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# Supporting Transportation System Management and Operations Using Internet of Things Technology

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**Final Report VTRC 21-R24**

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**FINAL REPORT**

# SUPPORTING TRANSPORTATION SYSTEM MANAGEMENT AND OPERATIONS USING INTERNET OF THINGS TECHNOLOGY

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## ABSTRACT

Low power wide-area network (LPWAN) technology aims to provide long range and low power wireless communication. It can serve as an alternative technology for data transmissions in many application scenarios (e.g., parking monitoring and remote flood sensing). In order to explore its feasibility in transportation systems, this project conducted a review of relevant literature to understand the current status of LPWAN applications. An online survey that targeted professionals concerned with transportation was also developed to elicit input about their experiences in using LPWAN technology for their projects. The literature review and survey results showed that LPWAN's application in the U.S. is still in an early stage. Many agencies were not familiar with LPWAN technology, and only a few off-the-shelf LPWAN products are currently available that may be directly used for transportation systems. To conceptually explore data transmission, a set of lab tests, using a primary LPWAN technology, namely LoRa, were performed on a university campus area as well as in a rural area. The lab tests showed that several key factors, such as the mounting heights of devices, distance between the gateway and sensor nodes, and brands of devices affected the LPWAN's performance. Building upon these efforts, the research team proposed a high-level field test plan for facilitating a potential Phase 2 study that will address primary technical issues concerning the feasibility of transmitting data of different sizes, data transmission frequency and transmission rate, deployment requirements, etc.

## FINAL REPORT

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## INTRODUCTION

As of 2021, the Virginia Department of Transportation (VDOT) owns and operates various intelligent transportation system (ITS) assets, including (but not limited to) 3,029 signalized intersections, 1,024 traffic cameras, 464 dynamic message signs (DMS), and 96 weather stations across the Commonwealth (based on information from VDOT's Integrated Maintenance Management System). The success of ITS applications largely relies on advances in sensors and communications technologies. For example, as of 2021, VDOT used 1,600 miles of the 5,055 miles of resource sharing fiber (RSF), along its right-of-way (ROW), to access broadband to support various applications, according to VDOT's Operation Division. Despite the growing need, current RSF only covers less than 10% of the 57,867-mile state-maintained highway system. A large portion of the roadway system, especially in rural and suburban areas, has limited coverage in terms of ITS communications. Extending fiber infrastructure along the ROW is expensive, as it would cost VDOT \$200,000-\$260,000 per mile (VAC, 2018). In addition, subscribing to and maintaining broadband service also involves substantial costs. For example, VDOT usually pays \$50-\$60 per month for broadband service for each intersection or portable DMS (VAC, 2018;VDOT, 2019). For traffic operations in underserved regions, alternative cost-effective and reliable solutions are needed to meet the communications demands of these regions. The emerging Internet of Things (IoT) technology has shown promising potential and VDOT has considered related applications in some pilot projects. For example, VDOT has deployed the Resensys structural health monitoring system on the structure of the Robert O. Norris Jr. Bridge to monitor floor beams and girders, based on 25 high-rate strain SenSpot sensors, two solar-powered SeniMax data logger and remote communication gateways, and five solar-powered signal repeaters (AI Engineers, 2015;Resensys, 2016). Recently, there has been significant interest in Low Power Wide-Area Network (LPWAN) technologies in support of IoT devices to wirelessly communicate with various applications over a relatively long range.

LPWAN is a promising wireless communication technology for supporting the development of IoT devices (Mekki et al., 2019), which often requires a long-range, wide coverage, and low data transmission rate. As shown in Figure 1, compared with other existing technologies, LPWAN supports long range and low bandwidth (BW) wireless communication. Limited by the low BW, LPWAN cannot guarantee real-time and high data rate communication, but it is superior when connecting a massive number of sensors for the purpose of large-scale IoT applications (Lavric and Popa, 2018). Emerging LPWAN technologies offer a great potential for advancing many existing VDOT applications, such as DMS, weather sensors, traffic sensors, etc. Without the network infrastructure in place, many sensors will not be able to communicate with VDOT's data management units. Thus, VDOT has a strong interest in leveraging the LPWAN technologies and has already referenced the use of the technology in its CY 2018-2021 Business Plan, item 4.7.

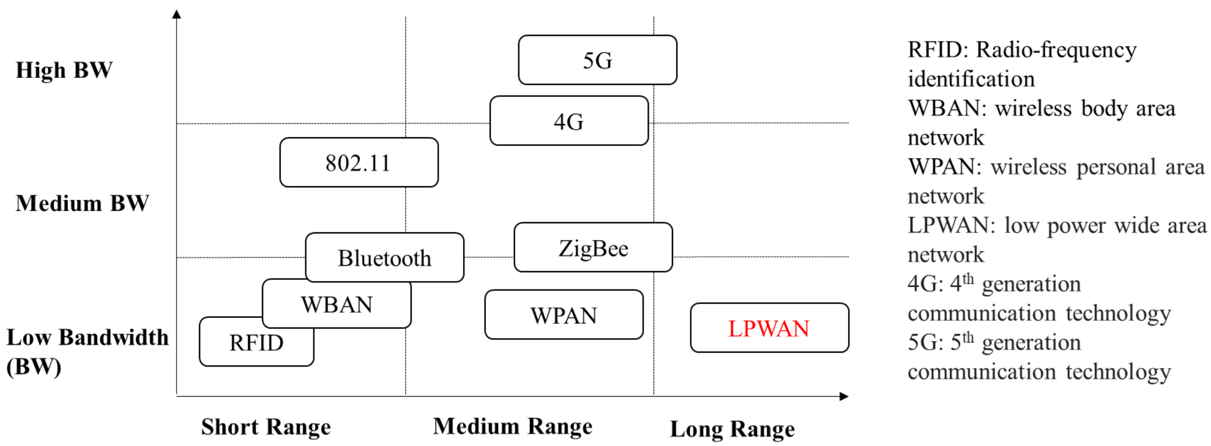



**Figure 1. Major Wireless Communication Technologies**

While there are promising aspects for using LPWAN technology, it is imperative to fully understand its strengths, weaknesses, opportunities, and challenges in supporting transportation system management and operations before implementing those technologies at scale. However, VDOT's experience with LPWAN is still limited and many technical aspects of these technologies, deployed in the context of transportation applications, are not well explored. For example, what is the coverage range of LPWAN technology in a typical traffic environment? What is the stable data transmission rate and transmission frequency in a transportation context? Will the data transmission success ratio be significantly affected by the distance between sensor nodes and gateways and the mounting heights of devices? To answer such questions, this research project intends to examine the technical specifications, as well as the advantages and disadvantages, and performance of LPWAN. This report focuses on a literature review, online survey, and lab tests to understand the relevant technologies and practices. This preliminary investigation was used to develop a field test plan with the aim of guiding extensive field tests in a potential Phase 2 to quantitatively assess the LPWAN technologies for transportation applications.

## PURPOSE AND SCOPE

The primary goals of this project were to:

- explore the state-of-the-art of LPWAN technology;
- understand and assess LPWAN technology in lab tests; and
- develop a field test plan for LPWAN for a possible future field study.

To accomplish these goals, a survey of existing practices in using LPWAN technology in the U.S. was conducted to explore its applicable uses, advantages, and limitations. More specifically, the research team solicited feedback from state DOTs and other transportation agencies to understand their current practices, with respect to LPWAN. Their feedback was summarized as a guide for lab tests and the development of a field test plan.

Building upon a comprehensive literature review, online survey, and comparative evaluations, lab tests of LPWAN were developed and related experimental results were made available to VDOT. As shown in Figure 2, due to the impact of COVID-19, the research team recorded and presented results of a set of experimental tests in video format in the fall of 2020. This was followed by the development of a field test plan.


**Figure 2. Sample Test Demonstrations**

## METHODS

Four main tasks were performed to achieve the study objectives:

1. Identify and review the literature related to LPWAN technology and its applications in the U.S.;
2. Conduct a survey and analyze relevant survey response data;
3. Perform lab tests to conceptually understand selected LPWAN technologies; and
4. Develop a high-level field test plan for a potential future field test.

## Literature Review

The literature was reviewed to identify information related to LPWAN technology. The reviewed references were identified through research databases and search engines, such as Google Scholar, the Transportation Research Board's Transport Research International Documentation (TRID), Web of Science, and Scopus. Research articles, publicly available presentation files, as well as reported information on webpages of agencies and vendors (related to LPWAN technology) were explored and synthesized.

## Online Surveys

Following the results of the literature review, the research team developed an online survey for transportation professionals to elicit input about their experiences in using LPWAN technology in their projects. The survey questions covered application scopes, concerns, suggestions, etc., related to the use of LPWAN technology. The research team identified potential respondents via IoT/Smart City conference participants, DOTs of different states and localities, TRB members of committees related to information and technologies, and other traffic agencies with LPWAN experiences in the U.S. One online survey instrument was designed and implemented. Detailed survey questions can be found in Appendix A.

## Lab Tests

The ODU research team purchased a limited number of gateways and sensor nodes for conceptual lab tests. Based on the literature review and an online survey, LoRa technology was found to be one of the most popular LPWAN technologies, with many off-the-shelf products available. After a discussion with the project technical review panel (TRP) members, LoRa was selected as the LPWAN technology for these lab tests. The model type of the tested gateway was MultiTech MTCDT-246A. Multiple sensor nodes (i.e., Laird sensor, ELT2 sensor, and an Adeunis radio-frequency (RF) network tester) were connected to the gateway and their measurements, such as temperature, were sent to the gateway. The Laird sensor measures temperature and humidity (Laird, 2020). The ELT2 sensor measures temperature, humidity, acceleration, and atmospheric pressure (ELT2, 2020). The Adeunis RF network tester can help check signal strength (Adeunis, 2020) and display such information on its screen and in log records. It should be noted that such sensors and network tester would code and decode information based on its specific rule. For example, one payload of Laird sensor is "01013047281905057A04A4", which will be decoded as follows: {"AlarmMsgCount": 31237; "BatteryCapacity": "80-100%"; "BcklogMsgCount": 41988; "MsgType": "Send Temp RH Data Notification"; "Options": "Inform Server to send UT to sensor in the next downlink transmission"; "humidity": 182.24; "temperature": 64.4}.

As shown in Figure 3, LoRaWAN was used to transmit the information. Both indoor and outdoor tests were conducted. For indoor scenarios, visualization tools, such as the ResIoT platform, were utilized to interactively check the received data. For outdoor scenarios, a laptop was connected to the gateway to check the received data of selected sensor nodes and the gateway (shown in Figure 4). As depicted in Table 1, the research team first experimented with an indoor test to prove its feasibility and calculated the success ratio over a long period of time (e.g., one week). Then, the research team performed an outdoor test in three different locations: the Deep Creek Park in a rural area, the parking garage of Old Dominion University (ODU) in an urban area, and the waterfront area of ODU in an urban area. Due to power supply limitations, the research team carried the charged battery for the gateway in three outdoor tests, and the test duration at each site was only 10 minutes. The number of received messages for each site was calculated.

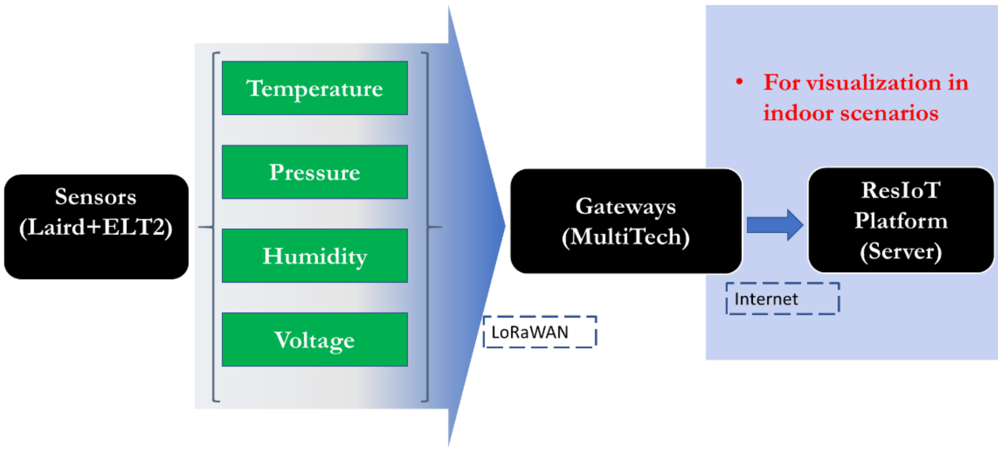



**Figure 3. Framework of Lab Tests**

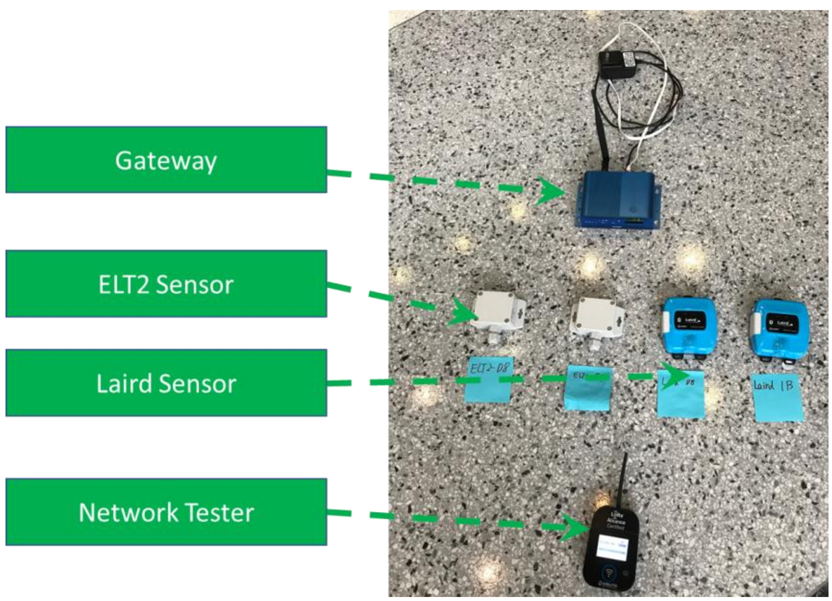



**Figure 4. Sensors and Gateway Used in Lab Tests**

**Table 1.Test Scenarios of Lab Tests**

| Test Scenario | Location | Duration | Performance Measure |
|---|---|---|---|
| Indoor | An apartment | One week | Success ratio |
| Outdoor test - rural area | Deep creek Park | 10 minutes per site | Number of received messages |
| Outdoor test - urban area | Parking garage at Old Dominion University (ODU) | 10 minutes per site | Number of received messages |
| Outdoor test - urban area | Waterfront area in ODU | 10 minutes per site | Number of received messages |

## Indoor Test

First, the research team conducted simple experiments to test the basic functionalities of LoRa in an indoor setting. As shown in Figure 5, different sensors and gateways were deployed on the floor with spacings of around 5 feet. The signal transmission interval was set as 1 minute for Laird sensors and 2 minutes for ELT2 sensors. The collected information was directly sent to the gateway and the ResIoT server (Note: This is a subscription-based service. Similar services provided by other vendors are also commercially available.) As shown in Figure 6, the real-time measurements (e.g., temperature) were available to users, once the gateway uploads data to the server. The research team calculated the performance measure, namely success ratio $\mathrm{R}_{success}$, to evaluate its transmission performance.

$$\mathrm{R}_{success} = \frac{n_{received}}{n_{sent}} \quad (1)$$

where, $n_{received}$ and $n_{sent}$ were the number of received messages and sent messages, respectively.

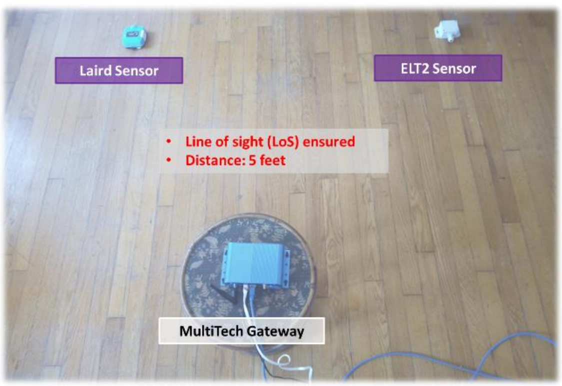



**Figure 5. Indoor Test Scenario**

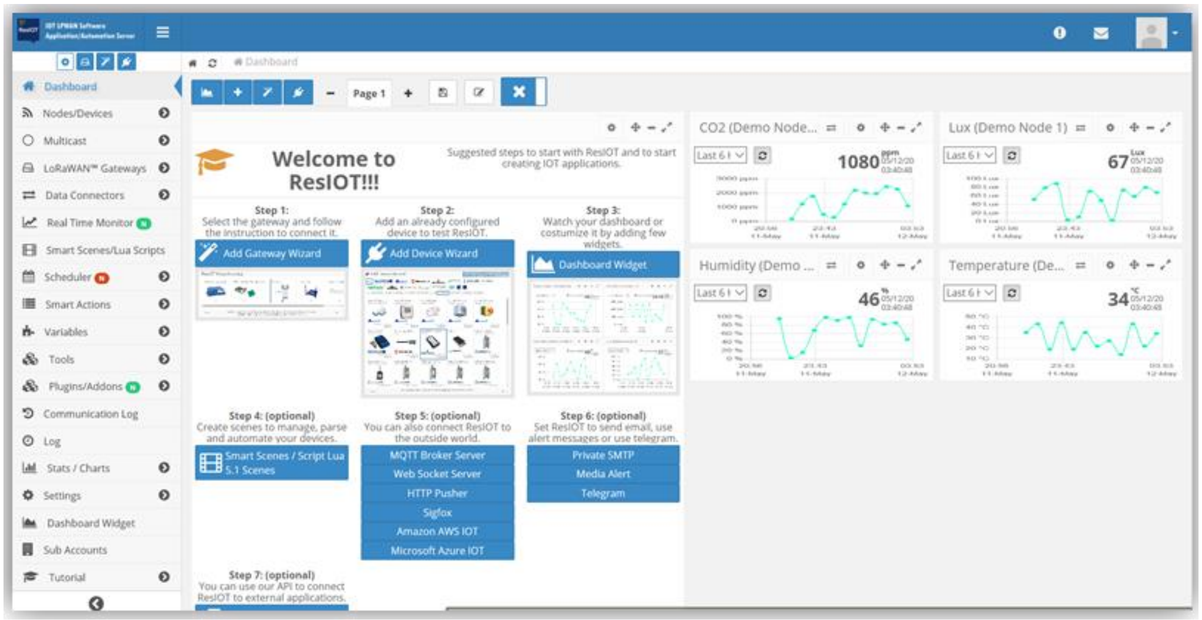



Figure 6. An Interface of the Subscribed ResIoT Server for Data Visualization

## Outdoor Test (Rural Area – Deep Creek Park)

Based on an indoor test, the research team further conducted a set of outdoor tests. It should be noted that the outdoor tests were short-term tests which aimed to explore whether such LPWAN technologies can conceptually work over a relatively long distance. Thus, even though the communicated messages were recorded, the research team did not calculate long-term (e.g., 1 week) evaluation metrics, such as the success ratio in these outdoor tests.

The research team customized a 16-ft pole to mount the gateway at a higher position. The first test site was at the Deep Creek Park (36.720309, -76.348243), near George Washington Hwy S, in Chesapeake, VA. As shown in Figure 7(b), the MultiTech Gateway was located at the green dot. The actual setup of the gateway is shown in Figure 7(a). Five different sites were randomly selected as the locations to host sensor nodes (Figure 7(b)). The difference in distance between concentric rings in Figure 7(b) was 0.25 mile. The research team stopped at each site for about 10 minutes to verify if messages could be successfully sent to the gateway. One researcher monitored the laptop connected to the gateway while another researcher took the sensor nodes to different test sites. The research team visited the sites in the area in the following order: site 1, site 2, site 3, site 4, and site 5. Detailed locations are listed in Appendix B. These sites were not pre-selected. Instead, the researcher randomly picked them based on whether there was a safe space to park a vehicle. At each site, the tested sensor nodes were placed on top of the parked vehicle. The researcher communicated by phone with the individual monitoring the gateway status to check to see if messages were successfully received.

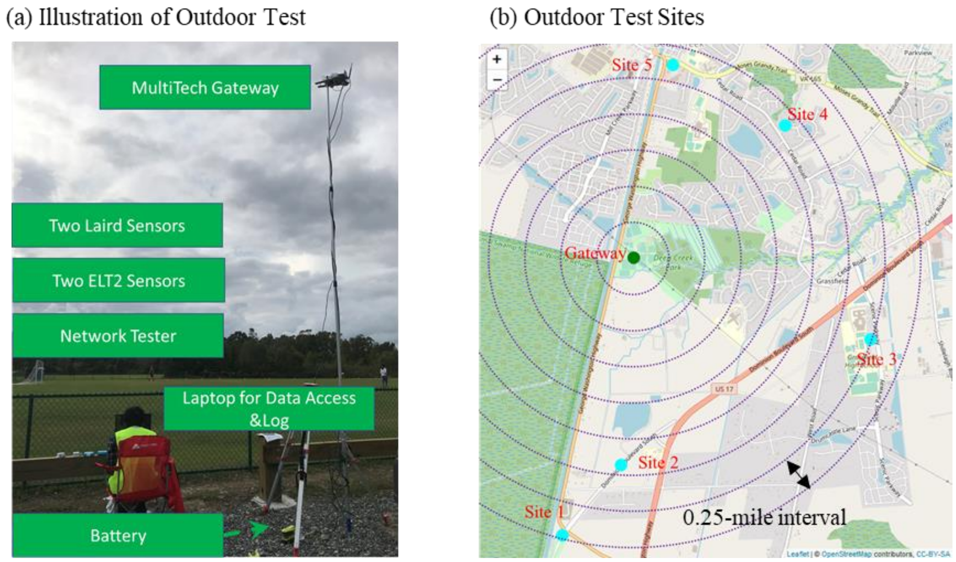



**Figure 7. Outdoor Test in a Rural Area in Chesapeake, VA**

## Outdoor Test (Urban Area- Parking Garage)

As the customized mounting pole was at a relatively low height, the research team tested an extreme scenario to understand whether mounting height would significantly extend the range of communication. The research team installed the gateway on the 5th floor of a parking garage (36.887832, -76.305445) on the ODU campus, one of the highest buildings in the area. As shown in Figure 8, the MultiTech Gateway was located in the green circle shown in Figure 8(b) and placed on the side wall of the garage (Figure 8(a)). The difference in distance between concentric rings in Figure 8(b) was 0.25 mile. Twelve different sites were selected. In total, two Laird sensors, two ELT sensors, and one network tester were carried for the test. As in previous test scenarios, the research team stopped at each site for about 10 minutes to help verify whether messages were being successfully sent. The research team visited the sites in the following order: site 1, site 2, site 3, site 4, site 5, site 6, site 7, site 8, site 9, site 10, site 11, and site 12. Detailed locations are listed in Appendix B. Also, no additional facility was used for mounting sensor nodes. All of them were temporarily placed on the top of the researcher's parked vehicle at each site.

(a) Illustration of Outdoor Test (b) Outdoor Test Sites

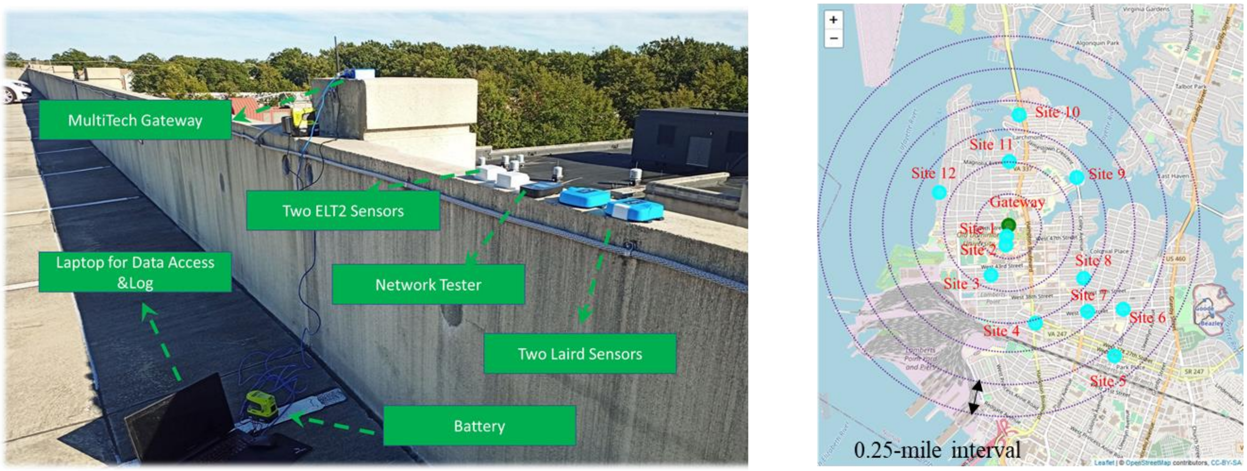



**Figure 8. Outdoor Test in an Urban Area – Parking Garage at Old Dominion University (ODU)**

## Outdoor Test (Urban Area- Waterfront Area)

Further, the research team installed the gateway in the Waterfront area (36.885870, -76.316666) on the ODU campus. As shown in Figure 9, the MultiTech Gateway was located within the green circle (shown in Figure 9(b)). The difference in distance between concentric rings in Figure 9(b) was 0.25 mile. Figure 9(a) illustrates the actual experimental settings. In total, 11 different sites were selected. Two Larid sensors, two ELT sensors, and one network tester (shown in Figure 9(a)) were taken to the test sites. As in previous scenarios, the research team also stopped at each site for about 10 minutes to confirm whether messages could be sent to the gateway from that spot. The sites were visited in the following order: site 1, site 2, site 3, site 4, site 5, site 6, site 7, site 8, site 9, site 10, and site 11. Detailed locations are listed in Appendix B.

(a) Illustration of Outdoor Test (b) Outdoor Test Sites

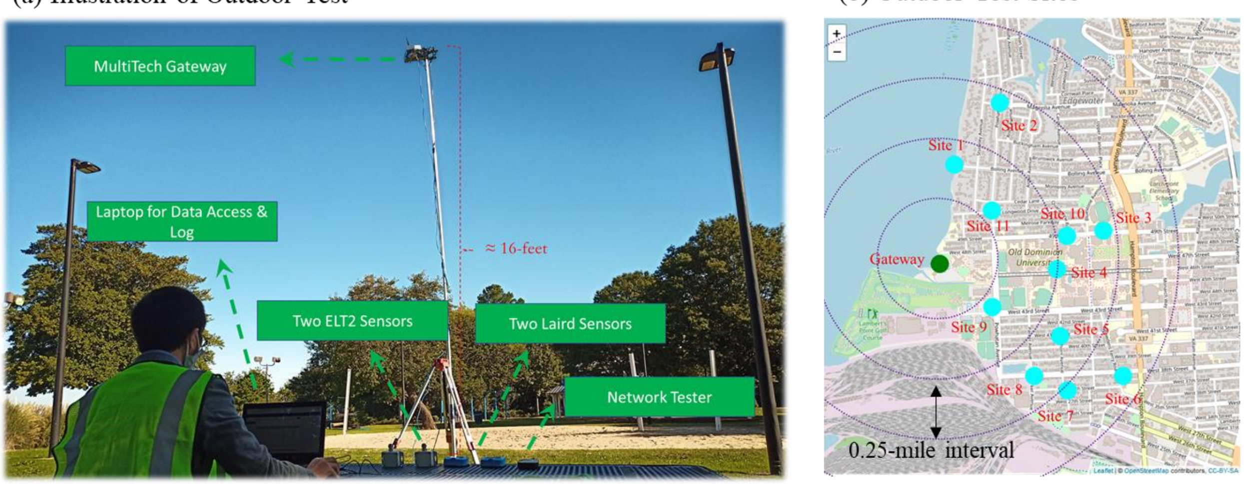



**Figure 9. Outdoor Test in an Urban Area – Waterfront Area at ODU**

## Development of Field Test Plan

Based on the lessons learned from the literature review, survey, and lab tests, a field test plan was developed to guide the selection and test of candidate LPWAN technologies for a possible future study. The research team demonstrated the feasibility of LPWAN technology and realized that some detailed information (e.g., performance under different scenarios and requirements) remained unclear. Thus, the research team conferred with TRP members, through several online meetings, to identify key interests (e.g., the feasibility of image transmission) and to define critical issues (e.g., the data transmission latency) that needed additional investigation.

# RESULTS AND DISCUSSION

## Literature Review

The research team conducted a comprehensive review of existing literature to identify technical features and applications of LPWAN technologies. The following sections summarize the major results with respect to each identified technology. The research team categorized these into two categories: unlicensed technologies, which operate on unlicensed bands and need VDOT for maintenance of the infrastructure; and licensed technologies, which operate on licensed bands and need the network operator (e.g., AT&T) to primarily maintain the infrastructure. Unlicensed technologies include Long Range (LoRa), Sigfox, IQMESH Radio-frequency (IQRF), Random Phase Multiple Access (RPMA), and Developers' Alliance for Standards Harmonization of International Organization for Standardization 18000-7 (DASH7). In addition, licensed technologies include Narrowband Internet of Things (NB-IoT), Extended Coverage Global System for Mobile Communication Internet of Things (EC-GSM-IoT), and Long Term Evolution Category M1 (LTE-CAT-M1).

### LoRa

LoRa is a low-power wide-area network (LPWAN) technology (Ferreira et al., 2019). It was developed by Cycleo of Grenoble, France, and acquired by Semtech, the founding member of the LoRa Alliance. Some of the major characteristics of LoRa are as follows:

- LoRa operates in the unlicensed Industrial, Scientific, and Medical (ISM) bands. Its duty cycle per day (i.e., the proportion of time it is in operation) is restricted to 1% in Europe. It should be noted that in the US915 band, the maximum transmission time over the same channel is 400 ms within a 20 s period of time (2%) (Alliance, 2015).
- LoRa includes three classes: bi-direction end-devices (class A), bi-directional end-devices with scheduled receive slots (class B), and bi-direction end-devices with maximal receive slots (class C) (Alliance, 2015).
- Instead of using frequency shifting keying (FSK) modulation as the physical layer for achieving low power, LoRa uses chirp spread spectrum (CSS) modulation, which maintains the same low power characteristics as FSK modulation. However, it significantly increases the communication range, and has been used in military and space communication for decades, due to the long distance that communication can be achieved and its robustness to interference (Alliance, 2015).
- The maximum transmission range can reach 15 km (Alliance, 2015).

- The transmission peak data rate is 27 kbps (Alliance, 2015).
- LoRaWAN defines the communication protocol and system architecture, while LoRa only defines the physical layer. The LoRaWAN network applies the long-range star architecture, and three modes of devices. End-devices communicate with one or many gateways through single-hop-LoRa communication, while all gateways are connected to the core network server via standard IP connections (Alliance, 2015) .

LoRa uses six spreading factors (varying from spreading factor 7 (SF7) to SF12) to adapt the data rate and range tradeoff. The higher spreading factors will allow a longer range, while sacrificing the transmission data rate. In short, the LoRa data rate is between 300 bps and 50 kbps, depending on the SF and channel bandwidth.

The LoRa components and LoRaWAN ecosystem are relatively mature and production-ready now. Considering the costs of the spectrum, network, device, and deployment, the cost of LoRa technology is relatively low (e.g., ~$1,500 for a small-scale setting). It should be noted that a large area could be covered by one gateway or base station of LoRa. However, the coverage range of LoRa will degrade in urban areas. For example, a study (Mikhaylov et al., 2018) found that the effective coverage range of LoRa was shorter than the proclaimed 15 km, due to multiple obstacles along the line of sight. Another study (Petajajarvi et al., 2015) showed that the packet loss rate was lower than 20% within 5 km. The packet loss rate increased to 40% at distances of 5 to 10 km. When the distance exceeded 10 km, the majority of sent packets were lost. More research is still needed to test its reliability and performance.

In addition, LoRa devices have a long coverage range and degrade their own performances when coexisting with each other. For example, when four LoRa networks co-exist, the throughput of each was reduced by almost 75 percent (Voigt et al., 2016). One promising solution is to combine multiple LPWAN devices. Studies (Mikhaylov et al., 2018) and (Ferreira et al., 2019) made some preliminary tests when integrating LoRa with NB-IoT/Bluetooth. It should be pointed out that the optimal selection of multiple LPWAN technologies and devices still needs more field trials.

LoRa has been used in many fields, such as smart parking and smart lighting. For example, a study (Sotres et al., 2018) presented global smart-parking use cases, based on data streams sourced from Santander in Spain and Busan in South Korea. Another study (Pasolini et al., 2018) presented a project in the city of Bologna that measured environmental qualities, such as temperature, humidity, luminosity, and $CO_2$. LoRa was utilized, and it was concluded that researchers need to select proper parameters to cover large urban areas, while keeping the time-on-air sufficiently low to guarantee satisfactory low packet losses. Similarly, public buses were monitored in the City of Nonoichi, through LoRa (Tanaka et al., 2017), and a field trial of vehicle monitoring was implemented by the University of Murcia in Spain (Santa et al., 2019). Another study (Nor et al., 2017) also collected traffic data, via LoRa, in Malaysia to help make more efficient traffic signal schedules to relieve congestion. Similarly, the PNI Sensor Corporation used LoRa for smart parking (Sotres et al., 2018). Robust and high-accuracy wireless occupancy sensors, which were allocated to each parking space, communicated with the gateway, via LoRa, to help the parking management system notify drivers of open spaces. Telensa also used the ultra-narrow band technology and developed a multi-sensor pod (MSP), an array of streetlight-mounted units, to measure how people used city facilities, the mix of traffic on roads, hyper-local air quality, and noise levels.

LoRa has the following primary benefits:

- It uses Chirp Spread Spectrum (CSS) technology that increases its anti-interference and long-range capacity.
- Theoretically, it has a relatively long coverage range.
- It has relatively more related products (e.g., sensor nodes) in the U.S. market when compared to other LPWAN technologies.

LoRa has the following main limitations:

- Its latency increases with the increment of the number of sensor nodes and gateways.
- Its throughput can be reduced when multiple sensor nodes co-exist with each other.
- Its parameters need to be carefully configured to obtain satisfactory performances (e.g., to cover large urban areas with a low packet loss ratio).
- It works in ISM bands and is limited by the duty cycle.

**Sigfox**

Sigfox is a French global network operator founded in 2010. It builds wireless networks to connect low-power objects, such as electricity meters and smartwatches that operate continuously and collect small amounts of data (Zuniga and Ponsard, 2016). Some of the major characteristics of Sigfox are as follows:

- Sigfox devices send 140 messages (maximum) per day and, the rest of the time, the devices remain in sleep mode (Vejlgaard et al., 2017).
- The end device can only communicate with the base station and transmit each message three times on three different frequencies. The Sigfox network protocol uses both time and frequency diversity. The Sigfox base station transmits a signal by using a random frequency and time division multiple access (RFTDMA) (Zuniga and Ponsard, 2016).
- Sigfox enables communication by using the Industrial, Scientific and Medical (ISM) radio band, which uses 868 MHz in Europe and 902 MHz in the U.S. (Vejlgaard et al., 2017).
- Sigfox uses Differential Binary Phase Shift Keying (DBPSK) modulation for uplink and Gaussian Frequency Shift Keying (GFSK) modulation for downlink (Ferré and Simon, 2018).
- The data rate is 100 bps or 600 bps (Ferré and Simon, 2018).
- The number of messages is up to 6 per hour and up to 140 per day (Ferré and Simon, 2018).
- The uplink payload is 12 bytes, while the payload for downlink is 8 bytes (Ferré and Simon, 2018).

Since Sigfox uses the ALOHA based protocol to randomly access the wireless medium frequency and time domain, without any containment method, its benefits include the following: frequency diversity (broadcast a message in three different frequencies), time diversity (broadcast the message at three different times), spatial diversity, noise robustness, and spectrum interference avoidance, and no need for time synchronization or beacon packets. It should be noted that Sigfox frames are not encrypted by the protocol. The encryption is done by the client at the application layer (Ferré and Simon, 2018). The Sigfox coverage can achieve 20–50 km and 3–10 km in rural and urban areas, respectively. Sigfox shares the same frequency as LoRa and, thus, follows the same duty cycle regulations.

Sigfox initially only supported uplink communication and then evolved to bi-directional technology. It applies an ultra-narrowband modulation technique and, accordingly, supports a lower data rate than other techniques. For example, it only allows 140 12-byte messages per day for uplink. However, the maximum number of messages over the downlink is only 4, with 8 bytes. Since Sigfox lacks adequate confirmation acknowledgements from gateways, in order to address the potential data loss issue, messages are transmitted multiple times (Xiong et al., 2015). The default number of transmissions is three and the transmission is over different frequency channels. Base stations can receive messages simultaneously over all channels and end devices can randomly choose a frequency channel to transmit messages.

Sigfox has been successfully applied in the U.S. and other countries. There are many users of Sigfox, such as 7-Eleven, Airbus, and Nestle. For example, bicycles periodically send their locations to a bike-sharing company via Sigfox in Singapore and Taiwan to facilitate user behavior analysis and to provide better services (muRata, 2016). Meanwhile, one study (AirBus, 2017) showed the use of Sigfox to track assets to help improve the supply chain. According to tests, the battery life was estimated to be 3 years, assuming an average of 20 messages per day. Another study (Puri, 2017) discusses the use of Sigfox sensors to monitor waste water in San Francisco. Additional applications, such as wildfire detection, connected seals within container shipping, and tracking assets are also supported by Sigfox.

Sigfox has the following primary benefits:

- It has low power needs.
- It has been developed with extensive research in many regions.

Sigfox has the following main limitations:

- Its radio frequency interference is relatively high.
- It maintains relatively low security due to its 16-bit encryption.
- Its maximum number of messages that can be sent per day is only 140.

## IQRF

IQRF is a technology for wireless packet-oriented communication via radio frequency (RF) technology in sub-GHz ISM bands (IQRF, 2020). It aims to support wireless connectivity for industrial control, automation of buildings and cities, and IoT. Some of the major characteristics of IQRF are summarized as follows:

- IQRF uses mesh network topology and can support maximum 239 nodes per coordinator (IQRF, 2020).
- The modulation of IQRF uses GFSK (IQRF, 2020).
- The transmission range is up to 5 km (IQRF, 2020).
- IQRF allows for communication on 915 MHz in the U.S. It can use up to 67 channels in this frequency with a 100 kHz bandwidth (IQRF, 2020).
- The actual broadcasting has a speed of up to 20 kbps, and the individual packets have a size of up to 64 bytes (IQRF, 2020).

Similar to the Bluetooth Low Energy, IQRF devices support the so-called mesh networking by default. Therefore, an IQRF device will forward a received message in its coverage range. This leads to the benefit of resistance to interference at the cost of increased energy consumption. It should be noted that the standard in IQRF design has been enhanced with LoRaWAN technology and now integrates both LPWAN wireless networks (IQRF, 2019). Therefore, it is feasible to transmit aggregated data independently, without the need for Internet connectivity through the LoRaWAN network, which saves data by sending only substantial information. It had been used in applications, such as smart cities, smart parking, and smart lighting (Pies and Hajovsky, 2017).

IQRF has the following primary benefits:

- It has been used in smart parking and smart lighting.

IQRF has the following main limitations:

- Its price is relatively high compared with LoRa.

**RPMA**

Ingenu RPMA is a technology that utilizes Random Phase Multiple Access (RPMA) to improve coverage and capacity (RPMA, 2020). It aims to minimize the total expense while increasing the range and link capacity compared with those of LoRa and Sigfox (Queralta et al., 2019). Some of the major characteristics of RPMA are summarized as follows:

- The peak data rate for RPMA is 80 kbps and the transmission range is up to 15 km (RPMA, 2020).
- RPMA uses technology patented in 2010 by Ingenu. On top of it, Ingenu has developed a LPWAN technology that allows a much higher link capacity than LoRa and Sigfox. It operates on the 2.4 GHz ISM band, in contrast with most LPWAN technologies that use sub-gigahertz frequencies (Queralta et al., 2019).
- RPMA is based on the direct-sequence spread spectrum (DSSS) modulation technique. Its communication is two-way and devices perform scanning in the background with handover so that the best access point is chosen for each transmission (RPMA, 2020).
- RPMA supports parallel demodulation of up to 1,200 signals on the same frequency (RPMA, 2020).
- The adaptive spreading factor of the transmission is used to reduce the power consumption based on channel conditions at each transmission time (RPMA, 2020).

RPMA operates at 2.4 GHz. However, the 2.4 GHz is widely used by many other technologies, including Wi-Fi and Bluetooth and, therefore, it is more likely to experience interference due to the congested spectrum. RPMA requires all gateways in the same network to be synchronized, so that end-devices are aligned in time with them. One of the key advantages of RPMA over LoRa and Sigfox is the network capacity. It was claimed that one gateway can handle up to 2 million devices per access point (Queralta et al., 2019). However, a higher frequency, such as 2.4 GHz, also implies that penetration through most materials is less effective. This means it will have less range in cities or in large indoor facilities.

While the access points for RPMA are currently cheaper than other LPWAN technologies, sensors that support RPMA are also much more expensive, so the cost difference will likely depend on the number of access points and sensors required for specific applications. Several cities in the U.S. have deployed RPMA (e.g., San Diego used RPMA technology for smart metering and smart grid services and applications (RPMA, 2020)).

RPMA has the following primary benefits:

- It provides more area coverage compared with LoRa or Sigfox.
- It possesses a better link capacity.

RPMA has the following main limitations:

- It suffers higher interference from buildings, Wi-Fi, and Bluetooth.

**DASH7**

The DASH7 Alliance Protocol originated from the ISO/IEC 18000-7 standard (DASH7, 2020). It focuses on military logistics and defines the 433 MHz ISM band air interface for active RFID. Later, the DASH7 alliance updated the original standard toward a wireless sensor network technology for commercial applications. Some of the major characteristics of DASH7 are listed, as follows:

- DASH7 Alliance Protocol (D7A) is an open-source Wireless Sensor and Actuator Network protocol, which can operate in the 433 MHz, 868 MHz, and 915 MHz unlicensed ISM band/SRD band. It covers all sub-GHz ISM bands, making it available globally (Weyn et al., 2015).
- The transmission range of DASH 7 is up to 2 km, with low latency for connecting with moving things and a very small open-source protocol stack (Weyn et al., 2015).
- AES 128-bit shared key encryption is applied (Weyn et al., 2015).
- Data transfer speed is up to 167 kbps (Weyn et al., 2015).
- The modulation technology of DASH7 is GFSK (Weyn et al., 2015).
- DASH7 specifies the unique acronym BLAST: bursty (data traffic pattern), light (maximum packet size of 256 bytes), asynchronous (synchronization not required), stealth (only replies to approved devices), and transitional (mobility) (Weyn et al., 2015).

DASH7 consists of endpoints, sub-controllers, and gateways. Gateways keep active continuously. Sub-controllers act in the same role as gateways, but in low power and with sleep cycles. For example, the asynchronous duty-cycle in DASH7 helps the nodes function at a lower latency, but it increases power consumption (Ayoub et al., 2018). Nodes need to periodically check the communication channel for any downlink messages. Thus, the Low Power Wake-up mode is applied to reduce the power consumption. The query node sends a beacon advertising the timestamp at which it will send the data. The listening node notices a signal above the noise level and records the timestamp at which data is to be received. The listening node then goes to sleep, until the timestamp is reached, when it wakes up to receive the data.

DASH7 provides a full-stack solution for LPWAN, where end nodes can establish communication without being concerned about the complexities of network media access control (MAC) or physical layers. The default network topology, used by DASH7, is a tree topology. It should be noted that star topology is also available if needed (Weyn et al., 2015).

DASH7 has the following primary benefits:

- It has good penetration against interference for both the outdoor and indoor environment.
- It has low network latency.
- It has the flexibility of using tree or star network topology.

DASH7 has the following main limitations:

- The asynchronous duty cycle will increase power consumption.

**NB-IoT**

Narrowband IoT (NB-IoT) is a 3rd Generation Partnership Project (3GPP) radio technology standard that addresses the requirements of IoT (Sinha et al., 2017). NB-IoT provides improved indoor coverage, support of a massive number of low throughput devices, low delay sensitivity, ultra-low device cost, low device power consumption, and optimized network architecture (Sinha et al., 2017). Some of the major characteristics of NB-IoT are as follows:

- NB-IoT technology uses Quadrature Phase Shift Keying (QPSK), Orthogonal Frequency-division Multiple Access (OFDMA), and Single-carrier Frequency-division Multiple Access (SC-FDMA) for modulation (Adhikary et al., 2016).
- NB-IoT uses licensed bandwidth. 3GPP has defined a set of frequency bands that NB-IoT can be used. The bandwidth varies among different regions. Specifically, the bandwidth used in North America are B4 (1700), B12 (700), B66 (1700), B71 (600), and B26 (850) (Adhikary et al., 2016).
- Power saving mode (PSM) is used to help IoT devices conserve battery power and potentially achieve a 10-year battery life. This is achieved by several tracking area updating periods that include the waking period and the power-saving mode period. For example, a device will close its radio module and negotiate a 24-hour time interval with the network controller. During the sleep period, the device turns its radio off to conserve battery power. The device subsequently needs to reattach to the network when the radio is turned on. Once an activation condition is detected, the device will instantly wake up its radio module to communicate with the network controller (Sinha et al., 2017).
- The peak data transmission rates are 250 kbps and 170 kbps for the uplink and downlink, respectively (Sinha et al., 2017).

- NB-IoT supports up to 50,000 devices per cell with the minimum 180 kHz bandwidth (Wang et al., 2017). The number of devices supported decreases as the bandwidth requirement increases.
- The security and encryption of NB-IoT follow the global 3GPP licensed standard for security and certification (Sinha et al., 2017).

Compared with LoRa technology, NB-IoT works at a licensed bandwidth and uses the time slotted synchronous protocol to better guarantee the quality of service (QoS). On the other hand, due to the regular synchronization function in NB-IoT, nodes consume more battery energy, and OFDM/FDMA technology requires more peak current (120/130 mA) for a linear transmitter while LoRa only has 32 mA (Sinha et al., 2017). Therefore, the battery life of NB-IoT devices is generally shorter than that of LoRa. NB-IoT is more suitable for applications that require low latency and high data rates.

It should be noted that some modules of NB-IoT can switch between NB-IoT and LTE-CAT-M1, and NB-IoT is designed to be compatible with the LTE network. Since the LTE network has worldwide coverage, it is convenient to subscribe to a network operator required by the NB-IoT technology. However, it should be noted that since the deployment of NB-IoT is limited to locations with LTE base stations, NB-IoT's performance will degrade in rural or suburban regions, which may not have good LTE service (Martinez et al., 2019).

NB-IoT has been tested with real-life applications, such as smart metering and tracking in Brazil (Tanaka et al., 2017), NB-IoT at sea in Norway, and smart city applications in Las Vegas, NV (Pasolini et al., 2018). Different vendors, such as AT&T and T-Mobile (as shown in Table 2), provide solutions for supporting applications in smart parking, smart metering, and manhole cover/tracking. For example, AT&T mentions that it currently offers pricing plans for as low as $5/year/device (AT&T, 2020).

**Table 2. Sample Applications of NB-IoT**

| Vendor | City/State | Applications | Ref |
|---|---|---|---|
| T-Mobile | Las Vegas, NV | Smart city;<br>Smart light-emitting diode (LED) lighting;<br>Sensor based monitoring of gas, temperature | (Pasolini et al., 2018) |
| AT&T | San Francisco, CA | Human body tracking;<br>$5/year/device;<br>(smart parking, smart metering) | (AT&T, 2020) |

Overall, NB-IoT has the following major benefits:

- It is possible to reuse cellular hardware based on the LTE.
- It supports many LTE features like localization, security, and authentication.

On the other hand, NB-IoT also has the following main limitations:

- It has low performance when the network has heavy data and voice traffic.

**EC-GSM-IoT**

EC-GSM is the IoT-optimized GSM network, the wireless protocol that 80 percent of the world's smartphones use (3GPP, 2016). EC stands for Extended Coverage.EC-GSM can be deployed in existing GSM networks (a huge advantage in terms of practicality and modularity), since a simple piece of software enables EC-GSM connectivity within 2G, 3G, and 4G networks. Some of the major characteristics of EC-GSM-IoT are as follows:

- EC-GSM-IoT uses in-band GSM (3GPP, 2016).
- For downlink and uplink, EC-GSM-IoT uses Time-division Multiple Access (TDMA)/ Frequency-division Multiple Access (FDMA), Gaussian Minimum Shift Keying (GMSK) and 8PSK (optional) (3GPP, 2016).
- The bandwidth of EC-GSM-IoT is 200 kHz per channel (Sjöström, 2017).
- The peak rates for downlink and uplink of EC-GSM-IoT are 70 kbps (GMSK) and 240 kbps (BPSK), respectively (3GPP, 2016).
- While considering power saving technology, power saving mode (PSM) and I-Discontinuous Reception (I-DRX) are applied. The battery life is estimated to be 10 years of operations with a 5-Wh battery (3GPP, 2016).
- The power class is 33 dBm (3GPP, 2016).
- The transmission latency is 700 ms to 2 seconds (3GPP, 2016).

EC-GSM-IoT is designed to be backward compatible to the existing GSM network. It defines new control and data channels mapped over legacy GSM and allows multiplexing of new devices and traffic with legacy Enhanced Data rates for Global Evolution (EDGE) and General Packet Radio Service (GPRS). It does not require new network carriers of GSM network, and new software on existing GSM networks is sufficient to provide a combined capacity of up to 50,000 devices per cell on a single transceiver (Liberg et al., 2017). Many companies are working towards making EC-GSM-IoT widespread. It should be noted that the majority of current applications are in Africa. EC-GSM-IoT has the following primary benefits:

- It is possible to reuse current GSM networks like 2G, 3G, and 4G networks.
- The expected battery life is around 10 years.
- It has variable rates using GMSK/8PSK.

EC-GSM-IoT has the following main limitations:

- It has been investigated less than NB-IoT in the U.S.

**LTE-CAT-M1**

LTE-M (LTE-MTC [Machine Type Communication]), which includes eMTC (enhanced MTC), is a type of LPWAN radio technology standard developed by the 3GPP to enable a wide range of cellular devices and services (specifically, for machine-to-machine and IoT applications) (Hsieh et al., 2018). Some of the major characteristics of LTE-CAT-M1 are summarized as follows:

- LTE-CAT-M1 uses in-band LTE for deployment (3GPP, 2016).
- The downlink transmission technology includes OFDMA, 15 kHz tone spacing, Turbo code, and 16 Quadrature Amplitude Modulation (QAM). The uplink transmission technology uses SC-FDMA, 15kHz tone spacing, Turbo code, and 16 QAM (3GPP, 2016).
- The bandwidth for LTE-CAT-M1 is 1.08 MHz (3GPP, 2016).
- The peak rate for downlink and uplink is 1 Mbps (3GPP, 2016).
- In order to save energy, PSM, I-DRX, and C-DRX are applied (3GPP, 2016).
- The power class is 23 dBm (3GPP, 2016).

LTE-CAT-M1 is multiplexed over a full LTE carrier, can be deployed in any LTE spectrum, and coexists with other LTE devices. It can reuse existing LTE-base stations with a software update. It supports frequency division duplex (FDD), time division duplex (TDD), and half duplex modes. LTE-CAT-M1 support for positioning with Enhanced Cell ID (E-CID) and Difference of Arrival (oTDoA), as well as multicast with SC-PTM (3GPP, 2016).

A previous study (Kozma et al., 2019) examined the communication performance of LTE-CAT-M1 and showed that its transmission delays were at least 100 ms. It should be noted that, with background traffic, the transmission delay could significantly increase by up to several seconds. The devices failed to connect with each other with a signal level of around -115 dBm.

Some applications of LTE-CAT-M1 include vehicle tracking and pet monitoring. For example, it has been used in smart collars for pet monitoring (Wang et al., 2018). Meanwhile, another study (EElinktech, 2020) deployed devices for vehicle tracking based on LTE-CAT-M1. Voice talk is also supported, and the estimated battery life is about 5 years.

LTE-CAT-M1 has the following primary benefits:

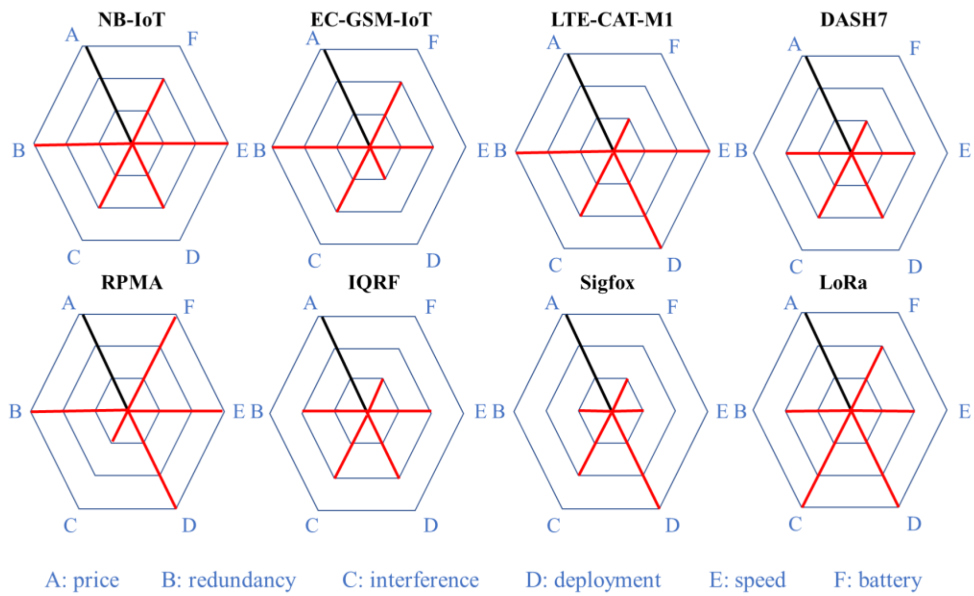
- It is possible to reuse cellular hardware based on LTE.
- It can allow over 100,000 devices per cell.
- It supports LTE features like localization, security, and authentication.
- It can coexist with 5G technology.

LTE-CAT-M1 has the following main limitations:

- Its latency increases due to packet aggregation.

## Comparison of LPWAN Technologies from Literature Review

Based on literature review, Figure 10 provides a high-level comparative evaluation of LPWAN technologies that considers the following aspects: (A) price, (B) redundancy capacity, (C) interference capacity, (D) deployment convenience, (E) speed, and (F) battery life. A longer red line indicates better performance. However, it should be noted that the relationship between the performance and the length of that line is not linear. In addition, the price is marked in grey since the research team only acquired limited information on the end node's price (summarized in Table 3). Some technologies did not provide price information on their official webpages. In addition, licensed technologies, such as NB-IoT, provided limited information on items, such as node price, but the costs for utilizing the network and maintenance fees were unclear. Thus, the research team could not quantitatively measure the costs for each technology. On the other hand, quantitative information (e.g., data rate, range) are listed in Table 4.




Note: LoRa - Long Range; IQRF - IQMESH Radio-frequency; RPMA - Random Phase Multiple Access; DASH7 - Developers' Alliance for Standards Harmonization of International Organization for Standardization 18000-7; NB-IoT - Narrowband Internet of Things; EC-GSM-IoT - Extended Coverage Global System for Mobile Communication Internet of Things; LTE-CAT-M1 - Long Term Evolution Category M1.

**Figure 10. Comparison of Different LPWAN Technologies**

**Table 3. Sample Prices of Typical LPWAN nodes**

| Technology | Node Price ($) | Reference |
|---|---|---|
| Sigfox | $20.34 | (Sigfox, 2020) |
| LoRa | $15.95 | (LoRa, 2020) |
| RPMA | NA | NA |
| DASH7 | $2-$3 | (DASH7, 2020) |
| NB-IoT | $6 | (AT&T, 2020) |
| EC-GSM-IoT | NA | NA |
| LTE-CAT-M1 | NA | NA |

Note: LoRa - Long Range; IQRF - IQMESH Radio-frequency; RPMA - Random Phase Multiple Access; DASH7 - Developers' Alliance for Standards Harmonization of International Organization for Standardization 18000-7; NB-IoT - Narrowband Internet of Things; EC-GSM-IoT - Extended Coverage Global System for Mobile Communication Internet of Things; LTE-CAT-M1 - Long Term Evolution Category M1.

The locations of some identified applications of current LPWAN technologies in the U.S. are shown in Figure 11. More detailed information on the sample applications, inside and outside of the U.S., is listed in Appendix C and Appendix D, respectively. Only a few cities in the U.S. have used LPWAN technology in the context of smart transportation and smart cities, and most of them do not provide detailed information on the implementation of the technology.

**Table 4. Primary Features of Existing Low Power Wide Area Network (LPWAN) Technologies**

| Technology | NB-IoT | EC-GSM-IoT | LTE Cat M1 | LoRa | Sigfox | IQRF | RPMA | DASH7 |
|---|---|---|---|---|---|---|---|---|
| Modulation | QPSK, OFDMA (UL), SC-FDMA (DL) | GMSK, 8PSK | QPSK | CSS | DBPSK, GFSK | GFSK | DSSS, CDMA | GFSK |
| Band | Licensed, Sub-GHz | Licensed, Sub-GHz | Licensed, Sub-GHz | Unlicensed, Sub-GHz | Unlicensed, Sub-GHz | Unlicensed, Sub-GHz | Unlicensed 2.4 GHz | Unlicensed, Sub-GHz |
| Max Range (km) | 15 | 15 | 15 | 15 | 10 | 0-5 | 15 | 0-5 |
| Peak data rate (kbps) | 250 (UL), 170 (DL) | 474, 2,048 | 375 | 27 | 1 | 20 | 80 | 9.6,55.6,166.7 |
| Security | Y | Y | Y | Y | Y | Y | Y | Y |
| Indoor | Y | Y | Y | Y | N | Y | Y | N |
| Link budget (dB) | 164 | 164 | 164 | 164 | NA | NA | 177 | NA |
| Mobility | Y | Y | Y | Y | Y | Y | Limited | NA |
| Expected Battery lifetime (Years) | 10 | 10 | 5 | 10 | 5 | 5 | 15 | 5 |

Note: LoRa - Long Range; IQRF - IQMESH Radio-frequency; RPMA - Random Phase Multiple Access; DASH7 - Developers' Alliance for Standards Harmonization of International Organization for Standardization 18000-7; NB-IoT - Narrowband Internet of Things; EC-GSM-IoT - Extended Coverage Global System for Mobile Communication Internet of Things; LTE-CAT-M1 - Long Term Evolution Category M1; QPSK - Quadrature phase shift keying; OFDMA - Orthogonal frequency-division multiple access; SC-FDMA – Single-carrier frequency-division multiple access; GMSK - Gaussian minimum shift keying; 8 PSK – 8 phase shift keying; CSS - Chirp spread spectrum; DBPSK - Differential binary phase shift keying; GFSK - Gaussian frequency-shift keying; DSSS - Direct-sequence spread spectrum; CDMA - Code divided multiple access. Actual battery lifetime depends on sensors, working environment, etc.

In terms of the licensed technology, it is obvious that NB-IoT outperforms other technologies in terms of transmission speed. It is suitable for applications in urban areas that require QoS and a high transmission data rate. It can coexist with EC-GSM-IoT/LET-CAT-M1, and is convenient for application in an urban area if VDOT subscribes to the service from operators such as AT&T.

On the other hand, if VDOT selected the unlicensed LPWAN technology, LoRa and Sigfox could outperform other candidate technologies, based on the following:

- LoRa and Sigfox operate at ultra-low bandwidth, which facilitates a long coverage range. Meanwhile, LoRa and Sigfox utilize unlicensed spectrum at sub-GHz ranges. Unlike NB-IoT, which operates on a licensed bandwidth, LoRa and Sigfox are more likely to not experience interference from widespread Wi-Fi networks, which operate in the unlicensed 2.4 GHz. It should be noted that their nodes are limited by the duty cycle for commercial usage.
- LoRa utilizes the CSS technology, which is primarily applied in military fields. CSS has proven resistant to interference and can support a long coverage range for wireless communication. LoRa adjusts the scale coefficients so that the speed rate can change, based on the applications. Other LPWAN technologies using PSK, FSK, and other modulation methods are prone to more interference, when compared with LoRa.
- The deployment of LoRa and Sigfox is more flexible, compared with other technologies. For example, NB-IoT/EC-GSM-IoT/LTE-CAT-M1 is designed to be compatible with existing networks, such as GSM and 4G. The successful deployment of such technologies relies on the license of operating vendors, and cannot provide high performance in locations such as mountainous areas.
- LoRa/Sigfox technologies have been used in the U.S. Meanwhile, LoRa technology can co-exist with other technology, such as DASH7.

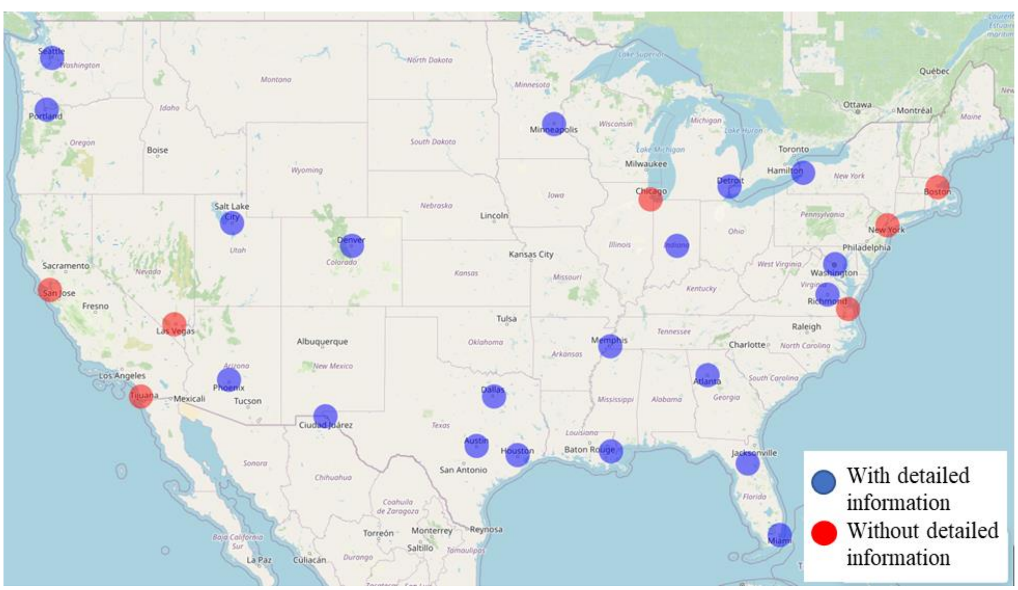
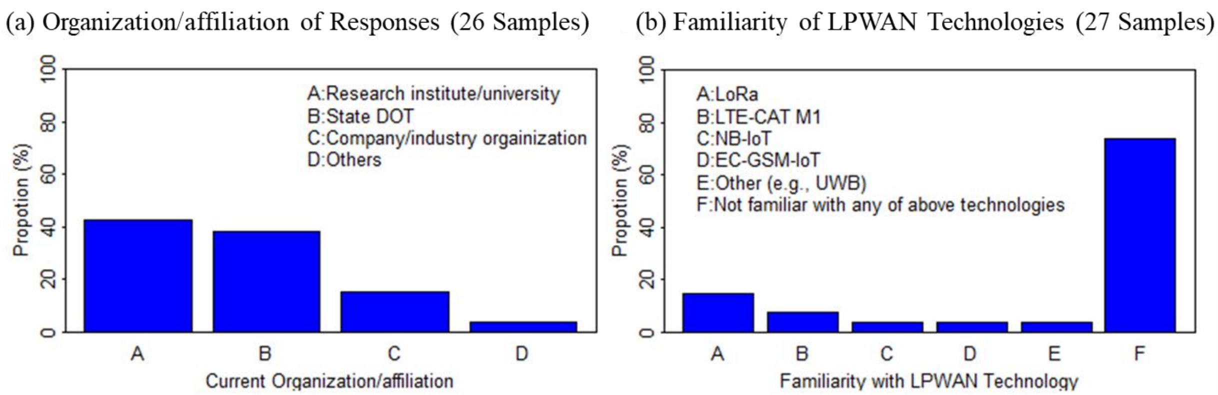



**Figure 11. Identified Low Power Wide Area Network (LPWAN) Technology Sample Applications in the U.S.**

## Summary of Survey Results

To better understand the practices of using LPWAN technology in the U.S., the research team conducted a survey in the summer of 2020. Online survey questionnaires were sent to 201 potential users from State DOTs, city agencies, etc. The major contacts were those managers/engineers from the Information Technology Departments of these organizations. A total of 27 responses were collected. The relatively low response rate should be largely attributed to the fact that the majority of them did not have much experience in using LPWAN technology in their organizations, which is evidenced by the limited responses in Figure 12(b). Below is a summary of the survey results for some key questions.




Note: DOT – department of transportation; UWB – ultra wideband; LoRa - Long Range; NB-IoT - Narrowband Internet of Things; EC-GSM-IoT - Extended Coverage Global System for Mobile Communication Internet of Things; LTE-CAT-M1 - Long Term Evolution Category M1.

**Figure 12. Summary of Responses Regarding Low Power Wide Area Network (LPWAN) Technologies**

As shown in Figure 12(a), the majority of the responses were from research institutes/universities (42.3%) and State DOTs (38.5%). However, a majority of the responses (74%) stated that they were not familiar with any LPWAN technologies. Only 14.8% responses were familiar with LoRa Technology. This matched the result from the literature review, that the LoRa technology is one of the most well known of the LPWAN technologies. However, most of the transportation agencies in the U.S. are still not familiar with LPWAN technologies.

When being asked whether the individual interviewed, or his/her organization, had ever used LPWAN technologies (e.g., LoRa, NB-IoT, Sigfox, etc.) before, only 1 out of 27 responses (3.7%) stated that they have had such experience. The one respondent did not describe his/her organization's LPWAN project but did answer some of the questions about the project. The project focused on traffic data collection (traffic count, flow, speed, etc.). LoRa technology and 0-10 environmental sensors were used at several selected sites (e.g., several parking lots). The estimated initial investment cost of the LPWAN project was $5K, or less, and the estimated annual operational cost of the LPWAN project was $5K, or less. It took 1-3 months to make the project operational. The expected data transmission speed of the project was 10 kbps-100 kbps. It was not clear whether the deployed LPWAN systems had suffered from interference from other signal sources. The typical transmission frequency in the project was at the second level, and the environmental setting was a flat urban area. The organization planned to continue/expand the use of the LPWAN technology in transportation/smart cities applications. Main issues encountered in the project included: a) Devices required frequent maintenance; and b) Battery life was short, or batteries were replaced frequently.

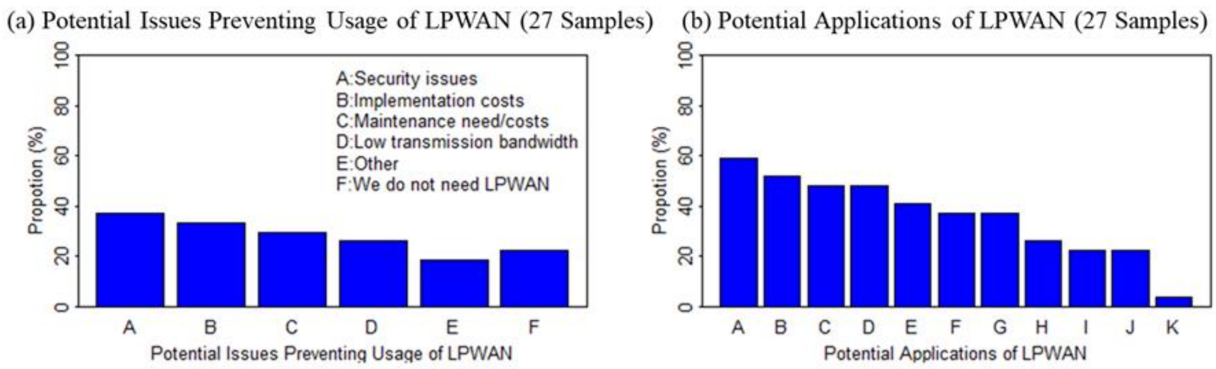
Table 5 summarizes the respondent's opinions about the developed project. Notably, the low cost of the project is very attractive, but data transmission security and reliability of the service raise more concern.

**Table 5. Satisfaction Regarding the Overall Performance of the Project**

| How satisfied are you regarding the overall performance of the project described above in terms of the following areas? | Response |
|---|---|
| Overall experience | Neutral |
| Data transmission security | Dissatisfied |
| Reliability of service | Dissatisfied |
| Data transmission latency | Satisfied |
| Cost effectiveness | Very satisfied |
| Installation effort/complexity | Satisfied |
| Data sampling frequency | Satisfied |

Although not many respondents had used LPWAN technology, the survey also asked for their opinion on such new technologies. As shown in Figure 13, the major concerns that prevented the use of LPWAN technology were security issues (n=10, 37%), followed by implementation costs (n=9, 33.3%), and maintenance need/costs (n=8, 29.6%). Only 22.2% of the responses (n=6) claimed that they do not need LPWAN. When being asked what potential applications would benefit from the usage of LPWAN, the most frequently selected option was traffic data collection (traffic count, flow, speed, etc.,) (n=16, 59.3%). This was followed by environmental sensors (wind, temperature, rain, etc.) (n=14, 51.8%) and traffic operations (work zone, variable speed limit, etc.) (n=13, 48.1%) and smart lighting (n=13, 48.1%). This result was in accordance with findings in the literature. For example, a project in Virginia used environmental sensors to monitor flooding conditions in the Hampton Road area (StormSense, 2020).

It is obvious that the application of LPWAN technology is still in its early phase. It is expected that LPWAN technology, like LoRa, will play an active role in potential applications, such as traffic/environmental data collection in the near future.




Note: (b)- A: Traffic data collection (traffic count, flow, speed, etc.); B: Environmental sensors (wind, temperature, rain, etc.); C: Traffic operations (work zone, variable speed limit, etc.); D: Smart lighting system; E: Other asset management (e.g., roadway facilities such as signs); F: Public parking system; G: Intersection signal operations/control; H: Transit operations; I: Smart metering system; J: Others; K: None of the above

**Figure 13. Respondents' Concerns and Expected Applications of LPWAN**

## Results of Lab Tests

The research team conducted the lab test in indoor and outdoor environments. The outdoor environments consisted of both rural and urban areas. Test results are discussed in detail in this section.

### Indoor Test

As shown in Figure 14, messages received/lost by a Laird sensor can be visualized in the ResIoT server platform in real time. The visualizations of sensor nodes, detailed information, and signal strength are provided in Appendix E. Even though the distance between the gateway and sensor nodes was only 5 feet and the line of sight (LOS) was perfectly guaranteed, there were still a few missed messages during the long test period.

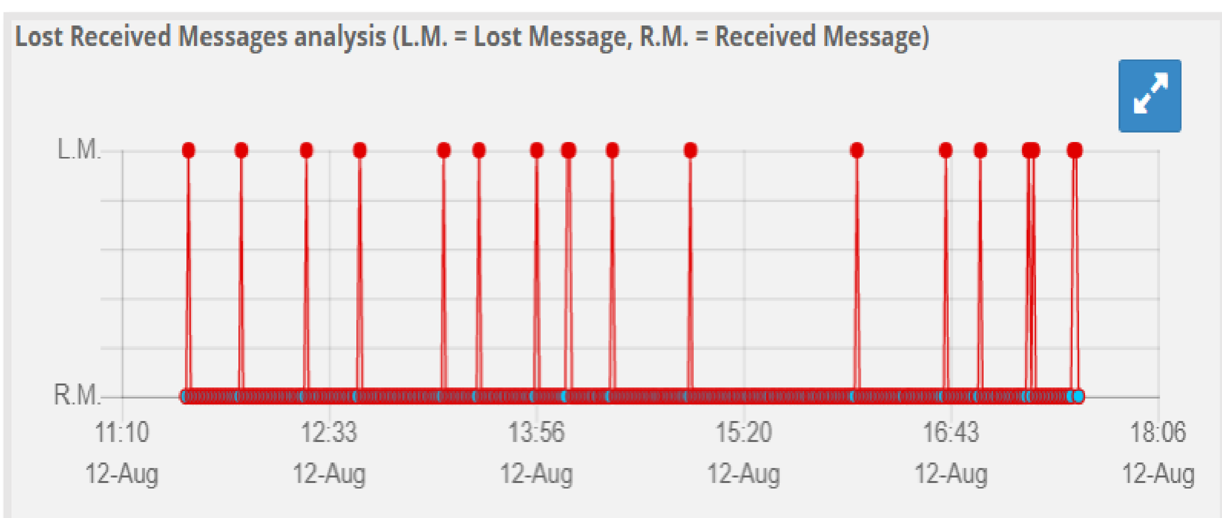



**Figure 14. Visualization of Messages Lost/Received in ResIoT**

As shown in Figure 15, the research team calculated the success ratio of the indoor test for a 1-week period. The success ratio of the Laird sensor was around 98.28%, while the message transmission interval was 1 minute. On the other hand, the success ratio of the ELT2 sensor was around 98.46%, while the message transmission interval was 2 minutes. It should be noted that the time interval for receiving the messages may be longer than the preset transmission interval (e.g., 2-minute intervals). Slight (non-constant) offsets to the planned sending schedules could happen due to the necessary transmission time (which varies by distance and environment).

(a) Success ratio of Laird (b) Success ratio of ELT2


**Figure 15. Ratio of Success of Indoor Tests**

## Outdoor Test (Rural Area in Chesapeake)

**As shown in Figure 16, five sensors were used to send messages to different sites. Red nodes indicate points that successfully received LoRa signals. Blue points are raw GPS trajectories collected while the researcher was driving between sites. The research team visited sites 1, 2, 3, 4, and 5 in a counter-clockwise way. Only a few messages were received. As shown in**

Table 6, for all of the sites, the messages could not be received by the gateway due to the increased distance, or for other unknown reasons (e.g., antenna of gateway), as the LOS in this test is relatively clear. Only Laird A and Laird B received one message, when the vehicle was moving to site 5, with a distance of nearly 1.25 miles. For those successfully sent messages, the coverage range of LoRaWAN was up to 1 mile in this test scenario.

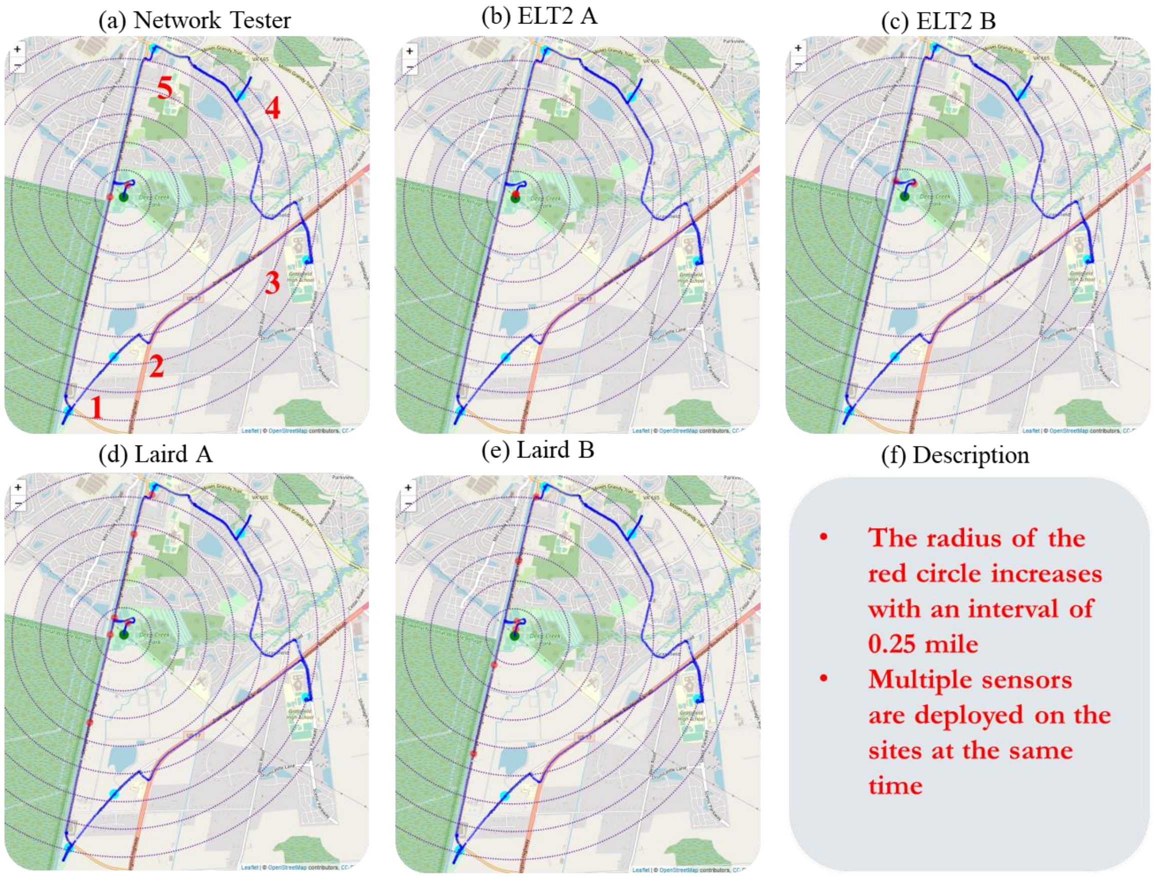



**Figure 16. Outdoor Test Results in a Rural Area (Small Red Dots: Sites with Successful Communication; Big Cyan Dots: Locations for Sensors Placed on Top of a Parked Vehicle)**

**Table 6. Received Messages out of Sent Messages for Rural Area in Chesapeake**

| Site | Distance | Network Tester | ELT2A | ELT2B | Laird A | Laird B |
|---|---|---|---|---|---|---|
| Site 1 | 2.04 miles | 0 out of 10 | 0 out of 5 | 0 out of 5 | 0 out of 10 | 0 out of 10 |
| Site 2 | 1.48 miles | 0 out of 10 | 0 out of 5 | 0 out of 5 | 0 out of 10 | 0 out of 10 |
| Site 3 | 1.78 miles | 0 out of 10 | 0 out of 5 | 0 out of 5 | 0 out of 10 | 0 out of 10 |
| Site 4 | 1.43 miles | 0 out of 10 | 0 out of 5 | 0 out of 5 | 0 out of 10 | 0 out of 10 |
| Site 5 | 1.40 miles | 0 out of 10 | 0 out of 5 | 0 out of 5 | 0 out of 10 | 0 out of 10 |

## Outdoor Test (Urban Area – 5th Floor of a Parking Garage)

As shown in Figure 17, five sensor nodes were deployed at different sites. Like the previous scenario, red nodes represent locations that successfully received LoRa signals. Blue points were raw GPS trajectories when moving between sites with a vehicle. The research team visited sites 1 to 12 in counter-clockwise order. It was obvious that the Laird sensor outperformed the ELT2 sensor, given the larger number of red nodes. More messages were received at a closer distance. When the distance between sensor nodes and the gateway was longer, few messages were received, and even no message was successfully sent to site 10. Detailed information, regarding the messages received, out of the messages sent, are listed in Table 7. In order to maintain a reasonable success ratio, the coverage range needed was around 0.8 miles. Although the increase in the mounting height of the gateway extended the coverage range, it was not as wide as reported.

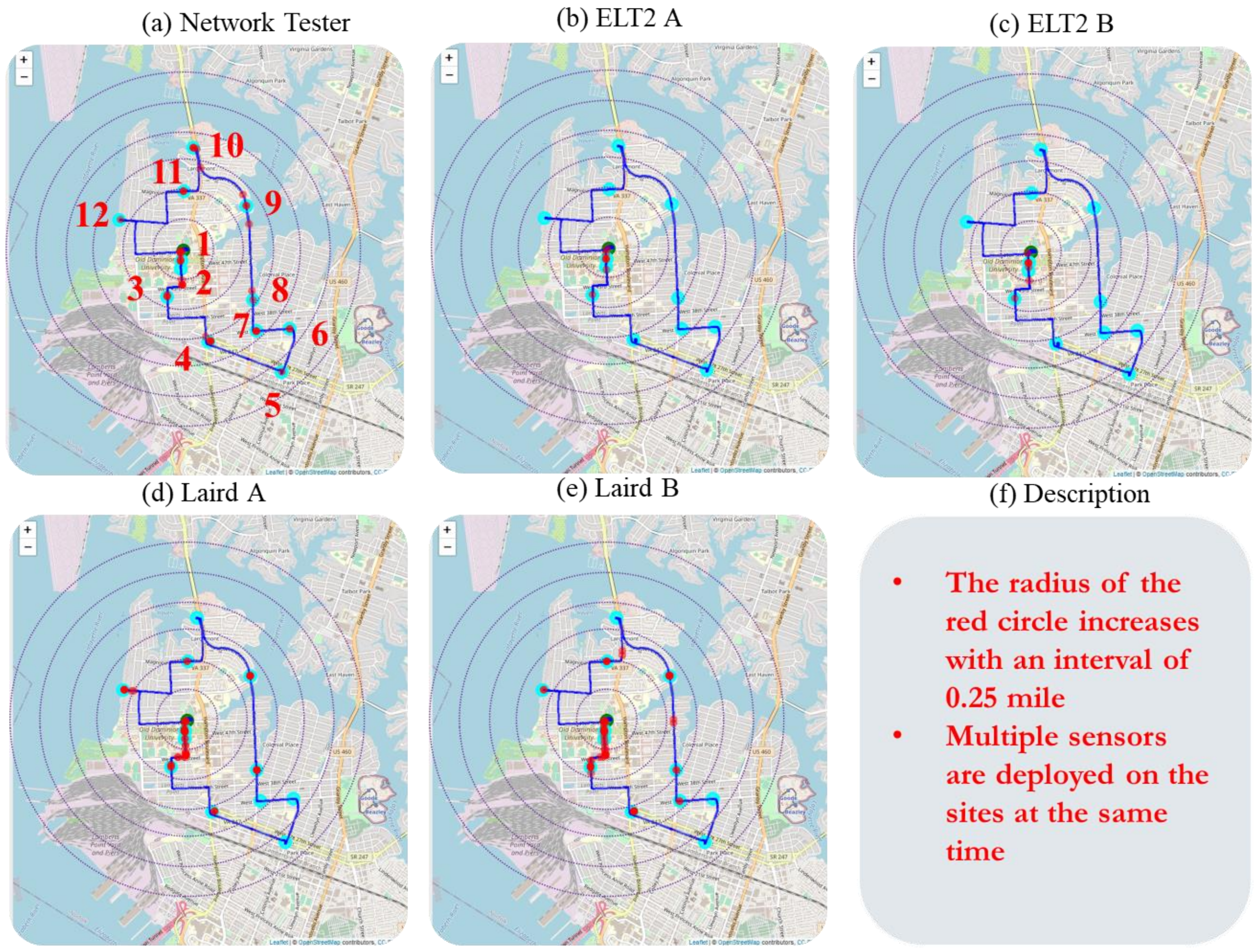



**Figure 17. Outdoor Test Results (Urban Area-5th Floor of a Parking Garage; Small Red Dots: Sites with Successful Communication; Big Cyan Dots: Locations for Sensors Placed on Top of a Parked Vehicle)**

**Table 7. Received Messages out of Sent Messages for Urban Area in a Parking Garage**

| Site | Distance | Network Tester | ELT2A | ELT2B | Laird A | Laird B |
|---|---|---|---|---|---|---|
| Site 1 | 0.16 mile | 10 out of 10 | 5 out of 5 | 5 out of 5 | 10 out of 10 | 10 out of 10 |
| Site 2 | 0.09 mile | 10 out of 10 | 5 out of 5 | 5 out of 5 | 10 out of 10 | 10 out of 10 |
| Site 3 | 0.42 mile | 10 out of 10 | 3 out of 5 | 3 out of 5 | 10 out of 10 | 10 out of 10 |
| Site 4 | 0.8 mile | 8 out of 10 | 0 out of 5 | 0 out of 5 | 8 out of 10 | 8 out of 10 |
| Site 5 | 1.33 miles | 6 out of 10 | 0 out of 5 | 0 out of 5 | 0 out of 10 | 0 out of 10 |
| Site 6 | 1.12 miles | 5 out of 10 | 0 out of 5 | 0 out of 5 | 0 out of 10 | 0 out of 10 |
| Site 7 | 0.92 mile | 5 out of 10 | 0 out of 5 | 0 out of 5 | 0 out of 10 | 3 out of 10 |
| Site 8 | 0.73 mile | 7 out of 10 | 0 out of 5 | 0 out of 5 | 4 out of 10 | 4 out of 10 |
| Site 9 | 0.66 mile | 7 out of 10 | 0 out of 5 | 0 out of 5 | 4 out of 10 | 4 out of 10 |
| Site 10 | 0.88 mile | 8 out of 10 | 0 out of 5 | 0 out of 5 | 0 out of 10 | 0 out of 10 |
| Site 11 | 0.5 mile | 9 out of 10 | 0 out of 5 | 0 out of 5 | 9 out of 10 | 8 out of 10 |
| Site 12 | 0.61 mile | 8 out of 10 | 0 out of 5 | 0 out of 5 | 8 out of 10 | 8 out of 10 |

## Outdoor Test (Urban Area – Waterfront Area on ODU Campus)

As shown in Figure 18, the research team also did an outdoor test similar to the previous one. Instead of placing the gateway on the 5th floor of a parking garage, the gateway was mounted to a customized 16-ft mounting pole. This test helped the team to verify that the mounting height will affect the connectivity between the gateway and sensor nodes. Five sensors were used to send messages to different sites. As before, red nodes in Figure 18 show the locations to which messages were successfully sent. Blue points were raw GPS trajectories of the driven vehicle. The research team visited 11 sites in total. The Laird sensor was found to outperform the ELT2 sensor, as evidenced by the larger number of red nodes. No signals were received when the distance between the sensor nodes and the gateway was 1 mile or more. Compared with the outdoor test on top of a parking garage, the mounting height of the gateway was much lower, which resulted in an unstable connectivity and reduced coverage of LoRaWAN. Detailed information regarding the messages received out of messages sent are listed in Table 8. In short, the coverage range can reach around 0.7 miles in urban areas, with a stable connection for some tested devices. From the test results, we can also see that locations with the same distance may not have the same connectivity due to the restrictions of LOS. For example, from the gateway to the right of the map, the area is the main campus of ODU, that has many tall buildings, which could block the line of sight between devices. In contrast, the area in the south portion of the map is a residential area that does not have many buildings with three or more floors. This helped maintain the LOS and resulted in better communication performance.

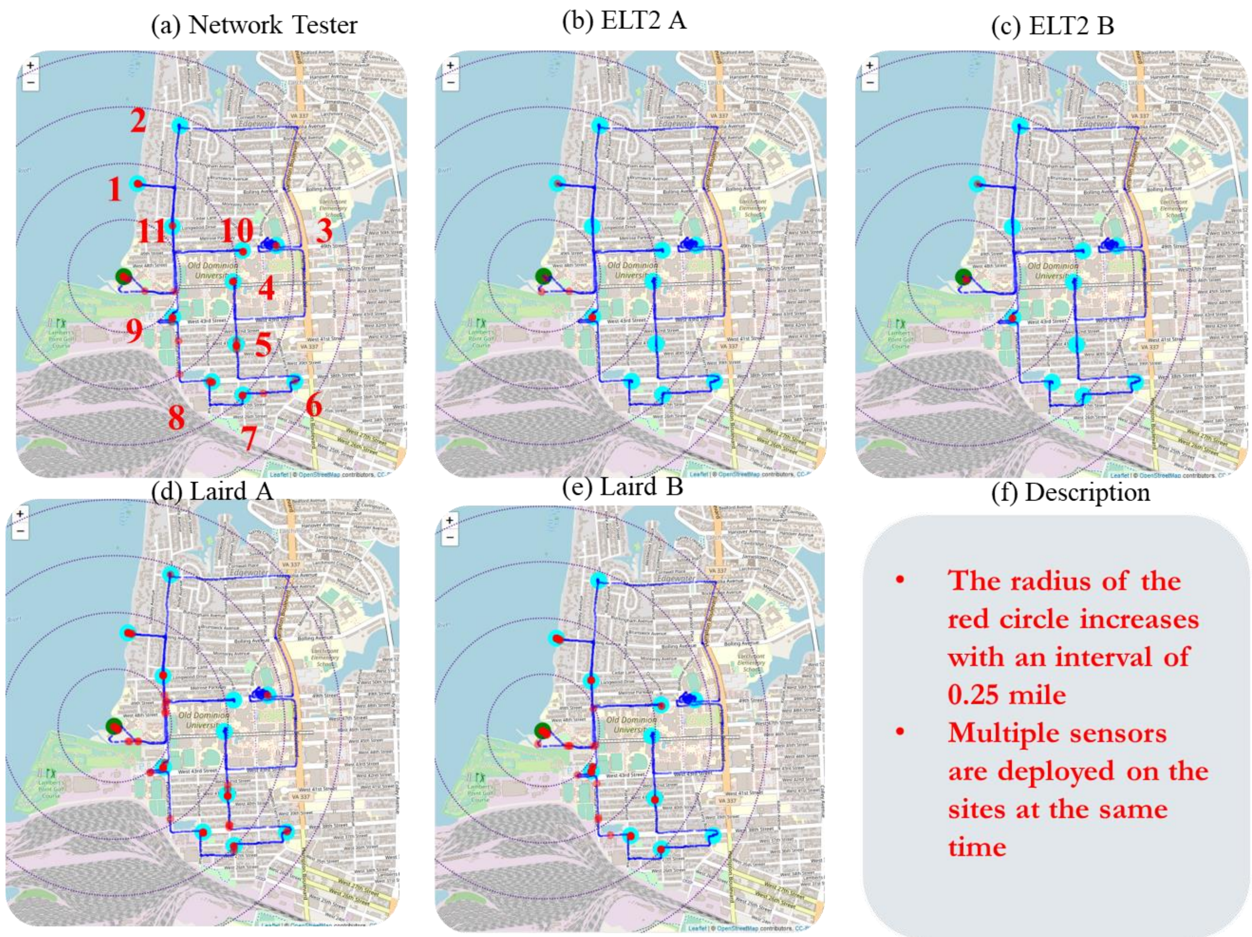



**Figure 18. Outdoor Test (Urban Area-Waterfront Area at Old Dominion University; Small Red Dots: Sites with Successful Communication; Big Cyan Dots: Locations for Sensors Placed on Top of a Parked Vehicle)**

**Table 8. Messages Received of Messages Sent in Urban Area of the Waterfront Area at Old Dominion University (ODU)**

| Site | Distance | Network Tester | ELT2A | ELT2B | Laird A | Laird B |
|---|---|---|---|---|---|---|
| Site 1 | 0.4 mile | 10 out of 10 | 1 out of 5 | 1 out of 5 | 10 out of 10 | 10 out of 10 |
| Site 2 | 0.69 mile | 0 out of 10 | 0 out of 5 | 0 out of 5 | 4 out of 10 | 0 out of 10 |
| Site 3 | 0.67 mile | 5 out of 10 | 0 out of 5 | 0 out of 5 | 6 out of 10 | 0 out of 10 |
| Site 4 | 0.47 mile | 8 out of 10 | 0 out of 5 | 0 out of 5 | 0 out of 10 | 0 out of 10 |
| Site 5 | 0.56 mile | 7 out of 10 | 0 out of 5 | 0 out of 5 | 9 out of 10 | 7 out of 10 |
| Site 6 | 0.86 mile | 2 out of 10 | 0 out of 5 | 0 out of 5 | 7 out of 10 | 0 out of 10 |
| Site 7 | 0.72 mile | 2 out of 10 | 0 out of 5 | 0 out of 5 | 8 out of 10 | 6 out of 10 |
| Site 8 | 0.59 mile | 8 out of 10 | 0 out of 5 | 0 out of 5 | 10 out of 10 | 8 out of 10 |
| Site 9 | 0.27 mile | 10 out of 10 | 2 out of 5 | 2 out of 5 | 10 out of 10 | 10 out of 10 |
| Site 10 | 0.52 mile | 9 out of 10 | 0 out of 5 | 0 out of 5 | 0 out of 10 | 2 out of 10 |
| Site 11 | 0.3 mile | 9 out of 10 | 0 out of 5 | 0 out of 5 | 9 out of 10 | 10 out of 10 |

Based on the lab test, the following points listed below can be summarized:

- The coverage range of LoRa technology, based on the tested MultiTech gateway, is around 1 mile.
- Area type, i.e., urban vs. rural, affects the signal coverage range. For example, the potential interference from other signal sources and high/tall buildings in urban areas are likely to block signal propagation and reduce the signal coverage range.
- Different types of LoRa sensors can coexist with each other.
- Not only distance, but also the surrounding environment affects the performance of LoRaWAN since obstacles can block LOS and impede signal propagation and, hence, degrade data transmission.
- Mounting height of the gateway has an impact on the coverage range of LPWAN, while the relationship between height and performance is nonlinear.

## Field Test Plan

A field test plan was developed to explore issues identified based on the results of literature review, survey, and lab tests. It aimed to guide future field tests to methodically evaluate LPWAN technologies for potential transportation applications.

### Framework of Field Test Plan

The key issues shown in Figure 19 were expected to be addressed in a potential Phase 2. The following variables would be explored in tests: the number of sensor nodes, a long-term performance test, device differences, distances between sensor nodes and gateways, mounting heights of devices, feasibility of downlink data transmission, data (e.g., image) size, transmission rate, and transmission frequency. It is expected that the relationships between the performance indicators (e.g., success ratio) and explored variables will be uncovered through the field tests for a potential Phase 2.

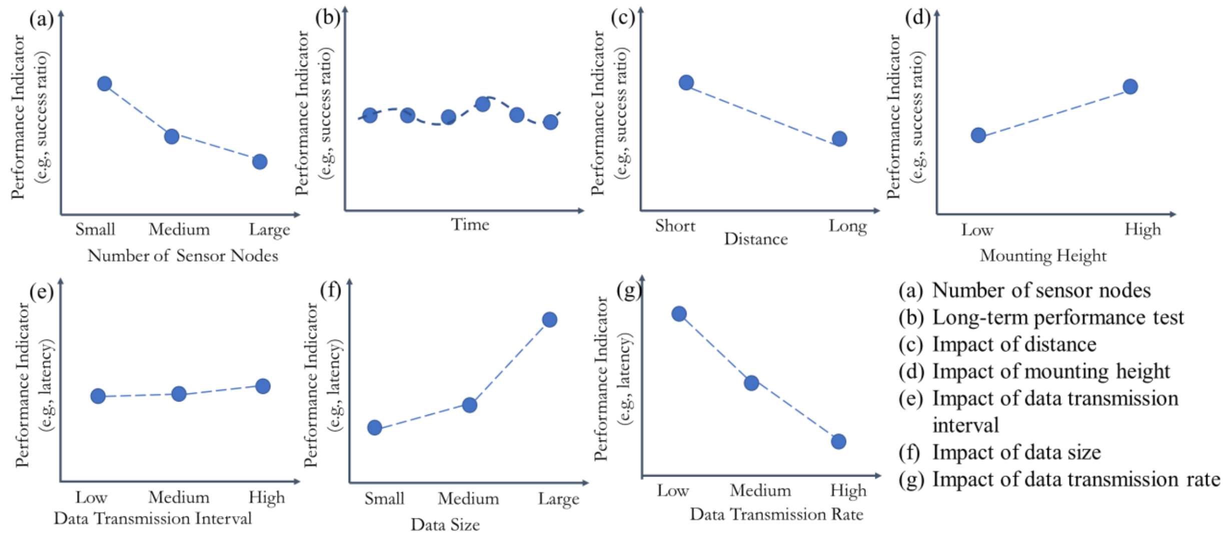



**Figure 19. Key Issues That Need to Be Examined in Field Tests**

Figure 20 shows the framework of the proposed field test plan, building on the target issues to be explored. First, the data transmission needs and deployment environment will be determined. Then, different installation configurations will be created, based on the factors identified above. For each configuration, detailed performance data will be collected and evaluated.

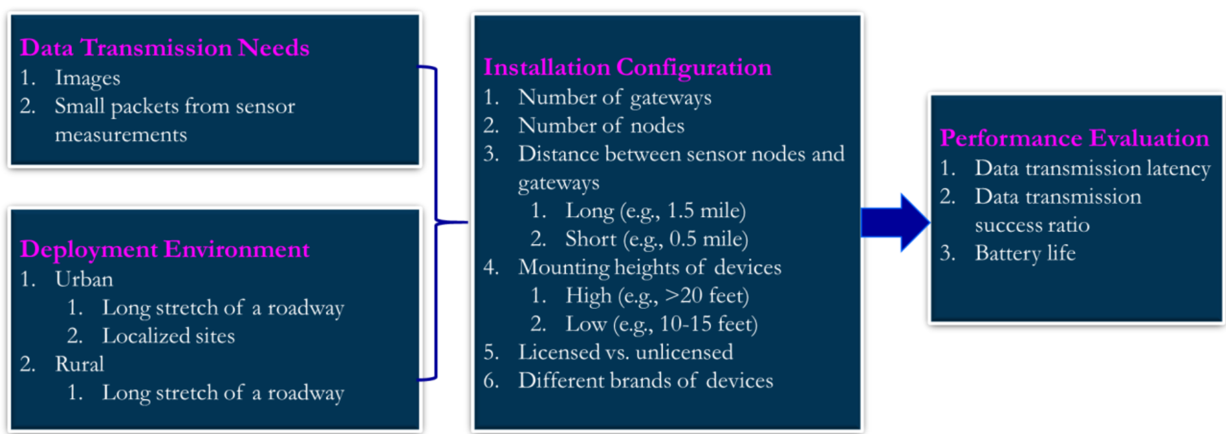



**Figure 20. Framework of Field Test Plan**

Since it is impractical to address all possible combinations of the options shown in the framework, several reasonable potential experimental scenarios are proposed, as listed in Table 9. These scenarios will cover both large packets (e.g., images) and small packets from sensor measurements, and will be tested both in urban and rural areas.

## Key Factors and Performance Measures

The performance of a given LPWAN technology can be measured in terms of various metrics, including data transmission latency and success ratio. These performance metrics can vary significantly depending on the distance between the sensor node and the gateway, the mounting height of the gateway and sensor, and the data transmission rate. In addition, various field tests can be designed by considering different combinations of these factors, as illustrated in Figure 21.

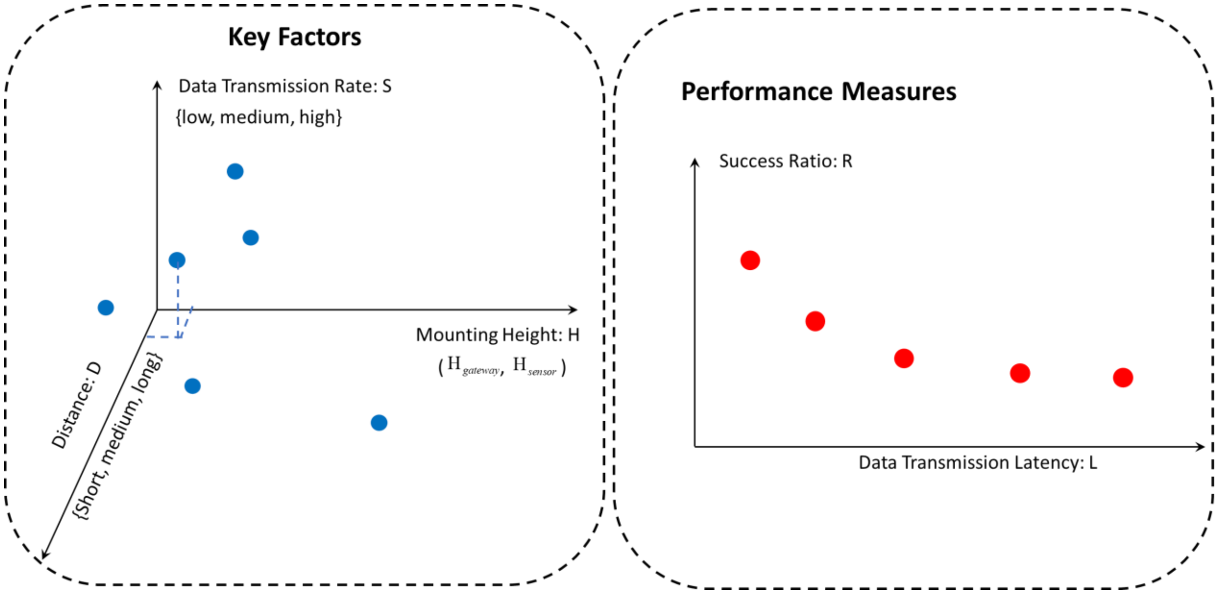



**Figure 21. Key Factors and Performance Measures**

The following sections provide detailed descriptions of the key factors and the associated performance measures to be tested.

- **Distance between gateways and sensors**: Distance $D$ is calculated, based on latitude and longitude of gateways and sensor nodes, with the Haversine formula. Three different levels of range (*short*, *medium*, and *long*) will be considered. For example, 0.25 miles can be considered as short, while 2 miles can be considered as long. The specific values of the range will be determined, based on the selected devices, as their technical parameters may vary.

- **Mounting heights of gateways and sensors**: $H_{gateway}$ denotes the height of the gateway and $H_{sensor}$ is the height of the sensor node. Different combinations of $H_{gateway}$ and $H_{sensor}$ will be explored. It is expected that the combination of a high $H_{gateway}$ and a high $H_{sensor}$ can meet the line of sight (LOS) requirement with the highest probability and, therefore, is more likely to lead to better LPWAN transmission performance. The height can be specified based on the available mounting facilities at the test sites.

- **Data transmission rate**: Different LPWAN technologies have different standards for data transmission rates. For example, NB-IoT can support high volume data transmission, such as images, whereas LoRa and Sigfox focus on transmission with a lower data rate. Different data transmission rates will be tested, depending on the types of LPWAN technologies to be evaluated. Based on the literature review, online survey, and lab tests, the researchers recommend the unlicensed technology LoRa for small packet transmission, and the licensed technology NB-IoT for large size data transmission (e.g., image).

- **The number of sensor nodes and relative sensor density:** The number of sensor nodes and relative sensor density can affect the wireless packet collision rate and the LPWAN's performance. Different applications may have different sensor density needs, and different numbers of sensor nodes should be explored. Meanwhile, the capacity of the gateway will be evaluated by adding the number of sensor nodes and observing the success ratio.

With a combination of the above key factors, the field tests need to evaluate the following key performance measures:

- **Data transmission latency**: Data transmission latency $L$ will be determined based on the difference between $t_{received}$ and $t_{sent}$. $t_{received}$ is the time stamp when a LPWAN signal is received by the gateway, and $t_{sent}$ is the time stamp when a LPWAN signal is sent by the sensor node. It should be noted that the time stamp information is usually not enclosed in the information transmitted by sensor nodes. Sensor nodes use their local time stamps to count and periodically send messages. The time synchronization between sensor nodes and gateways is ignored in LPWAN, with the benefit of a low transmission cost (except for NB-IoT that can support real-time and high-volume data transmission). Thus, the data transmission latency during a field test based on a predefined sending schedule $t_{sent}$ will be evaluated. It should be noted that there might exist a slight difference between the predefined $t_{sent}$ and the actual $t_{sent}$. Thus, the data transmission latency can be evaluated under different conditions. For example, LoRa technology supports different transmission speeds with multiple spreading factors (SFs). Thus, different SFs and their impacts on the transmission latency should be examined.

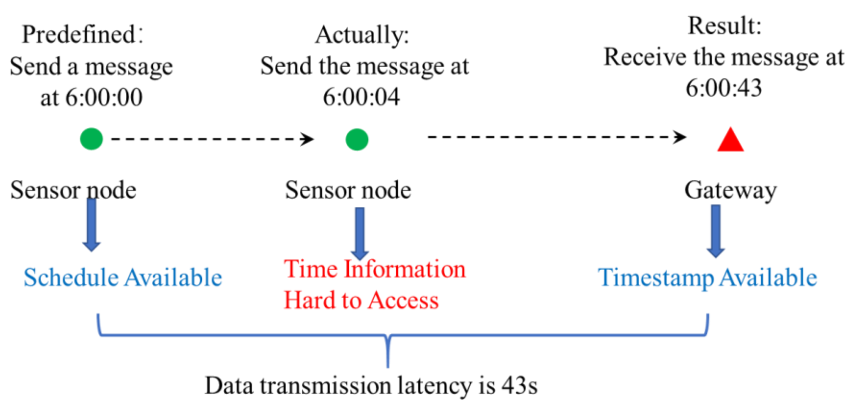



**Figure 22. Determination of the Latency of Data Transmission**

- **Data transmission success ratio**: The data transmission success ratio $R$ is defined as the ratio of successfully received messages $n_{success}$ to the number of sent messages $n_{sent}$ during a test period. For example, a sensor node is scheduled to send a message per minute. Assuming the gateway receives 54 messages in 1 hour. Then, the success ratio $R$

will be 54/60=90%. Depending on the needs, a similar indicator can be calculated based on other temporal aggregations, such as daily, weekly, and monthly intervals.

Other than the above performance measurements, a few other practical test objectives need to be addressed:

- **Test the cybersecurity aspects of LPWAN**. The jamming attack in a LPWAN network will be explored. Multiple sensor nodes will be added along with target sensors in the LPWAN network and send messages with their highest frequency to jam the communication channels. The data transmission latency and success ratio of the target sensor nodes will be evaluated. Opportunities to explore other types of cyber-attacks may be explored depending on the configuration of the deployed application.

- **Test image transmission feasibility of LPWAN**. The feasibility of transmitting images in LPWAN will be examined. As to the high-definition images captured by cameras, NB-IoT technology will be considered due to data transmission rate requirements. Different data transmission rates and sizes of images/videos will be explored. On the other hand, compressed images will be transmitted using LoRa/Sigfox technology, given a lower data transmission rate. Different data transmission intervals will also be explored. For example, traffic signal lights might need a short transmission interval (e.g., every 10 seconds), while the long data transmission interval (e.g., every 5 minutes) would be sufficient in other scenarios, such as for parking lots. As shown in Figure 23, the test will consider off-the-shelf devices first. If not available, customized camera sensor nodes will be developed using tools such as Arduino to support the test. The transmission latency, transmission time interval, and success ratio will be measured to evaluate the feasibility.

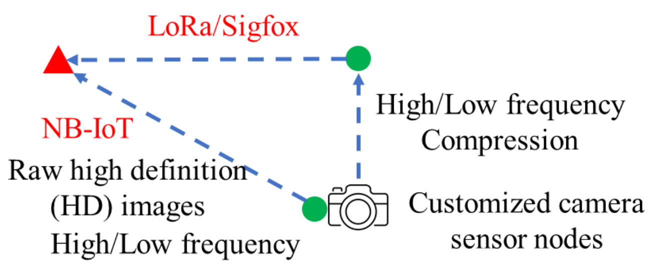



**Figure 23. Testing Feasibility of Image Transmission with LPWAN**

- **Test battery consumption**. The majority of gateways require a power supply, while sensor nodes utilize portable batteries. Some batteries are chargeable, while some need to be replaced after their claimed life spans. It should be noted that the claimed life span is usually long (e.g., 3-5 years), with a long data transmission interval (e.g., once per hour). For example, the parking senor node Moko Smart Parking Sensor LW005-PS claims that it can support 5 years, given a data report 25 times per day (SMART, 2020). However, it is impractical to wait for 5 years to validate its life span. It should be noted that, only a few sensors have smartphone apps which can reveal a detailed remaining battery level. Thus, in order to test the life span of a battery in a short period, it is necessary to measure the original power and remaining power of the battery before and after a given time period of deployment (e.g., one month), using devices (e.g., multimeters) to calculate its estimated life span according to consumption. As illustrated in Figure 24, the estimated life span would be 2.5 months, if the energy consumption is around 40%, after a month.

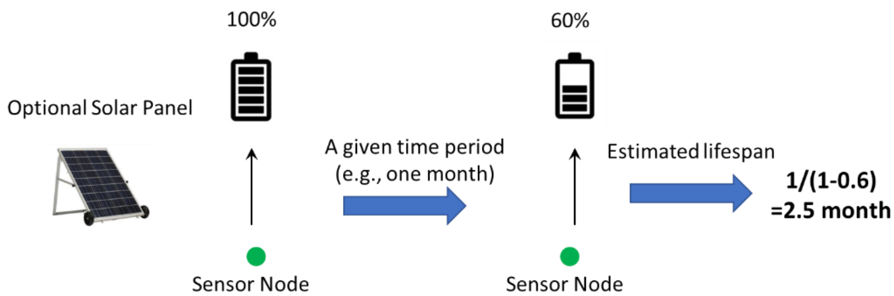



**Figure 24. Test the Battery Consumption**

**Comparison between different vendor products**. Multiple sets of gateways, antennas, and sensor nodes from different vendors will be examined to test their performance and whether they can co-exist with each other. For example, a directional antenna (either external or interval) can significantly increase the deployment cost (especially precisely aiming the right direction for a high-gain directional antenna), compared to an omnidirectional antenna. Different sensor nodes and gateways may have different requirements for antenna types. The discussion with VDOT on how many vendor products should be tested is necessary. Based on the previous lab tests at ODU, two types of LoRa sensor nodes (i.e., Laird and ELT2) can co-exist with each other, whereas one outperformed the other in terms of coverage range and success ratio. Given the availability of other vendors' products, additional lab tests with a small set of devices before purchasing more devices at one time are recommended. Once the purchased sample devices have been tested for their functionalities by the lab test, additional units for field tests can be acquired.

- **Test downlink capability of LPWAN**. Gateways collect data by an uplink and send commands to sensor nodes via the downlink. For example, when a gateway collects enough information from a work zone, it can send commands (e.g., adjusted speed limit) to sensor nodes to adjust dynamic message signs. Since existing traffic control devices or data collection systems may not offer access to LPWAN sensors, it will be difficult to directly test the downlink capability. In order to validate the downlink communication capability, it is necessary to purchase a small set of development boards/kits and perform the lab test, as illustrated in Figure 25. Several sensor nodes will collect information and send it to the gateway. Upon receiving the messages from the sensor nodes, the gateway will send orders to the downlink to adjust the status of the liquid crystal display (LCD). For example, if the average temperature collected by sensor nodes exceeds a threshold, the LCD will display an alert message.

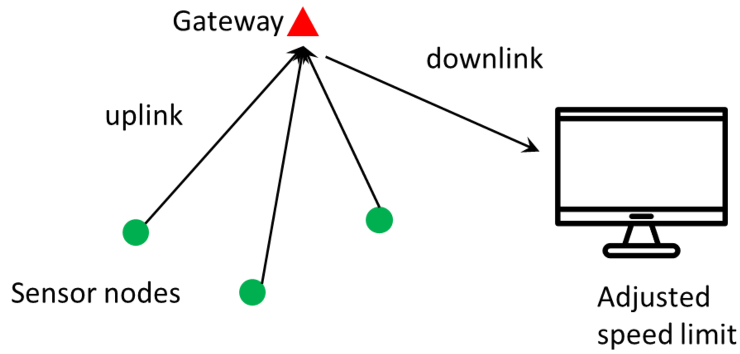



**Figure 25. Downlink Demonstration in Lab Test**

Given the aforementioned key factors and performance measures, the potential application scenarios for a localized area include sites like parking lots, rest areas, and/or intersections, as shown in Figure 26. This can be matched with scenario numbers 1-9 in Table 9. For those licensed LPWAN technologies (e.g., NB-IoT), the maximum distances between gateways and sensor nodes are left blank since they do not need the gateway to provide connectivity. The telecommunication infrastructure (e.g., 5G network) will provide such connectivity, and it should be noted that, in those rural areas where no signals can be received (e.g., in mountainous areas), such test scenarios might not be applicable. For scenarios 3, 4, 7, and 8, it would be reasonable to test different distances between sensor nodes and gateways, and different mounting heights of devices. As for scenarios 10 and 11, different numbers of sensor nodes will be deployed to perform a stress test. The goal is to find whether the LPWAN can support a large number of sensor nodes with a relatively high data transmission performance. For example, multiple sensor nodes can be deployed in a parking lot (e.g., park and ride sites). The coverage radius of a parking lot is expected to be smaller than 1 mile and, thus, one LPWAN gateway should be enough to cover a parking lot. The gateway can be installed in the central area of the parking lot to ensure that all sensor nodes in different directions can receive a signal with a relatively higher signal strength value. Sensor nodes (e.g., Covert Scouting Cameras LORA LB-V3) will periodically take images and send those images to the gateway. In addition, sensor nodes (e.g., ELT2 and Laird), which collect weather information such as temperature and humidity, can also be installed. The aforementioned performance measures will be calculated to verify the impact of different numbers of sensor nodes.

As shown in Figure 27, the potential application scenarios for a long stretch of roadway include freeway/highway road segments, work zones, and/or rural highway segments. Since the distance between the gateway and sensor nodes is expected to be long, it is more reasonable to transmit small data packets. Scenarios 12-16 consider several combinations of licensed/unlicensed technologies, mounting heights, and maximum distances between nodes and gateways.

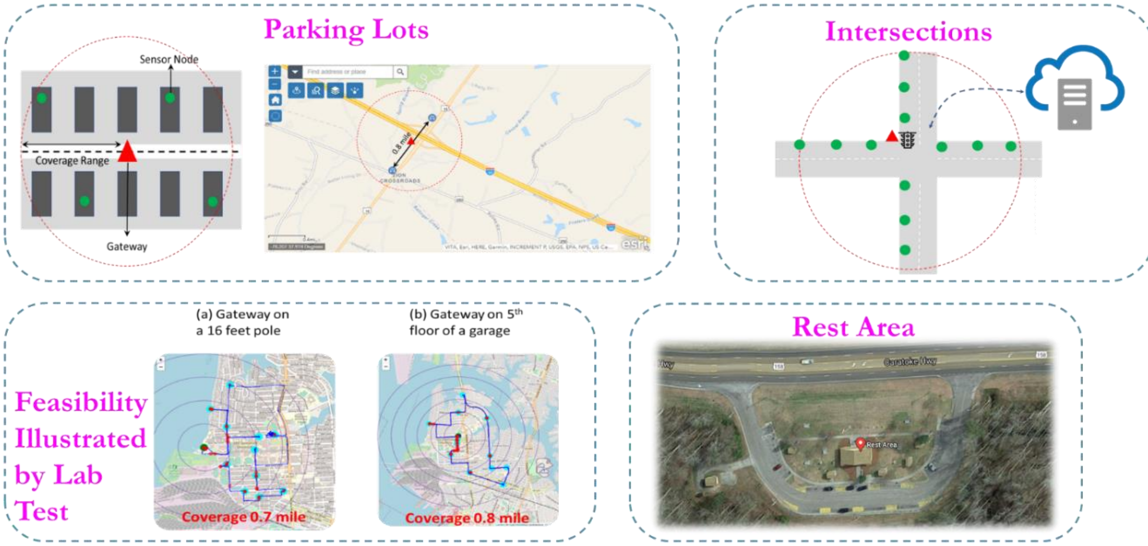



**Figure 26. Potential Test Environments - Localized Area**

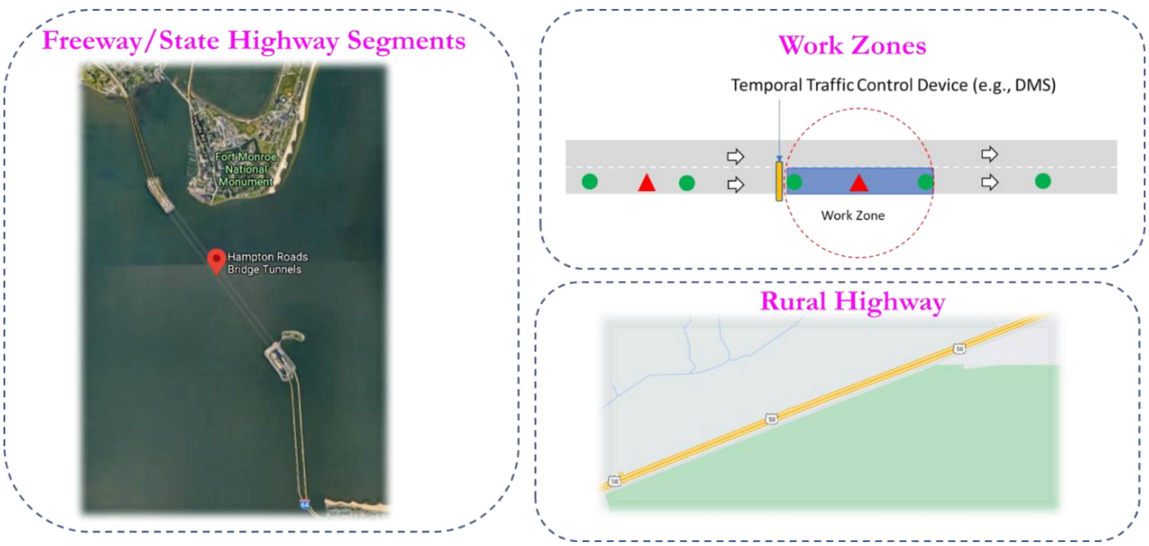



**Figure 27. Potential Test Environments – A Long Stretch of a Roadway**

**Table 9. Potential Test Scenarios**

| Scenario Number | Data Type | Urban vs Rural | Long Stretch vs Localized | No. of Gateways | No. of Nodes | Max Distance between Nodes & Gateways | Mounting Heights of Devices | Licensed vs Unlicensed | Notes |
|---|---|---|---|---|---|---|---|---|---|
| **1** | Images | Urban | Localized | 1 | 2-4 | - | High | Licensed | NB-IoT doesn't need gateways to provide connectivity. |
| **2** | Images | Urban | Localized | 1 | 2-4 | - | Low | Licensed | NB-IoT doesn't need gateways to provide connectivity. |
| **3** | Images | Urban | Localized | 1 | 2-4 | Short | High | Unlicensed | Line of sight may be an issue even when the range is short; so both low and high mountings are considered. |
| **4** | Images | Urban | Localized | 1 | 2-4 | Short | Low | Unlicensed | Line of sight may be an issue even when the range is short; so both low and high mountings are considered. |
| **5** | Images | Rural | Localized | 1 | 2-4 | - | High | Licensed | NB-IoT doesn't need gateways to provide connectivity. |
| **6** | Images | Rural | Localized | 1 | 2-4 | - | Low | Licensed | NB-IoT doesn't need gateways to provide connectivity. |
| **7** | Images | Rural | Localized | 1 | 2-4 | Long | High | Unlicensed | Naturally, for long range, we should consider a higher mounting instead of a lower one. |
| **8** | Images | Rural | Localized | 1 | 2-4 | Short | High | Unlicensed | |
| **9** | Images | Rural | Localized | 1 | 2-4 | Short | Low | Unlicensed | |
| **10** | Small packets | Urban | Localized | 1 | 5/10/20 | Short | High | Unlicensed | Stress test with a high mounting |
| **11** | Small packets | Urban | Localized | 1 | 5/10/20 | Short | Low | Unlicensed | Stress test with a low mounting |
| **12** | Small packets | Urban | Long stretch | 2 | <10 | Long | High | Unlicensed | Lab test already showed that a low mounting cannot cover a long distance, so there is no need to test a low mounting. |
| **13** | Small packets | Rural | Long stretch | 2 | <10 | - | High | Licensed | NB-IoT doesn't need gateways to provide connectivity. |
| **14** | Small packets | Rural | Long stretch | 2 | <10 | - | Low | Licensed | NB-IoT doesn't need gateways to provide connectivity. |
| **15** | Small packets | Rural | Long stretch | 2 | <10 | Long | High | Unlicensed | |
| **16** | Small packets | Rural | Long stretch | 2 | <10 | Long | Low | Unlicensed | |

## Potential Devices for Field Test

Based on our lab tests, a survey, and literature review in this Phase, three major technologies are recommended for further testing: Sigfox, LoRa, and NB-IoT. Some of the available gateways and sensor nodes were investigated and some key information that was obtained is listed in Table 10 and Table 11, respectively. It should be noted that this was only a preliminary exploration, and the market can change in several aspects (e.g., new products enter the market; existing prices for devices might change, etc.). The actual devices to be tested (e.g., sensor nodes, gateways, and antennas) will need to be determined based on future discussions with VDOT. It is possible that changes in the technology will require an update of these lists as the next phase of this research begins.

**Table 10. List of Possible Off-the-Shelf Gateways/Solutions for Field Test**

| **Name** | **Price** | **Technology** | **Max Coverage (based on lab test)** | **Max Coverage range (specified)** | **Transmission speed** |
|---|---|---|---|---|---|
| MultiTech IP Base Station 266 | Around $1,300 | LoRa | ~2 mile (Based on deployment on 5th floor of a building) | 10 miles | 980 bps – 5470 bps |
| USR-LG220 | Around $300 | LoRa | - | 10 miles | 980 bps – 5470 bps |
| DLOS8 Outdoor LoRaWAN Gateway | Call for sale | LoRa | - | 10 miles | 980 bps - 5470 bps |
| Access Station Micro SMBS-T4 | Around $500 | Sigfox | - | 5 miles | 600 bps |
| AT&T Provided Solution | 500 kb for $1/month | NB-IoT | - | 10 miles | 250 kbps |
| Verizon with IoT solution | Call for sale | NB-IoT | - | 10 miles | 250 kbps |
| Dragino LoRa IoT Development Kit | Around $200 | LoRa | - | 10 miles | 980 bps – 5470 bps |
| ZIYUN FiPy-Five Network IoT Development Board | Around $100 | LoRa, Sigfox, NB-IoT | - | 10 miles | 980 bps – 5470 bps, 250 kbps, 600 bps |

Note: the lab test was performed at the Norfolk residential neighborhood and a rural area in Chesapeake.

**Table 11. List of Potential Off-the-Shelf Sensor Nodes for Field Test**

| Name | Purpose | Price | Technology | Transmission Interval | Battery |
|---|---|---|---|---|---|
| Larid | Weather condition monitoring (temperature) | ~ $150 | LoRa | Minimum 1 minute | 2 × AA – replaceable battery |
| ELT2 | Weather condition monitoring (temperature, humidity) | ~ $150 | LoRa | Minimum 2 minute | Replaceable sensor battery ER14505 |
| Moko Smart Parking Sensor LW005-PS | Parking data | Contact Sale | LoRa | 5 years (based on data report of 25 times per day) | NA |
| AWARE Flood Sensor | Flooding detection | Contact Sale | Verizon/AT&T LTE-M & International NB-IoT | NA | seven days with zero solar charge |
| Wireless No-Probe Temp Sensor | Weather condition monitoring (temperature) | ~ $60 | Sigfox | NA | 20 Weeks |
| Adeunis RF Network Tester | Signal strength | ~ $400 | LoRa | Minimum 15 seconds | Chargeable |
| LSN50 | Weather condition monitoring (temperature) | Contact Sale | LoRa | NA | Li/SOCl2 battery |
| SimpliSafe Motion Sensor | Motion detection | About $50 | Not specified | NA | NA |
| Dorman 505-5408 Speed and Tachometer Sensor | Speed detection | $50 | Not specified | NA | NA |
| Covert Scouting Cameras LORA LB-V3 | Camera | $800 | LoRa | NA | 12 AA Batteries |
| Half wave 915 MHz antenna | Antenna | $5 | LoRa | NA | NA |
| ROSA-900-SNF: IoT Antenna for LoRa | Antenna | $54 | LoRa | NA | NA |

Note: This list is subject to change based on a discussion with Virginia Department of Transportation (VDOT).

It should be noted that the prices of some gateways and sensor nodes are not displayed on their official websites and the vendors require that their sales departments be contacted to obtain detailed information. In addition, some listed sensors need external access to LPWAN sensor nodes. Also, some development kits (e.g., Raspberry Pi/Arduino sets) are also necessary, in case specific tests require such devices (e.g., the demonstration of downlink communication). More detailed information for the acronyms and glossary is listed in Appendix F and G.

### Field Test Implementation

With the approval of the TRP, the following key procedures should be implemented to start the field test:

- **Select suitable sites for test**. For each field test, it is necessary to identify candidate tests within an appropriate time window (e.g., 1 month). Several high-level selection criteria are as follows:
    - **Terrain**. In a flat area, gateways can be deployed in the center of the application area. Given sufficient height for the gateway, LOS requirements can be achieved. However, in terms of a mountainous area, such as Charlottesville, gateways may be installed at higher positions (e.g., top of a hill).

    - **Urban/rural area**. It is expected that LPWAN in an urban area will be more prone to interferences and it will be harder to guarantee the perfect LOS requirements between sensor nodes and gateways. For example, tall buildings in denser areas will affect the coverage range of gateways in specific directions. Although field tests will be mainly conducted in rural areas, the specific sites will still need to be examined and determined based on likely VDOT operational domains.

- **Select a suitable battery charging plan**. It should be noted that sensor nodes usually use replaceable batteries that are supposed to provide a relatively long battery life (e.g., 2-3 years). However, if the test scenario requires that data be transmitted at a high rate (e.g., images), the battery life will be lower. On the other hand, the charging issues of gateways need to be examined. Based on exploration in the current phase, most gateways are required to be connected to a power source (i.e., very few are battery-powered). It should be noted that the solar panels could serve as an alternative plan in case no external power source is available. Nevertheless, such solar panels are often subject to the influence of weather and, therefore, may affect the normal functioning of LPWAN gateways. The normal working period would be assessed, if such a powering plan is deployed.

- **Determine specific configurations for sensor nodes and gateways**. Sensor nodes can potentially be deployed in all positions, as shown in Figure 28(a). The limitations of the gateways will be explored. For example, when the duty cycle parameter is set to 0.1% (it is noted that the maximum available value is 1%), the LoRa node can communicate only 3.6 seconds per hour, while the maximum supported number of sensor nodes is 1,000 at a high success ratio of around 80% (Lavric and Popa, 2018). Only five sensor nodes were explored in the lab test at ODU, and the occurrence of collisions among sensor node signals was not noticed. Based on the lab test, the success ratios may differ in two locations within the same distance but located in different directions from the gateway. The performance metrics, such as signal strength and success ratio, can be measured at all such positions. Several sensor nodes will be purchased, and their limitations will be explored.

Based on different requirements and geographical characteristics, different plans, such as Plan A and Plan B (shown in Figure 28(b) and Figure 28(c)) will be designed after a discussion with TRP. For example, Plan A will sparsely distribute sensor nodes, while a tradeoff between the success ratio and signal strength is desired. On the other hand, if tall buildings are located in different directions from the gateway, sensor nodes will be deployed (as in Plan B) to meet the requirements of LOS.

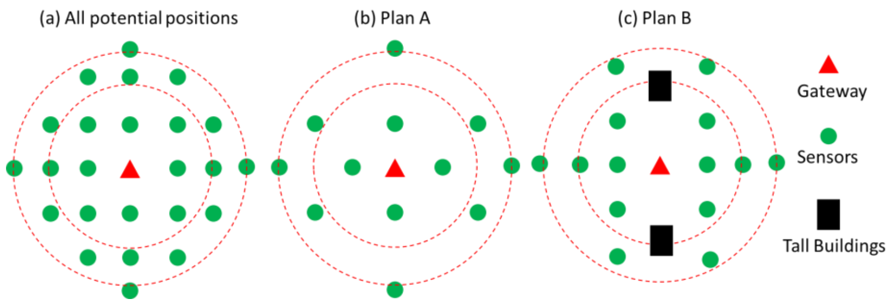



**Figure 28. Locations of the Sensor Nodes**

Similarly, the locations of gateways, based on different plans, need to be discussed. For application in a localized site, one gateway would be sufficient, and it is suggested that it be located at the center of the site. For an application along a roadway, if multiple gateways are needed, it is suggested that they be allocated along the road segments, at certain intervals, in accordance with the feasible coverage ranges of the gateways. For an application covering a relatively larger area, Plan B in Figure 29 may be considered. Similarly, the performance metrics, such as signal strength and success ratio will be measured in a selected deployment plan. It should be noted that it is suggested that such gateways be installed at a higher position to better guarantee that LOS requirements are met. For example, an ideal location would be high electricity poles along road segments.

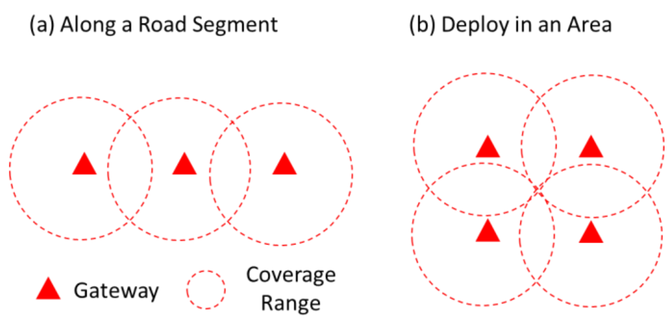



**Figure 29. Possible Layout for Multiple Gateways**

In addition, the impact of the heights of gateways and sensor nodes will be explored. This requires the examination of available mounting facilities at the test sites. As shown in Figure 30, LOS will be guaranteed with a higher gateway and sensor node if there is a one-floor building in the way. However, if the gateway or the sensor node is at a lower height, the LOS cannot be guaranteed. The height of gateways in lab tests had been examined, and it was found that, if installed at a higher location, its coverage range can increase. As shown in Figure 31, the achieved coverage range of a gateway

(MultiTech MTCDT-246A) mounted on a 16-ft pole was about 0.7 mile at a few selected sites, whereas it reached 0.8 miles after being installed on the 5th floor of a garage on the ODU campus. Thus, after the selection of sites for gateways and sensor nodes, experiments will help determine the best height combinations for them.

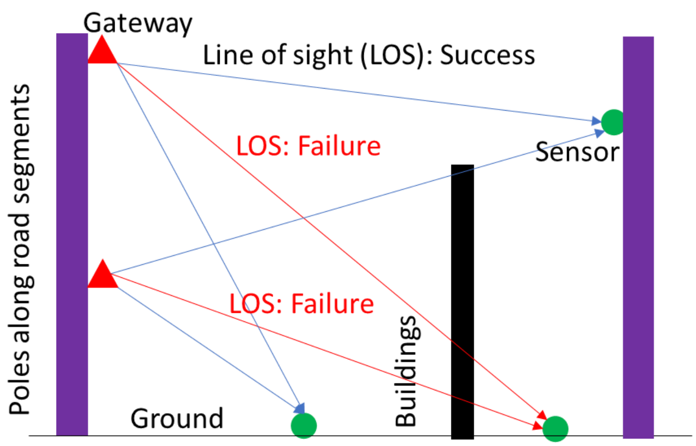



**Figure 30. Impact of Heights of Gateways and Sensor Nodes on LOS**

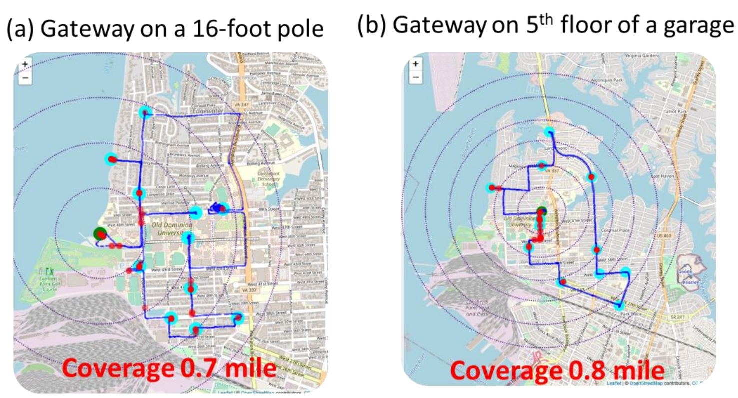



**Figure 31. Previous Lab Test of Different Heights of Gateway Deployment (Small Red Dots: Sites with Successful Communication; Big Cyan Dots: Locations for Sensors Placed on Top of a Parked Vehicle)**

- **Determine the duration of each test scenario**. It is expected that conducting a long-term test scenario will take several weeks or months (including site visits, preparation, and field tests). It should be noted that, in order to obtain satisfactory and reliable results, the duration of each test will be long enough to gather sufficient test samples, especially for those scenarios with a low transmission frequency (e.g., one message per hour). Even though the sensor nodes and gateways to transmit messages at a higher frequency to obtain a large enough sample size can be manually revised, it may be different from realistic applications. Issues missed by tests, such as battery depletion and severe weather conditions, could affect the results if they are not revealed in a short test period. Thus, the duration for each test scenario needs to be carefully determined after a discussion with TRP members.

- **Determine the internet access of gateways**. It is expected that gateways can get access to the internet and transmit received messages to a server that can visually check data and identify potential issues (e.g., loss of connection). One solution is to use cellular internet access (e.g., NB-IoT) to allow the gateway to send information to the server. If this is not possible, data will be stored on internal memory cards attached to the gateways.

### Support Needed from VDOT

The proposed test plan will need support from VDOT during the implementation process for the following primary aspects:

- **Test scenario design**. The discussion with VDOT and the TRP to specify final test scenarios is needed. Some customizations of the test scenarios will be made in preparing detailed test plans in a potential Phase 2, including sensor types, number of devices, installation details, evaluation indicators, logistics, etc.
- **Site selection**. The cooperation with VDOT and the TRP to identify potential sites and feasible locations for safely mounting gateways and sensor nodes is necessary. It might be necessary to visit selected sites during the field tests and acquire the permission and potential assistance of the VDOT staff, if necessary.
- **Installation of sensors/gateways on the infrastructure**. The support from VDOT to install devices on selected facilities (e.g., bridges, parking lots, and poles) owned by VDOT is needed. For example, gateways can be installed on signal poles or surveillance towers that are owned by VDOT, if possible. Bucket trucks might be needed if the mounting position is too high. The permission and help from VDOT to install such devices and to remove them might also be needed.
- **Power supply**. A majority of the gateways will need a power supply if solar panels or portable batteries are not used. The collaboration with VDOT engineers to check the availability of power sources at its existing facilities is needed. If solar panels are installed, the support to safely mount them is needed.
- **Maintenance**. The claimed lifespan of sensors varies from vendor to vendor. Devices may need to be replaced during the test. The support from VDOT (e.g., providing access to sites) in maintaining or replacing deployed devices is needed.

## CONCLUSIONS

- *Different LPWAN technologies (e.g., LoRa, Sigfox, and NB-IoT) are available, but their technical specifications are quite different.* For example, NB-IoT utilizes licensed bandwidth and can support a high data transmission rate of 250 kbps for uplink. On the other hand, LoRa utilizes an unlicensed band, and can only support a data transmission rate of 27 kbps.

- *Based on examination of the literature, there are only a limited number of off-the-shelf LPWAN products that have been tested in the U.S.* For example, Laird sensor nodes, ELSYS's ELT2 sensor nodes, and MultiTech gateways are available for collecting and transmitting general environmental information, such as temperature. In addition, it should be noted that only a few LPWAN products are designed with a focus on applications in transportation systems. For example, Moko Smart Parking Sensor LW005-PS focuses on collecting parking information by using LPWAN technology.

- *Only one out of 27 survey respondents indicated actual LPWAN deployment.* The application of LPWAN in supporting transportation system management and operations in the U.S. is very limited. Respondents showed interest in using LPWAN for smart transportation/cities projects, whereas they were also concerned about the reliability of LPWAN and related security issues.

- *Based on limited lab tests, it was found that the coverage range of a tested LPWAN technology, specifically LoRa, was less than 2 miles when deployed in customized settings, in both rural and urban areas*.

- *The mounting height of gateways affects the coverage of LPWAN*. In general, the coverage range is positively correlated with the mounting height.

- *Based on conducted experiments, different LoRa sensor nodes can co-exist with each other*. For example, Laird and ELT2 sensor nodes can transmit messages when placed at the same site. Nevertheless, their performance, in terms of success ratio, latency, etc., can be different. For example, Laird sensor nodes have a higher success ratio and longer coverage range as compared with ELT 2 sensor nodes. The minimum data transmission frequency is 1 minute for Laird sensor nodes, while it is 2 minutes for ELT2 sensor nodes.

- *LPWAN technologies show the potential for supporting wireless communications in some transportation applications*. However, more extensive field tests should be conducted to further evaluate these technologies in terms of their pros and cons in different application scenarios.

## RECOMMENDATIONS

*VTRC should consider supporting a Phase 2 study to test LPWAN technologies in the field under the different conditions and configurations listed in this report*. Among the available LPWAN technologies, VTRC/VDOT should select more established options (e.g., LoRa, Sigfox, and NB-IoT) for field testing in a potential Phase 2. It is impractical to test all LPWAN technologies, as all of them do not have a wide spectrum of off-the-shelf sensor nodes and a well-established development community (e.g., software/hardware developers and service providers) for supporting field deployments in transportation systems. In particular, considering the available services, devices, and practices, NB-IoT is recommended as a licensed technology and LoRa as an unlicensed technology to be tested.

# IMPLEMENTATION AND BENEFITS

## Implementation

VTRC anticipates that the second phase of the research recommended in this report will begin within six months of the publication of this report. The ODU research team is expected to conduct the field test in Phase 2, if granted. The findings of the literature review, survey, and lab tests will be used in combination with the proposed field study plan to define a final scope of work.

## Benefits

The field tests to be conducted in a potential Phase 2 will generate rich data that will permit a comprehensive evaluation of LPWAN technologies. The results will help VDOT identify the appropriate solutions for field deployment in different transportation contexts (e.g., traffic monitoring at park-and-ride sites and in rest areas; environmental conditions monitoring in rural areas). Deploying LPWAN-based IoT solutions in the field will help reduce equipment and communications costs and allow VDOT to employ more economical IoT service options across the Commonwealth, especially at locations without cellular or fiber optic coverage. It is expected that many issues such as last-mile connection and rural data communication and transmission needs can be addressed by utilizing the LPWAN technology. With the test results, the potential Phase 2 project will prepare VDOT for embracing the LPWAN technology with informative facts beyond vendors' specifications.

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# APPENDIX A. QUESTIONNAIRE ON THE USE OF LPWAN TECHNOLOGIES

This survey is about the use of low-power wide-area network (LPWAN) technologies to support different Internet of Things (IoT) solutions. LPWAN technologies, such as LoRa, NB-IoT, and Sigfox, enable long-range wireless communications at low cost and low energy consumption. LPWAN technologies can support various smart cities and intelligent transportation systems (ITS) applications.

This survey is part of an on-going project, led by a research team at Old Dominion University (ODU), with support from the Virginia Department of Transportation (VDOT). The Principal Investigators of the project are Drs. Hong Yang, Mecit Cetin, and Yuzhong Shen at ODU. The information collected will help practitioners evaluate the capabilities, usefulness, and challenges of LPWAN technologies. The survey will take about 5~8 minutes to complete.

If you have any questions about the survey, please contact Dr. Hong Yang (hyang@odu.edu) or Tancy Vandecar-Burdin (tvandeca@odu.edu). We greatly appreciate it if you could also share the survey with other fellow agencies/organizations with related experience in deploying LPWAN technologies. Thank you very much.

***Disclaimer**:* Your participation is voluntary, and your responses will not require any personal/private information. The survey responses will only be analyzed and reported in an aggregated way.

*(Note to programmer: The survey will be organized online. Multiple answers: ☐; Single answer ○)*

**Note**: Low Power Wide Area Network (LPWAN) uses low power and long-range wireless communication technologies to support information exchange between sensor nodes and a server. LPWAN technology includes a number of competing standards and vendors' support. Many representative LPWAN technologies include LoRa, NB-IoT, Sigfox, DASH7, LTE Cat M1, EC-GSM-IoT, IQRF, RPMA, etc. Figure 1 illustrates LPWAN's focus area and main characteristics.

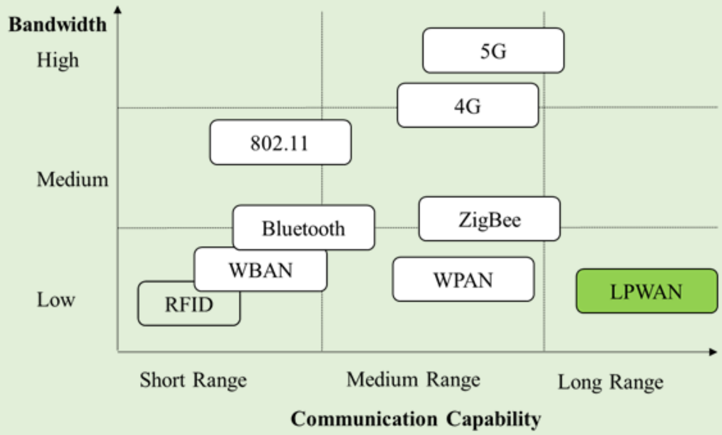


**Figure 1. The Main Characteristics of LPWAN Technology**

LPWAN has shown great potential in many fields in support of a variety of Internet of Things (IoT) applications. Some examples include: water level monitoring, via LoRa technology in the StormSense project, in the Hampton Roads area, VA; supply chain operation optimization, via LoRa by Senet, in North America; and smart lighting/gas/city via NB-IoT by T-Mobile, in Las Vegas.

1. What is your current organization/affiliation?
    a. State DOT ○
    b. County/city/municipal transportation division ○
    c. MPO ○
    d. Public transit agency ○
    e. Other city organizations ○
    f. Research institute ○
    g. Company/industry organization ○
    h. Other Click or tap here to enter text.

2. Are you familiar with any one, or more, of the following LPWAN technologies' applications?
    a. LoRa ☐
    b. Sigfox ☐
    c. NB-IoT ☐
    d. LTE-CAT M1 ☐
    e. EC-GSM-IoT ☐

f. RPMA ☐
g. DASH7 ☐
h. IQRF ☐
i. Other Click or tap here to enter text.
j. Not familiar with any of the above technologies ☐

3. Have you or your organization used LPWAN technology before? (If "**Yes**", please answer questions 4-18; if "**No**", please answer questions 19)
   a. Yes ○
   b. No ○

***[Questions 4-18 are for those who replied "Yes" to Q3]***

4. Which of the following scenarios/applications have you used LPWAN for?
   a. Smart metering system ☐
   b. Public parking system ☐
   c. Smart lighting system ☐
   d. Intersection signal operations/control ☐
   e. Traffic data collection (traffic count, flow, speed, etc.) ☐
   f. Traffic operations (work zone, variable speed limit, etc.) ☐
   g. Environmental sensors (wind, temperature, rain, etc.) ☐
   h. Other asset management (e.g., roadway facilities such as signs) ☐
   i. Transit operations ☐
   j. Other Click or tap here to enter text.

5. Please briefly describe one of your or your organization's LPWAN projects that you are most familiar with. Please include a weblink to this project if available.
   Click or tap here to enter text.

6. Which is the primary LPWAN technology used in the project described above?
   a. LoRa ○
   b. Sigfox ○
   c. NB-IoT ○
   d. LTE-CAT M1 ○
   e. EC-GSM-IoT ○
   f. RPMA ○
   g. DASH7 ○
   h. IQRF ○
   i. Other Click or tap here to enter text.

7. What is the approximate number of sensor nodes used in the project that you described above?
   a. 0-10 ○
   b. 11-50 ○

c. 51-100 ○
d. 101-300 ○
e. 301-500 ○
f. More than 500 Click or tap here to enter text.
g. Unknown ○

8. What is the coverage range of the deployed LPWAN system in the project described above?
   a. Several selected sites (e.g., several parking lots) ○
   b. Facility level (e.g., parking garages) ○
   c. Street level (e.g., along an arterial/corridor) ○
   d. District/neighborhood level ○
   e. Citywide/regional level ○
   f. Fleet tracking ○
   g. Other Click or tap here to enter text.

9. What is the estimated initial investment cost of the LPWAN project described above?
   a. Less than $5K ○
   b. More than $5K~$10K ○
   c. More than $10K~$50K ○
   d. More than $50K~$100K ○
   e. More than $100K~$300K ○
   f. More than $300K ○
   g. Unknown ○

10. What is the estimated annual operational cost of the LPWAN project described above?
    a. Less than $5K ○
    b. More than $5K~$10K ○
    c. More than $10K~$50K ○
    d. More than $50K~$100K ○
    e. More than $100K ○
    h. Unknown ○

11. How much time did it take to make the project described above operational?
    a. < 1 month ○
    b. 1-3 months ○
    c. 4-6 months ○
    d. 7 months - 1 year ○
    e. More than 1 year ○
    i. Unknown ○

12. What is the expected data transmission speed of the project described above?
    a. Less than 1 kbps ○
    b. 1 kbps- 10 kbps ○
    c. 10kbps- 100 kbps ○
    d. 100 kbps- 1Mbps ○
    e. >1Mbps ○

f. Unknown ○

13. During the operation of the project described above, have the deployed LPWAN systems suffered from interference from other signal sources?
    a. Never ○
    b. Yes ○
    c. Unknown ○

14. How satisfied are you regarding the overall performance of the project described above in terms of the following areas?

| **Performance** | **Very dissatisfied** | **Dissatisfied** | **Neutral** | **Satisfied** | **Very Satisfied** |
|---|---|---|---|---|---|
| Data transmission security | ○ | ○ | ○ | ○ | ○ |
| Reliability of service | ○ | ○ | ○ | ○ | ○ |
| Data transmission latency | ○ | ○ | ○ | ○ | ○ |
| Cost effectiveness | ○ | ○ | ○ | ○ | ○ |
| Installation effort/complexity | ○ | ○ | ○ | ○ | ○ |

15. What is the typical data transmission frequency in the project described above?
    a. Second level ○
    b. Minute level ○
    d. Hourly level ○
    c. Daily level ○
    d. Other Click or tap here to enter text.

16. What is the environmental setting of the project described above?
    e. Flat urban area ○
    f. Mountainous urban area ○
    g. Flat rural area ○
    h. Mountainous rural area ○
    a. Other Click or tap here to enter text.

17. Please indicate any of the following regarding issues you encountered in the project described above:
    a. No issues experienced ☐
    a. Data transmission was not secure, and we experienced malicious attacks or jamming attacks ☐
    b. Devices required frequent maintenance ☐
    c. The package loss rate was high ☐
    d. Battery life was short, or batteries were replaced frequently ☐

e. Other Click or tap here to enter text.

18. Does your organization plan to continue/expand the use of the LPWAN technology in transportation/smart cities applications?
    i. Yes ○
    j. No ○
    k. Unknown ○

***[Questions 19-20 is for those who replied "No" to Q3]***

19. LPWAN technologies can support various smart cities and intelligent transportation systems (ITS) applications. If you are thinking about using LPWAN technology, would any of the following issues prevent you from using it?
    a. Implementation costs ☐
    b. Maintenance need/costs ☐
    c. Security issues ☐
    d. Low transmission bandwidth ☐
    e. Others Click or tap here to enter text.
    f. I do not see any of our project will need LPWAN ☐

20. Considering the low power, low bandwidth, and long-range features of LPWAN, do you think any of the following scenarios/applications can benefit from the use of LPWAN?
    a. Smart metering system ☐
    b. Public parking system ☐
    c. Smart lighting system ☐
    d. Intersection signal operations/control ☐
    e. Traffic data collection (traffic count, flow, speed, etc.) ☐
    f. Traffic operations (work zone, variable speed limit, etc.) ☐
    g. Environmental sensors (wind, temperature, rain, etc.) ☐
    h. Other asset management (e.g., roadway facilities such as signs) ☐
    i. Transit operations ☐
    j. Other Click or tap here to enter text.
    k. None of above.

21. Please share any other details regarding your experience with the use of LPWAN technologies below. Please feel free to provide links to additional information or projects on the use of LPWAN technologies. Thank you! Click or tap here to enter text.

22. If you are willing, please enter your organizational contact information below. The information will only be used to follow up on details about your project/experience with LPWAN technologies. Thank you! Click or tap here to enter text.

# APPENDIX B. LIST OF TEST SITES FOR LAB TEST

**Table B1. List of Test Sites for Lab Test**

| Rural Area in Chesapeake | Location | Urban Area - 5th Floor of a Parking Garage | Location | Urban Area - Waterfront Area on ODU Campus | Location |
|---|---|---|---|---|---|
| Site 1 | 36.691747, -76.357428 | Site 1 | 36.885558, -76.305847 | Site 1 | 36.891641, -76.315605 |
| Site 2 | 36.698983, -76.349876 | Site 2 | 36.886576, -76.305738 | Site 2 | 36.895236, -76.312306 |
| Site 3 | 36.711907, -76.317799 | Site 3 | 36.882109, -76.307965 | Site 3 | 36.887802, -76.304796 |
| Site 4 | 36.733907, -76.328774 | Site 4 | 36.876604, -76.301615 | Site 4 | 36.885561, -76.308163 |
| Site 5 | 36.740143, -76.343209 | Site 5 | 36.872855, -76.290327 | Site 5 | 36.881677, -76.307933 |
| | | Site 6 | 36.878207, -76.289078 | Site 6 | 36.879355, -76.303359 |
| | | Site 7 | 36.877935, -76.294178 | Site 7 | 36.878515, -76.307392 |
| | | Site 8 | 36.881748, -76.294735 | Site 8 | 36.879355, -76.309814 |
| | | Site 9 | 36.893306, -76.295721 | Site 9 | 36.883360, -76.312852 |
| | | Site 10 | 36.900485, -76.303952 | Site 10 | 36.887493, -76.307437 |
| | | Site 11 | 36.895128, -76.305361 | Site 11 | 36.888976, -76.312886 |
| | | Site 12 | 36.891590, -76.315350 | | |

Note: ODU - Old Dominion University.

# APPENDIX C. SUMMARY OF LPWAN APPLICATIONS (IN U.S.)

**Table C1. Summary of Identified LPWAN Sample Applications (in U.S.)**

| Technology | Field Test | Application | Type | Descriptions | Reference |
|---|---|---|---|---|---|
| NB-IoT | Las Vegas, NV | Smart city<br>Smart LED lighting<br>Sensor based monitoring of gas, temperature | Company project | T-Mobile provide the solution of LPWAN | (Pasolini et al., 2018) |
| NB-IoT | San Francisco, CA | Wireless personal area network 5$/year/device<br>(smart parking, smart metering) | Company project | AT&T provide the solution of LPWAN | (AT&T, 2020) |
| Sigfox | Chicago | Traffic monitoring<br>River monitoring | Hacking house project | Sigfox provide the solution of IoT | (Sigfox, 2019) |
| Sigfox | New York | Asset tracking | Company project | Supply chain asset tracking | (Sigfox, 2020) |
| Sigfox | North America | Low power wireless monitoring system | Cooperative company project | Cooperation with MCCI | (Sigfox, 2020) |
| LoRa | North America | Supply chain operation optimization | Company project | Cooperation with Senet | (Senet, 2020) |
| LoRa | San Diego | Water management and monitoring | Cooperative company project | Cooperation with Trimble | (LoRa, 2020) |
| NB-IoT | Boston | Autonomous vehicles<br>Intelligent parking lots<br>Interactive public art | Smart city pilot project | Cooperation with Verizon | (Boston, 2019) |
| LoRa | Norfolk, VA | Water level monitoring | Pilot project | StormSense | (StormSense, 2020) |

Note: LED - Light-emitting diode; LPWAN – Low power wide area network; NB-IoT – Narrowband internet of things.

# APPENDIX D. SUMMARY OF LPWAN APPLICATIONS (OUT OF THE U.S. & SIMULATION)

**Table D1. Summary of Identified LPWAN Sample Applications (out of U.S. & Simulation)**

| Technology | Field Test | Application | Type | Descriptions | Reference |
|---|---|---|---|---|---|
| LoRa+Drone | No<br>Matlab | Urban surveillance | Paper | Proposed a solution for communication between drones and sensors | (Sharma et al., 2018) |
| Sigfox | Singapore Taiwan | Bicycle location tracking | Project | Bikes send location data at periodic intervals | (muRata, 2016) |
| Telensa | NA | Smart lighting | Company product | Smart streetlight infrastructure for creating data-driven cities | (Telensa, 2019) |
| LoRa | Bologna | Smart city | Project | Measured environmental qualities | (Pasolini et al., 2018) |
| LoRa+NB-IoT | No<br>University of Oulu | Multi device | Paper | LPWAN supporting multiple radio access technologies (RATs) devices | (Mikhaylov et al., 2018) |
| Sigfox | No | Short-range sensor object tracking system | Paper | Proposed a LPWA tracking platform | (Chung et al., 2018) |
| LoRa | Nonoichi, Japan | Bus location | Project (compared with previous Wi-SUN system) | Raspberry pi and LoRa | (Tanaka et al., 2017) |
| LoRA+Bluetooth | Testbed | Smart city | Paper | LPWAN+WPAN (wireless personal area network) | (Ferreira et al., 2019) |
| LTE CAT M1 | Antwerp's City of Things testbed | Air quality anomaly detection | Paper | Collecting data from sensors | (Santos et al., 2018) |
| LoRa | No<br>SUMO simulation | Internet of bikes | Paper | Bike to bike station communication | (Zguira and Rivano, 2018) |
| LoRa | University of Murcia in Spain | Vehicular monitoring platform | Paper | Monitoring vehicles | (Santa et al., 2019) |
| LoRa | Shah Alam in Malaysia | Smart traffic light | Paper | Monitoring traffic congestion for better traffic light | (Nor et al., 2017) |
| LoRa | Spain South Korea | Smart parking | Project | Using data streams to help smart parking | (Sotres et al., 2018) |

Note: SUMO - Simulation of urban mobility; LPWAN – Low power wide area network; NB-IoT – Narrowband internet of things; LTE CAT M1 - Long Term Evolution Category M1.

# APPENDIX E. VISUALIZATION IN RESIOT

| State | Child Of | Name | DevEUI | AppEUI | DevAddr | Date Last Message | Authentication | ADR Settings |
|---|---|---|---|---|---|---|---|---|
| | | Sentrius 2 | 0025ca0a0000c01b | f9c60ecea3adc6bd | | Aug 5 2020, 14:31:55 | OTAA Class A | ADR:Enabled, DChR:Disabled |
| | | Laird RS191A | 0025ca0a0000bfdb | f9c60ecea3adc6bd | | Aug 5 2020, 14:31:27 | OTAA Class A | ADR:Enabled, DChR:Disabled |
| | | Elsys ELT-2B | A81758FFFE04E3D9 | 0000000000000000 | | Aug 5 2020, 14:32:05 | OTAA Class A | ADR:Enabled, DChR:Disabled |
| | | Elsys ELT-2A | A81758FFFE04E3D8 | 0000000000000000 | | Aug 5 2020, 14:32:14 | OTAA Class A | ADR:Enabled, DChR:Disabled |

**Figure E1. Sensor Nodes Connected in ResIoT**

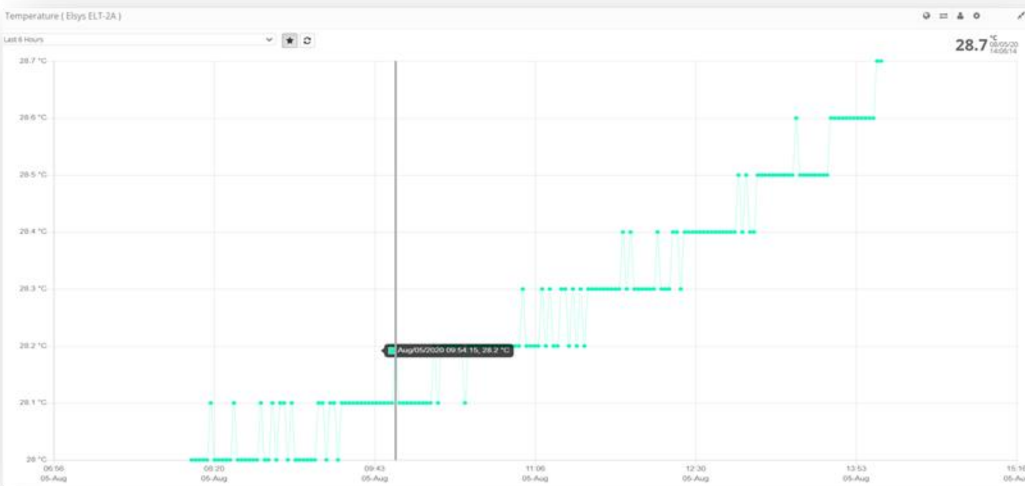


**Figure E2. Visualization of Messages Received in ResIoT**

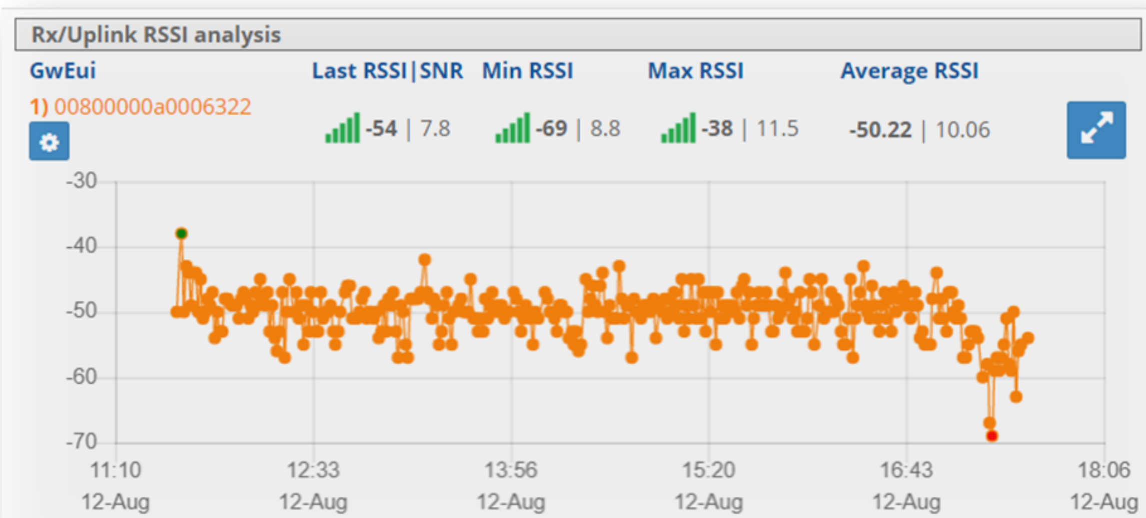


**Figure E3. Signal Strength Visualization in ResIoT**

# APPENDIX F. ACRONYMS

**Table F1. Acronyms**

| Acronym | Full Name |
|---|---|
| 3GPP | 3rd Generation Partnership Project |
| BW | Band width |
| CDMA | Code divided multiple access |
| CSS | Chirp spread spectrum |
| DBPSK | Differential binary phase shift keying |
| DMS | Dynamic message sign |
| DOT | Department of transportation |
| DSSS | Direct-sequence spread spectrum |
| E-CID | Enhanced cell ID |
| EDGE | Enhanced data rates for global evolution |
| FDD | Frequency division duplex |
| FDMA | Frequency-division multiple access |
| FEC | Forward error correction |
| FSK | Frequency-shift keying |
| GFSK | Gaussian frequency-shift keying |
| GMSK | Gaussian minimum shift keying |
| GPRS | General packet radio service |
| GSM | Global system for mobile communications |
| I-DRX | I-discontinuous reception |
| ISM | Institute for supply management |
| LoRaWAN | Long range wide area network |
| LoS | Line of sight |
| LPWAN | Low power wide area network |
| LTE | Long term evolution |
| ODU | Old dominion university |
| OFDMA | Orthogonal frequency-division multiple access |
| oTDoA | Difference of arrival |
| PSM | Power saving mode |
| QAM | Quadrature amplitude modulation |
| QoS | Quality of service |
| IoT | Internet of things |
| ITS | Intelligent transportation systems |
| PSK | Phase-shift keying |
| RFID | Radio-frequency identification |
| ROW | Right-of-way |
| RPMA | Random phase multiple access |
| RSF | Resource sharing fiber |
| SC-FDMA | Single carrier frequency division multiple access |
| SC-PTM | Single cell point To multi-point |
| TAU | Tracking area updating |
| TDD | Time division duplex |
| TDMA | Time divided multiple access |
| TRID | Transport Research International Documentation |
| TRP | Technical review panel |
| VDOT | Virginia Department of Transportation |
| VTRC | Virginia Transportation Research Council |
| WBAN | Wireless body area network |
| WPAN | Wireless personal area network |

# APPENDIX G. GLOSSARY

**Table G1. Glossary**

| **Category** | **Glossary** | **Description** |
|---|---|---|
| Modulation Technology | Phase-shift keying (PSK) | A digital modulation process that conveys data by changing (modulating) the phase of a constant frequency reference signal (the carrier wave). Any number of phases can be used to construct a PSK constellation. For example, BPSK is 2 phases while QPSK is 4 phases. It should be noted that 8-PSK is usually the highest order PSK constellation deployed. |
| | Differential phase shift keying (DPSK) | A phase modulation that conveys data by changing the carrier wave's phase. |
| | Chirp spread spectrum (CSS) | A spread spectrum technique which encodes information using wideband linear frequency modulated chirp pulses. |
| | Direct-sequence spread spectrum (DSSS) | A spread-spectrum modulation technique for reducing overall signal interference. |
| | Orthogonal frequency-division multiplexing (OFDM) | A type of digital modulation by encoding digital data on multiple orthogonal carrier frequencies. |
| | Frequency-shift keying (FSK) | A frequency modulation scheme which transmits digital information through discrete frequency changes of a carrier signal. |
| | Code-division multiple access (CDMA) | A form of spread spectrum communications where multiple transmitters can simultaneously send information over a single channel. |
| | ALOHA | A mechanism for randomized multiple channel access. |