Real-time visualization and further data analysis are both crucial for indoor crowd population monitoring. This paper presents a low-cost, maintenance-free, non-invasive alternative for indoor crowd tracking. The system is composed of self-powered name badges, signal receivers, and a cloud platform. The self-powered name badges harvest ambient light energy to broadcast Bluetooth packets, while the signal receivers collect these packets and upload the information to the cloud for data visualization. A field test was conducted to validate this idea and its feasibility in real-world applications. The recorded data can be utilized for further analysis to provide customized services.

Moreover, those largely distributed self-powered BLE badges are maintenance-free and environment-friendly. It closely meets the recent call on ambient IoT realizations. By optimizing the system configuration, the solution ensures real-time statistics on the number of attendees during conferences, even under the lowest light conditions in conference rooms.

In the future, we plan to further optimize the system's energy consumption at both the hardware and software levels. From the software perspective, we can simplify the Bluetooth chip operations and packet content by removing unnecessary code and information carried by each packet, thereby reducing the energy required for packet transmission and shortening the transmission interval at the same light intensity. We will also consider hardware adjustments, such as optimizing capacitor sizes to balance quick packet transmission upon energy receipt against improved reception success rates, albeit at the cost of reduced transmission efficiency. Additionally, we will systematically test the performance of the badges under different light intensities and spectral ranges. We will also optimize the badge design to minimize antenna obstruction during wear, thereby enhancing the effective reception range.

References

[1] Johann Bouclé, Daniel Ribeiro Dos Santos, and Anne Julien-Vergonjanne. 2023. Doing More with Ambient Light: Harvesting Indoor Energy and Data Using Emerging Solar Cells. *Solar* 3, 1 (2023), 161–183. https://doi.org/10.3390/solar3010011

[2] Abhisek Chakraborty, Giulia Lucarelli, Jie Xu, Zeynab Skafi, Sergio Castro-Hermosa, A.B. Kaveramma, R. Geetha Balakrishna, and Thomas M. Brown. 2024. Photovoltaics for indoor energy harvesting. *Nano Energy* 128 (2024), 109932. https://doi.org/10.1016/j.nanoen.2024.109932

[3] Zijie Chen, Fei Gao, and Junrui Liang. 2022. Kinetic energy harvesting based sensing and iot systems: a review. *Frontiers in Electronics* 3 (2022), 1017511.

[4] Maisagalla Gopal, T Chandra Prakash, N Venkata Ramakrishna, and Bonthala Prabhanjan Yadav. 2020. IoT Based Solar Power Monitoring System. *IOP Conference Series: Materials Science and Engineering* 981, 3 (dec 2020), 032037. https://doi.org/10.1088/1757-899X/981/3/032037

[5] Litao Han, Hengjian Feng, Guoyu Liu, Aiguo Zhang, and Tao Han. 2024. A real-time intelligent monitoring method for indoor evacuee distribution based on deep learning and spatial division. *Journal of Building Engineering* 92 (2024), 109764. https://doi.org/10.1016/j.jobe.2024.109764

[6] Hande Hong, Girisha Durrel De Silva, and Mun Choon Chan. 2018. CrowdProbe: Non-invasive Crowd Monitoring with Wi-Fi Probe. *Proc. ACM Interact. Mob. Wearable Ubiquitous Technol.* 2, 3, Article 115 (sep 2018), 23 pages. https://doi.org/10.1145/3264925

[7] Nicholas Jarvis, John Hata, Nicholas Wayne, Vaskar Raychoudhury, and Md Osman Gani. 2019. MiamiMapper: Crowd Analysis using Active and Passive Indoor Localization through Wi-Fi Probe Monitoring *(Q2SWinet'19)*. Association for Computing Machinery, New York, NY, USA, 1–10. https://doi.org/10.1145/3345837.3355959

[8] Kang Eun Jeon, Tsz Ngai Lin, James She, Simon Wong, Rajesh Govindan, Tareq Al-Ansari, and Bo Wang. 2023. LuXSensing Beacon: Batteryless IoT Sensor, Design Methodology, and Field Test for Sustainable Greenhouse Monitoring. *IEEE Transactions on AgriFood Electronics* 1, 2 (2023), 86–98. https://doi.org/10.1109/TAFE.2023.3295383

[9] Kang Eun Jeon, James She, Jason Xue, Sang-Ha Kim, and Soochang Park. 2019. luXbeacon—A Batteryless Beacon for Green IoT: Design, Modeling, and Field Tests. *IEEE Internet of Things Journal* 6, 3 (2019), 5001–5012. https://doi.org/10.1109/JIOT.2019.2894798

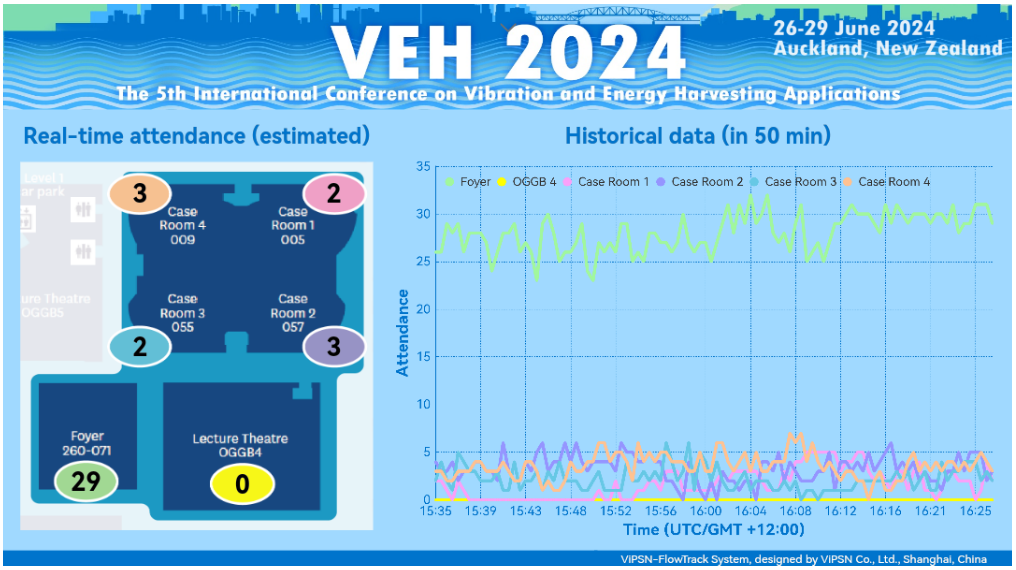
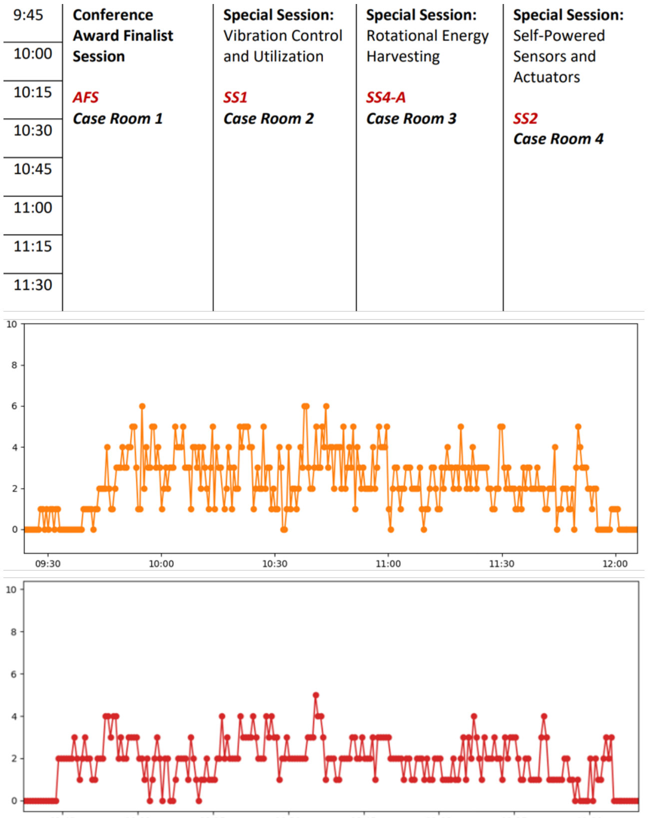


Figure 6: Visualization of real-time estimated attendance.



9:45	**Conference Award Finalist Session** *AFS* *Case Room 1*	**Special Session:** Vibration Control and Utilization *SS1* *Case Room 2*	**Special Session:** Rotational Energy Harvesting *SS4-A* *Case Room 3*	**Special Session:** Self-Powered Sensors and Actuators *SS2* *Case Room 4*
10:00				
10:15				
10:30				
10:45				
11:00				
11:15				
11:30				

Figure 7: Data collected for further analysis

[10] Gholamhosein Moloudian, Mohammadamin Hosseinifard, Sanjeev Kumar, Roy B. V. B. Simorangkir, John L. Buckley, Chaoyun Song, Gualtiero Fantoni, and Brendan O’Flynn. 2024. RF Energy Harvesting Techniques for Battery-Less Wireless Sensing, Industry 4.0, and Internet of Things: A Review. *IEEE Sensors Journal* 24, 5 (2024), 5732–5745. https://doi.org/10.1109/JSEN.2024.3352402

[11] Alexios Papaioannou, Charalampos S. Kouzinopoulos, Dimosthenis Ioannidis, and Dimitrios Tzovaras. 2023. An Ultra-low-power Embedded AI Fire Detection and Crowd Counting System for Indoor Areas. *ACM Trans. Embed. Comput. Syst.* 22, 4, Article 61 (jul 2023), 20 pages. https://doi.org/10.1145/3582433

[12] Valentin Radu, Lito Kriara, and Mahesh K. Marina. 2013. Pazl: A mobile crowdsensing based indoor WiFi monitoring system. In *Proceedings of the 9th International Conference on Network and Service Management (CNSM 2013)*. 75–83. https://doi.org/10.1109/CNSM.2013.6727812

[13] V.P. Singh, M. Kumar, R.S. Srivastava, and R. Vaish. 2021. Thermoelectric energy harvesting using cement-based composites: a review. *Materials Today Energy* 21 (2021), 100714. https://doi.org/10.1016/j.mtener.2021.100714

[14] Valeriu-Daniel Stanciu, Maarten van Steen, Ciprian Dobre, and Andreas Peter. 2021. Privacy-Preserving Crowd-Monitoring Using Bloom Filters and Homomorphic Encryption. In *Proceedings of the 4th International Workshop on Edge Systems, Analytics and Networking* (Online, United Kingdom) *(EdgeSys ’21)*. Association for Computing Machinery, New York, NY, USA, 37–42. https://doi.org/10.1145/3434770.3459735

[15] Li Teng, Haoyu Wang, Yu Liu, Minfan Fu, and Junrui Liang. 2024. A Three-Transistor Energy Management Circuit for Energy-Harvesting-Powered IoT Devices. *IEEE Internet of Things Journal* 11, 1 (2024), 1301–1310. https://doi.org/10.1109/JIOT.2023.3289091

[16] Cheng Tian, Zijie Chen, and Junrui Liang. 2024. A Battery-free and Sensorless Photovoltaic Tag for Real-time Indoor Light Illuminance Evaluation. In *2024 IEEE International Symposium on Circuits and Systems (ISCAS)*. 1–5. https://doi.org/10.1109/ISCAS58744.2024.10557975