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Supporting Transportation System Management and Operations Using Internet of Things Technology: Phase II Field Tests

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Abstract:

This Phase II report builds on Phase I findings, further examining the application of the Low Power Wide Area Network (LPWAN) technologies in supporting transportation system operations and management. Phase I included a literature review to understand the current state of LPWAN applications and an online survey targeting transportation professionals to gather their experiences with LPWAN technology. The recommendations from Phase I suggested Phase II should focus on key technical issues such as the feasibility of transmitting various data sizes, data transmission frequency and rate, and deployment requirements. Thus, Phase II focused on the field test of the Long-Range Wide Area Network (LoRaWAN) and Narrowband Internet of Things (NB-IoT) communication solutions.

Pedestrian counting solutions utilizing LoRaWAN and NB-IoT were tested at Old Dominion University and in Williamsburg, VA to assess their feasibility, performance, cost, and possible technical issues. In the experiments conducted in the field, LoRaWAN proved effective in areas with high-density devices; it covers wide areas with fewer gateways powered by solar panels, making it cost-effective and efficient. NB-IoT, which uses existing cellular networks, showed its flexibility across geographically dispersed areas, eliminating the need for additional supporting devices. Strategic placement of devices was found to be crucial for reliable data transmission, and robust power solutions are essential to reduce the impact of weather. Both technologies demonstrated scalability, with applications that potentially extend beyond pedestrian counting.

The field test results underscore the importance of tailored deployment strategies for the LPWAN technologies that consider environmental conditions, infrastructure density, and economic factors to optimize performance and reliability. The extensive evaluation of the LPWAN technologies provides a valuable reference for transportation agencies when deploying them for LPWAN-based transportation applications. The research team recommends that VDOT keeps monitoring advancements in LoRaWAN and NB-IoT technologies to stay informed about emerging commercial sensors for expanded transportation applications.

FINAL REPORT

SUPPORTING TRANSPORTATION SYSTEM MANAGEMENT AND OPERATIONS USING INTERNET OF THINGS TECHNOLOGY: PHASE II FIELD TESTS

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ABSTRACT

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INTRODUCTION

The integration of Internet of Things (IoT) technologies into transportation system management and operations holds the potential to significantly enhance efficiency, safety, and sustainability. Recognizing this potential, the Phase I study (Yang et al., 2021) assessed the feasibility of implementing Low Power Wide Area Networks (LPWAN) within the transportation sector. The findings revealed that despite the initial stage of LPWAN adoption, its capabilities for long-range communication and low-power consumption make it a promising candidate for transforming transportation management practices.

Building on the positive outcomes of Phase I, the Phase II project moves from conceptual understanding to practical applications, providing valuable data that will facilitate the use of IoT technologies in transportation systems. This phase, based on the recommendations from Phase I, is designed to conduct robust field tests of the selected IoT technologies, specifically two LPWAN technologies: Long Range Wide Area Network (LoRaWAN) and Narrowband Internet of Things (NB-IoT). These technologies were chosen for their distinct operational characteristics: LoRaWAN operates on unlicensed bands and requires maintenance by the

Virginia Department of Transportation (VDOT), while NB-IoT operates on licensed bands and relies on the network provider (e.g., AT&T) for infrastructure maintenance. Field tests were planned in two distinct environments including the campus of Old Dominion University (ODU) in Norfolk, VA and a selected area in Williamsburg, VA. In this phase, the tests were conducted through the deployment of the LPWAN devices for people counting. Commercially available sensors compatible with these LPWAN systems were also employed for testing. Through rigorous testing and analysis, Phase II showcases that the LPWAN-based solutions can be adopted for transportation applications. The findings serve as a reference for transportation agencies considering similar technological applications.

Below are brief descriptions of the LoRaWAN and NB-IoT frameworks that have been tested in this phase.

LoRaWAN Framework

LoRaWAN is a protocol for high-efficiency wireless data transmission that operates over long distances using low power. Its architecture is uniquely suited for IoT applications due to its ability to connect low-cost, battery-operated sensors over long distances in various environments. LoRaWAN facilitates bidirectional communication, which enhances the functionality of IoT applications by enabling not only data collection but also remote device management. Its adaptive data rate optimization features allow for a balance between communication range and message delivery duration and frequency. For Phase II, the deployment of LoRaWAN technology at ODU and in Williamsburg involves setting up gateways that receive messages from widely distributed sensor nodes. This setup demonstrates LoRaWAN's capability to efficiently obtain pedestrian count data without the need for extensive wiring or frequent maintenance. Figure 1 provides an overview of the LoRaWAN framework tested in this phase. The system operator is responsible for device installation and network server setup. For maintenance, the system operator needs to monitor the working status of the system and troubleshoot any issues if a device or gateway goes offline. More details are discussed in Methods section.

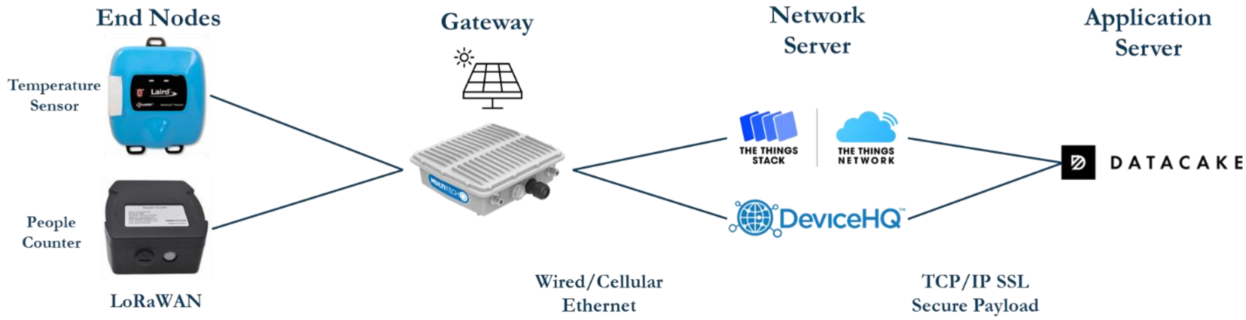


Figure 1. Overview of Long-Range Wide Area Network (LoRaWAN) Framework

NB-IoT Framework

NB-IoT is another LPWAN technology that has been employed in Phase II of the project. Unlike LoRaWAN, NB-IoT operates within a licensed spectrum which provides greater control over service quality and reliability, making it well-suited to applications that need consistent performance. NB-IoT devices are also designed to operate on minimal power, ensuring longevity without the need for frequent battery replacements, which makes it particularly suitable for applications in remote or inaccessible locations where power sources may be limited. Moreover, NB-IoT boasts wide coverage capabilities. Leveraging existing cellular infrastructure (e.g., AT&T, T-Mobile, and Verizon) eliminates the need for building dedicated infrastructure for communication, thereby reducing deployment costs (e.g., no additional gateway is needed). For security, it integrates encryption and authentication mechanisms to ensure the confidentiality and integrity of data transmitted between devices and networks. In summary, NB-IoT's utilization of licensed spectrum, coupled with low power consumption, wide coverage, and robust security features, makes it an excellent option for a variety of IoT applications in Phase II of the project. Like LoRaWAN, the system operator is responsible for device installation and network server setup. For maintenance, the system operator also needs to oversee the working status of the system and troubleshoot any issues if a device or gateway goes offline. Figure 2 illustrates the NB-IoT framework in detail. Further information will be provided in the Methods section.

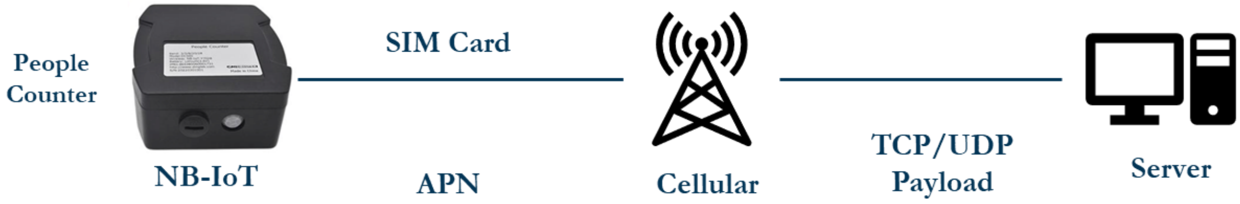


Figure 2. Overview of NB-IoT Framework

PURPOSE AND SCOPE

The main purpose of this project is to:

- **Assess the Performance and Cost-Effectiveness of LoRaWAN and NB-IoT Devices:** The project aims to evaluate the technical features, reliability, and cost-effectiveness of LoRaWAN and NB-IoT devices in various use cases. Through data collection and analysis, the project seeks to identify the strengths and limitations of each technology in different operational contexts.
- **Identify Lessons Learned from the Deployment and Operation of LPWAN Systems:** The project documents the challenges and limitations encountered during the installation and operation of IoT devices in selected test environments. Insights are gathered to inform and improve future installations, maintenance, and troubleshooting efforts.

METHODS

The following main tasks were performed to achieve the study objectives:

- **Procurement of LoRaWAN and NB-IoT devices:** The first step involves sourcing the necessary hardware components for both LoRaWAN and NB-IoT technologies. This includes selecting suitable people counting sensors, gateways, and other peripherals required for installation.
- **Selection of IoT Service Platform:** After procuring the devices, the next task is to choose appropriate IoT service platforms. These platforms would serve as the central hub for managing the data collected from the deployed devices. The selection process considers factors such as scalability, compatibility with the selected devices, and cost-effectiveness, ensuring the platform could support the project's needs as it scales.
- **Data Processing:** People counter only sends raw hexadecimal payloads. These messages need to be further processed to yield meaningful results.
- **Deployment of devices in the field:** With successful lab testing, the devices were deployed in the designated field locations. This involves installing people counting sensors and gateways at selected sites to capture pedestrian traffic.
- **Cost Comparison:** A comprehensive cost analysis was conducted to compare the expenses associated with deploying LoRaWAN and NB-IoT devices. The analysis included the costs of devices, services, installation, and estimated maintenance efforts.

Device Procurement

Guided by the results of the Phase I exploration, the ODU research team identified and acquired suitable gateways and sensor nodes for the Phase II study. The equipment procured included three LoRaWAN gateways, seven LoRaWAN people counters, and six NB-IoT people counters. Among the LoRaWAN gateway models selected were MultiTech MTCDTIP-L4N1-266A and MultiTech MTCDTIP-L4N1-267A, as shown in Figure 3. The latter model features Wi-Fi and Bluetooth modules, offering enhanced accessibility through wireless connections. It simplifies the maintenance and troubleshooting process on-site and improves user interaction with the device.

For the task of people counting, the devices chosen were the Dingtek DC500_LoRaWAN and Dingtek DC500_NB-IoT sensors. These devices were among the few commercially available products falling into the scope of this project. Additionally, the team procured specialized online services designed for the transmission and secure storage of data collected by the deployed LPWAN devices.

Figure 3. MultiTech LoRaWAN Gateways (Left: MTCDTIP-L4N1-266A; Right: MTCDTIP-L4N1-267A)

During the campus testing phase, one MultiTech MTCDTIP-L4N1-266A model was utilized. In contrast, for the testing in Williamsburg, VA, two MultiTech MTCDTIP-L4N1-267A models equipped with Wi-Fi/Bluetooth features were employed to enhance the connectivity and accessibility of the network. The integration of Wi-Fi/Bluetooth offers the benefit of simplified setup and maintenance, including wireless rebooting and monitoring capabilities.

The people counters (i.e., Figure 4) operate with infrared sensors to detect pedestrian movement, and they are powered by a 3.8V battery. The key difference between the LoRaWAN and NB-IoT systems is the type of communication module each employs. These modules are responsible for sending the data that the infrared sensors collect.

Figure 4. NB-IoT and LoRaWAN Sensors.

The research team also tested devices functionality and configuration for field deployment, particularly in areas which lacked traditional internet access. This involved connecting the gateways to a computer to configure LoRaWAN settings, such as frequency plans and authentication keys. The research team anticipated the absence of a stable internet connection in the deployment areas and prepared to establish a cellular network connection for the gateways using SIM cards. This setup allowed the gateways to transmit data collected from end nodes to the network server via cellular data services. Configuring the gateways for cellular connectivity included selecting an appropriate data plan, activating SIM cards, and setting up necessary Access Point Name (APN) settings to maintain data transmission in remote locations.

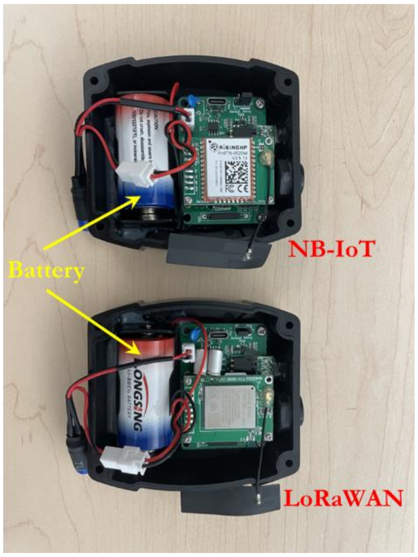


Figure 5. Disassembly Diagram of the People Counter

To configure the LoRaWAN and NB-IoT people counters, the research team physically opened the device cases and connected them to a computer using a USB Type-C cable for the setup process, as shown in Figure 5. This connection enabled the research team to access and modify devices' settings (e.g., people counting threshold, upload frequency, server address, etc.). For the LoRaWAN people counters, the research team linked all seven devices to the gateways. LoRaWAN latency and signal strength were also evaluated. The configuration process for the NB-IoT people counters involved setting the receiving server's IP address and port. This setup directs the devices to transmit their collected data to the specified server for processing and analysis. NB-IoT communication latency was evaluated.

It is important to note that NB-IoT devices rely on cellular service, and an unstable connection can result in unsuccessful message transmissions. If the cellular service is offline or the signal is weak, NB-IoT devices are unable to transmit messages effectively. In contrast, for LoRaWAN gateways, cellular service is employed in field deployments where conventional networks are unavailable to communicate with the network server. To address potential issues with poor cellular service, an external storage device can be added directly to the gateway. This storage solution helps ensure data integrity and continuity because it mitigates message loss during periods when cellular service is offline.

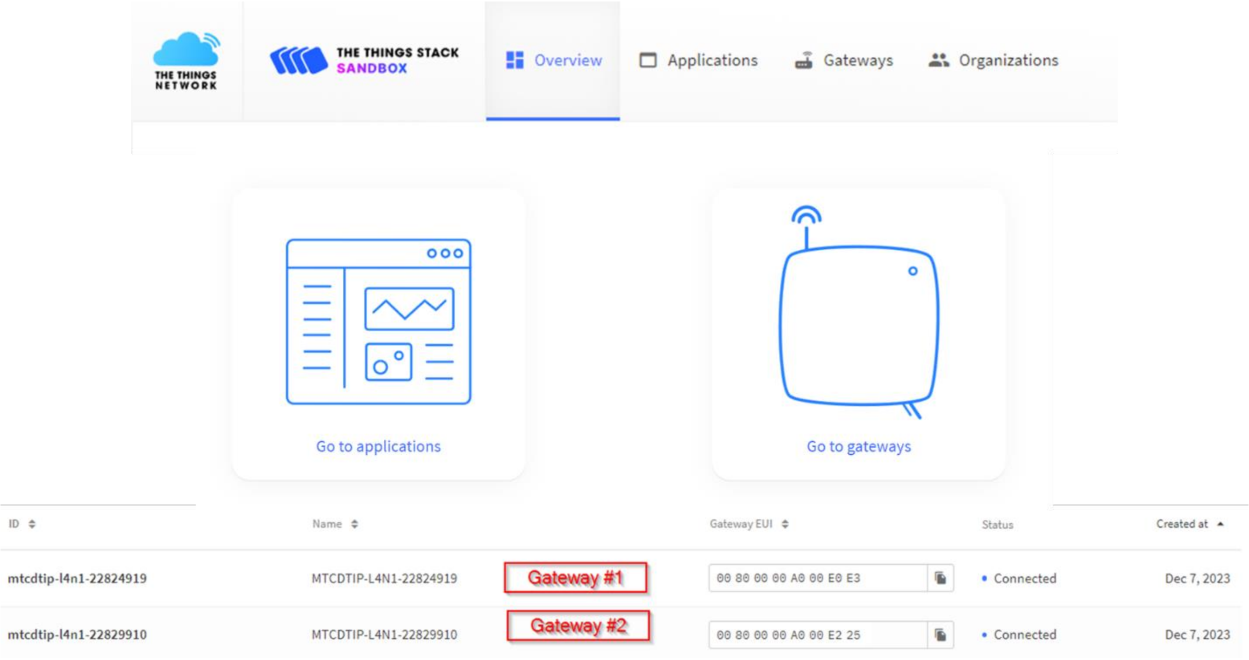
Service Platform Selection

For detailed specifications on LoRaWAN and NB-IoT technologies, please refer to the Phase I report (Yang et al., 2021). In the selection of infrastructure for data transmission, processing, and management, the research team opted for The Things Network (TTN) for handling LoRaWAN communications. TTN facilitates efficient message transmission and processing for LoRaWAN devices and provides a scalable and reliable platform for IoT applications (The Things Industries, 2024). For data storage and visualization, the team employed Datacake (Datacake, 2024), a versatile platform that offers user-friendly data visualization tools and data management capabilities. Datacake can generate daily reports.

NB-IoT messages, on the other hand, require a more tailored approach. The team established a customized server designed specifically for receiving and processing NB-IoT messages. The server was equipped with programs capable of decoding NB-IoT payloads, thereby ensuring compatibility with the cellular network's requirements for data transmission and security protocols. It also included tools for monitoring message integrity and managing device connectivity, thus maintaining reliable data flows from deployed NB-IoT sensor nodes.

The Things Network

TTN is a global, open-source, decentralized infrastructure that facilitates the wireless transmission of data from IoT devices using LoRaWAN technology. It provides the backbone for this communication, enabling developers to build and deploy IoT applications with minimal investment in network infrastructure. The dashboard is illustrated in Figure 6.



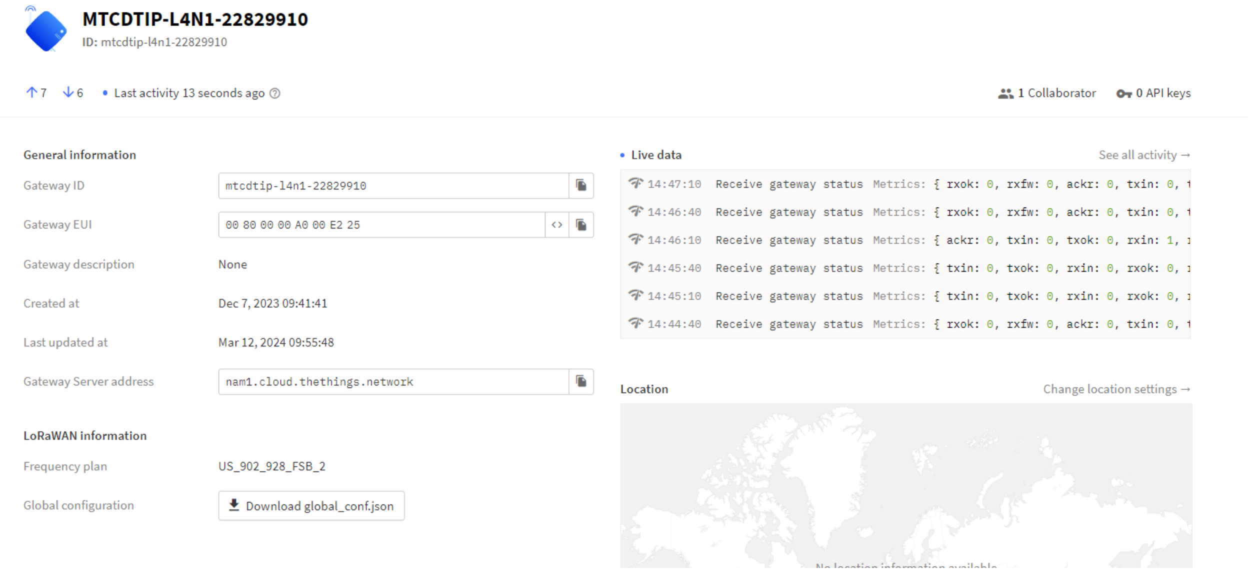
ID	Name		Gateway EUI	Status	Created at
mtcdtip-l4n1-22824919	MTCDTIP-L4N1-22824919	Gateway #1	00 80 00 00 A0 00 E0 E3	• Connected	Dec 7, 2023
mtcdtip-l4n1-22829910	MTCDTIP-L4N1-22829910	Gateway #2	00 80 00 00 A0 00 E2 25	• Connected	Dec 7, 2023

Figure 6. The Things Network Dashboard

Here are the main components of TTN:

- **Gateways:** These are physical devices that receive LoRaWAN messages from sensors and devices (nodes) and relay them to the TTN network. A single gateway can cover up to several miles in rural areas and connect thousands of devices. Crucial for network scalability and reliability, gateways act as a bridge between end devices and the internet.
- **Applications:** In the context of TTN, an application is a logical grouping of devices that share common functionality or are part of a single project. Applications receive data transmitted by devices through the gateways and TTN network. Developers can use TTN's Application Programming Interfaces (APIs) to integrate this data into their own software applications, enabling a wide range of IoT solutions, from monitoring temperatures to counting people.
- **Devices:** These are the IoT sensors that communicate with the network using LoRaWAN. Each device is uniquely identified within the network by its DevEUI (Device Extended Unique Identifier), allowing secure and efficient communication.
- **Integration:** TTN allows for integration with third-party platforms and services for further processing, storage, or visualization of the data. This is facilitated through webhooks, MQTT, and other API services provided by TTN that enable the flow of data from devices to end-user applications or databases.
- **Network Server:** The network server is the core of the TTN infrastructure, managing the network's operation, including device registration, message routing, and application integration. It ensures secure communication across the network and handles tasks such as encryption/decryption of messages and managing join requests from devices.
- **Console:** TTN provides a user-friendly console for managing gateways, devices, and applications. Users can register new devices, configure gateways, create applications, and set up integrations, making it easier to manage and scale IoT deployments.

All LoRaWAN gateways and end nodes were registered in TTN. The live status and details of both gateways (e.g., Figure 7) and devices (e.g., Figure 8) were accessible via the dashboard.



MTCDTIP-L4N1-22829910
ID: mtcdtip-l4n1-22829910

↑7 ↓6 • Last activity 13 seconds ago

1 Collaborator 0 API keys

General information

Gateway ID	mtcdtip-l4n1-22829910
Gateway EUI	00 80 00 00 A0 00 E2 25
Gateway description	None
Created at	Dec 7, 2023 09:41:41
Last updated at	Mar 12, 2024 09:55:48
Gateway Server address	nam1.cloud.thethings.network

LoRaWAN information

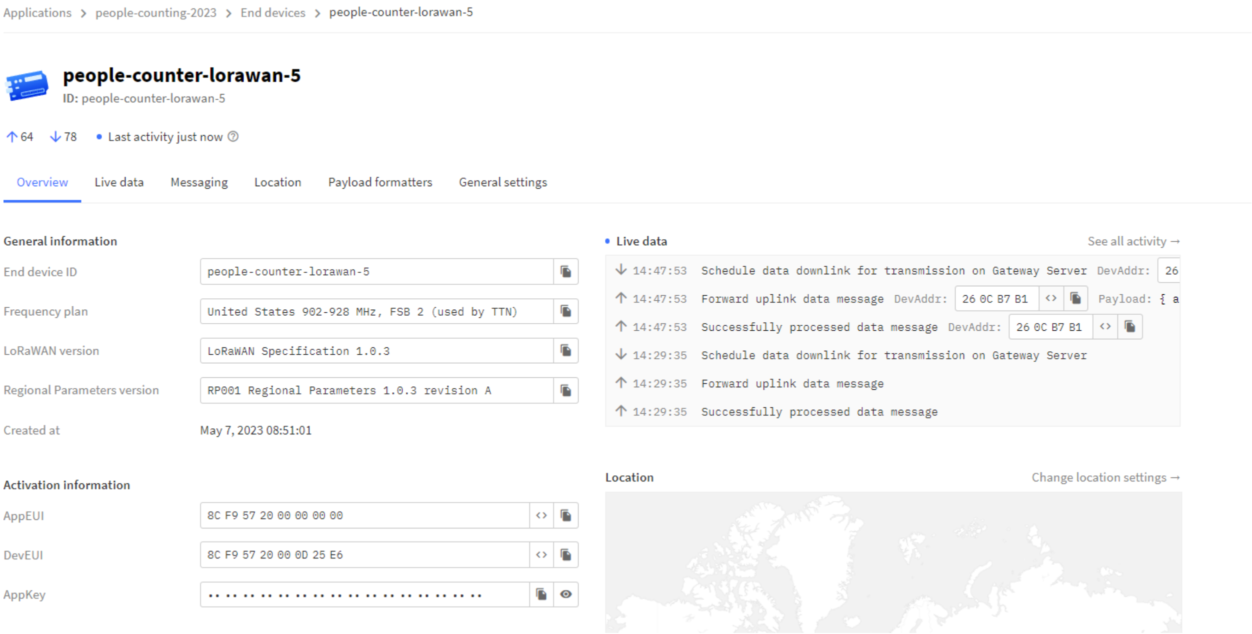
Frequency plan	US_902_928_FSB_2
Global configuration	Download global_conf.json

• Live data — See all activity →

```
14:47:10  Receive gateway status Metrics: { rxok: 0, rxfw: 0, ackr: 0, txin: 0,
14:46:40  Receive gateway status Metrics: { rxok: 0, rxfw: 0, ackr: 0, txin: 0,
14:46:10  Receive gateway status Metrics: { ackr: 0, txin: 0, txok: 0, rxin: 1,
14:45:40  Receive gateway status Metrics: { txin: 0, txok: 0, rxin: 0, rxok: 0,
14:45:10  Receive gateway status Metrics: { txin: 0, txok: 0, rxin: 0, rxok: 0,
14:44:40  Receive gateway status Metrics: { rxok: 0, rxfw: 0, ackr: 0, txin: 0,
```

Location — Change location settings →

Figure 7. The Information of LoRaWAN Gateway in TTN Dashboard



Applications > people-counting-2023 > End devices > people-counter-lorawan-5

people-counter-lorawan-5
ID: people-counter-lorawan-5

↑64 ↓78 • Last activity just now

General information

End device ID	people-counter-lorawan-5
Frequency plan	United States 902-928 MHz, FSB 2 (used by TTN)
LoRaWAN version	LoRaWAN Specification 1.0.3
Regional Parameters version	RP001 Regional Parameters 1.0.3 revision A
Created at	May 7, 2023 08:51:01

Activation information

AppEUI	8C F9 57 20 00 00 00 00
DevEUI	8C F9 57 20 00 0D 25 E6
AppKey	•• •• •• •• •• •• •• •• •• •• •• •• •• •• •• ••

• Live data — See all activity →

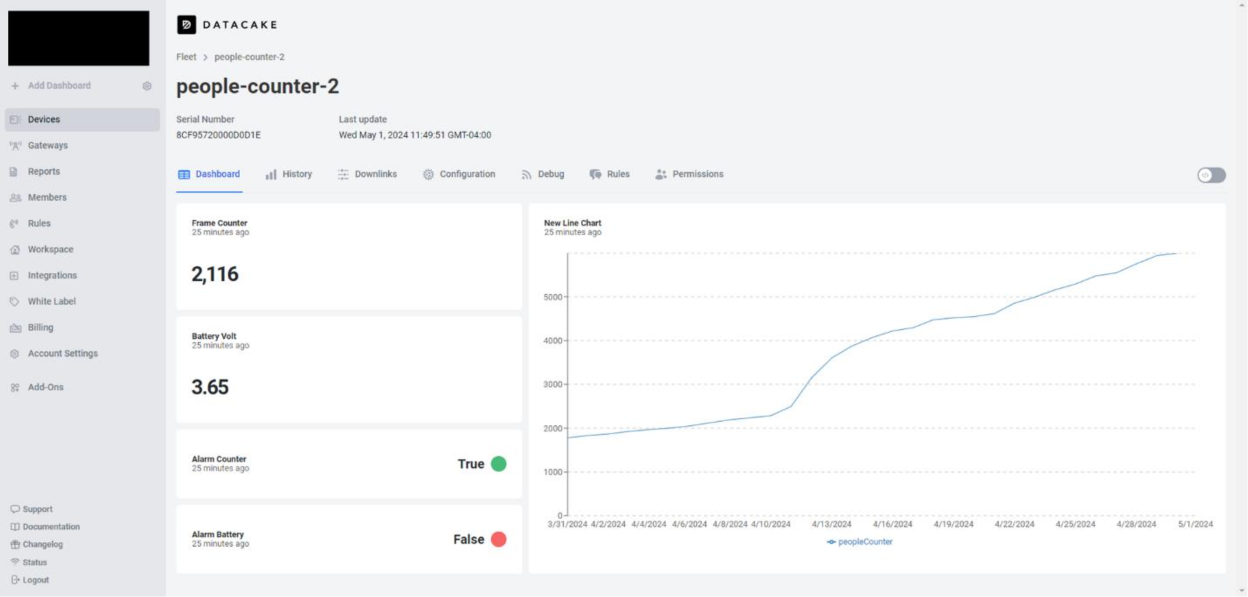
```
↓ 14:47:53  Schedule data downlink for transmission on Gateway Server DevAddr: 26
↑ 14:47:53  Forward uplink data message DevAddr: 26 0C B7 B1  Payload: { a
↑ 14:47:53  Successfully processed data message DevAddr: 26 0C B7 B1
↓ 14:29:35  Schedule data downlink for transmission on Gateway Server
↑ 14:29:35  Forward uplink data message
↑ 14:29:35  Successfully processed data message
```

Location — Change location settings →

Figure 8. The Information of LoRaWAN People Counter in TTN Dashboard

Datacake

Datacake is a cloud-based platform that offers a comprehensive tool for IoT project development, focusing on data storage, visualization, and management. The data visualization dashboard for one of our deployed sensor nodes is illustrated in Figure 9.



people-counter-2

Serial Number: 8CF95720000D0D1E

Last update: Wed May 1, 2024 11:49:51 GMT-04:00

Frame Counter (25 minutes ago): 2,116

Battery Volt (25 minutes ago): 3.65

Alarm Counter (25 minutes ago): True ●

Alarm Battery (25 minutes ago): False ●

Figure 9. Datacake Data Visualization Dashboard

Here are the main components of Datacake:

- **Data Storage:** Datacake can store large volumes of data coming from various sources, including IoT devices and sensors with the support of different data types.
- **Data Visualization:** Users can design custom dashboards to display real-time and historical data in various formats (e.g., graphs, charts, and gauges). This capability makes it easier to monitor trends and perform analysis.
- **Device Management:** Datacake allows users to manage multiple IoT devices. Each device can be individually configured, and the platform supports a wide range of device types and connectivity options.
- **Alerts and Notifications:** The platform enables the setting up of alerts based on specific data thresholds or events. Users can receive notifications via email, SMS, or webhooks.

All collected end node data were stored in Datacake. The research team has set up automatic daily report generation.

Customized Server

Since the selected NB-IoT devices were not compatible with Datacake, the team used an alternative approach for storing and processing the collected data. The NB-IoT devices were configured to use Transmission Control Protocol (TCP) to send data to a specific IP address and port corresponding to the team's server. Upon receiving the data, the server automatically saves the incoming data as log files. These log files serve as a raw data repository, capturing the information transmitted in a format that requires further decoding and processing to be analytically useful.

To efficiently manage the data collected from the NB-IoT devices, the team implemented a Python script to establish a server specifically designed for this purpose. This server acted as a central node, where all the data transmitted by the devices was first collected. The Python script was critical for setting up the TCP server, defining the process to receive the data, and handling the initial storage into log files. The Python script included error-handling mechanisms to manage any potential issues during data transmissions, such as connection timeouts or data corruption. This setup ensured that the data was not only collected reliably but also stored securely for further processing. The data processing including encoding and decoding of NB-IoT messages is further discussed in the Section of Data Processing – NB-IoT.

Data Processing

People counters transmit data in raw hexadecimal form, which is not immediately usable for analysis. To extract meaningful insights from the raw data, a processing step is essential. This involves decoding the hexadecimal segments into a more comprehensible and structured format, thus converting raw data into human-readable values that can be used for further analysis. The processing step typically includes translating the hexadecimal data into decimal values to identify specific data points such as the number of detected pedestrians, battery levels, and timestamps.

Field Deployment

On-Campus Test

The ODU campus installation included a setup of LoRaWAN gateways, solar panels, batteries, and people counters to create a robust network for monitoring pedestrian traffic. The deployment of people counters enables the capabilities to gather data on pedestrian flow at selected locations. This setup ensured continuous operations, leveraging solar power to sustain the gateways and sensors without reliance on external power sources. The solar panels charged the batteries, which in turn powered the LoRaWAN gateways, enabling them to effectively transmit data even in remote or power-scarce areas. This infrastructure demonstrated the potential for sustainable, low-maintenance IoT solutions in outdoor environments.

It is important to note that the LoRaWAN gateway operates on battery power, supplemented by solar panels for recharging. In contrast, the LoRaWAN and NB-IoT people counters are powered by C batteries. The LoRaWAN people counter relies on the gateway for communication. Although the sensor itself operates continuously, it can only upload data when the gateway is operational. Conversely, the NB-IoT people counters operate independently from a gateway. By utilizing their own cellular communication infrastructure, the NB-IoT sensors can directly upload data to the server provided the connection is established and operational.

The ODU research team initiated the field tests at ODU's Norfolk campus, installing a LoRaWAN Gateway approximately 15 feet high on a light pole as shown in Figure 10.

Figure 10. ODU Facility Management Staff Assisting in the Installation of a LoRaWAN Gateway, Solar Panel, and Battery Enclosure

The installation was aided by the staff from ODU Facilities Management and Construction Department, whose expertise and specialized tools ensured a proper and safe installation. After installation, the system required no further user intervention to operate. Initially, the system's battery was depleted, and it took about 4.5 hours of natural solar recharging for the system to return to an operational state. Specifications for the solar power system as shown in Figure 11 included:

- A 30W Solar Panel
- A 36Ah Battery Bank
- A 24V 8A PWM Solar Controller with 48V 30W Passive PoE and 24V 1.5A Auxiliary Output

Figure 11. The Installed LoRaWAN System Mounted on a Light Pole

The system's performance, powered by a solar source and utilizing a cellular SIM network for connectivity, is subject to a variety of operational factors. Adverse weather conditions (e.g., rain, overcast skies, and fog) can lead to insufficient sunlight, thereby hindering the solar charging process. The capacity for energy generation also depends on the size and number of solar panels deployed. Furthermore, the efficiency and reliability of the cellular service provider's server are crucial for data communication, while battery performance is susceptible to fluctuations with varying temperatures. Alongside these, a multitude of other environmental and technical factors may also play a role in the system's overall efficiency and reliability.

The ODU system went online at 12:30 PM on June 15, 2023. However, severe weather conditions impacted the area the following day. On June 17, 2023, at 1:00 AM, the system experienced a disconnection due to insufficient battery power, which was resolved when normal operations resumed at 10:00 AM the same day. All comprehensive data records related to weather conditions are included in the Results and Discussion section. It provides a detailed analysis of how weather variations impacted the system's performance, particularly with respect to the disconnection event following severe weather conditions and the system's subsequent recovery.

Figure 12. A Laird Temperature Sensor, a LoRaWAN People Counter, and an NB-IoT People Counter Housed in A Waterproof Enclosure, Mounted on a Light Pole at ODU's Norfolk Campus

To ensure the protection and functionality of the people counters, robust measures were implemented during installation. The counters were placed in waterproof enclosures to protect against weather conditions, as shown in Figure 12. For operational purposes, specifically to allow the sensors to detect people, two holes were carefully drilled into the side of these enclosures. To further secure the devices from vandalism and theft, the enclosures were fitted with combination locks, which provided an added layer of protection. Within the enclosure, a LoRaWAN and an NB-IoT people counter were set up, along with a temperature sensor. This sensor was designed to help us understand how temperature and humidity variations affect the battery life of the sensors, as well as to verify the stability of the network connection with its relatively high frequency of data transmission.

Three locations for people counters were selected for their relevance and high foot traffic potential on campus: one near a bus stop, another close to the sports complex, and the last next to a central campus area as shown in Figure 13. The sensors at these locations were oriented specifically to face the sidewalks, enabling the counting of passing pedestrians. It is worth mentioning that, due to the nature of infrared sensors, other objects passing on the sidewalk (e.g., bikes and scooters) will also be counted. A comprehensive analysis of the data collected from these counters, along with interpretations and implications of the pedestrian flow patterns observed, is provided in the Results and Discussion section.

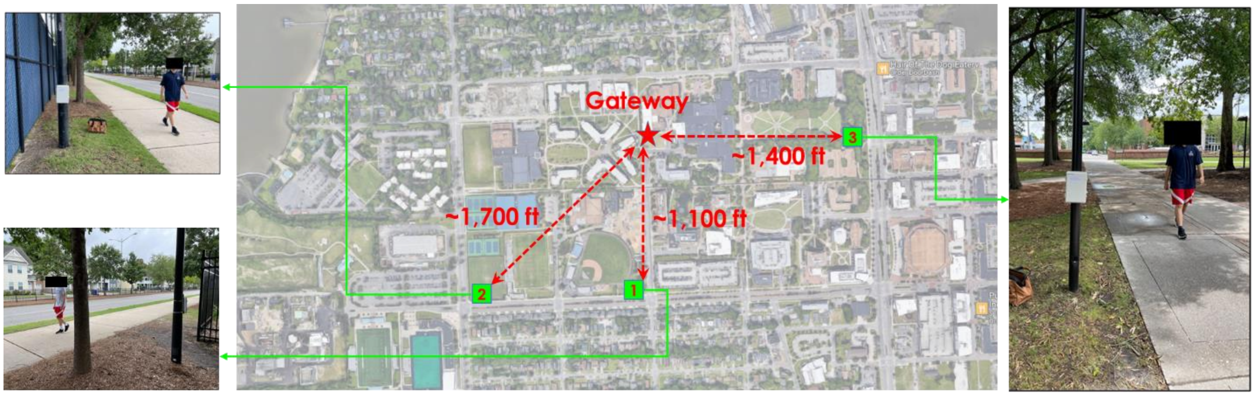


Figure 13. Map Showing the Location of the LoRaWAN Gateway and the Positions of Three Device Installation Sites, Including the Distances Between Each

Williamsburg Test

Following the campus installation experience, the research team developed a proposal to deploy both LoRaWAN gateways and people counters on VDOT properties in Williamsburg, VA. Based on lessons learned from on-campus test, two LoRaWAN gateways were deployed with dual solar panels to ensure sufficient power supply. The utilization of two LoRaWAN gateways serves multiple purposes. Not only does it provide redundancy, thereby enhancing network reliability, but it also allows for comprehensive coverage of the deployment area. Furthermore, deploying multiple gateways enables us to test message broadcasting capabilities and optimize network performance, particularly in areas where sensors may be located within the overlap zones of the gateways. Prior to field deployment, the gateways underwent operational testing to verify consistent performance and efficiency.

The gateways are designed to operate with an input voltage range of 37 to 57 VDA, and the solar power system includes a controller with Power over Ethernet (PoE) capability. The solar panels used in the setup each have a capacity of 30W and output a voltage of 24V. The batteries chosen for the system have a capacity of 36Ah and operate at a voltage of 24V. To achieve full battery capacity, the ideal charging time is 14.4 hours, which ensures the system can run efficiently during periods without sufficient sunlight.

Following discussions with the technical review panel of this project, it was agreed the research team would install one LoRaWAN gateway at the intersection of Monticello Ave and Ironbound Rd (37°16'32.9"N 76°44'18.9"W) with an elevation above sea level of 114.83 ft, as shown in Figure 14, and another at the intersection of Monticello Ave and Casey Blvd (37°16'30.2"N 76°44'58.1"W) with an elevation above sea level of 131.23 ft, as shown in Figure 15.

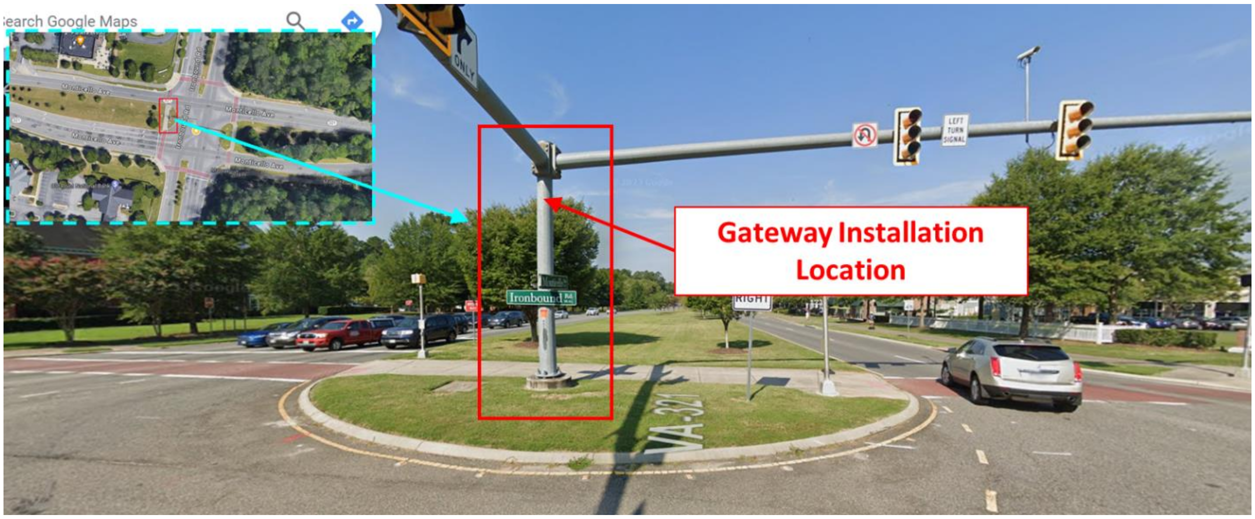


Figure 14. Gateway Installation Location #1 at the Intersection of Monticello Ave & Ironbound Rd in Williamsburg, VA (37°16'32.9"N 76°44'18.9"W)

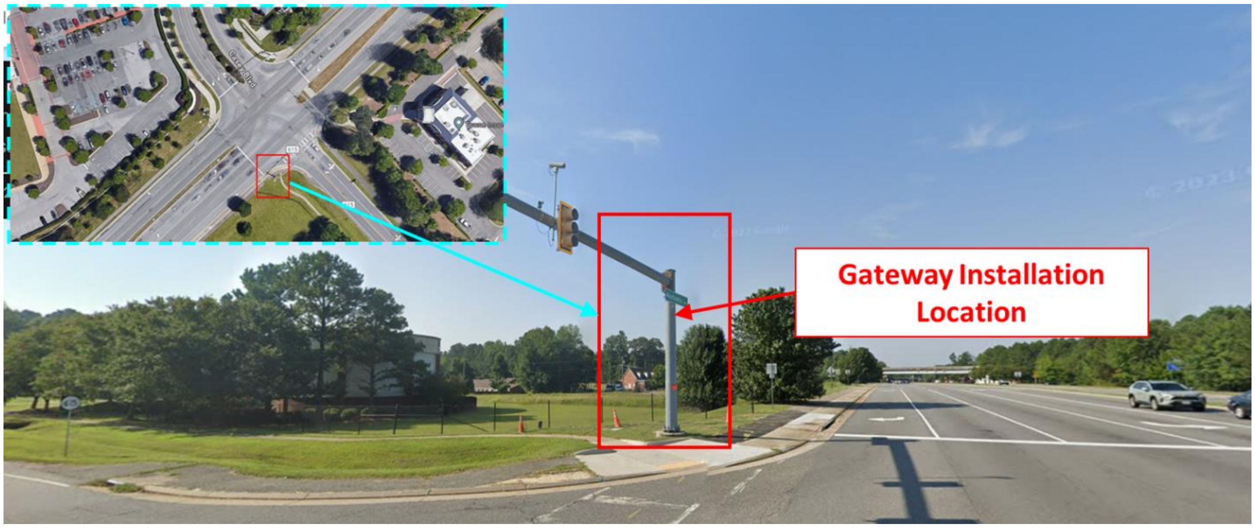


Figure 15. Gateway Installation Location #2 at the Intersection of Monticello Ave & Casey Blvd in Williamsburg, VA (37°16'30.2"N 76°44'58.1"W)

Both gateways were mounted on existing traffic signal poles. This approach ensured optimal coverage of a large area, while minimizing installation complexity and costs with typical infrastructure in the field. To mitigate potential distractions to drivers and ensure the safety and security of the infrastructure, the gateways were installed at a high level on the traffic signal poles. The high elevation serves to minimize visual disruption and prevent unauthorized access or vandalism, as the gateways are out of the reach of passing pedestrians. With the support of VDOT technicians, the research team ensured the installation respected the needs and concerns of the community.

On the installation day, February 26, 2024, the deployment team, comprised of two VDOT technicians and the ODU research team members, arrived at the designated locations with the necessary equipment and accessories. The VDOT technicians brought two utility trucks to help install the LoRaWAN gateways, solar panels, and battery enclosures, while the ODU team provided the required equipment, accessories (e.g., clamps, cables, etc.), and settings. The installation process commenced promptly, with the deployment team working efficiently to mount the LoRaWAN gateways, solar panels, and battery enclosures onto the designated traffic light poles. However, due to the substantial thickness of the poles, the mounting process took slightly longer than anticipated. After approximately 1.5 hours of effort, both LoRaWAN gateways were successfully installed. It is worth mentioning that throughout the installation process, safety protocols were strictly followed with measures in place to minimize any disruptions to traffic flow or pedestrian activity in the vicinity.

Following the installation, it is important to allow time for the batteries to charge fully before conducting testing. Due to the nature of solar-powered systems, an initial charging period is necessary to ensure the batteries reach the optimal capacity for operation. Figure 16 (a) shows VDOT technicians assisting with the installation of a LoRaWAN gateway, solar panels, and battery enclosure at the intersection of Monticello Ave and Ironbound Rd. Figure 16 (b) shows that the installation of the gateway on a thicker traffic light pole requires the assistance of two VDOT technicians and two utility trucks at the Intersection of Monticello Ave and Casey Blvd.

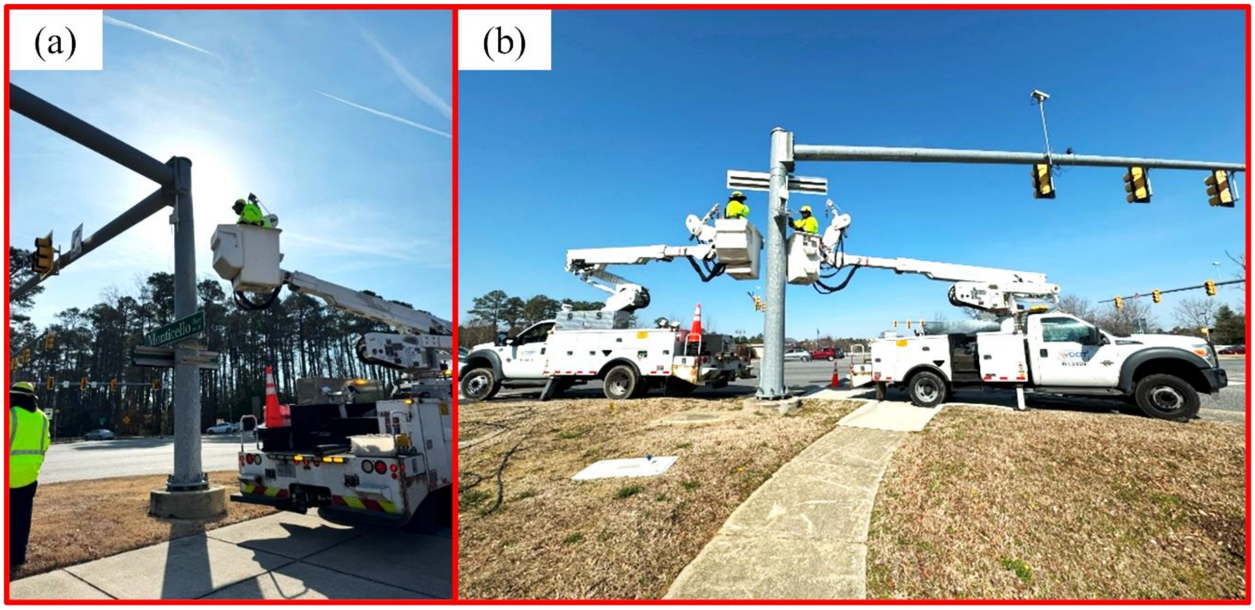


Figure 16. VDOT Technicians Assisting in the Installation of LoRaWAN Gateways, Solar Panels, and Battery Enclosures at: (a) the Intersection of Monticello Ave and Ironbound Rd; and (b) the Intersection of Monticello Ave and Casey Blvd

Six locations, shown in Figure 17, were selected for the installation of people counters in Williamsburg, VA:

1. 37°16'40.4"N 76°43'44.5"W, Monticello Ave Eastbound (Elevation above sea level: 83.27 ft).
2. 37°16'55.2"N 76°44'13.3"W, Ironbound Rd Southbound (Elevation above sea level: 102.82 ft).
3. 37°16'55.0"N 76°44'11.9"W, Ironbound Rd Northbound Close to Watford Ln (Elevation above sea level: 106.69 ft).
4. 37°16'22.1"N 76°44'19.8"W, Strawberry Plains Rd Northbound (Elevation above sea level: 100.10 ft).
5. 37°16'35.1"N 76°44'50.0"W, Monticello Ave Eastbound (Elevation above sea level: 92.16 ft).
6. 37°16'27.4"N 76°45'03.7"W, Monticello Ave Westbound (Elevation above sea level: 96.78 ft).

Detailed information on each location can be found in Appendix A. The distance from LoRaWAN Gateway #1 and #2 to each people counter is summarized in Table 1.

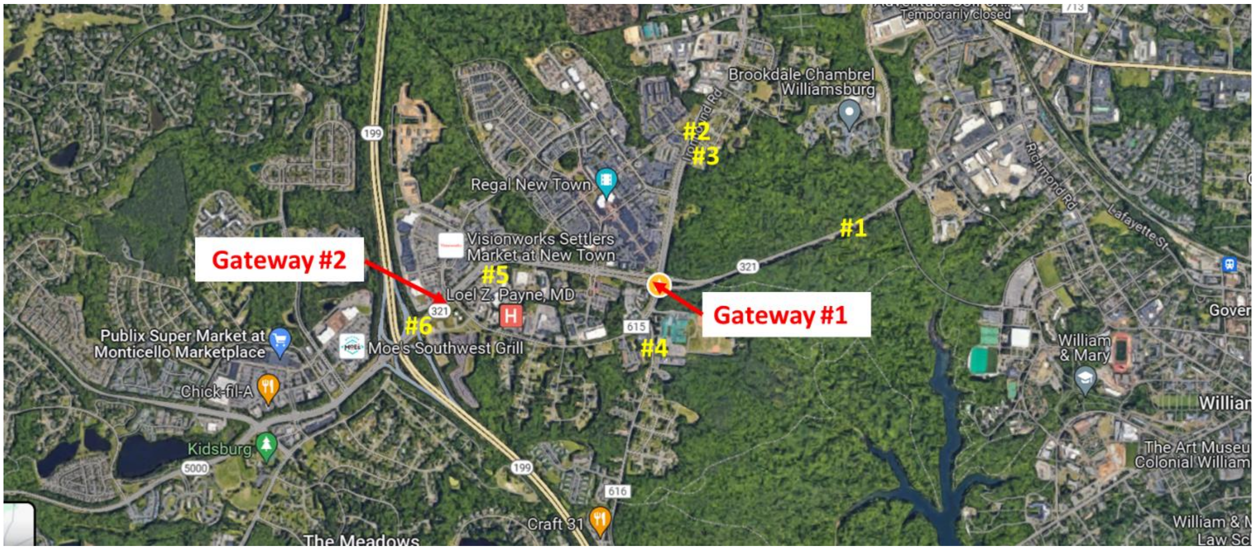


Figure 17. Map of People Counter Installation Locations in Williamsburg, VA

Table 1. Distance Between the LoRaWAN Gateways and People Counters

People Counter Location	Distance to Gateway #1	Distance to Gateway #2
Location #1	3,000 ft	6,000 ft
Location #2	2,300 ft	4,400 ft
Location #3	2,320 ft	4,500 ft
Location #4	1,150 ft	3,200 ft
Location #5	2,400 ft	920 ft
Location #6	3,500 ft	350 ft

To ensure consistency and efficiency, the same type of protective enclosure used for the campus installation was employed for these installations. Two members of the ODU research team completed the installation process for all six boxes. The chosen locations prioritize safety and minimize potential distractions for drivers. The boxes are mounted to warning sign poles, not regulatory ones like speed limit signs, to enhance safety and reduce the risk of legal issues stemming from distractions caused by installed boxes. To expedite the installation process, a power drill with a socket was used to install clamps for mounting. The clamps helped minimize installation time while ensuring secure and stable placement of the boxes.

Cost Comparison

Deployment and maintenance costs are crucial factors in decision-making processes for implementing network infrastructure technologies such as LoRaWAN and NB-IoT. These costs encompass hardware purchases and labor for deployment, and ongoing labor and time for maintenance. Consideration of these factors is essential for sustainable operation. This study also examined the deployment and projected maintenance costs associated with LoRaWAN and NB-IoT technologies over time spans of one, five, and ten years, particularly in varying geographic settings—rural and urban—where device distribution and density significantly differ. All cost estimates are from late 2023. It is anticipated that the performance of some devices may be reduced over the years, and additional units (e.g., solar panels) may require replacement or upgrades. Costs associated with device replacement or upgrade are not considered in this analysis.

The deployment costs for LoRaWAN include:

- **MultiTech LoRaWAN Gateway:** $1,600 per unit.
- **LoRaWAN People Counter:** $100 per unit.
- **Solar Power System:** $900 per unit.
- **The Things Network (TTN) Service:** Complimentary for up to 10 devices and gateways. For large-scale deployments, there is a plan available at $230 per month, which supports 1,000 devices and unlimited gateways.
- **Datacake Subscription:** $10 monthly.
- **SIM Card for Gateway:** $10 monthly or an annual option of $100.
- **Additional Costs:** May include waterproof enclosures, batteries, cables, clamps, labor, and related accessories of around $100 for each people counter.

For NB-IoT, the costs are:

- **NB-IoT People Counter:** $100.00 per unit.
- **SIM Card for Each People Counter:** $10 monthly or an annual option of $100.
- **Network Server:** Free of charge (the server can be set up on a standard PC connected to the internet).
- **Additional Costs:** May include waterproof enclosures, batteries, cables, clamps, labor, and related accessories of around $100 for each people counter.

RESULTS

Device Procurement

Once all gateways and people counters were procured and all setups were completed, the research team proceeded to conduct tests to verify the functionality of the counters. These involved having individuals walk past the sensors to see if the counters accurately recorded each event. To assess the reliability, the team evaluated the sensor accuracy ratio and the upload success rate by running 20 trials at each specified time interval. The research team also performed stress testing under extreme conditions with a single person triggering the sensor, following a preset pattern of walking past the counter at intervals of 5, 10, and 15 seconds as shown in Table 2. Subsequently, the configuration was adjusted so that the upload trigger would activate for every 10 people counted. The success of these uploads depended on the sensor's ability to accurately detect individuals passing by. Furthermore, a minimum time interval was set between each data upload. The accuracy of the people counter is a metric specific to the sensors themselves, not influenced by the data transmission technology, whether it's LoRaWAN or NB-IoT. It is assessed based on the sensors' ability to correctly detect and count the number of people passing by, regardless of the method used to transmit that data to the server.

Table 2. People Counter Accuracy Test

Interval	**Benchmark (Sensor Counts)**	**Actual Sensor Counts**	**Sensor Accuracy**
5-second	20	11	55%
10-second	20	20	100%
15-second	20	19	95%

The research team selected various locations to assess signal strength, investigating how significantly structures and landscape features can impact signal quality. Signal strength was measured using the Received Signal Strength Indicator level, where a lower Received Signal Strength Indicator value denotes a weaker signal. Instances of "Poor Signal" were identified when the network server received join requests from devices but failed to receive any payload data, indicating inadequate signal strength for complete data transmission. For benchmarking purposes, a Laird LoRaWAN temperature sensor from Phase I of the project was utilized as a reference device. Figure 18 provides a visual representation of the locations of the LoRaWAN gateway and people counters at ODU for signal strength measurement. Table 3 presents the signal strength of sensors relative to their distance from the gateway.

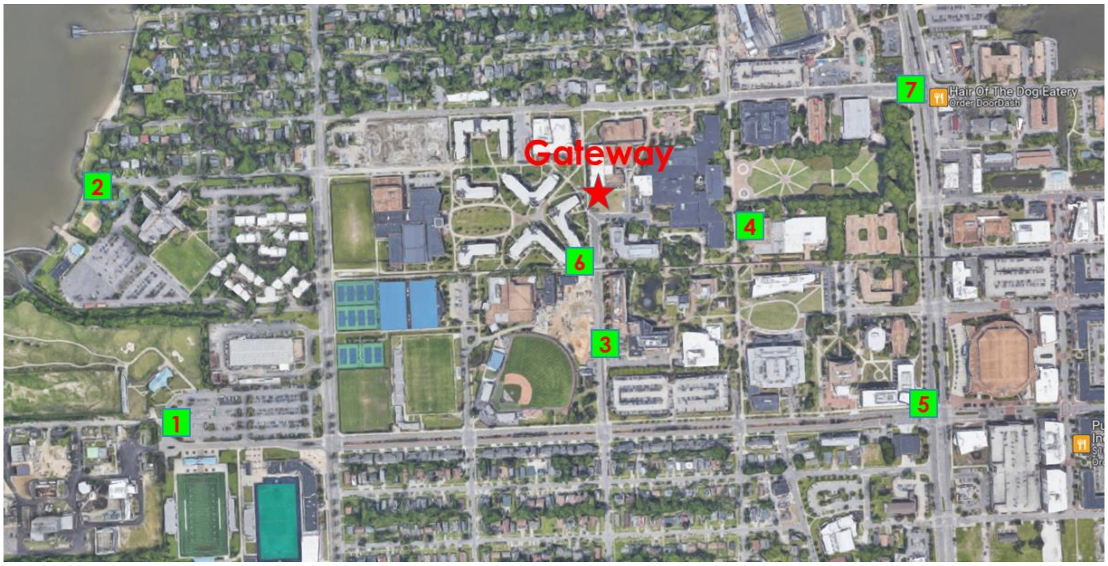


Figure 18. Locations of the Gateway and People Counters at ODU to Measure Signal Strength

Table 3. Signal Strength of Sensors Relative to Their Distance from the Gateway

Distance	Location	People Counter Signal Strength	Temperature Sensor Signal Strength
250 ft	6	-75 dBm	-75 dBm
820 ft	4	-155 dBm	-109 dBm
930 ft	3	-114 dBm	-86 dBm
1,600 ft	7	Poor Signal	-120 dBm
1,900 ft	5	-118 dBm	-120 dBm
2,210 ft	1	-113 dBm	-86 dBm
2,460 ft	2	Poor Signal	-129 dBm

The research team also executed signal strength tests in environments devoid of building obstructions. The results from these tests showed a marked improvement, underscoring the importance of clear line-of-sight for optimal signal transmission. Figure 19 illustrates the locations of sensors with unobstructed line-of-sight to the gateway and Table 4 displays the enhanced signal strength measurements. Consequently, the research team determined that the best locations for installing devices would be areas unimpeded by structures such as rooftops or signal towers, which could otherwise degrade signal quality. Indeed, the quality and design of antennas play a critical role in signal transmission and reception. High-quality antennas with appropriate design specifications can significantly enhance signal strength by improving gain, reducing interference, and increasing the efficiency of the radio frequency energy transmitted and received. Thus, in addition to selecting obstruction-free installation sites, investing in well-designed antennas is also critical for optimizing the performance of wireless communication systems. For reference, all tested people counters in this project have an internal antenna only. The design and refinement of sensors fall beyond the current scope of this project. However, their exploration remains valuable for potential future endeavors.

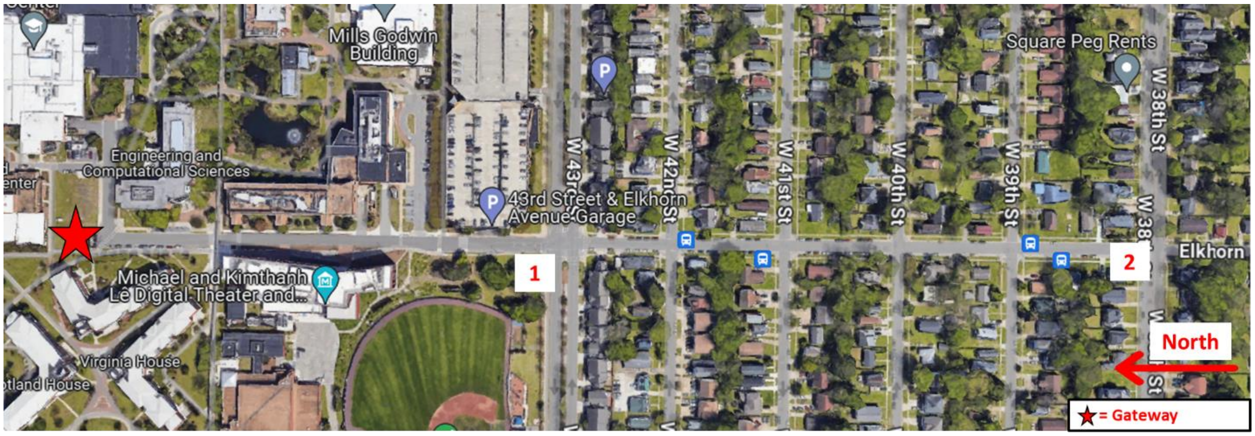


Figure 19. The Locations of Sensors with unobstructed Line-of-Sight to the Gateway

Table 4. Signal Strength of Sensors Relative to Their Distance from the Gateway with Unobstructed Line-of-Sight

Location	Distance	People Counter Signal Strength	Temperature Sensor Signal Strength
1	1100 ft	-89 dBm	-87 dBm
2	2460 ft	-101 dBm	-107 dBm

Service Platform Selection

TTN was used for handling LoRaWAN communications and Datacake was employed for data storage and visualization. A customized server was implemented to process data from NB-IoT devices. The team conducted transmission latency tests for both LoRaWAN and NB-IoT devices to evaluate the efficiency of data communication based on the service platforms. For the LoRaWAN, data obtained from TTN was saved in JSON format, with message timestamps logged in ISO 8601 UTC format. These timestamps were converted to Eastern Standard Time (EST) to align with the research team's local time zone, simplifying the analysis process. Figure 20 illustrates the LoRaWAN transmission latencies between different nodes.

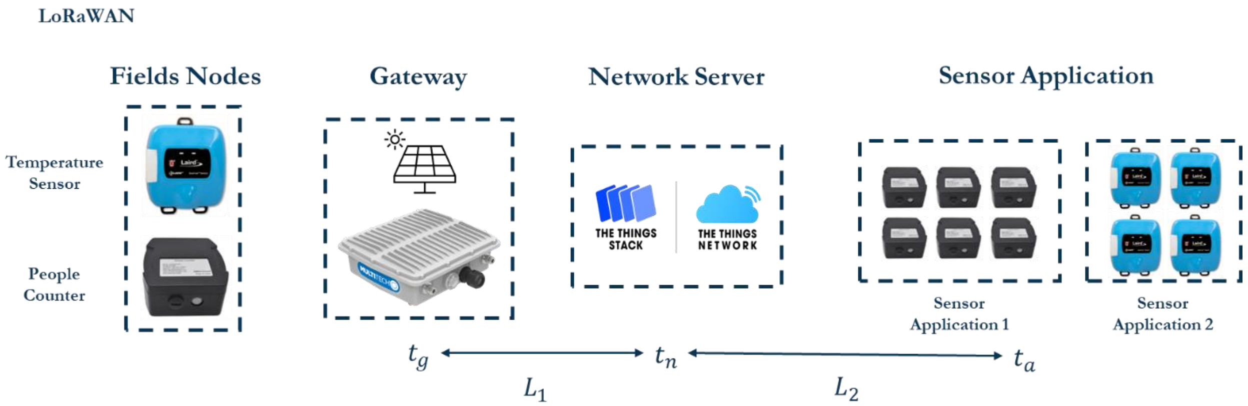


Figure 20. Illustration of LoRaWAN Transmission Latencies Between Different Nodes

During the analysis of data streams, the research team defined specific timestamps to identify and measure latency at different stages of the data transmission process:

- t_g: the timestamp when the uplink is received by the Gateway
- t_n: the timestamp when the uplink is received by the Network Server
- t_a: the timestamp when the message is received by the Application Server

With these timestamps, two types of latency were assessed:

- $L_1 = t_n - t_g$: This value represents the latency between the Gateway and the Network Server, indicating the time taken for a message to reach the Network Server after being received by the Gateway.
- $L_2 = t_a - t_n$: This value denotes the latency between the Application Server and the Network Server, indicating the time elapsed from the moment the Network Server receives a message to when it arrives at the Application Server.

Figure 21 illustrates a statistical analysis of latency metrics L1 and L2, highlighting multiple measures (e.g., mean, median, and standard deviation). Table 5 provides more details. The results indicate that the mean latency for both L1 and L2 is approximately 0.22 seconds, which does not impact the performance of LPWAN technologies, as these technologies are typically not designed for real-time communication. The low latency values, combined with the relatively small standard deviations, suggest a consistent and reliable performance of the LPWAN system. LoRaWAN Counter 1 experienced hardware issues and was unable to send messages to the gateway. Consequently, this counter was excluded from the test. LoRaWAN Counter 5 exhibited some fluctuations in results, which may be attributed to hardware inaccuracies.

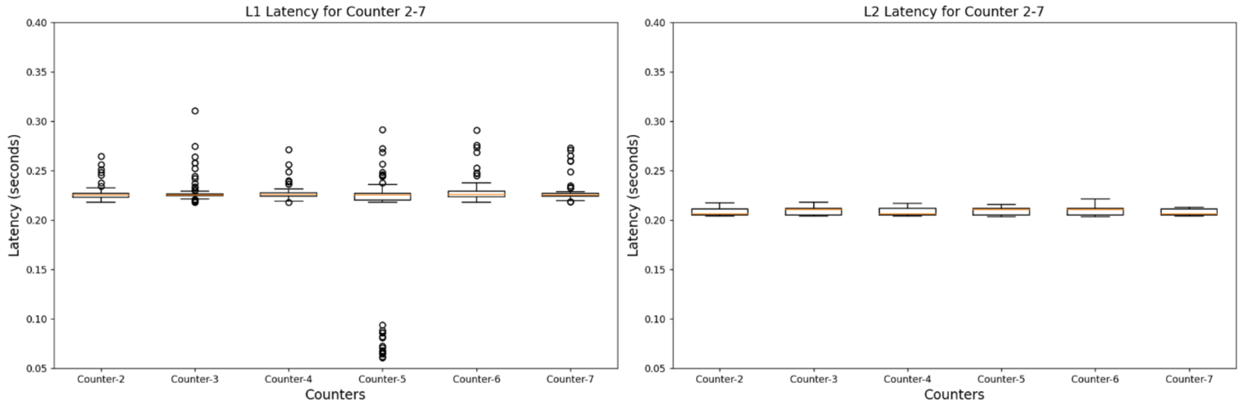


Figure 21. Visualization of L1 and L2 Latency

Table 5. Statistical Analysis of L1 and L2 Latency (Unit: Second)

Sensor ID	L1 Latency					L2 Latency				
	Count	Mean	SD	Min	Max	Count	Mean	SD	Min	Max
2	225	0.23	0.01	0.22	0.26	225	0.21	<0.01	0.20	0.22
3	300	0.23	0.01	0.22	0.31	300	0.21	<0.01	0.20	0.22
4	171	0.23	0.01	0.22	0.27	171	0.21	<0.01	0.20	0.22
5	303	0.21	0.05	0.06	0.29	303	0.21	<0.01	0.20	0.22
6	246	0.23	0.03	0.22	0.44	246	0.21	<0.01	0.20	0.22
7	156	0.23	0.01	0.22	0.27	156	0.21	<0.01	0.20	0.21

For NB-IoT, the team was able to capture timestamps for only two specific instances: t_d, when the people counter sends data, and t_s, when the server receives the data. The latency L is represented by the equation $L = t_s - t_d$, measuring the time taken for data to travel from the people counters to the server. Upon examining 63 data transmissions, it was observed that the latency between the NB-IoT devices and the server ranged from 11 to 13 seconds. The data's journey involves passing through multiple network nodes, including base stations and cellular gateways, which could contribute to the overall latency. Additionally, if the server handling the data has limited processing power, this could result in higher latency, further affecting the time from data transmission to reception.

Data Processing

LoRaWAN

The raw LoRaWAN payload is in hexadecimal format and contains various data points. The decoded information from the hexadecimal values (i.e., **80 00 02 01 15 00 39 10 00 01 6d 00 00 00 00 00 00 00 e4 00 81**) to their corresponding decimal representations is presented here, with an explanation for each segment:

- **Packet Head (80):** Marks the start of the packet.
- **Force Bit (00):** A control bit.
- **Device Type (02):** Specifies the type of device sending the data.
- **Report Data Type (01):** Indicates the type of data being reported.
- **Packet Size (15):** The total size of the packet, which is 21 bytes in decimal.
- **People Count (00 39):** The number of people counted, which is 57 in decimal.
- **People Count Status (01):** Status of the people count.
- **Battery Status (00):** A status indicator for the battery.
- **Reserved (00):** Space reserved for future use or additional information.
- **Battery (01 6D):** The battery level or voltage, which is 365 in decimal (3.65V).
- **Reserved (00 00 00 00 00 00):** Additional reserved space.
- **Frame Count (00 e4):** The frame count of the packets, which is 228 in decimal.
- **Default (00):** A setting for the packet structure.
- **Packet Tail (81):** Marks the end of the packet.

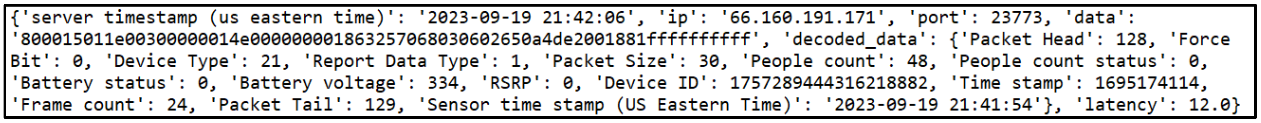
TTN processed the data to retrieve essential information for analysis, such as people count and battery voltage.

NB-IoT

The raw NB-IoT payload is in hexadecimal format and contains various data points. The decoded information from the hexadecimal values (i.e., **80 00 15 01 1E 00 32 01 00 01 4E 00 00 00 00 18 63 25 70 68 03 06 02 65 0A 4E 39 00 19 81**) to their corresponding decimal representations follows, with an explanation for each segment:

- **Packet Head (80):** Marks the start of the packet.
- **Force Bit (00):** A control bit.
- **Device Type (15):** Specifies the type of device sending the data.
- **Report Data Type (01):** Indicates the type of data being reported.
- **Packet Size (1E):** The total size of the packet, which is 30 bytes in decimal.
- **People Count (00 32):** The number of people counted, which is 50 in decimal.
- **People Count Status (01):** Status of the people count.
- **Battery Status (00):** A status indicator for the battery.
- **Battery (01 4E):** The battery level or voltage, which is 334 in decimal (3.34V).
- **Reserved (00 00 00 00):** Space reserved for future use or additional information.
- **Device ID (18 63 25 70 68 03 06 02):** A unique identifier for the device.
- **Time Stamp (65 0A 4E 39):** Unix timestamp, which is 1695174201 in decimal.
- **Frame Count (00 19):** The frame count of the packets, which is 25 in decimal.
- **Packet Tail (81):** Marks the end of the packet.

The payload received from the NB-IoT people counters requires interpretation using the customized server that follows predefined segmentation rules. These rules dictate the conversion of the raw data into meaningful information such as people counts and battery voltage. Once the server decodes this data, it is initially stored in a log file format. For the purpose of data analysis, these log files are subsequently saved and converted into CSV format, which allows for a more straightforward analysis of the data. Figure 22 presents the decoded and cleaned payload data transmitted by the deployed NB-IoT devices.



```
{'server timestamp (us eastern time)': '2023-09-19 21:42:06', 'ip': '66.160.191.171', 'port': 23773, 'data':
'800015011e00300000014e000000001863257068030602650a4de2001881ffffffffff', 'decoded_data': {'Packet Head': 128, 'Force
Bit': 0, 'Device Type': 21, 'Report Data Type': 1, 'Packet Size': 30, 'People count': 48, 'People count status': 0,
'Battery status': 0, 'Battery voltage': 334, 'RSRP': 0, 'Device ID': 1757289444316218882, 'Time stamp': 1695174114,
'Frame count': 24, 'Packet Tail': 129, 'Sensor time stamp (US Eastern Time)': '2023-09-19 21:41:54'}, 'latency': 12.0}
```

Figure 22. The Example of NB-IoT Message Log

Field Deployment

On-Campus Test Results

Data collection on the ODU campus was conducted from June 27 to December 30, 2023. Throughout this period, people counters at installation locations operated continuously without any major malfunctions. These counters were located at key transit and gathering points: Location #1 at a bus stop, Location #2 at the Sports Complex, and Location #3 at Monarch Hall in the central area of the ODU campus. The collected data presents a thorough description of pedestrian traffic and underscores the intricate relationship between external variables and campus dynamics. It reveals a correlation between fluctuations between pedestrians and external influences (e.g., weather variations and public holidays). These findings emphasize the impact of environmental and social factors on the flow of activities within the university campus. Figure 23 displays the people count at each location on the ODU campus.

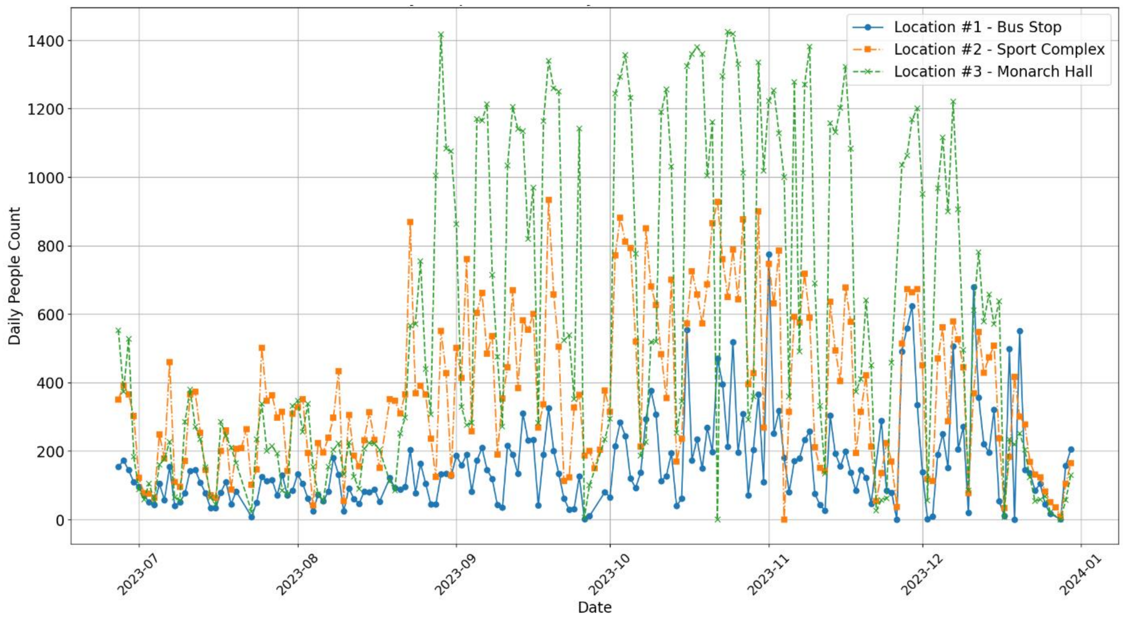
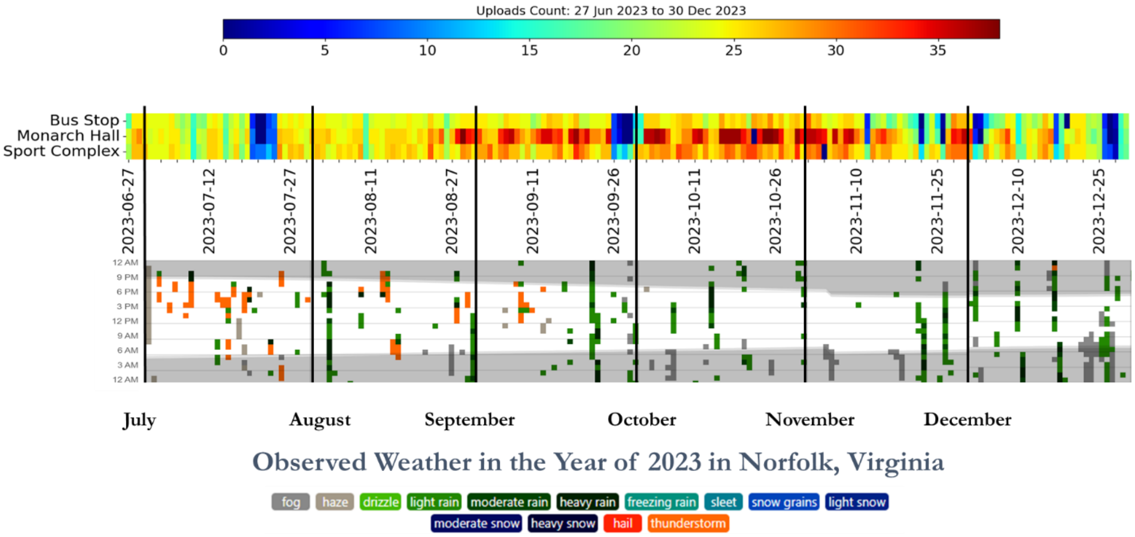


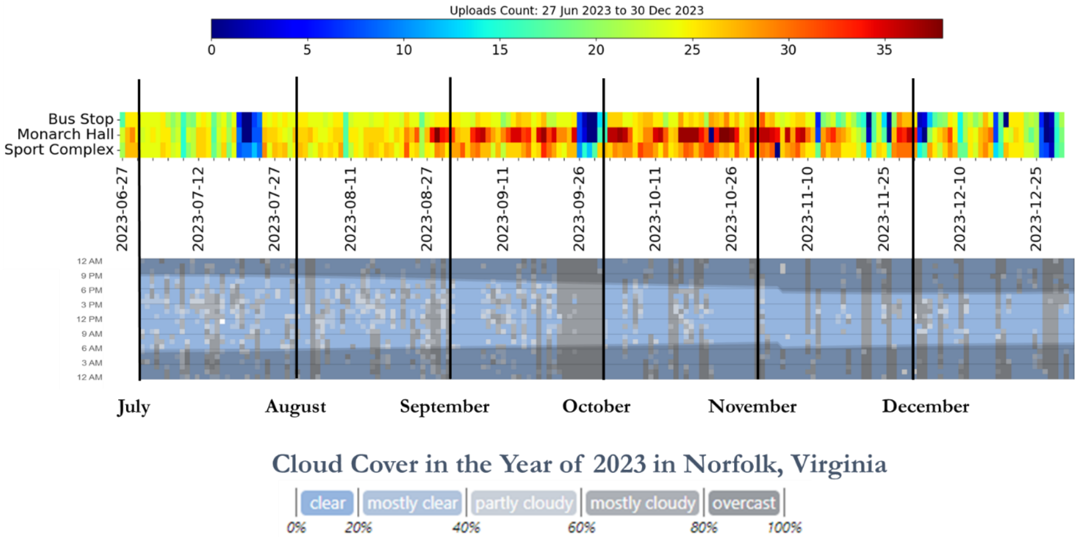
Figure 23. Daily Collected Pedestrian Count Data from Three Installation Locations at ODU Campus from June 27, 2023, to December 30, 2023

Rather than focusing on the counting performance, the research team assessed the functionality and online status of the tested LoRaWAN system. A critical factor affecting sensor uploads is the availability of power in the gateway. If the gateway lacks battery power, sensors cannot upload data. In addition to power considerations, weather conditions play a significant role in pedestrian activities and consequently, in sensor data collection. As winter approaches, pedestrian activity typically decreases, influenced by colder temperatures and shorter daylight hours. Similarly, adverse weather conditions (e.g., rain, snow, or strong winds) deter people from outdoor activities, reducing pedestrian traffic. Cloud cover also impacts sensor uploads, as prolonged overcast conditions can lead to decreased solar power generation, draining the gateway battery and affecting data transmission. Figure 24 and Figure 25 show the interplay among seasonal changes, weather patterns, and pedestrian flow. Implementing strategies to mitigate battery drainage during inclement weather conditions is crucial for maintaining consistent data collection and system functionality.



(Weather Data Source: Weather Spark)

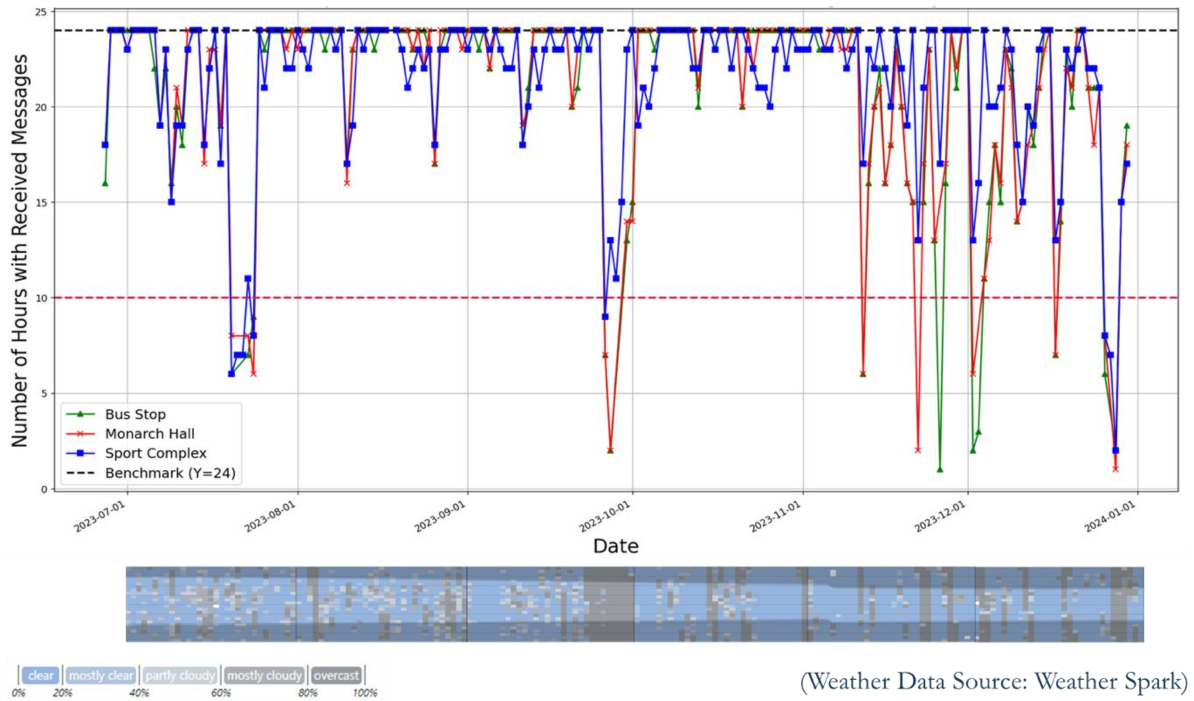
Figure 24. The Relationship Between People Counter Upload Frequency and Weather Conditions



(Weather Data Source: Weather Spark)

Figure 25. The Relationship Between People Counter Upload Frequency and Cloud Cover

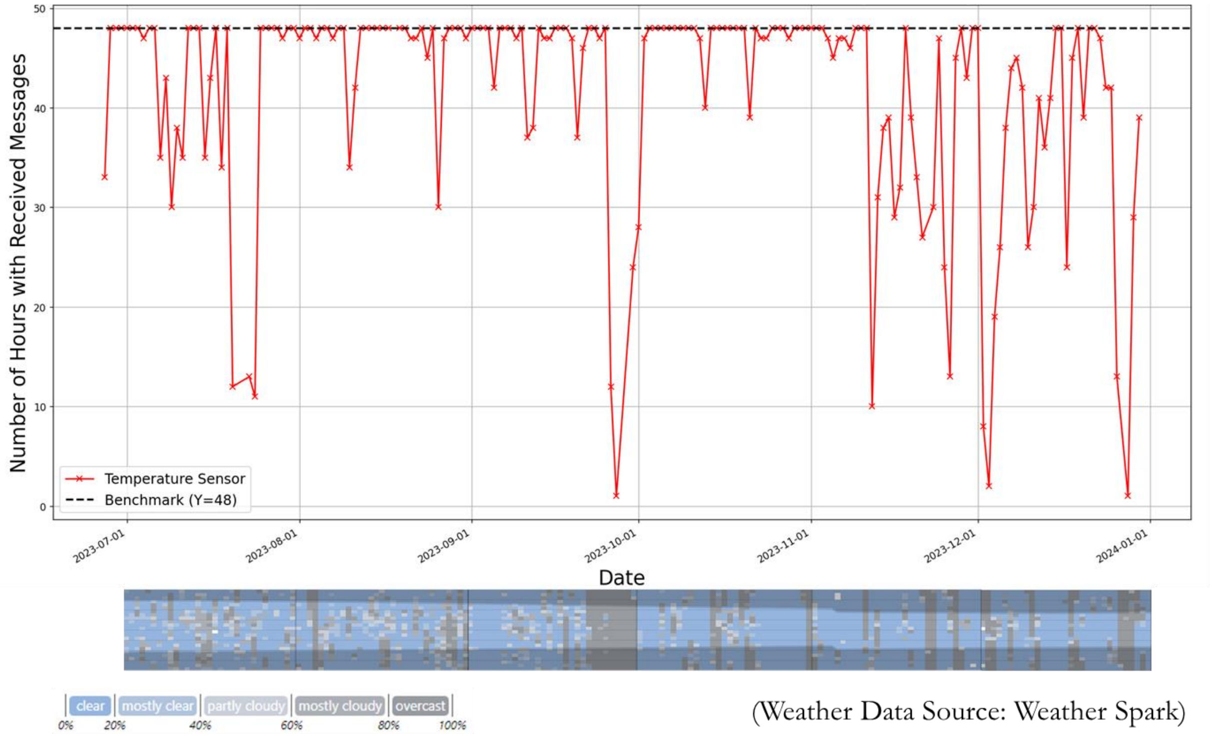
In addition to monitoring sensor upload counts, the team conducted an analysis of the sensor number of hours with received messages to ascertain the duration each sensor remains uploading throughout the day as shown in Figure 26 which reveals a correlation between cloud cover and the number of hours with received messages. Increased cloud cover reduces the sunlight available for solar panel input, thereby impacting the power supply. Additionally, the end of daylight savings time results in shorter daytime hours, further limiting solar power generation. Lower temperatures during late fall and winter also decrease battery efficiency due to the chemical characteristics of batteries. This could offer insight into the system's overall efficiency and reliability. By tracking the number of hours that each sensor remains online daily, the sensor's online time might reveal intermittent connectivity issues or power disruptions that hinder consistent operation. Each people counter was configured to upload data either every 100 counts or every hour, whichever comes first.



(Weather Data Source: Weather Spark)

Figure 26. The Relationship Between People Counter Number of Hours with Received Messages and Cloud Cover

To conduct a comparative analysis, the research team incorporated data from the LoRaWAN Laird temperature sensor utilized in Phase I and shown in Figure 27. The sensor was installed at Monarch Hall. This inclusion is essential as different sensors may exhibit varying performance characteristics, particularly in terms of reliability. Unlike the people counters, which are set to upload either 100 counts or hourly, the Laird temperature sensor follows a different plan, uploading data every 30 minutes. Despite this disparity in upload frequency, our observations reveal similar patterns across both sensor types. The research team introduced a concept of "number of hours with received messages under benchmark" which means instances where the gateway may experience power interruptions during the day, only to resume operation once sufficient battery power is restored. By comparing data from both sensor types, the research team can identify correlations, discrepancies, and potential issues. For instance, if the Laird temperature sensor consistently exhibits a longer number of hours with received messages under benchmark compared to the people counters, it may indicate a need for further investigation into hardware or battery issues.



(Weather Data Source: Weather Spark)

Figure 27. The Relationship Between Laird Temperature Sensor Number of Hours with Received Messages and Cloud Cover

After conducting the assessment following the campus test, it was discovered that the two NB-IoT devices deployed on campus had been completely drained of power. Additionally, there was a voltage drop of approximately 0.14 volts in the batteries of the LoRaWAN people counter devices as shown in Table 6. Despite these challenges, the LoRaWAN devices are persevering and operating under normal conditions. However, it was observed that two NB-IoT devices installed in the field encountered connectivity issues due to the previous IoT SIM card vendor issues. As a result, these devices experienced rapid battery depletion, as they continuously attempted to establish connections without success. The research team then selected another vendor EIOTCLUB and implemented robust connectivity solutions to mitigate similar issues for subsequent off-campus deployments. Proactive monitoring and maintenance of the sensor network could play a vital role in ensuring consistent performance and prolonging battery life.

Table 6. The Battery Levels of LoRaWAN People Counters Installed at ODU

Device Name	Initial Voltage (May 2023)	Ending Voltage (December 2023)
People Counter #2	3.8 V	3.63 V
People Counter #3	3.8 V	3.61 V
People Counter #4	3.8 V	3.67 V
People Counter #5	3.8 V	3.63 V
People Counter #6	3.8 V	3.60 V
People Counter #7	3.8 V	3.64 V

Williamsburg Test Results

Data collection in Williamsburg started on February 26, 2024. As a reminder, people counter installation locations are shown in Figure 17. The people counting results are presented in Figure 28. Different locations exhibit varying trends, with peaks and valleys observable on different days of the week. For example, around the weekend of April 13, Locations 1-3 around the test site show very high volume. The underlying reasons that cause such spikes deserve special attention as they may be attributed to special events or gatherings around the sites or sensor obstructions (e.g., temporarily blocked by some objects). Since the accuracy of the people counters depends primarily on the infrared sensor, other sidewalk users (e.g., cyclists or e-scooter riders) may also be recorded. To minimize this influence, all people counters were positioned at a certain angle facing the sidewalk. If a people counter went offline on any given day, the people count data could not be uploaded and stored.

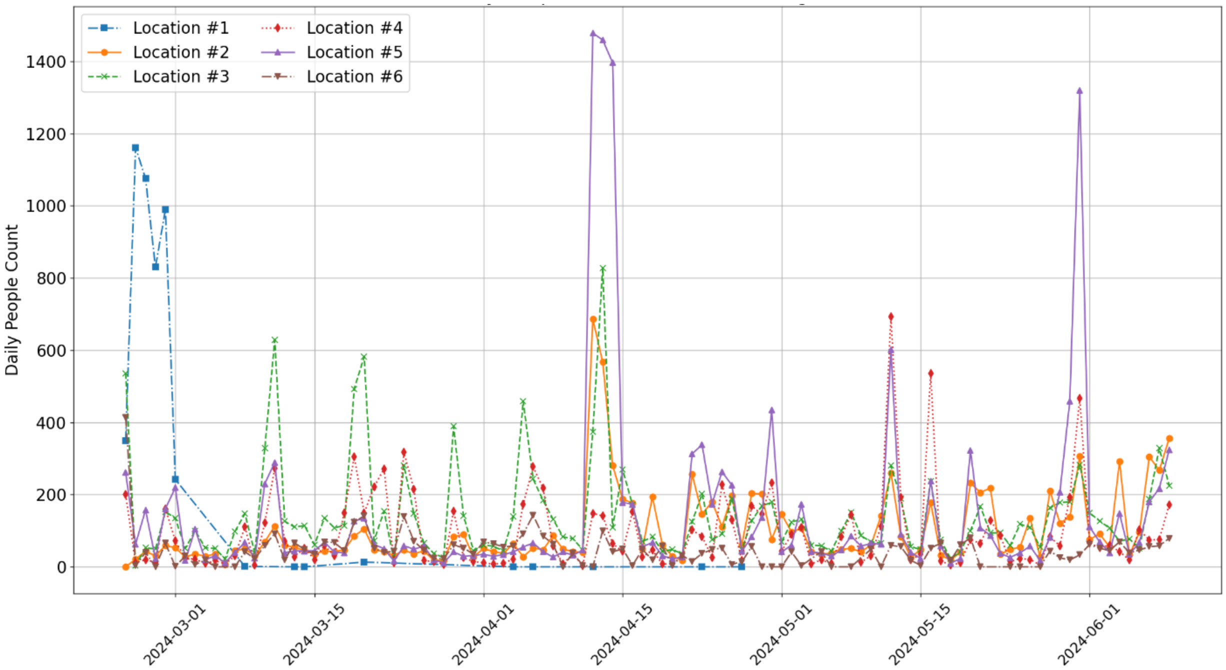


Figure 28. Daily Pedestrian Count at Williamsburg, VA Sites

The objective of this project is to investigate the effectiveness of LPWAN technology itself, rather than the performance of the people counting sensors. Therefore, the research team analyzed the sensor upload counts to determine if they were functioning properly during the operation period and to identify any periods of malfunction. It is worth mentioning that the gateways in Williamsburg are equipped with two solar panels each, doubling the solar power input from the ODU installation. This configuration has provided sufficient power to maintain continuous operation since installation. Consequently, the analysis of the Williamsburg data differs from the campus data due to this enhanced power reliability and consistency. The research team did not include weather data in this analysis to determine if the gateways were powered.

As shown in Figure 29, the number of messages received from each people counter varies based on location. The data collection frequency also varies, as shown in Table 7. For example, at Location #5, if 1000 counts are recorded, the theoretical number of daily uploads should be approximately 34, with some fluctuations due to sensor performance. At Location #1, many days show only a few counts (indicated in blue in the heatmap) due to low signal strength and unstable connection between the people counter and the gateways. The elevation difference between Gateway #1 and the pedestrian counter at Location #1 is 47.96 feet. The trees and terrain between the gateway and count could obstruct the signal from the pedestrian counter. Regular uploads in the first few days for the people counter at Location #1 are observed because the original people counter was malfunctioning and was replaced with a working sensor on February 29th, which already had some data.

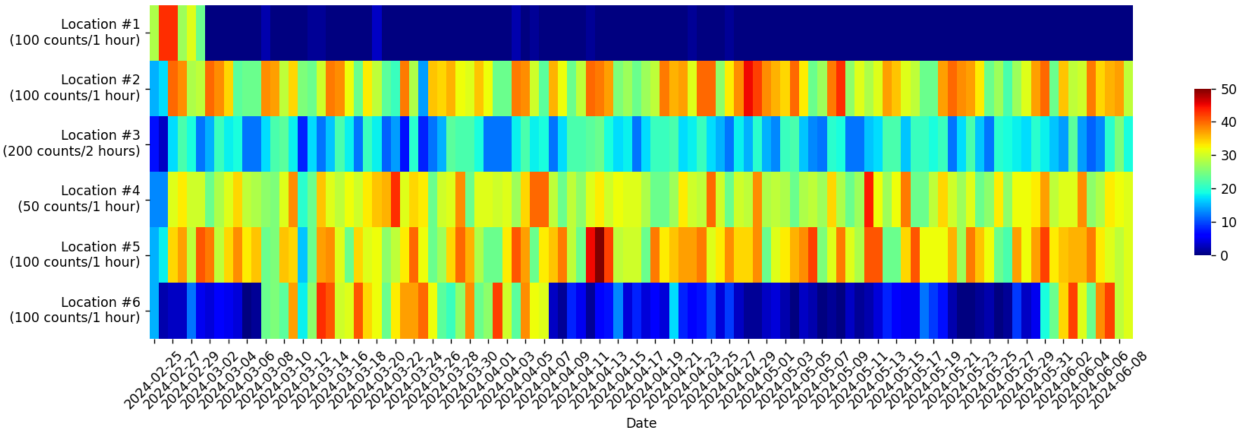


Figure 29. The Number of Messages Received from Each People Counter Per Day. (Preset Upload Frequency for Each Location is Indicated in Brackets)

Table 7. The Number of People Counter Upload Per Counts/Hour(s)

People Counter Location	**Upload Per Counts**	**Upload Per Hour(s)**
Location #1	100	1
Location #2	100	1
Location #3	200	2
Location #4	50	1
Location #5	100	1
Location #6	100	1

The people counter at Location #3 had relatively fewer uploads because it was set to upload data every 200 counts or 2 hours. The people counter at Location #6 had fewer uploads in the first and second halves of the period because Gateway #2 was not working properly during those times. Consequently, during these periods, it could only send messages to Gateway #1, which is farther from the counter, resulting in an unstable connection. The troubleshooting and maintenance of Gateway #2 is discussed in the next section.

Since two gateways were installed, and the area of some of the people counters overlap, the research team tested LoRaWAN broadcasting capabilities by analyzing messages sent from the people counter at location #5. The team aimed to determine if both gateways received the messages or if only the first one that received the message processed it. Eighteen days of data from June 1 to June 18, 2024 were extracted for this analysis. As shown in Figure 30, both gateways successfully received the messages sent from the people counter at location #5. Gateway #2 received more messages than Gateway #1 due to its closer proximity to the people counter with better signal strength.

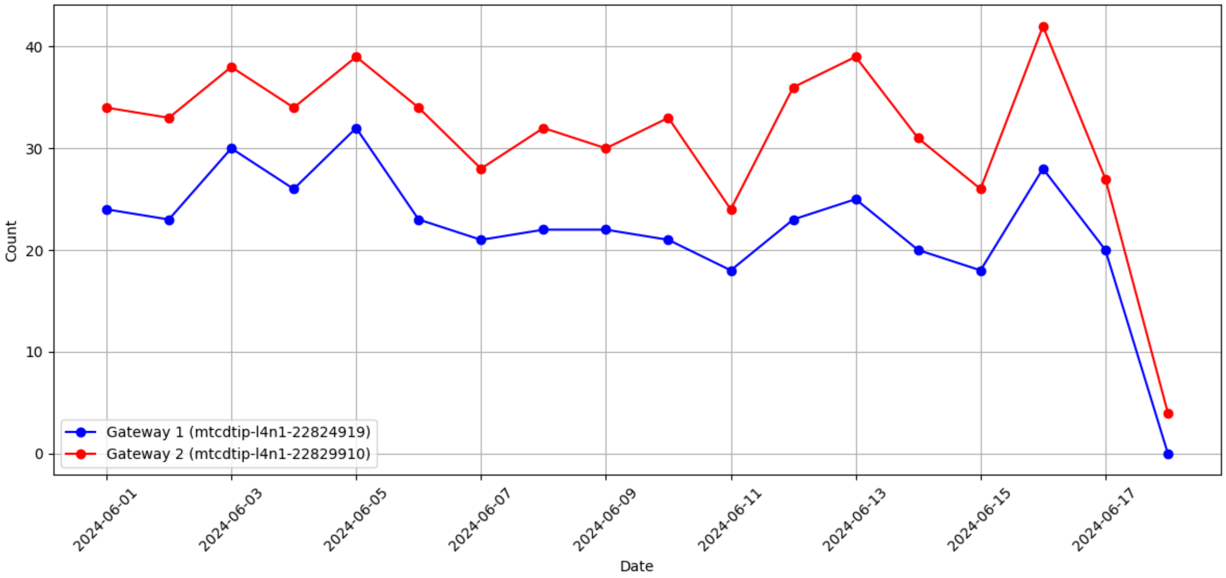


Figure 30. The Number of Messages from People Counter @ Location 5 Received by Gateways

In TTN, when an end node is in the overlapping area of two gateways, both gateways can receive the uplink messages from the end node. The end node broadcasts an uplink message, and both gateways in the overlap area receive it. Each gateway then forwards the received message to the Network Server, which detects that the same uplink message has been received from multiple gateways. Using the unique identifier of the message, the Network Server identifies and deduplicates the messages, and then only one copy of the uplink message is processed further; typically the message with the best Received Signal Strength Indicator is selected.

To further investigate the performance of LoRaWAN broadcasting capabilities, the research team analyzed all messages from each people counter at each location to determine how many messages were received by Gateway #1 and Gateway #2, as shown in Figure 31. If a people counter is within the coverage range of a gateway, its messages will be received by that gateway. If the counter is in the overlap area, the message is handled by the gateway with the stronger signal, typically the one in closer proximity. Location #1 is out of the range of both gateways, so messages could not be delivered. Locations #2 and #3 are on the boundary of Gateway #2’s signal range, so most messages were handled by Gateway #1. Locations #4 and #5 are within the overlapped area, so messages were delivered to the gateway with better signal strength. Location #6 is almost out of the range of Gateway #1, so most messages were handled by Gateway #2. It is important to note that Gateway #2 lost connection from April 9 to May 30, requiring manual on-site intervention. This outage explains why Gateway #2 received no messages during that period. More details about the gateway outage and the maintenance actions taken will be discussed in the section on maintenance efforts.

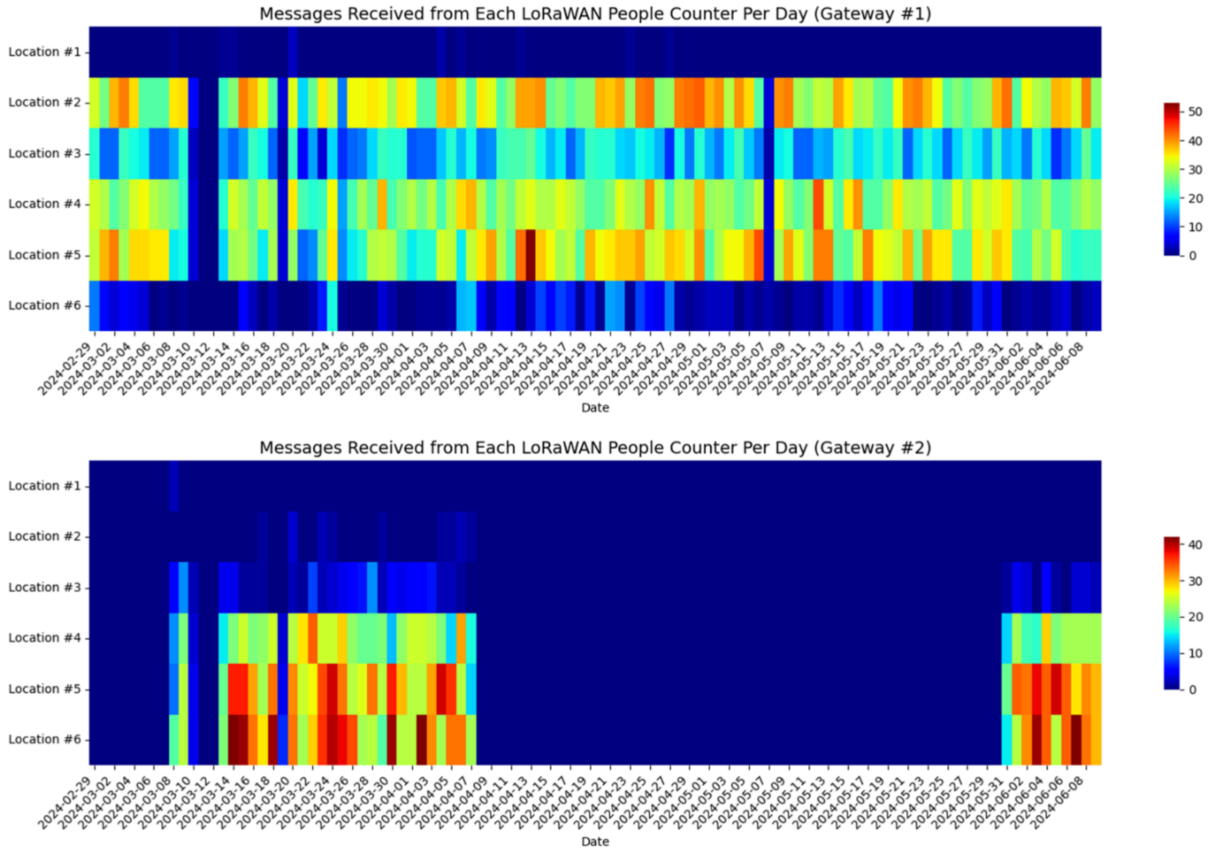


Figure 31. The Number of LoRaWAN People Counter Messages Received at each Location from Gateway #1 and #2

The research team also investigated the number of hours with received messages from each people counter, as shown in Figure 32. The benchmark is 24 hours, and the team aimed to determine if the counters were working properly every hour. People counters located closer to the gateways had the greatest number of hours with received messages, indicating that distance matters. Most of the number of hours with received message data for the people counter at Location #1 are missing because the connection was unstable and messages could not be transmitted to the gateways. For the people counter at Location #6, after the connectivity issues of Gateway #2 were fixed, the number of hours with received messages resumed to normal.

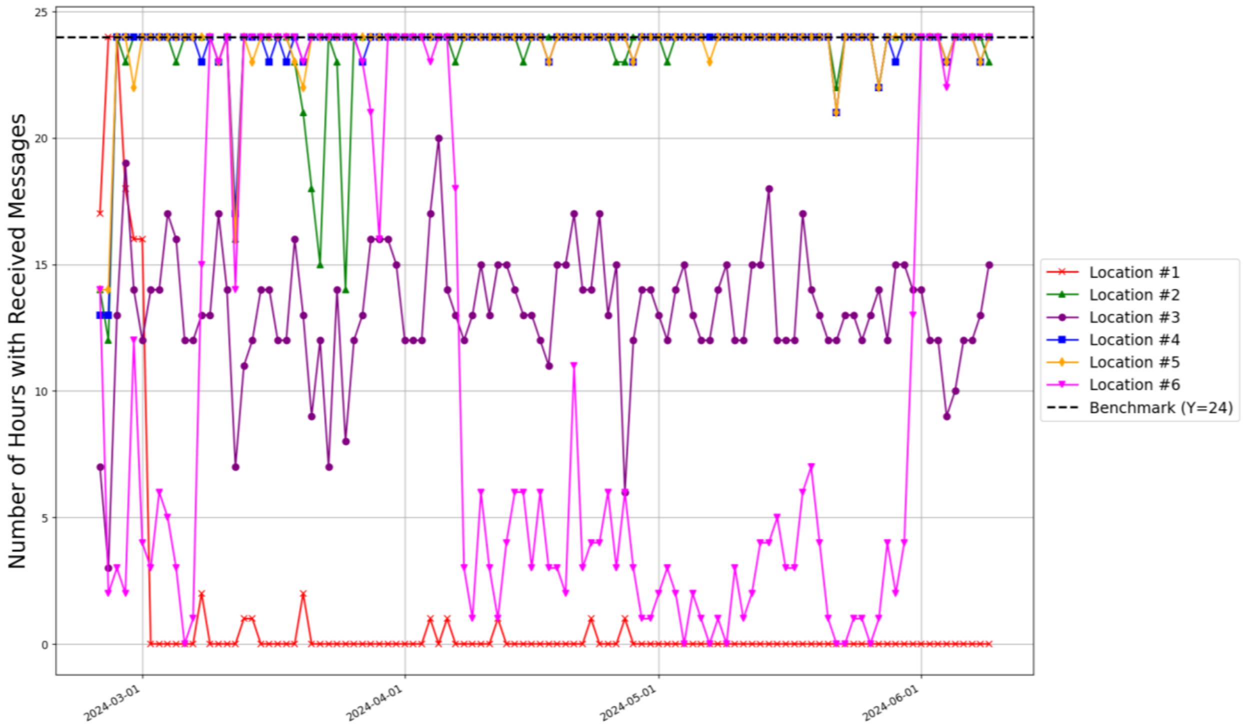


Figure 32. LoRaWAN People Counter Number of Hours with Received Messages at Each Location Per Day

For each LoRaWAN people counter location, the research team also installed NB-IoT people counters to conduct a comparison test. The data collection frequency is the same as shown in Table 7. The message upload counts and counter number of hours with received messages are depicted in Figure 33 and Figure 34. Table 8 displays the average battery levels of LoRaWAN devices. It is important to note that the battery level is measured by the sensor itself and is not directly related to the LPWAN technology. Voltage detection may not be stable, leading to some fluctuations. No major battery depletion was observed.

Table 8. The Battery Levels of LoRaWAN People Counters Installed in Williamsburg, VA

People Counter Location	Average Voltage (February)	Average Voltage (March)	Average Voltage (April)	Average Voltage (May)	Average Voltage (June)
Location #1	3.62 V	3.62 V	3.62 V	N/A	N/A
Location #2	3.66 V	3.65 V	3.65 V	3.66 V	3.66 V
Location #3	3.69 V	3.68 V	3.68 V	3.68 V	3.69 V
Location #4	3.66 V	3.64 V	3.64 V	3.65 V	3.66 V
Location #5	3.63 V	3.63 V	3.63 V	3.64 V	3.65 V
Location #6	3.48 V	3.52 V	3.42 V	3.57 V	3.65 V

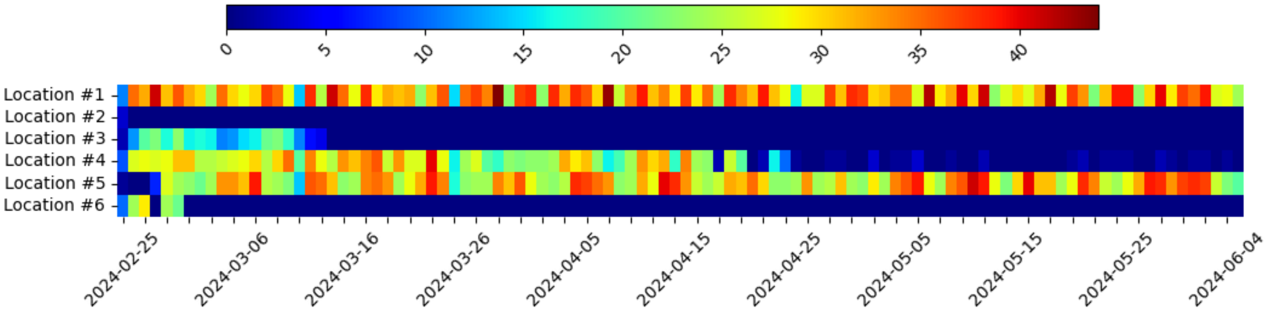


Figure 33. NB-IoT People Counter Uploads Count at Each Location in Williamsburg, VA

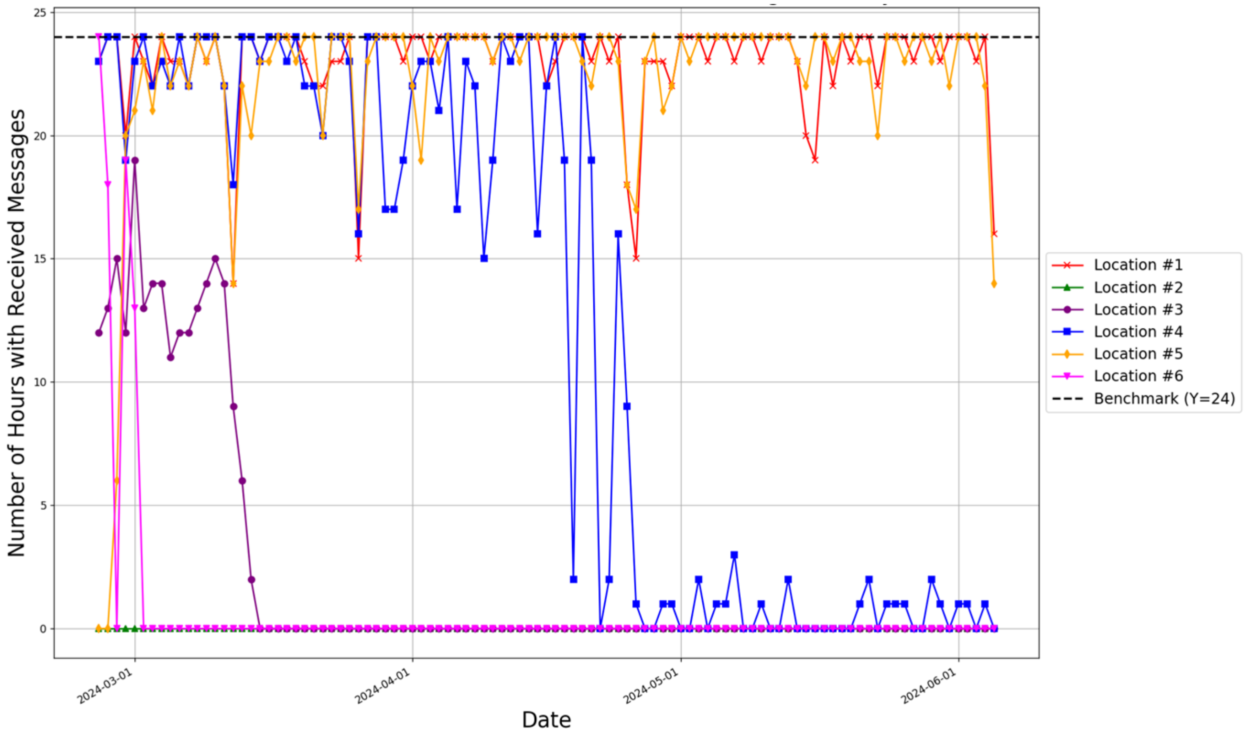


Figure 34. NB-IoT People Counter Number of Hours with Received Messages at Each Location in Williamsburg, VA

Table 9 presents the battery levels of NB-IoT People Counters installed in Williamsburg, VA. The research team observed that the counters at locations #2, #3, and #6 experienced rapid battery depletion. As illustrated in Figure 33, this is attributed to the NB-IoT communication module continuously searching for cellular service and repeatedly attempting to establish a connection, which accelerated battery drain. The data shows that at these locations, most messages failed to upload successfully to the server. This issue is likely due to the installation sites being either distant from the nearest cellular tower or lacking a clear line of sight, both of which can impair signal transmission. Additionally, the size and design of the NB-IoT cellular antenna play a crucial role. The cellular antenna is very small and located inside the enclosure of the counters, which could impact performance. Since the research team does not have information about the cellular tower locations in the area, an assessment of signal distance could not be conducted. In contrast, although the LoRaWAN antenna is of a similar size, its effective transmission distance is around 3,000 ft with a clear line of sight.

Table 9. The Battery Levels of NB-IoT People Counters Installed in Williamsburg, VA

People Counter Location	Average Voltage (February)	Average Voltage (March)	Average Voltage (April)	Average Voltage (May)	Average Voltage (June)
Location #1	3.62 V	3.62 V	3.63 V	3.63 V	3.64 V
Location #2	3.43 V	N/A	N/A	N/A	N/A
Location #3	3.62 V	3.62 V	N/A	N/A	N/A
Location #4	3.54 V	3.53 V	3.00 V	2.63 V	2.61 V
Location #5	3.63 V	3.62 V	3.63 V	3.63 V	3.63 V
Location #6	3.27 V	2.89 V	N/A	N/A	N/A

The research team also observed that the NB-IoT people counter at Location #1 had a stable connection, and messages were consistently uploaded to the server. However, the LoRaWAN people counter at this location could not upload messages due to its distance from the gateway. This likely reflects the relative location of the gateway compared to the cell tower.

Cost Comparison

Two deployment topologies were evaluated. For a linear deployment along a ten-mile trail, assuming each LoRaWAN gateway covers a one-mile radius, refer to Figure 35, Figure 36, and Figure 37.

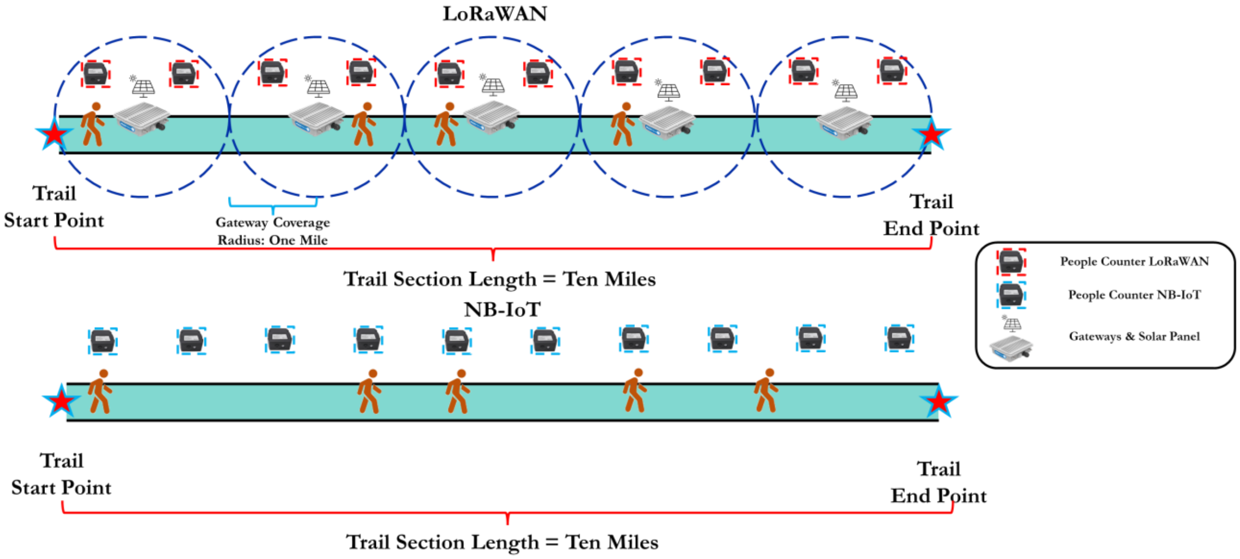


Figure 35. People Counter Linear Deployment (Ten Devices)

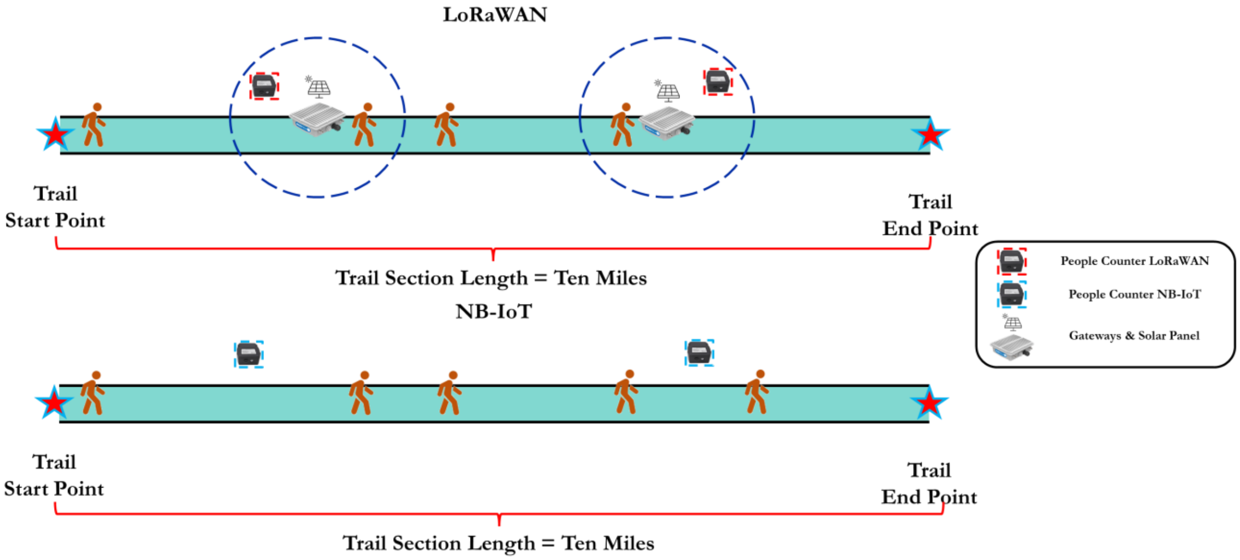


Figure 36. People Counter Linear Deployment (Two Devices)

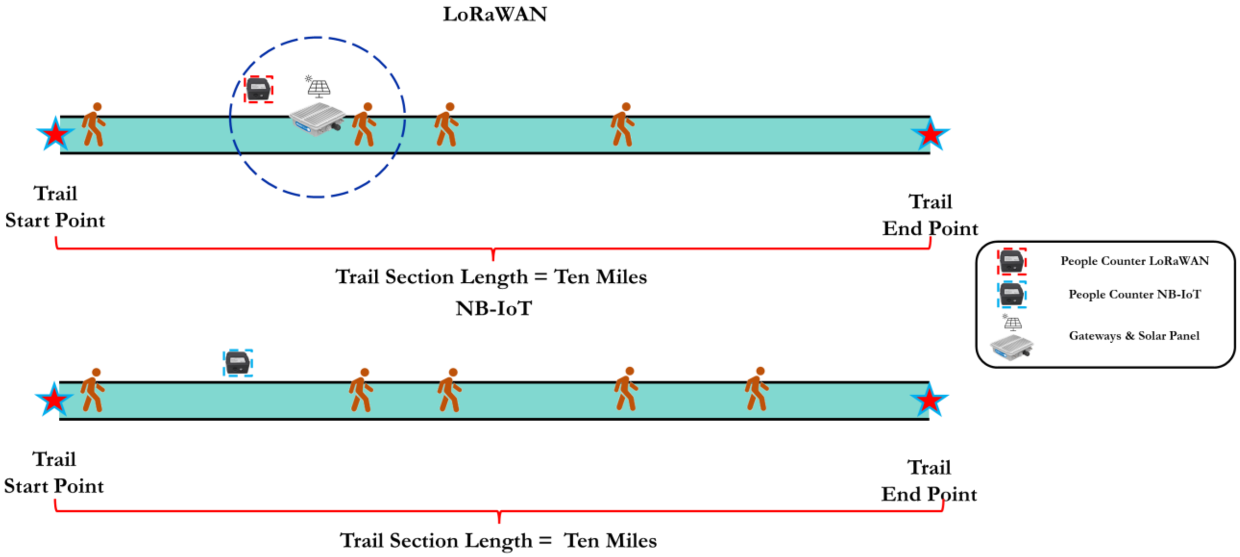


Figure 37. People Counter Linear Deployment (One Device)

For a network deployment, illustrated in Figure 38, the grid network is designed with each grid measuring 0.5 miles, and the gateways cover a one-mile radius. The cost comparisons for 20, 50, and 100 counters over one, five, and ten years are shown from Figure 39 to Figure 44.

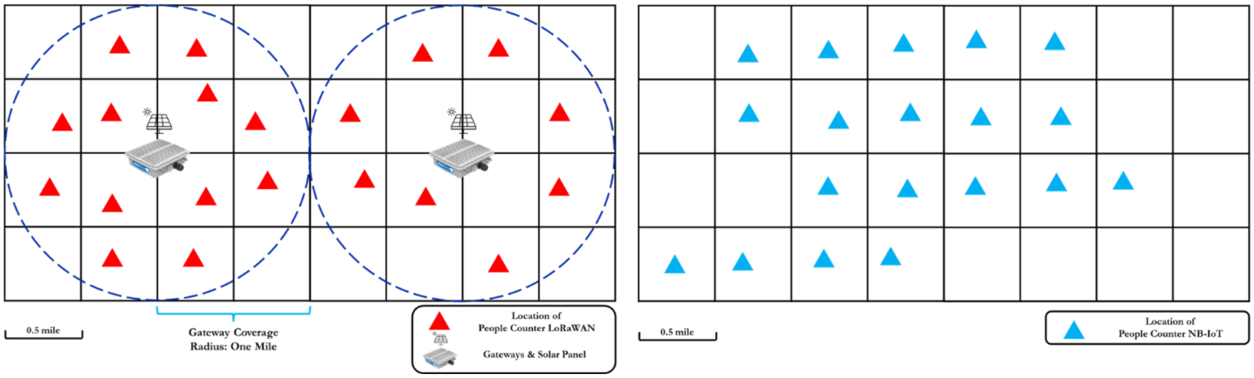


Figure 38. People Counter Network Deployment

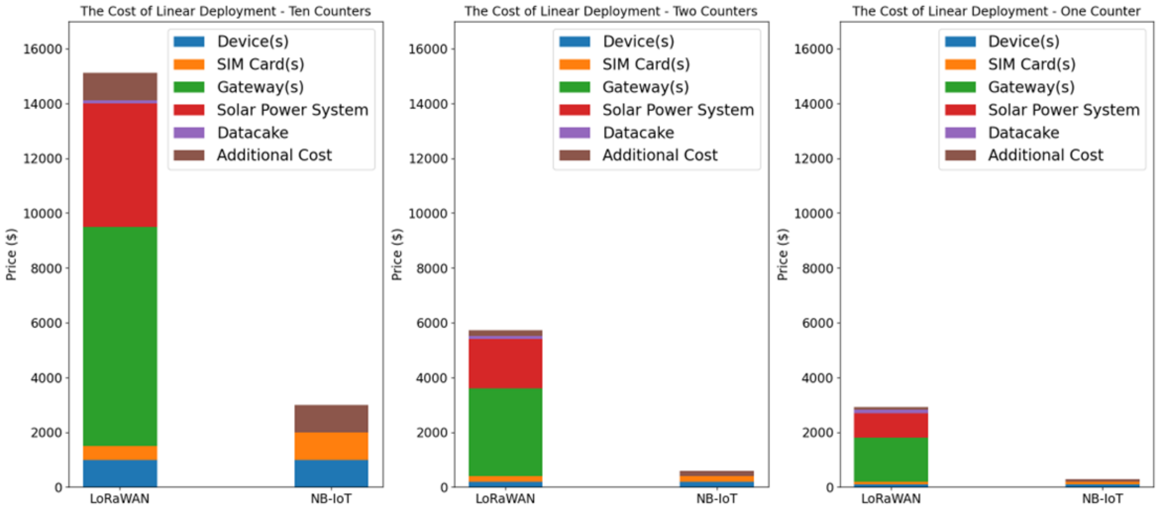


Figure 39. The Cost Comparison of Linear Deployment for One, Two, and Ten People Counters between LoRaWAN and NB-IoT over One Year

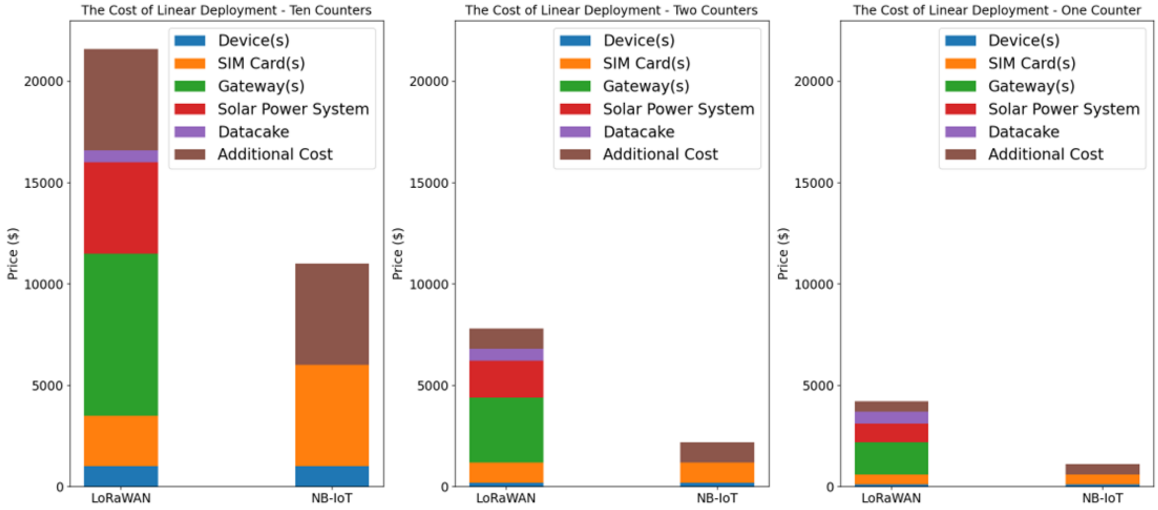


Figure 40. The Cost Comparison of Linear Deployment for One, Two, and Ten People Counters between LoRaWAN and NB-IoT over Five Years

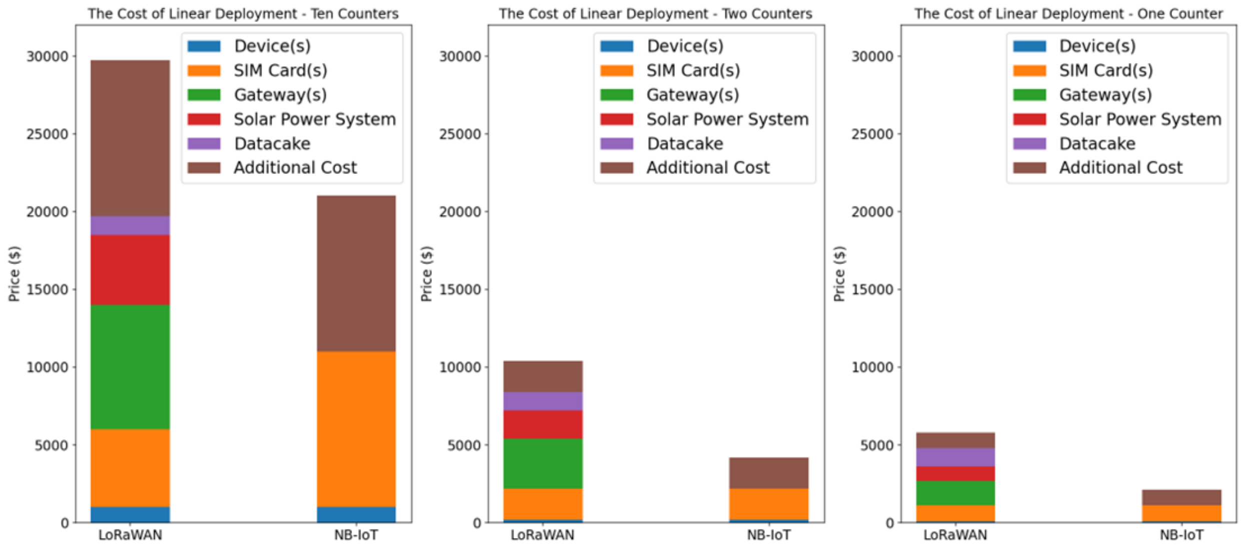


Figure 41. The Cost Comparison of Linear Deployment for One, Two, and Ten People Counters between LoRaWAN and NB-IoT over Ten Years

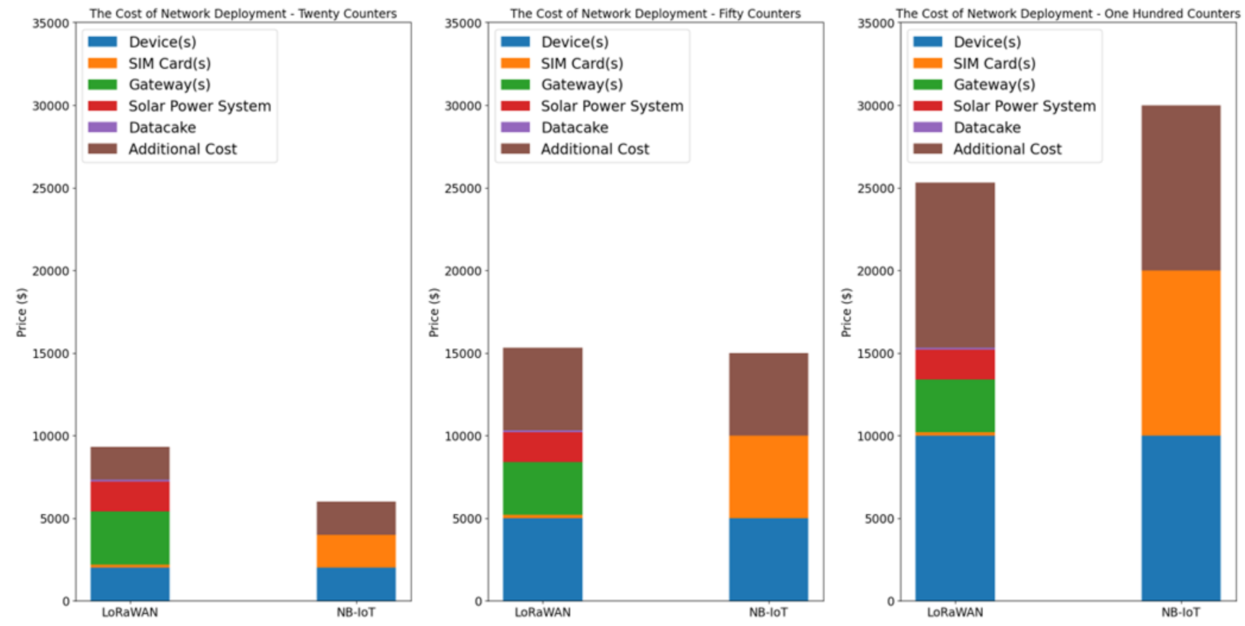


Figure 42. The Cost Comparison of Network Deployment for One, Two, and Ten People Counters between LoRaWAN and NB-IoT over One Year

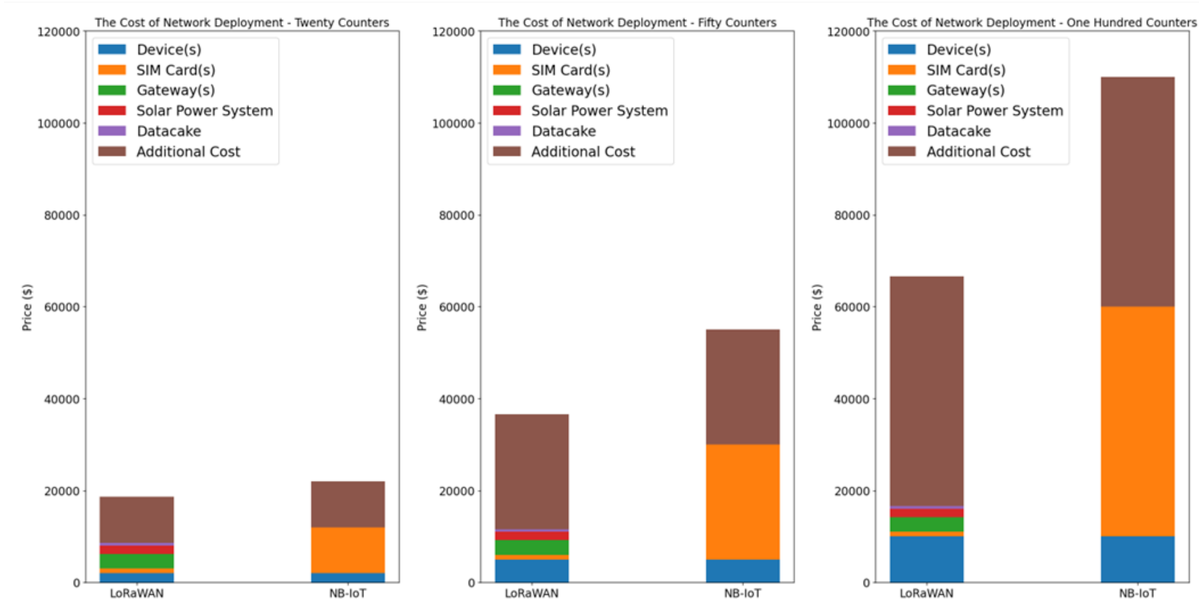


Figure 43. The Cost Comparison of Network Deployment for One, Two, and Ten People Counters between LoRaWAN and NB-IoT over Five Years

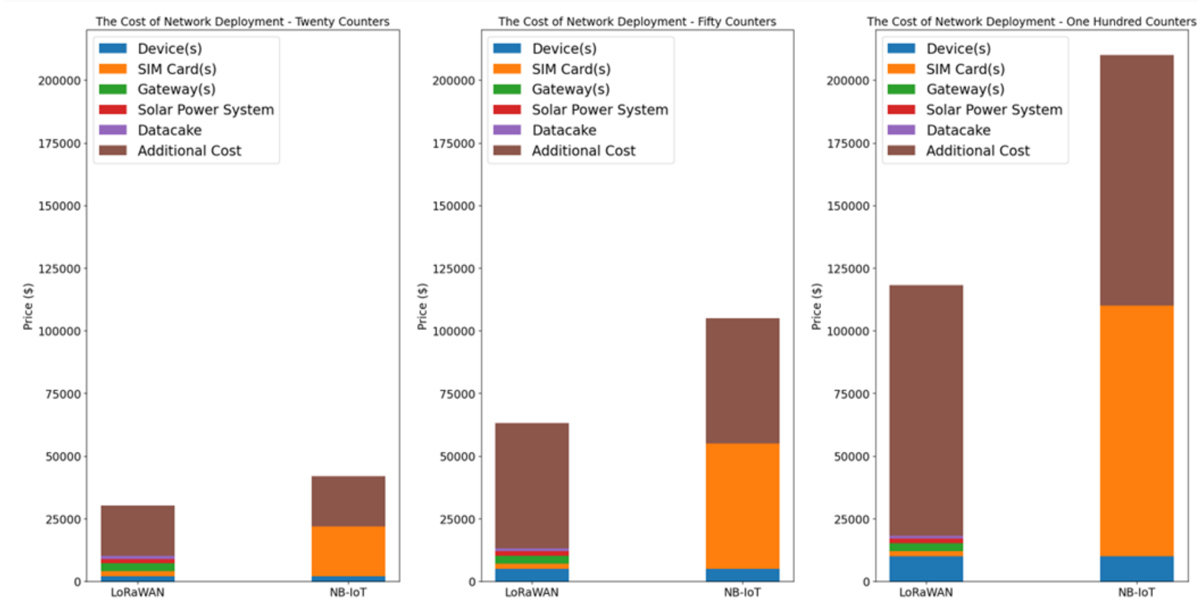


Figure 44. The Cost Comparison of Network Deployment for One, Two, and Ten People Counters between LoRaWAN and NB-IoT over Ten Years

LoRaWAN is particularly advantageous for scenarios involving densely located endpoints, where a single gateway can manage many devices over a wide area. This capability makes it highly effective in applications such as monitoring parking space availability within a park-and-ride facility, where sensors are densely concentrated. The ability of LoRaWAN gateways to cover extensive ranges reduces the need for multiple network nodes to optimize deployment costs and complexity. However, line-of-sight constraints may arise in urban environments, which could impact signal transmission. Additionally, solar power systems can enhance sustainability and reduce maintenance costs when access to power is challenging.

NB-IoT, on the other hand, is better suited for environments with sparse device distribution. Since NB-IoT devices connect directly to existing cellular networks, there is no need for separate gateway installations or additional infrastructure like solar panels. This direct connectivity makes NB-IoT ideal for remote or rural areas where devices are widely dispersed and installing additional infrastructure would be impractical and costly.

For urban environments or applications where device density is high, LoRaWAN should be considered due to its cost-effective coverage and lower infrastructure demands per device as the network scales. For rural or remote applications with fewer sensors spread over large distances, NB-IoT offers a practical solution with minimal infrastructure requirements, leveraging the widespread availability of cellular networks to ensure connectivity and reduce deployment costs. Linear deployment is well-suited for NB-IoT, while network deployment is more advantageous for LoRaWAN in the long run. However, a clear line of sight is crucial for LoRaWAN network deployment in dense urban scenarios. Installing gateways at high elevations, such as on rooftops or signal towers, can help minimize signal interference. The elevation of the terrain should also be considered. In field deployments, NB-IoT may also face challenges due to a lack of clear line of sight with the cellular signal tower. This underscores the need for strong cellular coverage for NB-IoT to function effectively. Maintenance efforts and costs for LoRaWAN are higher as more human resources are required to intervene if the system goes offline and cannot automatically resume. Since LoRaWAN gateways are typically installed at high elevations, additional effort is needed for maintenance compared to NB-IoT. This analysis considers the unique demands of different environments to help identify the most cost-effective technology and deployment scale. A side-by-side comparison of LoRaWAN and NB-IoT across various criteria is presented in Table 10.

Table 10. Comparison of LoRaWAN and NB-IoT across Various Criteria

Criteria	**LoRaWAN**	**NB-IoT**
Power Availability	Solar power for gateways; C cell batteries for sensors.	C cell batteries for sensors.
Sensor Distribution	Best for densely located sensors due to its ability to cover a large number of devices with a single gateway.	Suitable for sparse distributions.
Coverage Area	Long-range coverage.	Dependent on cellular network availability and signal strength.
Line-of-Sight Constraints	Requires clear line-of-sight for optimal performance, which may be a challenge in urban areas with tall buildings.	Less sensitive to line-of-sight issues but depends on cellular network coverage.
Cost of Deployment	Higher cost due to installations of gateways, solar panels, and battery enclosures.	Lower cost since only sensors need to be installed.
Maintenance Requirements	Maintenance requirements requiring regular checks on power sources and network connectivity.	Maintenance requirements requiring regular checks on power sources and network connectivity.
Sustainability	Sustainability is good if battery life and network connectivity are maintained.	Sustainability is good if battery life and cellular network connectivity are maintained.
Best Application Scenarios	Environment with dense sensor deployment (e.g., parking lots and road infrastructure monitoring).	Environment where cellular coverage is strong and consistent, and sensor locations are more spread out.

DISCUSSION

Maintenance Efforts

After the initial installation, maintenance, and troubleshooting were required due to the malfunctioning of the LoRaWAN gateway at the intersection of Monticello Ave and Casey Blvd on February 29, 2024. Fortunately, the gateway could be assessed wirelessly via Wi-Fi or Bluetooth, facilitating troubleshooting efforts. To address this issue, a Wi-Fi router and a portable power supply were brought to the site to power the router. This setup enabled the team to access the gateway wirelessly and diagnose the problem without the need for physical connections. Upon the investigation, it was discovered that the SIM card was poorly connected, despite attempts to reboot the gateway.

Subsequently, a new SIM card was ordered, and its replacement was scheduled with a VDOT engineer on March 8, 2024. After the SIM card was replaced, the gateway resumed normal operation. This incident underscored the importance of implementing sealing measures to prevent poor contact in outdoor environments, thereby ensuring the reliability and longevity of the infrastructure.

The research team later observed that Gateway #2 lost connection from April 9 to May 30, requiring manual on-site intervention. This connection loss caused the people counter at location #6 to have unstable network connectivity, though other counters were not affected. On May 31st, the research team went to the site to manually reboot the gateway. Two team members brought a ladder to reach the battery enclosure installed on the traffic signal. Since the gateway could not be connected via Wi-Fi, a manual reboot was conducted by plugging and unplugging the controller in the battery enclosure, allowing the gateway to reboot. After the reboot, the gateway reconnected to Wi-Fi, and its control panel could be accessed through a laptop on the same network. Figure 45 shows the on-site manual intervention.

Figure 45. Manual On-Site Intervention to Resolve Gateway #2 Connectivity Issues

For the people counter at location #1, the team observed unstable connectivity. Only message join requests could be received, and the payload information, including people counts, could not be uploaded to the Network Server. The team performed a manual reboot for the people counter at location #1, as shown in Figure 46, but the issues persisted. This instability is attributed to the people counter being at the proximity of the gateway's signal radius and the lack of a clear line of sight between the gateway and the people counter.

Figure 46. Manual Rebooting People Counter at Location #1

During the operation period, a major outage of the cellular service provider was detected, resulting in both gateways being unable to connect to the Network Server. The outage period lasted from June 4, 2024, at 14:23:37 EDT until June 4, 2024, at 15:08:10 EDT. After the service resumed, no manual intervention was needed to reboot the gateways, as they automatically reconnected to TTN.

In short, the maintenance efforts required for rebooting the devices is relatively minimal. However, since the gateway relies on an internet connection via a SIM card, any disruption in cellular service will prevent messages from being sent. In such cases, the maintenance crew must perform an on-site reboot, either via Wi-Fi or manually. If any devices become disconnected from the platform, their status should be monitored for a few days. If the devices do not reconnect automatically during this period, on-site maintenance will be necessary. Regular maintenance checks and quick response protocols can further enhance the system’s stability and performance.

Cybersecurity Concerns of Deployed LPWAN Systems

Deploying LPWAN systems (e.g., LoRaWAN and NB-IoT devices) within the Commonwealth of Virginia (COV) and VDOT networks involves ensuring compliance with established security standards. Both LoRaWAN and NB-IoT can meet these security requirements through their capabilities and configurations. The following shows how they align with the COV Security Standards. These LPWAN systems are not necessarily connected to the VDOT or COV network. Users may opt to use other cloud platforms or similar solutions.

- **Wireless Access (AC-18)**: LoRaWAN networks implement stringent controls for wireless access, including device authentication and encryption using Advanced Encryption Standard (AES)-128 at the network layer. Only authorized devices can access the network. NB-IoT networks implement strict access controls, including SIM-based authentication to ensure only authorized devices connect to the network.
- **Baseline Configuration (CM-2):** LoRaWAN Network Servers provide centralized management where configurations and security policies are defined and enforced. Network Servers and Gateways maintain logs and records of security configurations, device join requests, and network traffic, ensuring comprehensive records of all configurations applied. NB-IoT devices use SIM cards, which provide unique identifiers for each device and only authenticated devices can connect to the network.
- **Boundary Protection (SC-7):** LoRaWAN networks use gateways that monitor and control communication at network boundaries. NB-IoT networks use the cellular service provider’s network and firewalls to monitor and control data flow, protecting against unauthorized access to external networks.
- **Transmission Integrity (SC-8):** LoRaWAN employs encryption mechanisms (e.g., AES-128) to protect the integrity and confidentiality of data transmitted over the network, while NB-IoT employs standard Long-Term Evolution (LTE) encryption mechanisms.
- **Use of Cryptograph (SC-13):** LoRaWAN cryptographic keys are managed using AES-128. TTN manages user identification by a username or email address, protected by a password. Users can create applications and authorize other users to access these applications. Each application is identified by a unique Application ID, with one or more Access Keys used to access application data or manage devices. NB-IoT networks utilize standard cryptographic standards, with payloads encrypted by LTE encryption mechanisms. Further processing of payloads is required to derive meaningful results, as outlined in the Data Processing Section.

It is important to note that Wi-Fi and Bluetooth on the LoRaWAN gateway are used exclusively for troubleshooting. Data and messages are not transmitted via Wi-Fi or Bluetooth. These features are only for configuring the gateway settings wirelessly. For example, the user can directly establish a local area network (LAN) by using a router to facilitate communication between the PC and the gateway. LoRaWAN functions similarly to a mesh network, where sensors only send messages to the gateway, which then processes the data and forwards it to TTN.

CONCLUSIONS

- *The deployment of LPWAN technologies (i.e., LoRaWAN and NB-IoT) represents a significant advancement in transportation applications.* The field tests conducted in various environments (i.e., a university campus and an urban setting) provided a comprehensive understanding of each technology's adaptability and reliability under different operational conditions.

- *The dependency of the LoRaWAN system on solar power presented limitations during overcast or severe weather conditions.* It typically operates using AC power. However, in field deployments where AC power may be unavailable, solar power becomes the primary power source. This reliance on solar energy can be limited by weather conditions, such as overcast skies or severe weather, which can lead to interruptions in data collection and temporary system outages.

- *Challenges were noted for LoRaWAN in urban settings with dense infrastructure, where signal strength and data transmission reliability were occasionally impacted.* To mitigate these issues, the placement of sensors and gateways should consider elevation and maintain a clear line of sight to improve connectivity.

- *NB-IoT exhibited flexible connectivity by leveraging existing cellular networks, eliminating the need for additional local gateways.* The direct cellular connection provided reliable performance across geographically dispersed areas and reduced the complexity of the deployment. However, the signal strength of NB-IoT depends on factors such as signal power, antenna size, and distance to the cellular tower, making stable connections and successful data uploads problematic in certain locations. It is crucial to ensure that the cellular signal is strong enough to establish a stable connection in rural areas.

- *Economically, LoRaWAN is a cost-effective solution for areas with high device density, as it can cover extensive areas with few gateways.* This makes it a potential option for environments where infrastructure costs need to be minimized. Meanwhile, NB-IoT is more suitable for rural or less dense applications due to its lower infrastructure requirements (e.g., no need to use gateways and solar power systems).

- *Both LoRaWAN and NB-IoT demonstrated scalability, making them adaptable for various deployment contexts.* Their scalability allows for broader applications in different IoT scenarios (e.g., parking sensors).

- *The maintenance and troubleshooting of the LoRaWAN system highlighted the importance of reliable internet connectivity.* Occasionally, manual interventions were required to address issues such as poorly connected SIM cards and connectivity loss. Regular maintenance checks and quick response protocols are essential to maintain system stability and performance.

- *Environmental factors played a significant role in the performance of LoRaWAN systems.* Weather variations (e.g., overcast skies and severe conditions) affected the functionality and reliability of system operations based on solar power. In contrast, NB-IoT maintained operation by using 3.8V C batteries, which are not significantly influenced by environmental conditions.

- *Both LoRaWAN and NB-IoT systems are equipped with robust security measures that align with VDOT and COV cybersecurity standards.* The requirements for wireless access, baseline configuration, boundary protection, transmission integrity, and cryptographic management are followed.

- *The current lack of commercially available IoT sensors for transportation operations tasks makes it hard to adopt advanced traffic management solutions that use LPWAN.* This gap creates the need for developing specialized IoT sensors that use LPWAN technologies to meet the specific needs of transportation tasks.

- *Overall, the insights gained from these field tests highlight the importance of carefully planning and evaluating the deployment of LPWAN technologies.* Factors such as environmental conditions, infrastructure density, and economic considerations must be taken into account to optimize the performance and reliability of these systems in transportation applications.

RECOMMENDATIONS

1. *The research team recommends that VDOT actively monitor developments in LoRaWAN and NB-IoT technologies for broader transportation applications.* While the present study has demonstrated the potential of these technologies in collecting and transmitting pedestrian count data, the market still lacks a sufficient number of options for commercially available sensors specifically designed for transportation applications. By closely monitoring advancements in this field, VDOT can stay informed about the availability and maturity of commercial products, which will be crucial for the future development in various transportation tasks within and outside the transportation operations area.

IMPLEMENTATION AND BENEFITS

The researchers and the technical review panel (listed in the Acknowledgments) for the project collaborate to craft a plan to implement the study recommendations and to determine the benefits of doing so. This is to ensure that the implementation plan is developed and approved with the participation and support of those involved with VDOT operations. The implementation plan and the accompanying benefits are provided here.

Implementation

When an appropriate application scenario is specified, VDOT can adopt one or both LPWAN technologies for the extended study. For example, this could be a study that conventional pedestrian data collection is used and the LPWAN technologies can adopted as a comparison. It is expended that the research recommended in this report will commence within 6~12 months posted the publication of this report. The ODU research team will assist the planning, deployment, testing, and data processing and analysis in the extended study, if granted. The findings from current field tests, VDOT's data collection needs, and the availability of the off-the-shelf LPWAN sensors will help define the final scope of work.

Benefits

The extended study will help VDOT justify the feasibility of adopting the LPWAN technologies for different transportation applications. Due to the needs of different data collection scenarios, data transmissions may be at higher frequencies than the ones tested in this study. Also, the scale of needed sensors can be larger, or more sensors can be distributed in wider areas. Through the extended study, more comparative results can be obtained to help uncover the potential benefits and possible constraints of the LPWAN technologies employed for transportation applications. Additionally, this study could serve as a valuable reference for other agencies and organizations seeking LPWAN knowledge and information if they plan to deploy such technology. The findings could also be relevant to other functional areas within VDOT, such as structural health monitoring.

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APPENDIX: PEOPLE COUNTER INSTALLATION LOCATIONS IN WILLIAMSBURG, VA

Figure A1. People Counter Installation Location #1: 37°16'40.4"N 76°43'44.5"W, Monticello Ave Eastbound

Figure A2. People Counter Installation Location #2: 37°16'55.2"N 76°44'13.3"W, Ironbound Rd Southbound

Figure A3. People Counter Installation Location #3: 37°16'55.0"N 76°44'11.9"W, Ironbound Rd Northbound Close to Watford Ln

Figure A4. People Counter Installation Location #4: 37°16'22.1"N 76°44'19.8"W, Strawberry Plains Rd Northbound

Figure A5. People Counter Installation Location #5: 37°16'35.1"N 76°44'50.0"W, Monticello Ave Eastbound

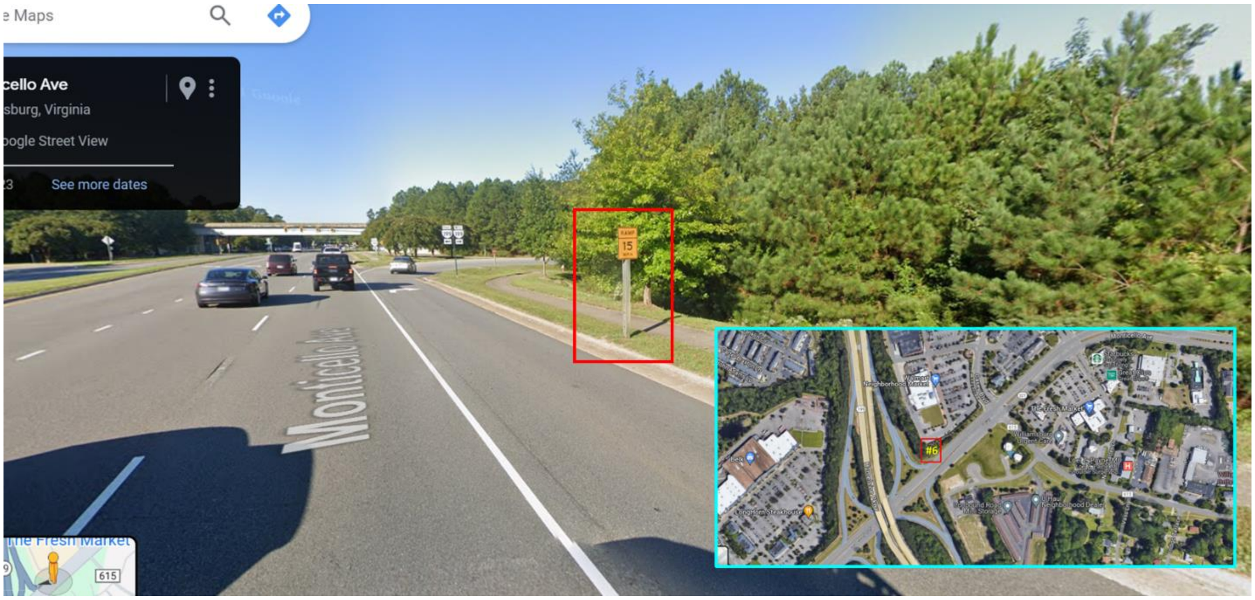

Figure A6. People Counter Installation Location #6: 37°16'27.4"N 76°45'03.7"W, Monticello Ave Westbound