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OPTIMAL BLUETOOTH LOW ENERGY (BLE) SYSTEM DEPLOYMENT STRATEGY PRIOR TO SYSTEM APPLICATION ON THE CONSTRUCTION SITE

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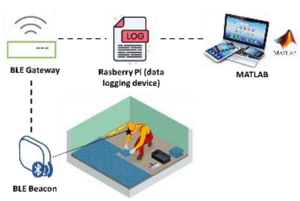
Graphical abstract



Abstract

The application of Bluetooth Low Energy (BLE) systems for labour tracking on construction sites is a popular research trend. Strategic system deployment is crucial for ensuring the overall reliability and feasibility of these systems. This study aims to identify the optimal BLE system deployment strategy for tiling work zones in three different renovation sites. The BLE system consists of BLE beacon, BLE gateway, Raspberry Pi (data logger), and MATLAB for data analysis. To ensure optimal placement of the BLE gateway, site visits were conducted to evaluate various conditions, such as power supply availability, signal blockage by structures, and potential disruption to the tiling work. In addition, the beacon transmission (Tx) levels were adjusted to enhance the detection accuracy of the system. The findings show that the optimum beacon Tx powers at sites A, B, and C are -12dBm (86.3% accuracy), -16dBm (94.6% accuracy), and -16dBm (91.1% accuracy), respectively. These findings will be adopted in future research on these sites. The study contributes to the understanding of optimal BLE system deployment strategies in construction sites, which can improve labour tracking accuracy and overall project management.

Keywords: BLE, labour tracking, deployment, transmission power, accuracy

Abstrak

Aplikasi sistem Bluetooth Low Energy (BLE) untuk pengesanan buruh di tapak pembinaan merupakan trend penyelidikan popular. Penempatan strategik sistem adalah penting untuk memastikan keseluruhan kebolehpercayaan dan kelayakan sistem ini. Kajian ini mencari strategi penempatan sistem BLE optimum bagi zon kerja pasang ubin di tiga tapak pengubahsuaian yang berbeza. Sistem BLE terdiri daripada BLE beacon, BLE gateway, Raspberry Pi (data logger), dan MATLAB untuk analisis data. Untuk memastikan penempatan BLE gateway yang optimum, lawatan ke tapak telah dijalankan untuk menilai pelbagai keadaan seperti ketersediaan bekalan kuasa, penghalang isyarat oleh struktur, dan gangguan potensi terhadap kerja pasang ubin. Selain itu, penyesuaian telah dibuat kepada kuasa penghantaran beacon untuk meningkatkan ketepatan pengesanan sistem. Keputusan menunjukkan bahawa kuasa penghantaran beacon optimum di tapak A, B, dan C adalah -16dBm (ketepatan 86.3%), -16dBm (ketepatan 94.6%), dan 8dBm (ketepatan 91.1%), masing-masing. Penemuan ini akan diaplikasikan dalam penyelidikan akan datang di tapak-tapak ini. Kajian ini menyumbang kepada pemahaman strategi penempatan sistem BLE optimum di tapak pembinaan yang dapat meningkatkan ketepatan pengesanan buruh dan pengurusan projek secara keseluruhan.

Kata kunci: BLE, pengesanan buruh, penempatan, kuasa transmisi, ketepatan

1.0 INTRODUCTION

The construction site is a complex workplace that comprises different workforce categories to conduct various types of activities. The construction industry, unlike other sectors, is primarily dependent on workers, also known as labours, to complete a project. Labour tracking is an approach that enables employers to monitor the labour working status and conditions during working hours. The information is useful for the construction management purposes, such as productivity monitoring and safety management [1]. Onsite labour tracking is initiated with manual observation and recording in log sheets from earlier decades [2]–[4]. However, the extra effort and paperwork required are among the top reasons discouraging the industry practitioner from performing labour productivity measurements [5]. Hence, extensive research has been conducted on sensor-based labour tracking in the construction industry [1], [6].

Several common sensors that detect the locations of labour include Global Positioning System (GPS), Radio Frequency Identification (RFID), and Bluetooth Low Energy (BLE). Previous studies classify the working status of the labours based on their staying zones detected by sensors. For example, [7] estimated labour travel time, working time and non-active time by classifying dam construction sites into travel zone, work zone, and non-active zone using GPS. By using passive RFID, [8] were able to identify the worker, material, and equipment close to the buck hoist and estimate the waiting, working, and travelling time. [9]–[11] also used BLE to detect labour presence at work zone to estimate direct work time. The different technologies have unique characteristics, such as the fact that GPS is only useful for outdoor tracking and passive RFID has short-range detection. In contrast, BLE can detect both indoor and outdoor positions and has a wider range than RFID, which is sufficient for covering the labours' staying zone. Among the available technologies, BLE appears to be the best option for indoor labours' presence detection in terms of cost, detection range, and accuracy [9]–[11].

BLE-based labour tracking is conducted by tagging labours with BLE beacons and installing BLE gateways at the targeted zones. The BLE beacon worn by labour acts as a transmitter to broadcast signal and the signal is received by the BLE gateway (receiver) in term of Received Signal Strength Indicator (RSSI). When three or more gateways are installed onsite, the RSSI value can be analysed by trilateration, triangulation, and fingerprinting to identify the beacon coordinates [12]–[14]. When there is only one gateway, the beacon is regarded as being present around the gateway so long as RSSI is detected [9], [10]. System timestamps can then be used to determine the presence time and duration. However, RSSI tends to fluctuate even at a fixed position due to the noise existence by sensors and other external factors like signal absorption, interference, and diffraction [12], [15], [16]. Hence, any existing surface, like walls, materials, and the human body, can cause RSSI signal dispersion and blockage and eventually influence detection accuracy.

Therefore, having a proper system deployment strategy onsite is significant before applying the system to minimise signal blockage and enhance detection accuracy [17]. Besides, previous studies show that adjusting beacon transmission (Tx) power can minimise signal fluctuation [12], [18]. Even though high Tx power leads to a wider detection range, it requires higher battery consumption, shortening the battery lifetime. In addition, high Tx power does not refer to more accurate data due to the aforementioned environmental factors [12], [14]. Hence, it is necessary to adjust the Tx power of the beacons to an appropriate level for each case study prior to application to ensure system reliability and feasibility.

In this study, the authors aim to identify the optimal deployment strategy for a BLE system on three different renovation sites by conducting site visits, identifying ideal gateway deployment spots, adjusting Tx levels, and evaluating the system's performance onsite. To achieve the aim, this research followed the system deployment guideline to deploy the system onsite, collected raw beacon data with different Tx power levels inside and outside the work zone boundary, statistically analysed the beacon detection accuracy based on timestamps using Matlab, and identified the most suitable Tx power. Our findings will guide practitioners on how to deploy BLE-based labour tracking systems in construction sites to maximise accuracy and efficiency.

2.0 METHODOLOGY

2.1 System Architecture

The BLE system used in this study consists of four components, which are the BLE beacon, BLE gateway, Raspberry Pi (data logger), and laptop with MATLAB installed, as illustrated in Figure 1. Table 1 also describes the models, specifications, and configurations of the components.

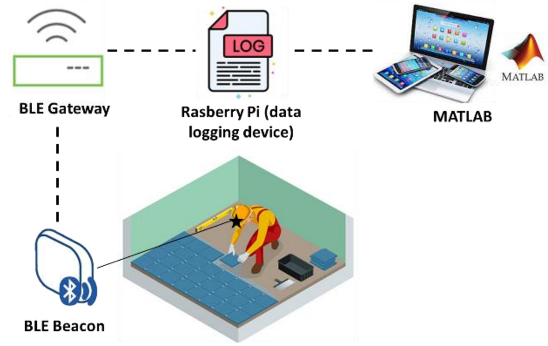


Figure 1 BLE system architecture

Table 1 The models, specifications, and configurations information of the components

Component	Model	Specifications & configuration
BLE Gateway	MKGW1	Wireless standard: IEEE 802.11b/g/n Bluetooth standard: Bluetooth 5.0 Bluetooth scanning range: 120m
BLE Beacon	H7	Main chip: Nordic nRF52 series Range: Up to 150 meters (ideal) Bluetooth standard: Bluetooth 4.2 Dimension: 57.4mm x 41.4mm x 18.7mm Sampling rate: 10Hz Tx power: (to be identified in this study)
Raspberry Pi	B+	Wireless standard: IEEE 802.11b/g/n/ac Bluetooth standard: Bluetooth 4.2
MATLAB	R2022b	-

The process of labour tracking by the four components is as follows: (1) The H7 BLE beacon was attached to the safety helmet, which can be identified by the unique media access control (MAC) address in the system. The beacon carries a battery that broadcasts the data to the surroundings via a BLE radio signal at regular intervals to make the beacon discoverable in the locating system. (2) BLE Gateway: The BLE gateway is the Bluetooth-equipped device that captures the signal transmitted by the beacon. It was deployed onsite at the targeted region. With the power supply to the gateway, the data received from beacons includes time stamps, battery voltage, MAC address, and Received Signal Strength Indication (RSSI). (3) Data logger: The data logger is made of Raspberry Pi and is responsible for receiving and storing data from the gateway for further analysis. (4) laptop with MATLAB installed: The raw data received from the beacons was forwarded to a local computer for display and analysis in MATLAB.

2.2 Subjects

The authors conducted the study at three tiling work zones, known as site A, site B, and site C, of three different renovation sites located in Universiti Teknologi Malaysia (UTM), Johor. While UTM is an established university with a history spanning more than 50 years, the majority of the buildings in the UTM are old and numerous renovation and upgrading projects are currently in progress. Tiling work, as one of the common renovation works, was therefore chosen to conduct this research. Site A, B, and C were selected for this study as they fulfil the criteria of renovation projects involving tiling work within existing buildings. The three tiling work zones studied in this research are are situated within existing buildings, where site A is a toilet (28m^2), site B is an ablution room (85.68m^2), and site C is a lobby (66.6m^2). Site A is smaller in size compared to sites B and C. Additionally, Site A has a greater number of partition walls, which can potentially cause signal blockage in that area. The client for the renovation projects is Jabatan Harta Bina, UTM, and each site employed a different tiling contractor. As a result, the working behavior, methods, and culture of each project are expected to differ. However, this paper presents the preliminary preparation for system deployment, where the labours' working process were not studied. A researcher participated in this preliminary study and was carried out during the labours' lunch break or rest time to prevent interference with the construction process.

2.3 System Deployment Strategy Planning

Prior to applying the BLE system for labour presence tracking, this preliminary study was conducted to determine the optimal deployment strategy for a BLE system on the tiling work zone of the three sites by conducting site visits, selecting the ideal gateway deployment spot, adjusting beacon's Tx levels, and evaluating the system's performance onsite. This study followed the steps outlined in the system manufacturer guide [17] and a previous related study [9] for planning the system deployment on the construction site:

1. To identify the system's purpose, which is to detect labor presence in the tiling work zone.
2. To obtain the renovation site's floor plan and conduct a site walk to understand the current site conditions.
3. To identify the ideal spot for gateway installation based on several criteria, including power supply availability, no disruption to tiling work, and minimum blockage of line of sight.
4. To mount the beacons onto safety helmets.
5. To install the gateway onsite based on the installation plan.
6. To configure the beacons to maximise detection accuracy.

Since the BLE system is deployed for labour presence detection in the tiling work zone in future studies, only one gateway was used and installed at the tiling work zone. During the site walk, the researcher assessed the site layout to determine the best location for gateway installation. Given that a construction or renovation site may not have a permanent power source, the researhcer considered temporary power sources available on the site when selecting the gateway installation location. The gateway was installed at a raised level or hung, without interrupting the tiling zone, and at a spot that was not blocked by walls or obstacles that could influence the system's accuracy. It is important to acknowledge that certain obstruction from pre-existing structures is anticipated given the renovation project's site conditions and varying layout. The researcher then mounted the beacons to the safety helmets and installed the gateway at the determined spot, as shown in Figure 2 and Figure 3.

Figure 2 Gateway placement on Site A, B, and C

Figure 3 Mounting beacon to the safety helmet

Finally, the researcher configured the beacons to the appropriate parameters to ensure the system's reliability and feasibility. The beacon parameters, such as the Tx power and sampling frequency, can affect the system performance. In this study, the sampling frequency was maximized and fixed at 10Hz, which means the signal is measured ten times per second, as higher sampling frequencies are known to provide more accurate data. To determine the optimal Tx power setting for the system's presence detection accuracy, the Tx power was evaluated across various levels, including -40dBm, -20dBm, -16dBm, -12dBm, -8dBm, -4dBm, 0dBm, and 4dBm.

2.4 Data Collection

The ideal spot for gateway deployment was identified following the strategy presented previously, as plotted in Figure 4-6. Next, data collection for Tx power adjustment was carried out. The researcher wore a safety helmet with a sensor attached and stayed stationary at the test points. The test points were randomly chosen depending on the site layout, some of which were within the work zone and others outside of it. It is important to note that, despite the availability of a large work zone at site B, the placement of test points and gateway deployment is restricted to the left-hand side, which is the designated area for research purposes. Each Tx power level was tested for 60 seconds at the test point. When the researcher was staying at the test points within the work zone, the beacon presence should be detected, indicated by the timestamps. On the other hand, when the researcher is staying at the test points outside the work zone, no beacon timestamps should exist for this period. The system hardware arrangement and test points on the three construction sites are as shown in Figure 4-6.

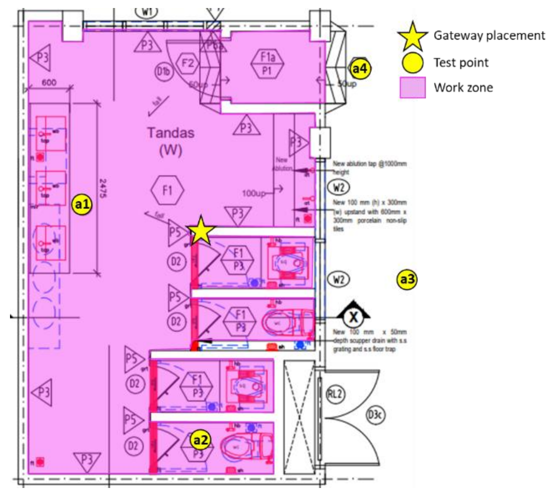


Figure 4 Site A layout

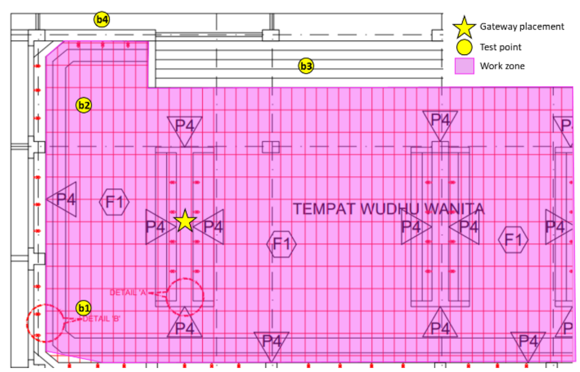


Figure 5 Site B layout

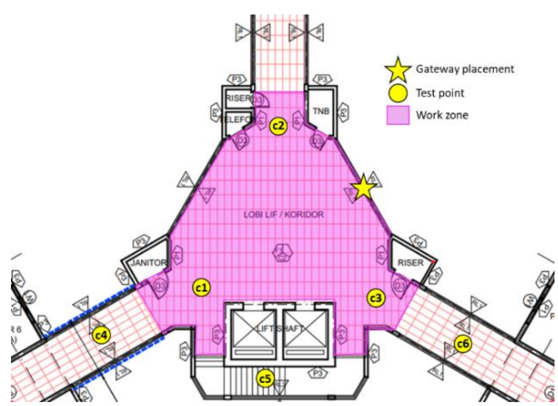


Figure 6 Site C layout

2.5 System's Performance Evaluation

To assess data accuracy, the system's recorded seconds of correct and incorrect detection were compared to the actual position of the researcher [9], [19]. MATLAB R2022b was used to analyse the recorded timestamps and to calculate the detected and non-detected duration at each test point. Then, statistical analysis was conducted on the output data to calculate the true positive, false negative, true negative, false positive, recall, specificity, and accuracy of the presence detection data [19]. The following is a definition of the classification criteria:

- Work zone = A zone where tiles are to be installed.
- Outside work zone = Not work zone.
- True positive: Stay in work zone and is detected in work zone.
- True negative: Stay outside work zone and is not detected.
- False positive: Stay outside work zone but is detected in work zone.
- False negative: Stay in work zone but is not detected.
- Recall: Measures the proportion of "stay in work zone" time that has been correctly identified using Equation 1.
- Specificity: Measures the proportion of "outside work zone" time that has been correctly identified using Equation 2.
- Accuracy: Measures the overall correctness of measurement by calculating the proportion of correct time classification to the total time using Equation 3.

$$Recall = \frac{True\ positive}{True\ positive\ + False\ negative} \quad (1)$$

$$Specificity = \frac{True\ negative}{True\ negative\ + False\ Positive} \quad (2)$$

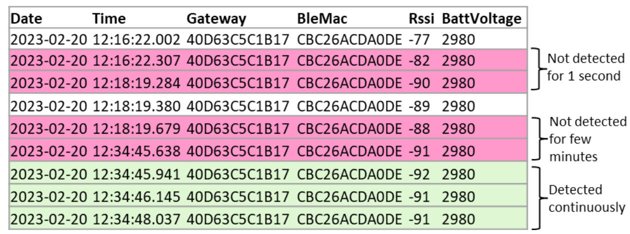
$$Accuracy = \frac{True\ positive + True\ negative}{(True\ positive + True\ negative + False\ positive + False\ negative)} \quad (3)$$

In order to ensure accurate detection of beacons within the designated work zone, it is crucial to utilise an appropriate Tx power level capable of detecting beacons within the work zone while not detecting beacons outside of it. In renovation projects, because the work zones are surrounded by existing walls, signal blockage is expected, leading to non-detection outside work zone. Recall and specificity explains how different Tx power level influences detection accuracy. Through this analysis, the Tx power level that yields the highest detection accuracy can be identified and recommended for future system applications.

3.0 RESULTS AND DISCUSSIONS

3.1 Raw Timestamp Data

Figure 7 displays an example of timestamps recorded in the data logger and demonstrates how presence and absence time can be identified. When the difference between adjacent timestamps is more than 1 second, which indicates no detection, it is considered as absent. In contrast, if the difference between adjacent timestamps is less than 1 second, the duration is considered as present. Table 2 – 4 summarise the results of beacon detected duration at the several test points and Tx levels on Site A, B, and C.



Date	Time	Gateway	BleMac	Rssi	BattVoltage
2023-02-20	12:16:22.002	40D63C5C1B17	CBC26ACDA0DE	-77	2980
2023-02-20	12:16:22.307	40D63C5C1B17	CBC26ACDA0DE	-82	2980
2023-02-20	12:18:19.284	40D63C5C1B17	CBC26ACDA0DE	-90	2980
2023-02-20	12:18:19.380	40D63C5C1B17	CBC26ACDA0DE	-89	2980
2023-02-20	12:18:19.679	40D63C5C1B17	CBC26ACDA0DE	-88	2980
2023-02-20	12:34:45.638	40D63C5C1B17	CBC26ACDA0DE	-91	2980
2023-02-20	12:34:45.941	40D63C5C1B17	CBC26ACDA0DE	-92	2980
2023-02-20	12:34:46.145	40D63C5C1B17	CBC26ACDA0DE	-91	2980
2023-02-20	12:34:48.037	40D63C5C1B17	CBC26ACDA0DE	-91	2980

Figure 7 Example of absence and presence time identification based on timestamps

Table 2 The total detected duration at different test points and Tx levels on Site A

Tx level (dBm)	Total detected duration in 60 secs			
	Test points (inside work zone)		Test points (outside work zone)	
	a1	a2	a3	a4
-40	60	32	13	0
-20	60	17	33	0
-16	60	35	27	0
-12	60	52	25	0
-8	60	17	36	0
-4	60	19	30	0
0	60	24	25	0
+4	60	11	25	0

Table 3 The total detected duration at different test points and Tx levels on Site B

Tx level (dBm)	Total detected duration in 60 secs			
	Test points (inside work zone)		Test points (outside work zone)	
	b1	b2	b3	b4
-40	60	60	0	23
-20	58	60	0	25
-16	60	59	0	12
-12	60	60	0	37
-8	60	59	0	19
-4	60	60	0	28
0	59	60	0	14
+4	60	60	0	19

Table 4 The total detected duration at different test points and Tx levels on Site C

Tx level (dBm)	Total detected duration in 60 secs					
	Test points (inside work zone)			Test points (outside work zone)		
	c1	c2	c3	c4	c5	c6
-40	60	56	46	23	0	0
-20	60	40	47	35	0	0
-16	59	55	55	21	0	0
-12	59	46	55	22	0	0
-8	57	50	53	20	0	0
-4	60	35	44	29	0	0
0	57	36	32	11	0	0
+4	60	37	50	24	0	0

The data presented in Table 2-4 highlights the variability in beacon detection durations across different test points within the work zone. This variability can be attributed to the absence of a clear line of sight between the beacon and the gateway in certain areas, despite efforts to identify an optimal deployment spot for the gateway. For example, points such as a2 and c3 at Site A are susceptible to signal degradation or loss due to surrounding obstacles and structures. However, when the beacon and gateway have a clear and direct view of each other without any physical obstructions, the detected duration is consistently close to 100% (60 seconds) for every Tx level, as demonstrated by test points a1, b1, b2, and c1.

Despite BLE signals having the ability to penetrate walls, their strength decreases as they pass through obstacles [20]. In the case of the renovation site, which featured dense pre-existing walls, the signal was completely blocked at certain areas. This characteristic helps to minimise false detections outside work zone, contributing to improved system specificity and accuracy. For example, some test points outside the work zone, such as a4, b3, c5, and c6 totally cannot be detected by the gateway. On the contrary, when walls do not fully separate the work zone, false detections can occur outside the work zone, as evidenced by test points a3, b4, and c4.

3.2 Statistical Results

Statistical analysis was done to get a clear picture of which Tx level on each case study conducts beacon detection most accurately. Table 5 summarises the statistical results for system detection accuracy at the different Tx levels and different sites.

Table 5 Statistical analysis for site A, B, and C

Site	Statistical analysis metrics	Tx level (dBm)							
		-40	-20	-16	-12	-8	-4	0	+4
A	True positive	92	77	95	112	77	79	84	71
	False negative	28	43	25	8	43	41	36	49
	True negative	107	87	93	95	84	90	95	95
	False positive	13	33	27	25	36	30	25	25
	Recall	76.7%	64.2%	79.2%	93.3%	64.2%	65.8%	70.0%	59.2%
	Specificity	89.2%	72.5%	77.5%	79.2%	70.0%	75.0%	79.2%	79.2%
	Accuracy	82.9%	68.3%	78.3%	86.3%	67.1%	70.4%	74.6%	69.2%
B	True positive	120	118	119	120	119	120	119	120
	False negative	23	25	12	37	19	28	14	19
	True negative	97	95	108	83	101	92	106	101
	False positive	0	2	1	0	1	0	1	0
	Recall	83.9%	82.5%	90.8%	76.4%	86.2%	81.1%	89.5%	86.3%
	Specificity	100.0%	97.9%	99.1%	100.0%	99.0%	100.0%	99.1%	100.0%
	Accuracy	90.4%	88.8%	94.6%	84.6%	91.7%	88.3%	93.8%	92.1%
C	True positive	162	147	169	160	160	139	125	147
	False negative	18	33	11	20	20	41	55	33
	True negative	157	145	159	158	160	151	169	156
	False positive	23	35	21	22	20	29	11	24
	Recall	90.0%	81.7%	93.9%	88.9%	88.9%	77.2%	69.4%	81.7%
	Specificity	87.2%	80.6%	88.3%	87.8%	88.9%	83.9%	93.9%	86.7%
	Accuracy	88.6%	81.1%	91.1%	88.3%	88.9%	80.6%	81.7%	84.2%

Based on Table 5, the findings suggest that the optimum Tx power level for accurately tracking people within the work zone varied across the three sites tested. The results showed that different BLE Tx power levels achieved different recall, specificity, and accuracy rates at each site. The highest rate of recall was achieved with a Tx level of -12 dBm at Site A and a Tx level of -16 dBm at Site B and C. The highest rate of specificity was achieved with Tx levels of -40 dBm at Site A, a Tx level of -40, -20, -12, and +4 dBm at Site B, and a Tx level of 0 dBm at Site C. At Site A, the highest accuracy rate was achieved with a Tx level of -12 dBm, while at Site B and C, the optimum Tx level was -16 dBm.

Overall, these findings highlight the importance of considering the unique characteristics of each site when determining the optimum BLE Tx power level. Factors such as the distance between the BLE device, the environment surrounding the work zone, and potential sources of interference that could affect signal strength need to be taken into account, especially in environments with dense structures and equipment, like a renovation site. However, our study will not investigate and analyse further the signal propagation and reception characteristics in such environments, which may be studied in the future.

By evaluating the recall, specificity, and accuracy rates for different Tx power levels at each site, it is possible to determine the most effective Tx level for accurately tracking people within the work zone. The final decision in selecting the suitable Tx power level would be to use a -12 dBm Tx level for Site A while using a -16 dBm Tx level for Sites B and C. This approach would ensure accurate measurements of beacon presence by the BLE device while conserving beacon battery power and ensuring system reliability and feasibility. This finding is also consistent with a previous study reporting that the higher Tx level does not represent better accuracy [12].

It should be emphasised that the results of this study may be specific to the particular environment and conditions at each site and may not be generalizable to other settings without further validation. Additionally, the performance of BLE tracking systems can be affected by various factors beyond the scope of this study, such as different orientations of the BLE beacons, the shape, size, and layout of the work zone, and potential sources of interference from other wireless devices or physical obstacles. Therefore, further research can be conducted to examine how these factors can impact the performance of BLE tracking systems and to develop more robust and adaptable solutions for various work zone scenarios. Moreover, it is recommended to continue monitoring and evaluating the performance of the BLE device over time to ensure that it maintains its accuracy and reliability in real-world conditions.

4.0 CONCLUSION

This study highlights the significance of an optimized BLE system deployment strategy prior to its implementation on construction sites to achieve both energy-efficient beacon battery usage and accurate detection data for labour tracking. The system gateway deployment of the system gateway was carefully planned, taking into consideration power supply availability, no disruption to tiling work, and minimum blockage of the line of sight. For beacon configuration, this study fixed the sampling rate at 10 Hz and investigated the optimum BLE Tx level based on detection accuracy. To conclude, the optimum Tx levels for sites A, B, and C are -12dBm (86.3% accuracy), -16dBm (94.6% accuracy), and -16dBm (91.1% accuracy). The identified gateway location and beacon parameters will be employed in further study for labour tracking on these sites. However, it is noteworthy that the identified optimum Tx level in this paper is limited to the sites investigated and may differ in different environments. The future study may refer to this paper as a guide for the BLE system deployment strategy.

Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper.

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References

[1] Li, H., Chan, G., Wong, J. K. W., & Skitmore, M. 2016. Real-time Locating Systems Applications in Construction. *Automation in Construction*. 63: 37-47. https://doi.org/10.1016/j.autcon.2015.12.001.

[2] Josephson, P. E., & Bjorkman, L. 2013. Why Do Work Sampling Studies in Construction? The Case of Plumbing Work in Scandinavia. *Engineering, Construction and Architectural Management*. 20(6): 589-603. https://doi.org/10.1108/ECAM-12-2011-0108.

[3] Hajikazemi, S., Andersen, B., & Langlo, J. A. 2017. Analyzing Electrical Installation Labor Productivity through Work Sampling. *International Journal of Productivity and Performance Management*. 66(4): 539-553. https://doi.org/10.1108/IJPPM-06-2016-0122.

[4] Gouett, M. C., Haas, C. T., Goodrum, P. M., & Caldas, C. H. 2011. Activity Analysis for Direct-work Rate Improvement in Construction. *Journal of Construction Engineering and Management*. 137(12): 1117-1124. https://doi.org/10.1061/(asce)co.1943-7862.0000375.

[5] Hwang, B.-G., & Soh, C. K. 2013. Trade-level Productivity Measurement: Critical Challenges and Solutions. *Journal of Construction Engineering and Management*. 139(11): 04013013. https://doi.org/10.1061/(asce)co.1943-7862.0000761.

[6] Rao, A. S., Radanovic, M., Liu, Y., Hu, S., Fang, Y., Khoshelham, K., Palaniswami, M., & Ngo, T. 2022. Real-time Monitoring of Construction Sites: Sensors, Methods, and Applications. *Automation in Construction*. 136(December 2021): 104099. https://doi.org/10.1016/j.autcon.2021.104099.

[7] Jiang, H., Lin, P., Qiang, M., & Fan, Q. 2015. A Labor Consumption Measurement System based on Real-time Tracking Technology for Dam Construction Site. *Automation in Constructionz*. 52: 1-15. https://doi.org/10.1016/j.autcon.2015.02.004.

[8] Costin, A., Pradhanaga, N., & Teizer, J. 2012. Leveraging Passive RFID Technology for Construction Resource Field Mobility and Status Monitoring in a High-rise Renovation Project. *Automation in Construction*. 24: 1-15. https://doi.org/10.1016/j.autcon.2012.02.015.

[9] Zhao, J., Seppänen, O., Peltokorpi, A., Badihi, B., & Olivieri, H. 2019. Real-time Resource Tracking for Analyzing Value-adding Time in Construction. *Automation in Construction*. 104: 52-65. https://doi.org/10.1016/j.autcon.2019.04.003.

[10] Zhao, J., Pikas, E., Seppänen, O., & Peltokorpi, A. 2021. Using Real-time Indoor Resource Positioning to Track the Progress of Tasks in Construction Sites. *Frontiers in Built Environment*. 7(April): 1-18. https://doi.org/10.3389/fbuil.2021.661166.

[11] Vrijhoef, R. 2019. Studying Time Presence on Site as an Indicator of Productive Time use by Construction Workers. *Association of Researchers in Construction Management, ARCOM 2019 - Proceedings of the 35th Annual Conference*. 204-213.

[12] Mohanty, L., Chae, S., & Yang, Y. 2020. Identifying Productive Working Patterns at Construction Sites using BLE Sensor Networks. *Developments in the Built Environment*, 4(March): 100025. https://doi.org/10.1016/j.dibe.2020.100025.

[13] Qureshi, U. M., Umair, Z., Duan, Y., & Hancke, G. P. 2018. Analysis of Bluetooth Low Energy (BLE) based Indoor Localization System with Multiple Transmission Power Levels. *IEEE International Symposium on Industrial Electronics*. 1302-1307. https://doi.org/10.1109/ISIE.2018.8433787.

[14] Qureshi, U. M., Umair, Z., & Hancke, G. P. 2019. Evaluating the Implications of Varying Bluetooth Low Energy (BLE) Transmission Power Levels on Wireless Indoor Localization Accuracy and Precision. *Sensors (Switzerland)*. 19(15). https://doi.org/10.3390/s19153282.

[15] Sadowski, S., & Spachos, P. 2018. RSSI-based Indoor Localization with the Internet of Things. *IEEE Access*. 6: 30149-30161. https://doi.org/10.1109/ACCESS.2018.2843325.

[16] Mussina, A., & Aubakirov, S. 2018. RSSI Based Bluetooth Low Energy Indoor Positioning. *2018 IEEE 12th International Conference on Application of Information and Communication Technologies (AICT)*. 1-4.

[17] Matthew, L. 2021, April 9. *A Complete Guide to Bluetooth Beacon Gateway*. MOKO BLUE.

[18] Wang, J. Y., Chen, C. P., Lin, T. S., Chuang, C. L., Lai, T. Y., & Jiang, J. A. 2012. High-precision RSSI-based Indoor Localization using a Transmission Power Adjustment Strategy for Wireless Sensor Networks. *Proceedings of the 14th IEEE International Conference on High Performance Computing and Communications, HPCC-2012 - 9th IEEE International Conference on Embedded Software and Systems, ICESS-2012*. 1634–1638. https://doi.org/10.1109/HPCC.2012.239.

[19] Park, J., Kim, K., & Cho, Y. K. 2017. Framework of Automated Construction-Safety Monitoring Using Cloud-Enabled BIM and BLE Mobile Tracking Sensors. *Journal of Construction Engineering and Management*. 143(2): 05016019. https://doi.org/10.1061/(asce)co.1943-7862.0001223.

[20] Arslan, M., Cruz, C., & Ginhac, D. 2019. Visualizing Intrusions in Dynamic Building Environments for Worker Safety. *Safety Science*. 120(July): 428-446. https://doi.org/10.1016/j.ssci.2019.07.020.