Measuring Foot Traffic with Bluetooth Low Energy

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Abstract

In the realm of the Internet of Things (IoT) and ubiquitous connectivity, this paper presents a novel application of Bluetooth Low Energy (BLE) for foot traffic monitoring in public spaces. Our research explores using BLE's broadcasting capabilities and Received Signal Strength Indicator (RSSI) measurements to develop a cost-effective, energy-efficient solution for counting and analyzing foot traffic. The system employs two BLE-enabled devices: a broadcaster emitting signals and an observer calculating the RSSI values to estimate foot traffic.

Challenges such as the rotation of MAC addresses and broadcasting speed were addressed by implementing an Identity Resolving Key (IRK) and optimizing packet transmission rates. Our approach differs from existing methods by eschewing the need for expensive image recognition systems or the necessity for individuals to carry BLE devices. We conducted extensive testing on different BLE platforms, including the nRF5340 and Adafruit Feather, under varied conditions to establish a reliable RSSI threshold for accurate people counting.

The findings demonstrate that our BLE-based system can provide a more economical and adaptable alternative to conventional foot traffic counting methods, with potential applications in event management, retail spaces, and during health crises like pandemics. This research contributes to understanding BLE technology in unconventional use cases and opens avenues for future exploration in enhancing the accuracy and scalability of BLE-based monitoring systems.

Introduction

With the advent of IoT and ubiquitous connectivity, Bluetooth Low Energy (BLE) has emerged as a critical technology for short-range communication due to its low power consumption, which makes it ideal for low-powered devices. While its capabilities and features have grown over the years, exploring its potential, particularly in exploring data broadcasting to use RSSI (Received Signal Strength Indicator) measurements for foot traffic applications, remains an ongoing challenge. Our project introduces a unique application of BLE in the realm of foot traffic monitoring, an area that is pivotal for urban planning, retail analytics, and event management. Traditional methods of foot traffic monitoring often involve video surveillance or thermal imaging, which can be intrusive, expensive, and limited in scalability.
In contrast, our solution harnesses the RSSI feature for non-invasive, cost-effective, and scalable foot traffic analysis. The RSSI is a measure of the power present in a received radio signal, which we utilize to detect the presence and movement of people within the proximity of our BLE devices.

The innovation lies in our system's ability to interpret RSSI fluctuations caused by human movement. When a person passes between our BLE devices – one functioning as a broadcaster and the other as an observer – their body affects the signal strength. By setting a calibrated RSSI threshold, we can reliably count foot traffic. This approach negates the need for individuals to carry any specific device, making it universally applicable in public spaces. Moreover, our implementation using the nRF5340 and Adafruit Feather platforms demonstrates the feasibility of this approach with commonly available BLE hardware. This underscores our solution's adaptability to different hardware configurations and showcases its potential for widespread implementation in diverse environments.

There were a few challenges that we ran into and resolved. However, a few did persist. One issue was the rotation of MAC addresses. To fix this and press on, we use an identity resolving key (IRK) for both the broadcaster and observer so the observer can find the broadcast faster and create a quick beam connection. We also tested the foot traffic system's performance under different scenarios to identify the RSSI threshold. The systems will adjust the threshold based on RSSI values received as self-correcting progress when the scenario changes and the threshold is not manually updated. By focusing on the specific advertising channel, we successfully improve the probability of detection, hence making the connection more substantial and more effective at detecting foot traffic.

Foot traffic counting solutions for events, concert halls, classrooms, libraries, and building occupancy keep increasing. We test our foot traffic counting system on nRF 5340 boards and Adafruit Feather, which presents its compatibility with different BLE devices. Our project demonstrates that a BLE foot traffic counting system can be more cost-effective than more expensive image recognition solutions, depending on the scenario. These low-cost and easy-to-install foot traffic counters can be convenient tools for large-scale public places to control the population size in situations like the past pandemic.

Background

Traditionally, the beaconing system, a fundamental concept in BLE, allows devices to broadcast small packets of data in intervals to communicate with other BLE-like devices. This has adopted BLE in many applications due to its low power consumption, short-range communication capability, and widespread support in smartphones and other devices. While many adoptions exist, one that still needs to be explored is broadcasting dynamic data, like foot traffic applications. Previous endeavors have attempted to push the boundaries of BLE for data broadcasting and communication but have faced challenges, especially concerning real-time communication, scalability, range, and assumptions of other BLE devices accompanied by people.

Related Work

Foot traffic solutions are an important part of public traffic systems and business management. For business management, it helps stores determine the number of potential shoppers in their space with the help of a traffic counter. Foot traffic counters can provide valuable traffic information data, which helps managers avoid possible congestion, analyze people's habits, and favor specific locations. Many specialized traffic counter systems are based on thermal sensing, video detectors, inductive loops, and Wi-Fi systems.

The main drawback of those solutions is often low flexibility and significant maintenance cost, which make those solutions unworthy for small shops and public buildings where high detection accuracy is optional. Applications of Bluetooth low-energy systems can both afford traffic monitoring services and overcome those drawbacks. The article, *Road Traffic Monitoring System Based on Mobile Devices and Bluetooth Low Energy Beacons*, is an interesting reference to our project. Researchers utilized smartphone devices and BLE beacons to build up the road traffic monitoring system for detecting passing vehicles and recognizing their classes [1]. Therefore, we decided to work further on applying similar foot traffic counting systems that count passing people instead of vehicles with BLE beacons.

Other related works that are projected were influenced by the University of Tokyo. In the *Study of the Detection of Pedestrian Flow Using Bluetooth Low Energy*, analyzing human mobility data, particularly in urban and indoor spaces, is essential for various applications like urban planning, public safety, traffic management, and early detection of issues. The authors developed a novel BLE method to sense and track pedestrian movement. They relied on the RSSI of BLE beacons affixed to individuals to determine their velocity and direction [2]. In their experiments, they had a BLE beacon fixed to an individual. However, in our experiment, we had a beacon system (broadcaster and observer) that has no BLE beacon device on a person and detects when a person walks through if the threshold is met, removing the assumption and cost of a BLE beacon device a person may or may not have.

Motivation:

The project is motivated by the need for cost-effective and flexible foot traffic monitoring solutions, which can provide valuable data for businesses and public traffic systems. It seeks to improve existing methods and technologies, using BLE's low power consumption and short-range communication capabilities and finding the most appropriate threshold based on different scenarios.

Challenges We Faced:

- *Hardware Limitations* – One member faced an issue with the lack of multiple USB to USB C adapters, which limits simultaneous testing and development in two Feathers.
- *Inconsistent Behavior* – While testing, it was observed that two identical Feathers showed different behaviors when the same code was uploaded. One worked seamlessly, while the other exhibited a temporary blink and then ceased operation. The root cause is yet to be determined.
- *Development Environment* – While Nordic development kits come with an SDK, the application is not the greatest, so we opt-in for a Visual Studio Code extension, "nRD Connect," that made working with the development kits easier, particularly when flashing the applications onto the boards and viewing the terminal for debugging.
- *Bluetooth rotating MAC address* – A challenge resolved was the rotating MAC address of an advertiser (broadcaster), which originally made it difficult for a scanner (observer) to find the advertiser continuously. To solve this challenge, a pre-shared Identity Resolving Key (IRK) was added to help the observer find the broadcaster more easily.
- *Broadcasting speed* – To use the boards as a foot traffic counter, we will need a constant (or fast) beam of packets from the broadcaster to the observer at a rapid rate so we can catch minute details of RSSI anomalies that occur when a person walks past them to capture that moment better than a slower 1000 ms rate. We have changed it to 10 ms; lower would make data capture harder when reading it from a terminal.
- *Measuring RSSI fluctuations under high speed* – Capturing RSSI fluctuations when walking between the nRF5340 boards is challenging since we first need a baseline to know what's within normal range and requires a more constant beam of data to be sent and read to graph when a fluctuation occurs. To resolve that, increasing the broadcasting speed will help even if there is a lot of data, but creating a filter can help.
- *Distinguish stopping people* – If someone stops right between two boards or some obstacles are placed between them, the system will falsely constantly add foot traffic numbers since it receives RSSI higher than the threshold. We try to fix this by adding a self-adjusting threshold that can adjust the average RSSI and standard deviation given new RSSI input. Another solution is adding more pairs of foot traffic counters to reduce the possibility of these cases. When one goes wrong, you can still check with other traffic counters to manually adjust the problem.

Approach

Objective:

The project aims to explore using Bluetooth Low Energy (BLE) to develop a foot traffic monitoring system. The project aims to leverage BLE's broadcasting capabilities and RSSI measurements to count the number of people passing through a specific area. To accomplish our objective, the system uses two devices, one as a broadcaster and the other as an observer. The key goals include:

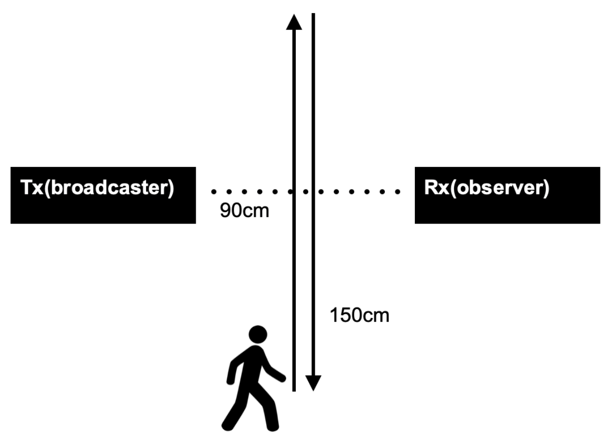
- Broadcasting data packets using BLE to detect foot traffic
- Addressing challenges such as rotating MAC addresses by using an identity resolving key (IRK)
- Calculating an RSSI threshold based on previous testing to count the number of people passing through
- Testing the system's performance under different scenarios and enabling it to self-adjust the threshold based on received RSSI values
- Developing a foot traffic monitoring prototype system using BLE beaconing methodology

The team delved into BLE's capabilities through emulation and implementation. Given the hands-on nature of the project, real-world testing on the provided hardware will be crucial. Performance evaluation will focus on data transfer rate, beaconing intervals, power consumption, and signal strength under various conditions. We will use two boards, one as a broadcaster and one as an observer, to communicate via a non-connectable but scannable protocol. Since security is not a focus, we will use a resolvable random private address for the broadcaster, and both will share a pre-shared key. By tracking significant signal strength changes between the transmitting and receiving boards and knowing the prediction, we could count how many times people pass two boards. In the next section are the details of our project and the observations we ran into.

Details of Work:

Environment Setup – All team members successfully set up their development environments and familiarized themselves with the hardware: Nordic nRF5340 “DK board” and Adafruit nRF52840 “Feather.”

We collect RSSI values in 30 seconds when no one passes through for the standard RSSI baseline. Then, one person walks through two boards back and forth. Each time, a person walks 150cm and turns around. The person would pass two boards ten times, with a total walking distance of about 15 meters. The figure to the right presents how we set up our experiments, the distance between the broadcaster and observer, and how much a person walked through at average walking speed.



Beacon Development – Initial experimentation with the Feather as a beacon began with a beacon sequence. An initial beacon non-connectable but scannable DK board has been made and used as a broadcaster. Then, we added a pre-shared Identity Resolving Key (IRK) to help an observer find the broadcaster more easily.

Scanner Development – We created a fine-tuned observer using one Nordic nRF5340 board to detect other BLE devices and use an IRK to filter for the broadcaster. Once the IRK was deployed, it made the process for the beacon-foot traffic system available to us to implement. We also simultaneously implemented a similar code for an observer and broadcaster on the Feathers to test and evaluate the efficacy of each BLE solution. After testing the outputs from each device that was coded with similar functionality, we ended up using the DK boards for the experimentation due to a slightly more consistent and reliable output at longer ranges, as well as some further flexibility in fine-tuning capabilities.

RSSI Baseline Setup – We conducted multiple experiments with our broadcasters and observers to analyze the RSSI baseline under different orientations of the nRF5340 board. We tested the RSSI values in 30 seconds with the line-of-sight transmission and no obstacles between the two boards. The distance between two nRF5340 boards is about 3ft (90cm). The two boards were placed in three orientations:

- Right side up
- The bottom of the boards facing each other
- The tops of the boards facing each other

After analyzing the RSSI values of three different orientations, we find that when the bottom of the boards faces each other, the BLE transmission between two nRF5340 boards has the best average RSSI values. The average RSSI value of the bottom-facing orientation is -51.2. The average RSSI value of the top-facing orientation is -54.6. The average RSSI value of the right-side-up orientation is -59.

Foot Traffic Counter Experiments – After setting up the RSSI baseline, we want to count foot traffic by detecting whether a person passes the two BLE devices. The human body, primarily composed of water and other materials, can absorb or reflect radio waves and interfere with the signal strength of the transmission. Therefore, we tried to determine whether a person passed by observing the unusual RSSI fluctuation. Firstly, we test one person walking through boards at an average walking speed. The RSSI fluctuation is not very significant from the baseline. We then tested slower walking speed. There is a considerable drop in RSSI values. After the initial attempt, we test our system's performance under different scenarios.

Evaluation

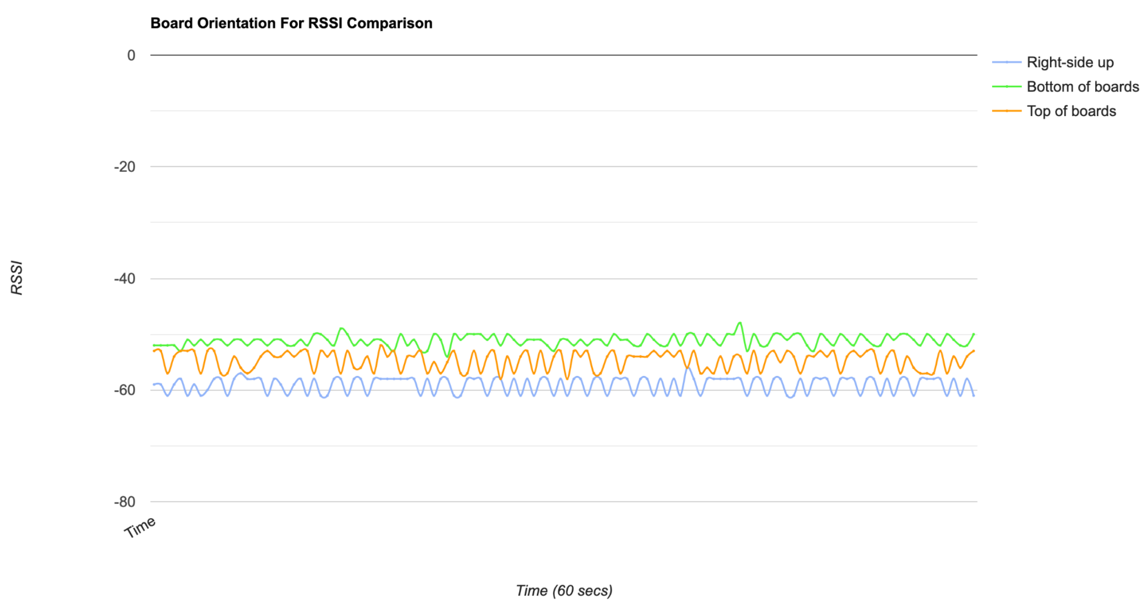
Evaluation Metrics:

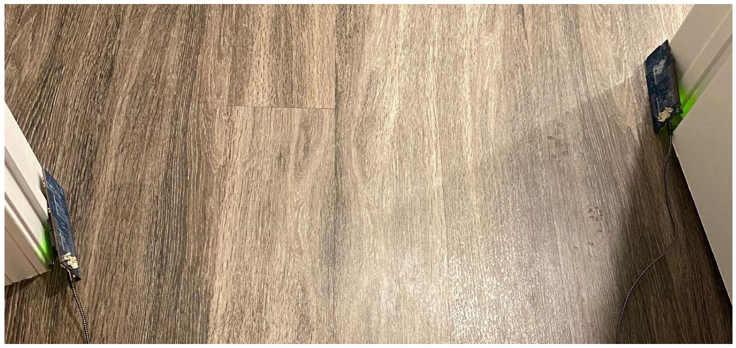
- *Received Signal Strength Indicator (RSSI)* – Using the measurement of the power level received by an antenna from a wireless device, the RSSI value indicates the strength and quality of the wireless signal. The closer the RSSI value is to zero, the stronger the signal is. An RSSI of -40 or better will show as good or excellent, whereas an RSSI of -60 or worse would show as poor.
- *Scalability* – Test how the system performs as more devices (either broadcaster/observer) were added to the foot traffic counter system.
- *Distance* – Test the foot traffic system in different scenarios and see if there are more fluctuations with RSSI measurements and if the system can apply to longer distances for large entranceways, for example.

First Attempt of Foot Traffic Counter

Finding Best Orientation

Since learning about Bluetooth antennas, like most practical antennas, are not isotropic. A Bluetooth antenna in a smartphone might be designed to provide better coverage in the direction typically facing the user. So, to find the best orientation for our use case, we first tested orientations of the nRF5340 board, which gives us the best baseline RSSI to get the best possible RSSI





(Boards Orientation: bottoms of the boards facing each other. Distance ≈ 3 ft)

The best orientation was the *bottom* of the boards facing each other since the Nordic nRF5340 has a printed monopole antenna (for 2.45GHz)[1]. Once we found the best orientation, we moved forward to test a person walking between the two boards.

Thresholding When Walking In Between Boards

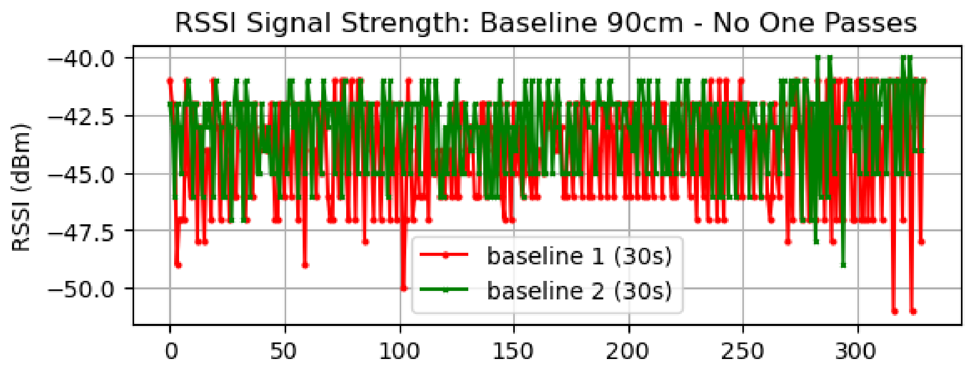
We tested a single person walking through the board at their average speed nine times in the first and second half of the graph. The significant drop of RSSI in the middle of the graph is when the person walks slowly to see if a person walking slowly can be detected. As the diagram shows, our initial foot traffic counter hardly detects a person walking through at their average speed. The main reason is that two boards are placed on the floor, making it harder to receive interference when persons pass through. The person might just stride over the boards and not land his feet between two boards. We found this loophole and improved our foot traffic counter by increasing the height of two boards to the same height as an average person’s abdomen.

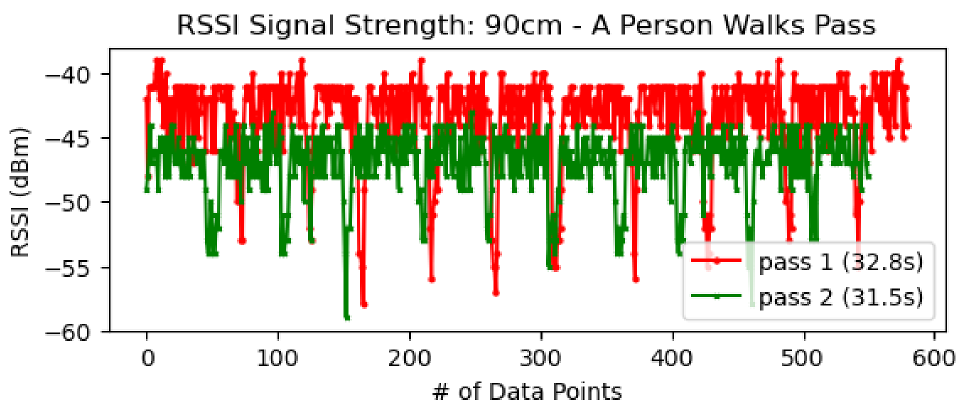
We plot the baseline vs. the initial results for easy comparison, and we can see multiple spikes of lowered RSSI values when a person walks between the boards multiple times. Now we have shown that RSSI values can be affected when a person walks by, we did more tests for different scenarios.

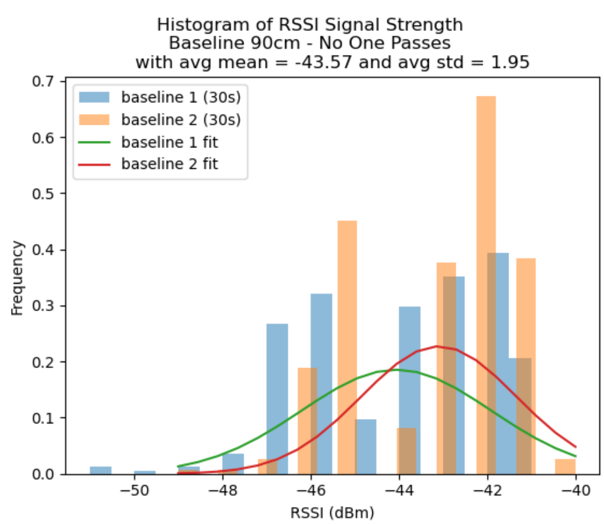
[1] https://infocenter.nordicsemi.com/pdf/nwp_008.pdf

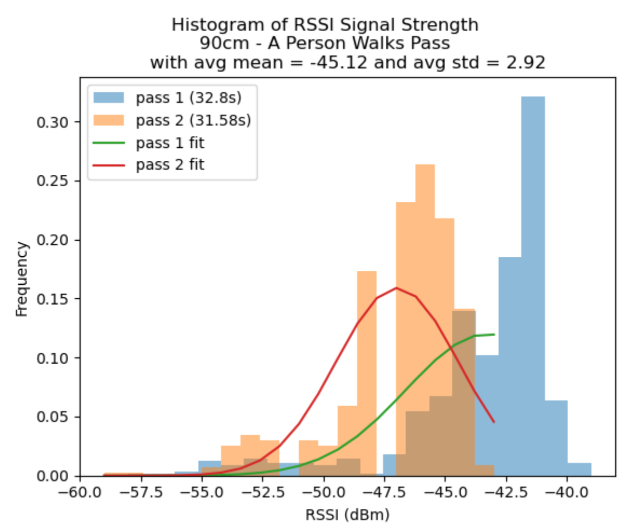
Standard RSSI baseline:

To establish a baseline for RSSI values, we initially gathered data over a 30-second interval in an environment where no one passes through. Subsequently, we conducted a test involving an individual walking back and forth between two boards. This exercise entails the person covering a distance of 150 cm in each direction, turning around after each segment. Throughout this test, the individual crosses between the two boards ten times, cumulatively walking approximately 15 meters. The figures below illustrate the variations in RSSI values observed as the person moves through the two boards at an average pace.





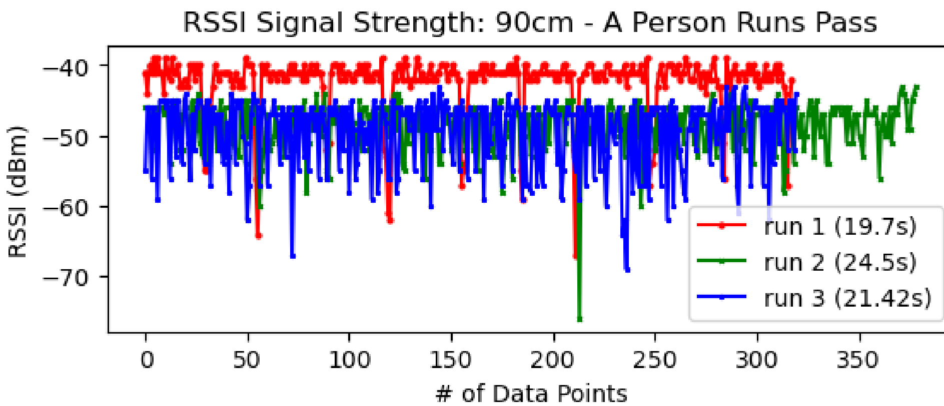


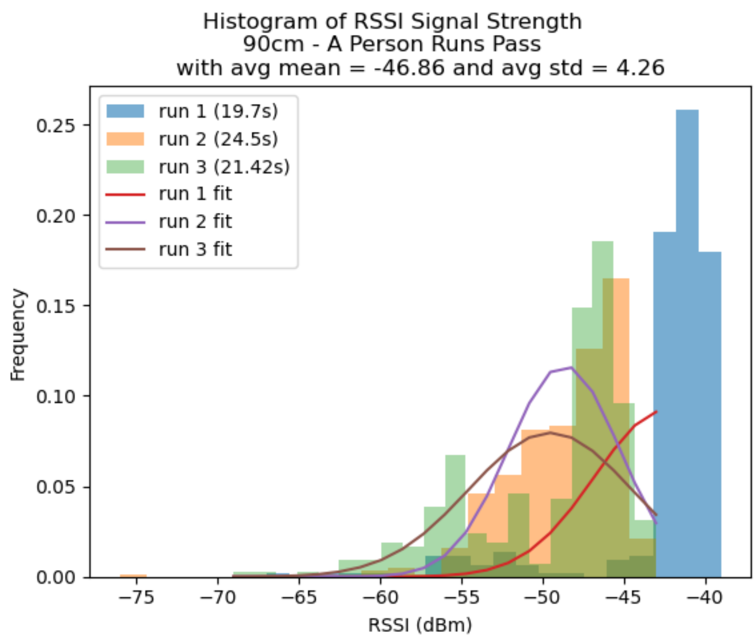


The data presented above clearly demonstrates a marked decrease in RSSI values when an individual passes through the tested area. Specifically, the average mean RSSI value for scenarios where no one passes is recorded at -43.57 (left-histogram), accompanied by a relatively stable average standard deviation of 1.95. Contrastingly, in tests where a person walks through, the average mean RSSI value experiences a notable decline to -45.12 (right-histogram), with the standard deviation increasing to 2.92, indicating more significant variability in the readings.

Test Scenario 1: Person Pass Speed Increase

We first test the foot traffic counting system's performance when the person's speed increases. With everything else unchanged, the person has to run back and forth through the two boards.

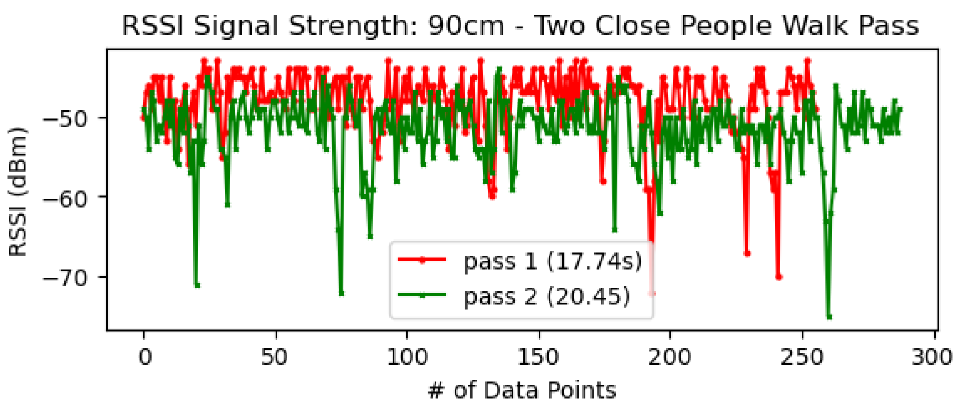


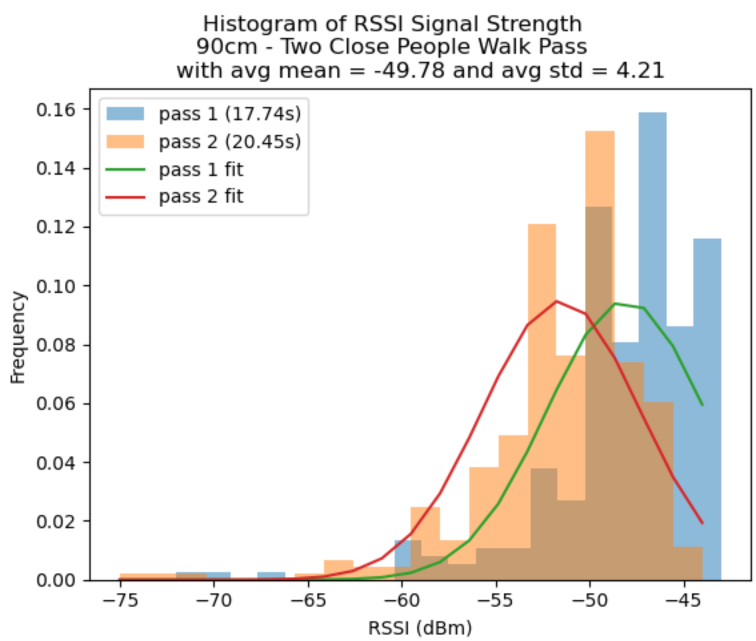


The data presented above demonstrates the capability of our system to accurately detect RSSI fluctuations, even when individuals move through the area at a fast pace, such as running. This was achieved by enhancing the broadcasting frequency from 1000 milliseconds to a more rapid 10 milliseconds. In the "Person Run Pass" tests, we observe an average mean RSSI value of -46.86, which is remarkably close to the value recorded in the "Person Walks Pass" scenario. However, it's notable that the standard deviation in the running tests is significantly higher, averaging at 4.26. This increase in variability is attributed to the greater fluctuation in RSSI values when individuals pass through at a higher speed compared to a walking pace.

Test Scenario 2: Multiple Persons Pass Closely

In the second scenario, we want to mimic the crowded situation when multiple people walk in a line-like arrangement. Two persons walk through the two boards at a close distance 5 times.

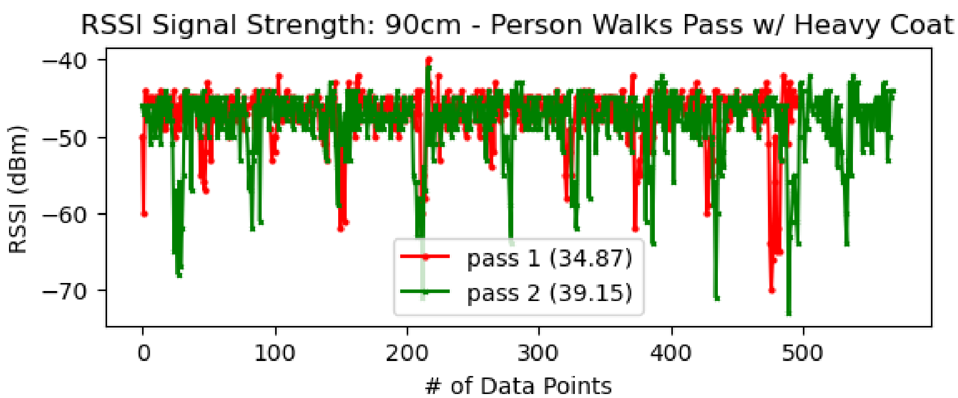


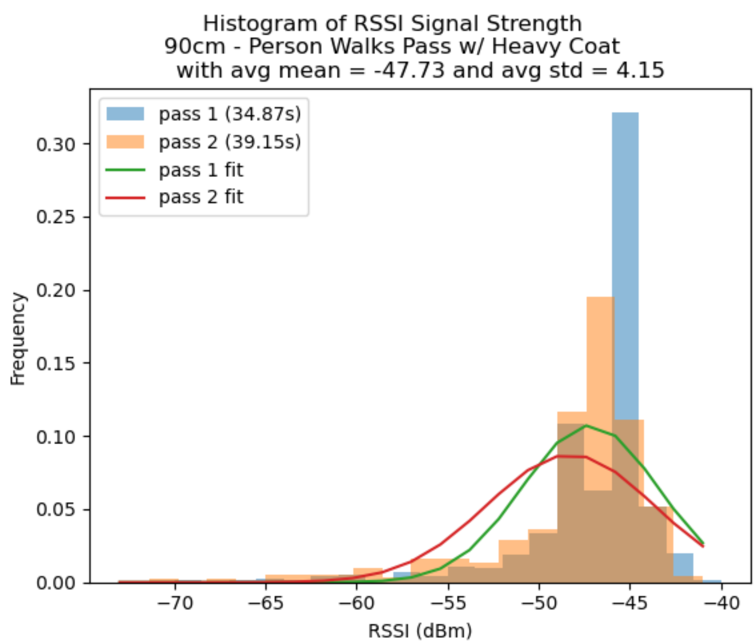


Ideally, the system should catch a person passing ten times. However, the figures above reveal that while our system is designed to detect an individual passing through ten times, it faces challenges in differentiating between multiple individuals passing simultaneously and a single person passing. In the "Multiple Persons Pass" tests, the average mean RSSI value decreases to -48.06, accompanied by an average standard deviation of 4.21. This standard deviation level, similar to that observed in the "Person Run Pass" scenario, is relatively high. This increase can be attributed to the more erratic RSSI fluctuations occurring when two persons pass through the area simultaneously, complicating the system's ability to distinguish between different passing events.

Test Scenario 3: Person With Heavy Coat & Laptop

We then test around winter scenarios when a person wears a heavy coat and carries large metal objects like laptops. The figure below shows that the heavy coat and laptop don't interfere with our system's accuracy.

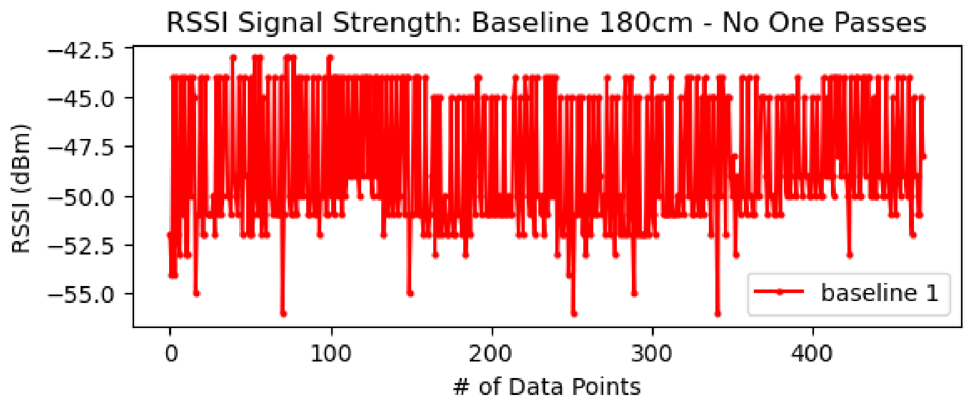




The average mean RSSI value is -47.73, with an average standard deviation of 4.15. Although the figure shows that the accuracy increases, we are unsure if the reason heavily depends on the laptops and heavy coats the person carries or the slower walking speed after carrying those items.

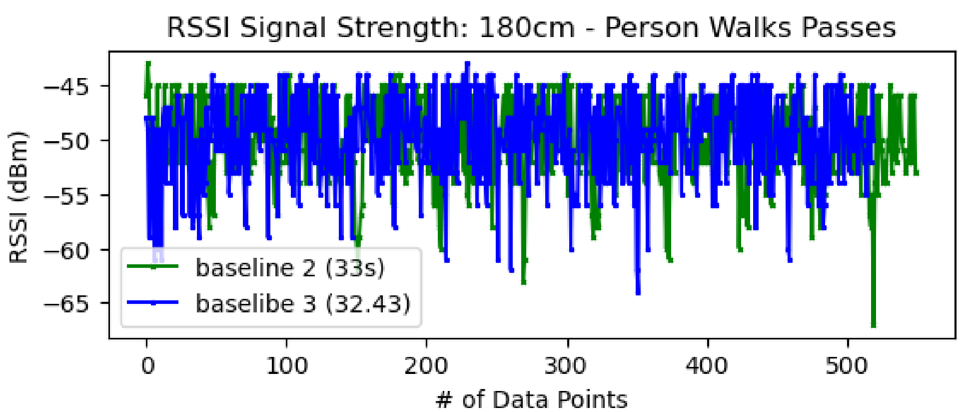
Test Scenario 4: Distance Between Boards Increase

The property of Bluetooth Low Energy decides that the performance of our BLE devices will significantly drop when the distance between the broadcaster and the observer increases. Therefore, we increase the distance between the two boards to 180cm. We then test our system's performance when the distance is doubled.



The figure above shows that the RSSI values drop significantly with the increasing distance between the broadcaster and the observer. Moreover, when the distance increases, the RSSI fluctuations are also more obvious. The mean RSSI of 180cm baseline is -48.50. Its standard deviation also increases to 3.22. As a reminder, the average mean RSSI of 90cm baseline is -43.57, accompanied by a relatively stable average standard deviation of 1.95. The result proves that BLE devices' performance decreases under longer communication distances.

After the baseline performance, we then test how the system works when a person walks through, given the double distance between the broadcaster and the observer.

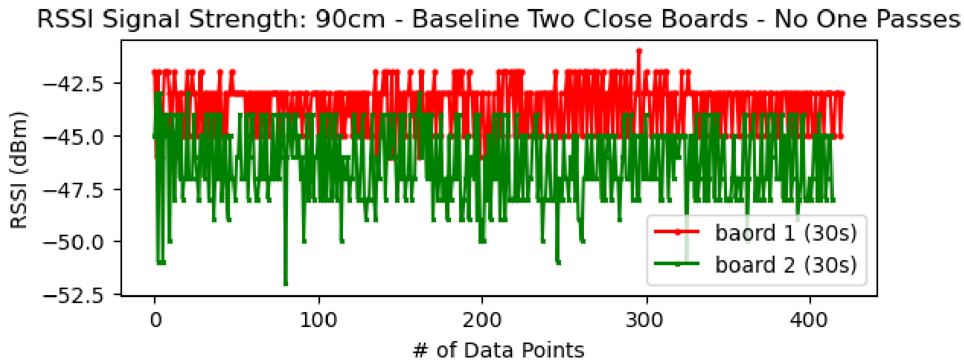


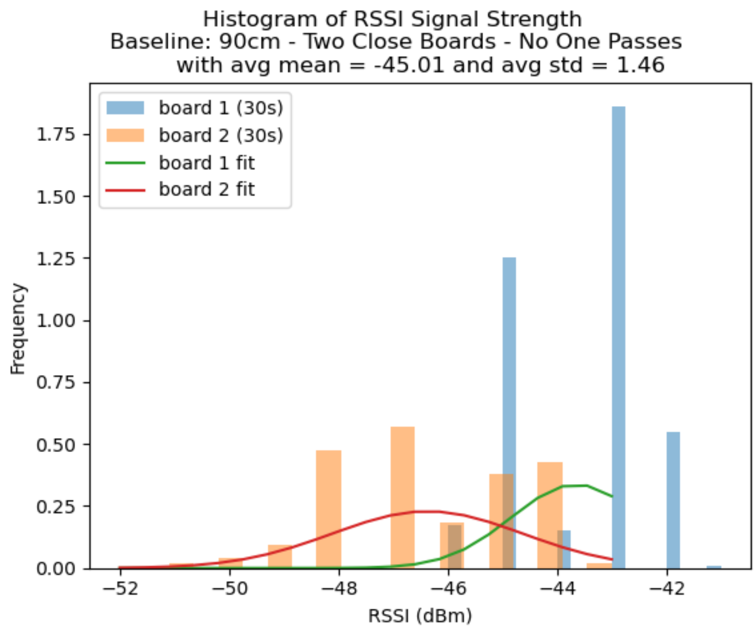
As the figure above shows, our foot traffic counting system is still able to catch the person who passes through the boards with decent accuracy. The average mean RSSI of the "180cm Person Walk Pass" test is -49.99, and the standard deviation is 3.89. The average mean RSSI and standard deviation are both worse than the standard 90cm scenarios. However, they would not significantly influence the accuracy of the foot traffic counting because we rely only on the RSSI fluctuations instead of the actual data the two boards transport to identify the person passing by.

Test Scenario 5: Multiple Boards Scalability

In the final experiment, we tested two scenarios to test the scalability of having more than one broadcaster-observer system that helps detect whether a person is walking better or worse. In one experiment, the two pairs of the broadcaster-observer system were placed next to each other. In the other, the distance between two pairs of foot traffic counters was 180 cm.

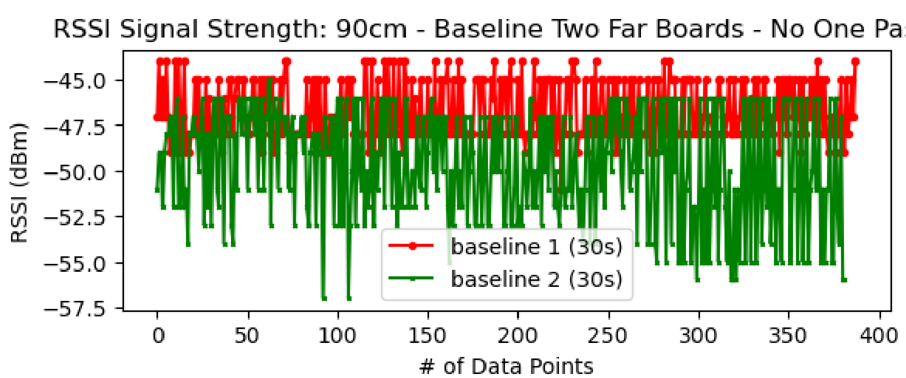
Two Close Boards:

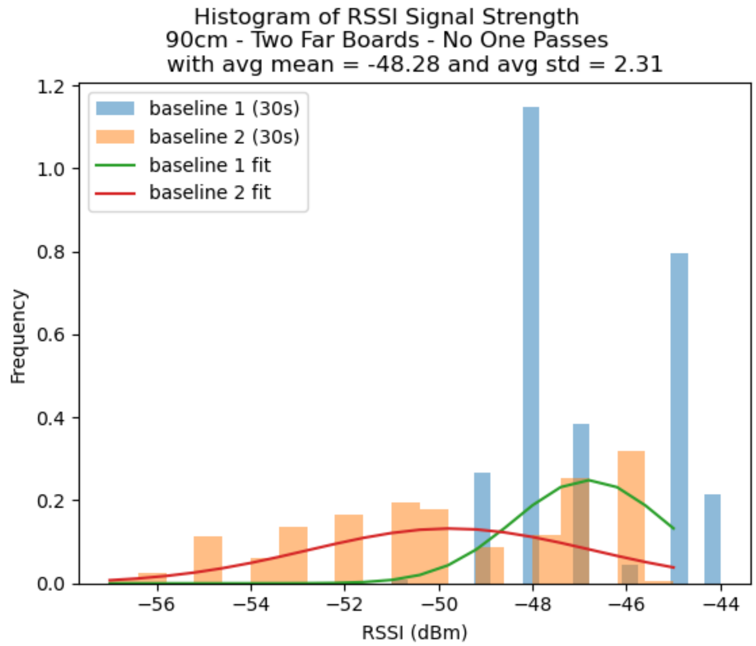




In terms of two observers and two broadcasters next to each other respectively (at 90 cm) and no one is passing to get a baseline, we see that the average standard deviation is relatively reasonable, being 1.46, but interesting the RSSI values do not overlap with each other compared to other values that came before. This may be due to interference.

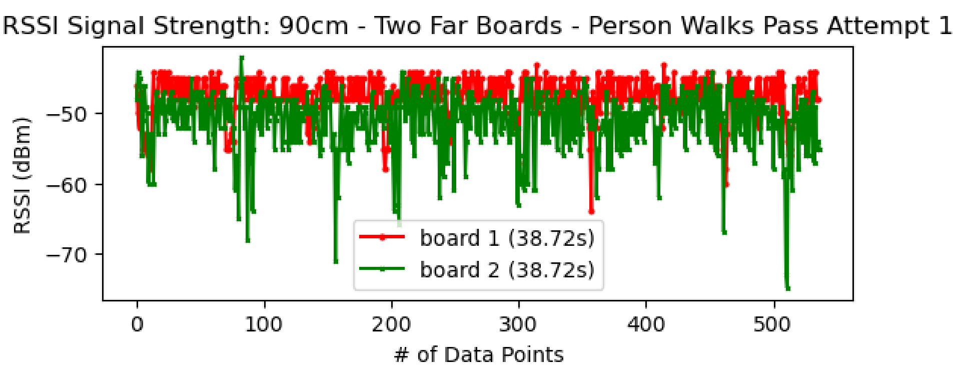
Two Far Boards:

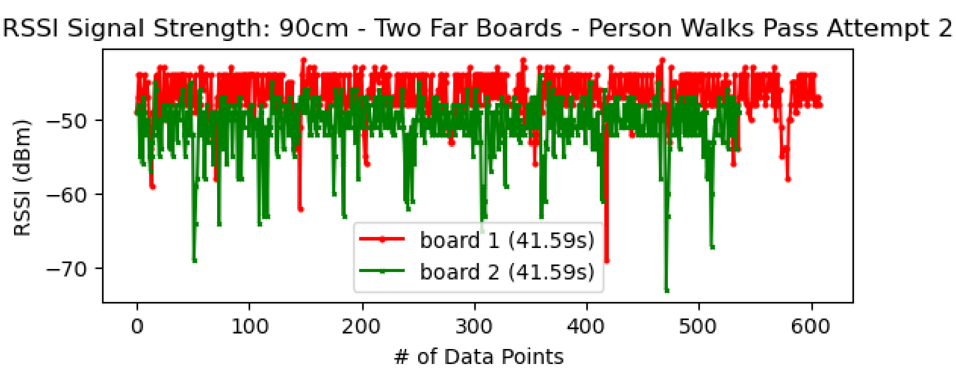


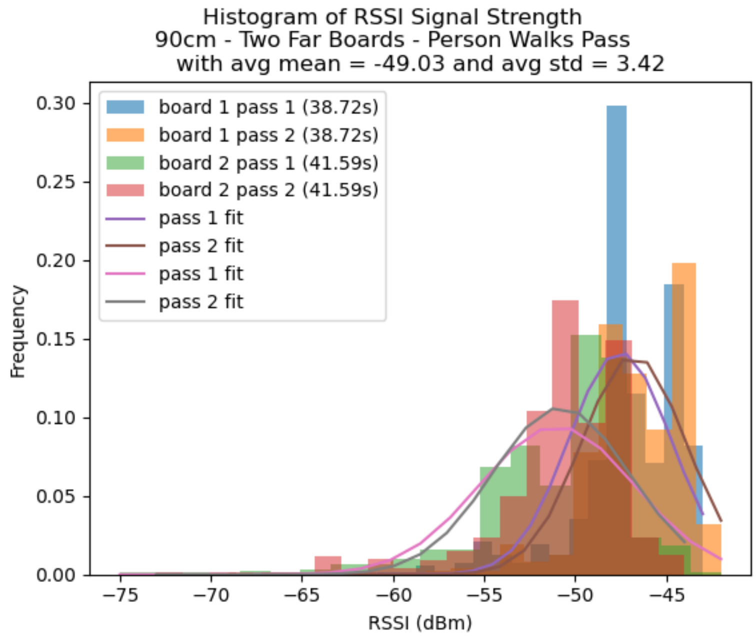


In terms of two observers and two broadcasters that are far apart, at least 90 cm from each other's respective counterparts (at 90 cm), we see that the average RSSI mean increased by at least -3 dDms and the average standard deviation also increased by ~1 unit. We see little difference.

Afterward, we tested with a person walking the two far-distanced boards, and the results are below:







For far boards, we can get similar results for both boards when one person walks through both systems. We get an average RSSI mean of -49.03 and an average standard deviation of 3.42 which seems higher than what we expected, but since this was 2 attempts, we believe if we had done more we could've seen a lower deviation. On a positive note, looking at the RSSI graph, we see that the boards do detect when a person walks through indicated from each spike, and we count 10 which matches how many times we walked through.

Tests Summary:

Overall, the foot traffic counting system is able to accurately catch person pass-through under different scenarios, including pass speed increase, persons wearing heavy coats and carrying laptops, longer distances, and multiple boards working simultaneously. When multiple persons walk through boards closely, the system is still capable of detecting person pass-through, but it is unable to find how many people pass, which still needs to be improved in the future.

Other Works & Improvements

RSSI threshold Self-Correction:

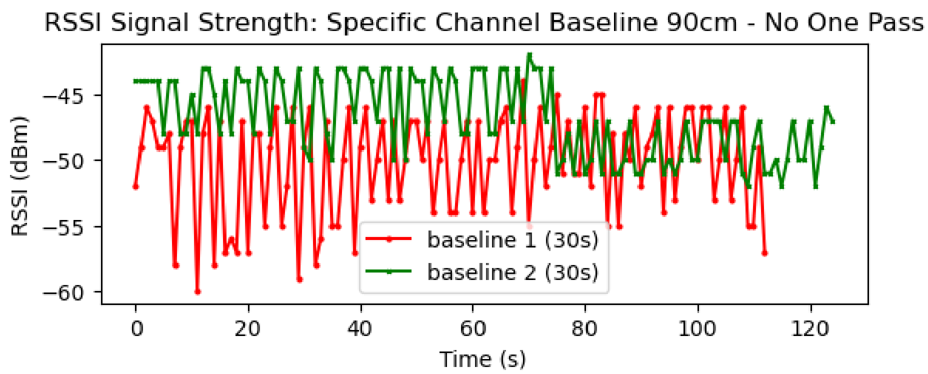
After the final presentation, we found that if someone keeps standing between the two boards, the foot traffic counting system would falsely add passing numbers since it recognizes the RSSI values are constantly higher than the RSSI threshold. The same logic applies to situations where obstacles are accidentally placed between two boards. Although the threshold can be manually adjusted, keeping track of the situation and recalculating the new RSSI threshold is complicated since we would not save the RSSI values due to storage space limitations.

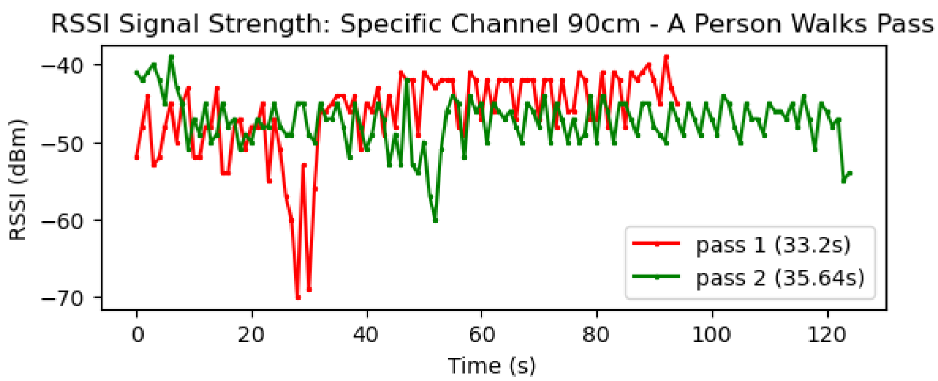
Therefore, we created a self-correcting process for our foot traffic counting system. The mean RSSI and standard deviation of RSSI are stored as global variables. Each time the system receives new RSSI values, it incrementally adjusts the mean RSSI values and standard deviation. We use the following equation to calculate the further mean RSSI and standard deviation: mean RSSI = mean RSSI + (RSSI - mean RSSI) / (n + 1); standard deviation = sqrt (standard deviation^2 + (RSSI - mean RSSI)^2/(n+1)). The n variable represents an assumed number of RSSI values received so far. By decreasing the n variable, you can increase the self-adjusting speed of the RSSI threshold.

The self-adjusting threshold is one of many solutions to the obstacle problem. Increasing more pairs of foot traffic counters and comparing their data should also reduce the possibility of those odd situations. It also can be a way for customers to identify the direction of a person by comparing the time the person triggers different foot traffic counters.

Advertising Specific Channel:

After the final presentation, we also improved our systems by advertising on a specific channel instead of broadcasting into all three advertising channels(37, 38, 39). By doing so, we plan to improve the probability of detection, hence making the connection more substantial and more effective at detecting foot traffic. It also reduces the number of RSSI data points we have to collect. As the figure below shows, there are only around 120 data points for the 90cm baseline tests, which is around one-third of the original system. The RSSI fluctuation, however, doesn't show well. Since Zhenyu did those tests alone, the result is not as accurate as the two-person testing, in which one person walks through the boards, and the other counts for time and checks devices. One of the boards was accidentally placed on a metallic table, which may also have interfered with the outcome.





Comparative Analysis: Adafruit Feather vs. Nordic nRF5340 Boards

In exploring Bluetooth Low Energy (BLE) for foot traffic monitoring, we employed two hardware platforms with unique characteristics: the Adafruit Feather and the Nordic nRF5340. The Adafruit Feather, powered by an ARM Cortex-M4F processor and supporting BLE 5.0, stands out for its compact size and user-friendly interface. It's particularly accessible for hobbyists and suitable for small-scale projects. However, it does have limitations, such as lower processing power and less flexibility in fine-tuning BLE parameters, which might restrict its use in more demanding applications.

On the other hand, the Nordic nRF5340, equipped with a dual-core ARM Cortex-M33 processor and BLE 5.1 support, offers higher processing power and advanced BLE features. This board provides greater flexibility in configuration and optimization, making it ideal for larger, more complex deployments. However, its complexity and higher cost may make it less accessible to beginners and hobbyists.

In terms of performance, the Adafruit Feather showed stable signal strength at shorter ranges but exhibited more variation in RSSI readings over longer distances and different orientations. In contrast, the Nordic nRF5340 demonstrated more consistent signal strength and less RSSI fluctuation, even at extended ranges and in various orientations. This aspect highlights the Nordic board's suitability for scalable and flexible applications, whereas the Adafruit Feather is more appropriate for smaller setups or individual monitoring points.

Regarding development and deployment, the Adafruit Feather is more straightforward to program and deploy, making it an excellent option for rapid prototyping and smaller projects. The Nordic nRF5340, while requiring more technical expertise, offers advanced features and customization options beneficial for complex and large-scale applications. Regarding power consumption, the Adafruit Feather is generally more energy-efficient due to its simpler architecture. Although the Nordic nRF5340 offers advanced power management options, it may consume more power owing to its dual-core processor and enhanced capabilities.

This comparative analysis underlines the versatility of our BLE-based foot traffic monitoring system, demonstrating its capability to function effectively across different BLE devices. By accommodating various hardware platforms, our system ensures adaptability to various application scenarios, making it a robust IoT and smart monitoring solution.

Addressing Power and Connectivity Issues with Adafruit Feather Boards:

The deployment of Adafruit Feather boards highlighted crucial considerations in power and connectivity in IoT device design. The primary challenge was ensuring a stable power supply, as the lack of traditional USB ports necessitated using USB-C adapters. This experience points to the necessity of designing IoT devices with flexible power and connectivity options.

In future iterations of the project, exploring alternative power sources becomes essential. Battery packs offer a portable and convenient power source, but more sustainable options, such as solar power, could be considered for long-term deployments. Solar-powered IoT devices could operate autonomously for extended periods, making them ideal for outdoor or remote foot traffic monitoring applications.

Additionally, ensuring broad connectivity compatibility is paramount. IoT devices should be able to connect seamlessly with various types of hardware interfaces. This could mean designing devices with multi-port options or providing adaptable connectors that can interface with USB, USB-C, and other common port types.

Limitations of Our System – Long Queues

There are occurrences when multiple people walk in a line-like arrangement that would make it difficult for the foot traffic counter system to recognize more than one person walking past without computer vision. Since the system is based on RSSI values, it can estimate the number of people that walked past it. This is where computer vision applications shine when there are a greater number of people walking. However, these solutions can be costly and limited to a few deployment locations, whereas a BLE deployment is cost-effective.

Conclusion:

Our project successfully demonstrates the feasibility and effectiveness of using BLE technology to monitor foot traffic, specifically through the nRF5340 and Adafruit Feather boards. This approach capitalizes on BLE's low-power consumption and broadcast capabilities, offering a cost-effective alternative to more traditional methods like image recognition or thermal sensing.

Using RSSI for detecting and counting foot traffic proved to be a practical approach. Despite initial challenges, such as the rotation of MAC addresses and varying behaviors of identical hardware units, we were able to devise effective solutions. Implementing an Identity Resolving Key (IRK) significantly enhanced the reliability of our system by ensuring consistent detection of the broadcaster by the observer.

Our system's adaptability in adjusting the RSSI threshold based on varying environmental conditions and scenarios was a notable achievement. This self-correcting mechanism ensures the system remains accurate and functional under different real-world conditions.

However, our study also highlighted certain limitations of using BLE for foot traffic monitoring. The most significant is the system's reduced effectiveness in high-density or movement scenarios, where individual detection becomes more challenging.

Future Directions:

Future research can significantly advance BLE-based foot traffic monitoring systems by addressing these areas, making them more accurate, reliable, and applicable to a broader range of scenarios.

1. Enhancing Accuracy in Diverse Environments: Future work should improve the system's accuracy in different environmental conditions and crowded scenarios. Advanced signal processing and data analysis algorithms could be employed to better distinguish between multiple simultaneous movements.

2. Scalability and Integration: Exploring the system's scalability by testing with more devices and over larger areas is essential. Integration with IoT devices and platforms could offer a more holistic traffic monitoring and management approach.

3. Addressing Hardware Inconsistencies: Further investigation is needed into the hardware inconsistencies noted during testing. A more thorough understanding of these issues will aid in developing more robust and reliable systems.

4. Real-World Implementation and User Studies: Conducting extensive real-world trials in various settings, such as shopping malls, concert halls, and public transportation hubs, will provide valuable insights into the system's practicality and user acceptance. Gathering feedback from these implementations can guide refinements and improvements.

5. Exploring Additional Applications: The BLE foot traffic monitoring system has potential applications beyond counting individuals. It could be adapted for smart building management, emergency evacuation, and urban planning.

6. Enhancing Security and Privacy Measures: As BLE technology involves wireless communication, ensuring data security and user privacy is paramount. Future developments should include robust encryption methods and privacy-preserving techniques.

7. Machine Learning and Predictive Analytics: Implementing machine learning algorithms could enhance the system's ability to predict and analyze foot traffic patterns. This would be particularly useful for businesses and urban planners in making data-driven decisions.

8. Energy Efficiency and Sustainability: Continued focus on optimizing the system's energy efficiency will be crucial, especially for large-scale deployments. Exploring sustainable power sources like solar energy could enhance the system's applicability and environmental friendliness.

References:

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Project Code Repository: https://github.com/SuP3RM/Foot-Traffic