NB-IOT AND LORAWAN PERFORMANCE TESTING IN URBAN AND RURAL ENVIRONMENT

by

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This thesis is dedicated to my mom.

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LIST OF ABBREVIATIONS

3GPP	3rd Generation Partnership Project
AT	Attenuation
CSS	Chirp Spread Spectrum
FCC	Federal Communications Commission
GPRS	General Packet Radio Service
GPS	Global Positioning System
GSM	Global System for Mobile Communications
IoT	Internet of Things
ISM Band	Industrial, Scientific and Medical Band
LAN	Local-Area Network
LoRa	Long-Range
LoRaWAN	Long-Range Wide-Area Network
LP	Low-Power
LPWAN	Low-Powered Wide-Area Networks
LTE	Long Term Evolution
M2M	Machine to Machine
NB	Narrowband
NB-IoT	Narrowband - Internet of Things
OFDMA	Orthogonal Frequency-Division Multiple Access
PHY	Physical Layer
RF	Radio Frequency
RSSI	Received Signal Strength Indicator
SC-FDMA	Single Carrier - Frequency Division Multiple Access
SIM	Subscriber Identification Module
WAN	Wide-Area Network
WiFi	Trademark for IEEE 802.11 standards

DEFINITIONS

Internet of Things	- any device connected to the internet is considered to be part of the Internet of Things
LoRaWAN	- low-power wide-area network proprietary to LoRa Alliance
Low-Power Network	- enables devices to communicate over long distances with low bit rate while utilizing battery-operated devices
Narrowband	- specific frequency range utilized for signal transferring
Noise Floor	- “the ambient or background level of radio energy on a specific channel” (Coleman, 2009, p. 122)
Wide-Area Network	- network spanning over multiple geographical locations

ABSTRACT

With technology advancements and the prices of electronic components reducing over the last fifteen years, many devices and systems that would have been proprietary only for large companies or industry giants are becoming an everyday household item. Various areas of technology have been benefiting from this but one of the biggest is the Internet of Things (IoT). With the prevalence of IoT, it has been integrated into houses, small businesses, farms, agriculture, building automation, etc. and the user population is now a resource to the industry as they complete personal projects. Within any project there are always limitations, this might be a limited time, limited funds, limited distance, or limitations of the devices being used. This study proposes to evaluate two low-powered networks, Narrowband Internet of Things (NB-IoT) and Long-Range Wide-Area Network (LoRaWAN), in different environments with the goal of understanding where the signal propagation is better and what distances can be reached despite obstructions. Distances and signal propagations, when measured by the manufacturers are often evaluated in ideal conditions which is rarely the case when utilized in the field. This creates a gap in the deployment and the end-users are frequently faced with diminished performances. As IoT is predominantly employed in urban and rural areas this study will focus on those two settings by testing the Received Signal Strength Indicator (RSSI) at various distances. The evaluation testing of the two systems showed each system performing more consistently in rural areas but neither had 100% coverage at any locations.

CHAPTER 1. INTRODUCTION

In this chapter of the document, the problem statement is presented by showing the gap in the research and by what margins there is a need for improvement. Following the problem statement, the significance and purpose of the study are introduced and finally, the research question will be shown. Following this, the assumptions, limitations, and delimitations are listed showing the magnitude of the study.

1.1 Problem Statement

While device manufacturers test the systems and the devices for baseline performance, often those tests are performed in ideal conditions and under specific circumstances. Those scenarios often do not translate to the various environments in these systems and/or devices will be deployed. Existing modeling solutions for signal propagation are often unknown for their performance. The problem addressed in this project is the insufficient amount of information on NB-IoT and LoRaWAN performance evaluation in certain scenario conditions such as urban and rural environments in North America. The sole purpose of the study is not to state one system is better than the other but rather to visualize the data gathered in order to better gain an understanding of network coverage in different scenarios and allow for future studies to be developed.

1.2 Significance

Testing and evaluating NB-IoT and LoRaWAN systems is vital due to IoT's versatility in multiple industries and applications. Understanding the capabilities and limitations of the networks will allow for better decision making while deploying the systems and will attempt to eliminate any unexpected unknown variables. Additionally, this can prove to be useful in reducing deployment times.

With the projection that smart cities will become a required infrastructure of most big cities due to the population and life expectancy increase (Mohanty et al., 2016), in the paper on "Everything You Wanted to Know About Smart Cities" predicts that "70% of the world population will live in urban areas by the year 2050" (Mohanty et al., 2016). Furthermore, this paper mentioned, the utilization of the IoT infrastructure can help in mitigating issues raised from swift change (Mohanty et al., 2016). The two systems have been chosen due to present and future integrations and potentials. NB-IoT “is expected to grow from USD 461 million by 2020 to USD 2,484 million by 2025”, according to the research presented by MarketsandMarkets™ INC. written by Mr. Aashish Mehra (n.d.). Furthermore, NB-IoT can utilize already existing cellular networks and speeds can reach up to 5Mbit/s. The benefits NB-IoT can bring to developed and undeveloped areas are immense for the relatively low cost of integration; rising the implementation of smart devices in various fields of the industry utilizing IoT propelled LoRaWAN to become one of the leaders in low-powered networks. According to Tracy Cozzens (2020) the “LoRaWAN market projected to grow by 47 percent” and predicts that the “LoRaWAN market is projected to reach US$5557.2 million, growing at a very high compound annual growth rate (CAGR) of 47.2% during 2019 to 2027, according to market research firm InForGrowth”. With that prediction, LoRaWAN will be introduced in more environments and with rapid changes and the increased population, there will be an effect on signal propagation through the cities and can cause issues with deploying the systems. Rural environment’s decreased population and spread have different circumstances to address. Signal loss over longer distances can be affected by large bodies of trees, crops, and elevation changes.

1.3 Purpose

As mentioned in the previous section, with IoT’s tremendous growth over the last few years and with the future expectations of development low-power networks in IoT have a sizable part to play in the market’s growth.

The purpose of this research is to test and evaluate the two environments and signal propagation by utilizing two low-power technologies and comparing them to existing wireless propagation modeling software. Additionally, with these tests conducted researchers will be able to have a baseline measurement of a particular system and will have the ability to compare and/or further the studies on NB-IoT and LoRaWAN systems.

1.4 Research Questions

The questions below are what the research intends to answer:

- What is the performance evaluation of NB-IoT in urban and rural scenarios?
- What is the performance evaluation of LoRaWAN in urban and rural scenarios?
- How does the performance evaluation of LoRaWAN in urban and rural scenarios translate to modeling radio propagation software?

1.5 Assumptions

The assumptions of the study are as follow:

- Specifications given by the manufacturers are a reliable source of information.
- Contrasting power levels on the radios are not comparable.
- Software utilized in the study is performing as expected.
- Access to the tools and materials required to build the systems will be granted.

1.6 Limitations

The limitations of the study are as follow:

- The study will follow the Federal Communications Commission (FCC) laws for the United States of America.
- The study will be limited to West Lafayette, Indiana and, New Richmond, Indiana area in the United States of America.
- The survey will be conducted on public areas and areas where landlords allow.
- Network performance will be dependent on components used in the system.
- Radio interference will be dependent on the environment.
- Measurements taken will be susceptible to the margin of error of the tools and devices used.
- NB-IoT testing was performed by Quectel’s BC66-TE-B-KIT.
- LoRaWAN testing was performed with MULTITECH’s IoT kit.
- Weather is a variable that cannot be controlled during the testing period.
- The study will use AT&T’s paid service for the NB-IoT system.

- The study is limited to the months of October and November of 2020.
- Propagation pattern of NB-IoT antenna is not available

1.7 Delimitations

The delimitations of the study are as follow:

- The study will be limited to only two low-power systems.
- The study will not be sponsored by any vendor.
- The study will be performed outdoors only.
- The number of nodes will be one per system.
- Only end nodes will move while measuring.
- Energy consumption will not be factored into this study.
- Data collected for this study is between October and November of 2020.

1.8 Summary

Conducting testing and showing the results of the research are the key values noted within this study. The analysis will be done to determine the performance of NB-IoT and LoRaWAN systems in rural and urban areas. Once this data is gathered, it will be refined in the results section and the methodology will be further defined to show the process of gathering the data. Finally, the conclusion will be drawn from the study and any recommendations observed during the research will be noted.

CHAPTER 2. REVIEW OF THE LITERATURE

This chapter demonstrates a review of the literature relevant to designing, building, and testing two low-power systems previously chosen for this study. The chapter opens with a review of NB-IoT and LoRaWAN designs which fall under the umbrella of low-power networks. Additionally, the chapter reviews the essential components necessary for the study to be completed. Lastly, different testing strategies were reviewed for testing methodology.

2.1 Low-Power Networks

With wireless networks becoming more prevalent in telecommunications systems, different technologies have been developing to accommodate the diverse needs of the industry and end-users. The spectrum of wireless technology ranges and varies in many ways; from long-distance communication to very short, and from very high throughput to very low throughput. All different variations have one or more uses in technology depending on the implementation environment. A prediction that “more than 50 billion devices will be connected through radio communication” (Mekki et al., 2019) by 2020 the need for low-power networks has been increased. Low-power networks consume less power than traditional wireless networks meaning that end devices can last in some instances up to 10+ years (Patel & Won, 2017). Usually, low-power networks operate in lower frequencies which gives them more range while sacrificing data rates compared to other wireless networks such as Wi-Fi and cellular networks. A visual representation of the range and data rate relationship is depicted in Figure 1 below.

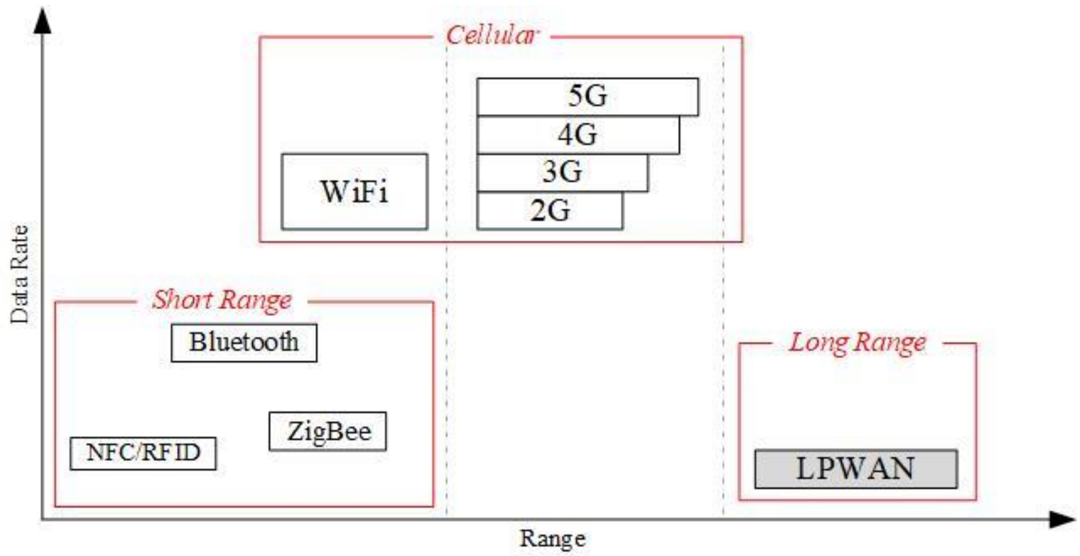

Figure 1. *Range vs. Data Rate in Wireless Communications (Mekki et al., 2019)*

Ever since 2013, when the term LPWAN was starting to be used technologies such as LoRa, NB-IoT, Sigfox and many more have emerged to aid IoT to serve thousands of sensor networks over licensed and unlicensed bands (Mekki et al., 2019). The terms and concepts of the licensed and unlicensed bands will be discussed in the coming sections.

2.2 LoRa and LoRaWAN

As revealed previously, balancing among many priorities, long-range communication has branched out over the years into subcategories based on need. LoRaWAN, short for Long-Range Wide-Area Network, is no exception. The separation from the original concept started because is believed by the creators of LoRaWAN that around 50% of the IoT devices will be connected to the low-power wide-area networks (*What Is the LoRa Alliance® | LoRa Alliance®*, 2015). What sets LoRaWAN apart from the other low-power systems is a wider range of applications that can be utilized having a bi-directional connection (*About LoRa Alliance® | LoRa Alliance®*, 2015). Furthermore, advanced encryption methods of LoRaWAN allow for secure communication from end to end. The ability to operate in an open band and/or licensed band gives LoRaWAN another advantage. This versatility is exactly what testing platforms need, as being able to interchange and modulate different parts of the network can allow testers to have greater control of the study.

2.2.1 Layers

LoRaWAN is a multi-layered communication system, consisting of three major layers. First is the Physical Layer, known as the PHY layer. The PHY layer facilitates communication between devices, this includes the frequency that the system is using (915 MHz in the United States of America) and LoRa Modulation fragment. LoRa Modulation will be discussed more in the next section of the document. The second layer of the LoRaWAN communications system is a LoRa MAC layer. This layer is part of the LoRa Alliance piece and is divided into three subclasses, Class A, Class B, and Class C (*A Technical Overview of LoRa ® and LoRaWAN ™ What Is It?*, 2015).

- Class A – Represents-energy efficient sensors that are battery-powered and are capable of connecting to all devices. Devices permit bi-directional communication to end-devices.
- Class B – End-devices accept receive slots. Unlike Class A, Class B devices have an extra window when receiving during scheduled times allowing synchronization.
- Class C – Devices utilize more power due to receive windows continuously being open and having maximum receive slots (LoRa Alliance, 2020).

Lastly, the application layer is implemented where a variety of different tools and applications from different companies including LoRa Alliance can be used to interact with devices. A visual representation of layers is depicted in Figure 2.

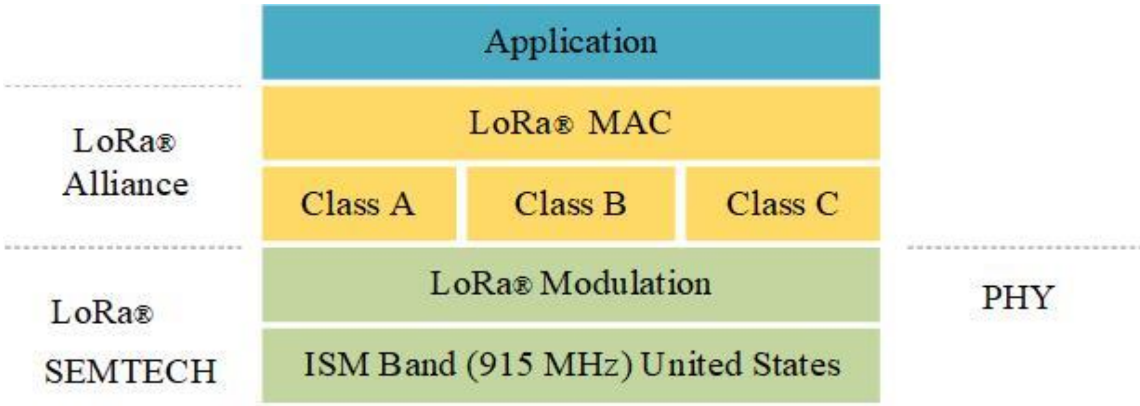

Figure 2. *LoRaWAN Layer Representation (A Technical Overview of LoRa ® and LoRaWAN TM What Is It?, 2015)*

2.2.2 Modulation

The main component that allows the communication of devices in a LoRaWAN driven environment is Chirps Spread Spectrum (CSS) modulation. In order to encode the message, modulation uses the spread spectrum technique applying chirp pulses under wideband linear frequency modulation (Springer et al., 2000). This can be explained as a change of frequency over a period of time. The frequency increasing over a certain period of time is called up-chirps and the frequency decreasing over a period of time is called down-chirps, portrayed in Figure 3.

CSS modulation has a variable that can be modified during signal transmission. Chip Rate, presented in chips per second is comparable to bandwidth; Symbol rate, calculated by dividing chip rate and two to the power of spreading factor which can be calculated by the number of the raw bits used; lastly, the data rate that can be calculated by multiplying spreading factor, symbol rate and coding rate represented in kbits/s (Lie, 2018).

This technology allows for the signal to carry well throughout the noise floor of the environment, over long distances. Distances, signal strengths, and limitations of the phenomenon have been tested in multiple studies (Adelantado et al., 2017) and (Petajajarvi et al., 2016).

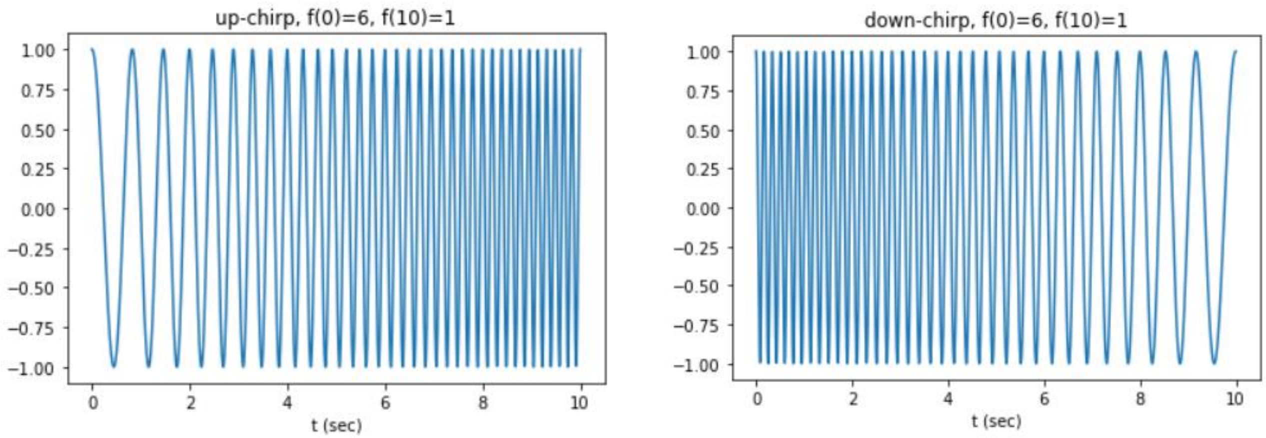

Figure 3. *Up-Chirp (left) and Down-Chirp (right) representation*

2.2.3 Network Architecture

The network architecture of LoRaWAN is relatively simple which makes it convenient and easy to deploy at small and large scales. Figure 4 shows the basic LoRaWAN star architecture. As *A technical overview of LoRa ® and LoRaWAN ™* stated, star architecture is better utilized in low-power networks compared to the mesh architecture due to preserving the battery life of the nodes and reducing the complexity of the architecture (2015). Mesh networks often can become overwhelmed since every node needs to be able to talk to each other.

As presented in the figure above, LoRaWAN nodes can be connected to multiple gateways, allowing for redundancy. Gateways need to allow for multiple protocols (1) LoRa and LoRaWAN and (2) TCP/IP connection, Cellular, or any other connection that can connect a gateway to a network server.

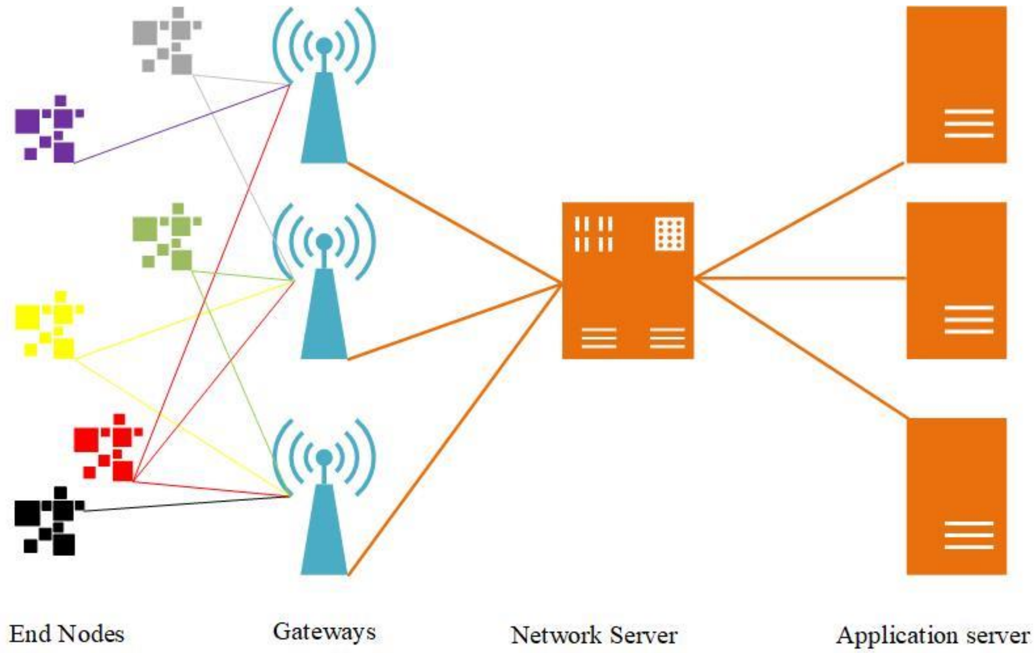

Figure 4. *LoRaWAN Network Architecture (A Technical Overview of LoRa ® and LoRaWAN ™ What Is It?, 2015)*

2.2.4 Implementation

Regarding the implementation of the LoRaWAN system, a thesis study *Measuring Environmental Effects on LoRa Radios in Cold Weather Using 915 MHz* completed by Riegsecker's (2018) shows step by step procedures using Raspberry Pis and Dragino LoRa as servers and clients. Although, the study is focused on environmental effects on LoRa radios the process used to build the system is a good reference for the purpose of this study. A few recommendations worth noting from Riegsecker's (2018) study include possible equipment failure if exposed to harsh conditions and the possibility of information not being received due to random node failure.

Additionally, Cattani, Boano, and Römer (2017) also suggest in order to reach the full capacity of the signal transmission an operator should use the highest power setting and the fastest PHY (Physical) option available. Outdoor testing performed by Augustin, Yi, Clausen, and Townsley (2016) shows that LoRa can perform well in residential areas up to 3 km distance with minimal losses. Besides the information previously mentioned both documents suggested similar approaches to the problem of designing the environment.

The information provided in the previous paragraph shows some of the boundaries and requirements are taken into consideration for the designing process of the study.

2.2.5 Application

While LoRaWAN cannot compete with cellular technologies due to its low data rates, LoRaWAN finds applications where distance and battery life takes precedence over high data rates. Most of these applications utilize sensors and actuators in network architecture. Network architecture is best known in the areas of agriculture (soil sensors, irrigation sensors, and actuators, monitoring livestock health and food consumption), smart cities (water meters, electricity meters, parking sensors, city lights, transportation, etc.), healthcare (assistive technologies, food safety, refrigerators used for medical purposes) and homes/buildings (security, emergency evacuations, utilities). Each area is interconnected with each other whether by common goals or common users.

2.3 NB-IoT

Another communication standard considered for this research and for implementation in the testing environment is Narrowband - Internet of Things (NB-IoT). The primary reason for this choice is the cost-efficiency in implementation and outstanding architecture and applicability in agriculture. Agriculture may not be a deciding factor but the predictions made by Research and Markets (2019) have suggested that “the Agriculture IoT Market is Expected to Grow from USD 12.7 Billion in 2019 to USD 20.9 Billion by 2024…” (p. 1). The capabilities NB-IoT can provide to agriculture are already excellent. Being able to collect data throughout multiple fields, store and analyze to help different projections is critical when certain industries intersect. NB-IoT is not just limited to agriculture, its applications in industrial controls, smart meters, and urban infrastructure are ever-growing (Zhang et al., 2018). As of right now, NB-IoT is the largest in Europe but many companies have been trying to implement in North America as well.

2.3.1 Standard

As the capabilities of wireless networks grew so did the need for them. The development of machine to machine communication has been testing and challenging wireless networks to adapt to them. In sensor/actuator networks machine to machine communication does not require frequent traffic or high throughputs. This setup allowed for a new field to be developed by cellular companies where they would not have to implement a lot of new infrastructures but rather build upon existing one. NB-IoT was firstly introduced by the 3rd Generation Partnership Project (3GPP) in the13th Release in 2016 (GSMA, 2016). There have been five more revisions, the last one was in 2020.

Deployment options can be gained by the provision of choices granted by providing various minimum system bandwidth options. This is due to the creation of 3GPP radio access technology known as NB-IoT which has the known limitation of not being compatible with former 3GPP devices. A benefit is gained alongside technologies such as Global System for Mobile Communications (GSM) and Long Term Evolution (LTE). One base requirement of NB-IoT for downlink and uplink is 180 kHz minimum system bandwidth. Two examples of how this can be used would be “a GSM operator can replace one GSM carrier (200 kHz) with NB-IoT. An LTE operator can deploy NB-IoT inside an LTE carrier by allocating one of the physical resource blocks (PRBs) of 180 kHz to NB-IoT” (Wang et al., 2017).

2.3.2 Modulation

While trying to obtain the most performance out of the technology and resources given, NB-IoT is using multiple modulation techniques. NB-IoT is using different modulation for uplink and downlink transmission. This is allowing for up to 100,000 devices in the network per cell with data rates of 200 kbps and 20 kbps for uplink and downlink respectively (Mekki et al., 2019).

Like LTE’s, NB-IoT’s downlink transmission scheme is founded on 15 kHz subcarrier spacing using Orthogonal Frequency-Division Multiple Access (ODFMA) (Wang et al., 2017). OFDMA is an enhanced version of OFDM technology employing multi-user translation. OFDM is one of the widely used technologies though often mistaken with spread spectrum technology due to similarities in data transmission such as using more bandwidth, and transmission under low power (Coleman, 2009, p. 200). OFDMA allows for channel dividing which allocates for more transmissions to occur. For the uplink, NB-IoT can use Singe Carrier - Frequency Division Multiple Access (SC-FDMA) multi-tone transmission and single-tone transmission.

2.3.3 Network Architecture

Unlike LoRaWAN, NB-IoT can be deployed in three different ways which were defined in 3GPP's document. The first way is the stand-alone method where the network is being deployed in a new spectrum; the second is an in-band deployment where the network is using LTE band; lastly, utilizing guard-band of LTE (Cao & Li, 2018).

The network architecture used throughout NB-IoT deployment is similar to each other with some minor variations depending on the application. As presented in Figure 5 the sensor network consists of a board that supports NB-IoT and a Subscriber Identification Module (SIM) card of the NB-IoT carrier. The base station, often related to a cell tower, is the provider's LTE station. The NB-IoT's core network is the system the LTE carrier has provided, the M2M engine can be hosted on the provider's network or can be hosted on private networks. The same goes for the server or servers that can be hosted by a user or a third-party company. Lastly, the end-user's device can access the information from the sensor network presented in a way already predefined in (Machine to Machine) M2M engine or the server.

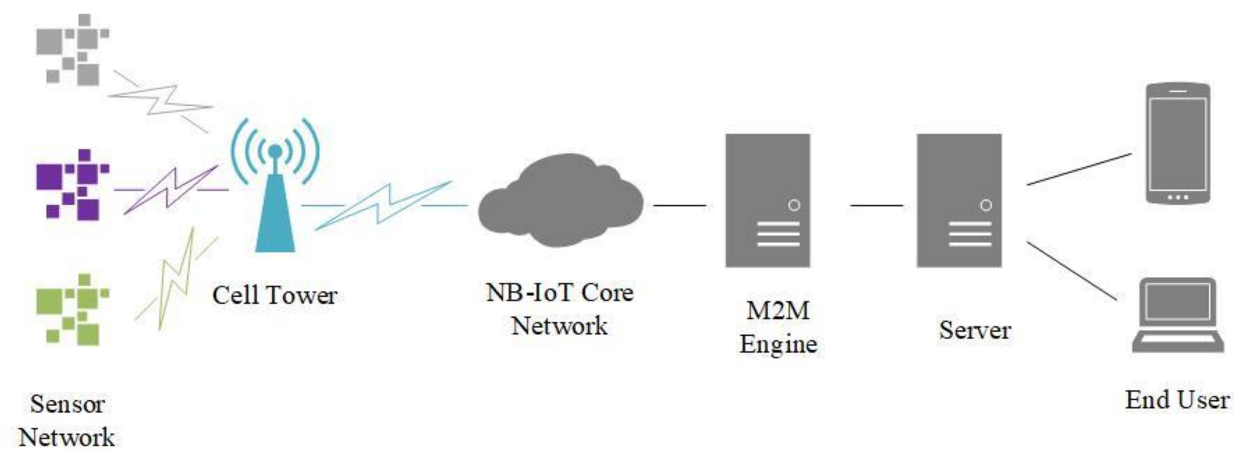

Figure 5. *NB-IoT Network Architecture (Cao & Li, 2018)*

2.3.4 Implementation

The implementation of NB-IoT does not require many components. The video series presented by Steve Doyle (2020), the principal technical architect for GSMA (the organization representing mobile networks around the world), presents all necessary components in order to build and make the system operational, one such system described was built in the United

Kingdom and showed differences in mobile operators and frequencies being used as compared to other countries. A simulator, as referenced by a study conducted by Foni et al. (2017), can distinguish adaptions within the NB-IoT that need to occur to the system in order for to be used in the United States of America. Although the simulation was still in development at the time, the basic functionality allows the ability to change different parameters and observe the results (Foni et al., 2017). An important observation made by the researcher is “to use new BLER curves for the NB-IoT modulation and coding schemes” (Foni et al., 2017, p. 4).

2.3.5 Application

The paper *Narrowband Internet of Things: Implementations and Applications* mentions non-traditional applications used with NB-IoT such as farming, smart cities, and agriculture, NB-IoT can be utilized in eHealth and IoT Public (Chen et al., 2017).

NB-IoT has been gaining presence across the world and will likely have an ever-increasing impact on technology in the United States. As the world is so connected through technology industries now have no borders and as such NB-IoT is a must to include in this study.

2.4 ISM Band

Industrial, Scientific, and Medical (ISM) band is a part of an open frequencies plan that can be operated without a license. This allows for private parties to develop and test their network as well as companies. An article from PCMag on the ISM band stated that
“In 1985, the FCC Rules (Part 15.247) opened up the ISM bands for wireless LANs and mobile communications. In 1997, it added additional bands in the 5 GHz range under Part 15.407, known as the Unlicensed National Information Infrastructure (U-NII)” (n.d.)

In variety a of applications that can utilize the ISM band there are some power limitations that need to be noted. Since this research is only using frequencies from 902 MHz to 928 MHz on the ISM band power limitations are shown in Table 1 below.

Table 1.

Power Limitations in ISM Band (PCMag.com, n.d.)

ISM Band (902 MHz to 928 MHz)	Power Limits (Watts)
Cordless Phones	1 W
Microwave Ovens	750 W
Industrial Heaters	100 kW
Military Radar	1000 kW

2.5 RSSI

The Received Signal Strength Indicator (RSSI) is predominantly used while verifying signal strength between wireless systems, this is characterized by 802.11-2016 standard as received metrics operated by 802.11 radios (Coleman, 2009, p. 124). The received sensitivity is directly correlated with the lowest signal a receiver can handle and the primary level of power for a radiofrequency signal (Coleman, 2009, p. 123). The speed of a given network is controlled by the received sensitivity, in the other words, if higher data rates are needed the receiver needs to produce more power (Coleman, 2009, p. 123). Another major factor that determines received sensitivity is the noise floor, in noisy conditions where the noise floor is higher than expected devices will require more power for the signal to be received successfully. RSSI is not a set value due to multiple variables that can impact the final number. RSSI is used across wireless manufacturers “as a relative measurement of the RF signal strength that is received by an 802.11 radio” (Coleman, 2009, p. 124). Table 2 below represents the correlation between RSSI and Receive Sensitivity Thresholds. While this table presents an optimal reference point, also reference the manufacturer’s documentation to get the best possible measurements.

Table 2.

RSSI Metrics (PCMag.com, n.d.)

RSSI	Receive Sensitivity Threshold	Signal Strength (%)	SNR	Signal Quality
30	-30 dBm	100%	70 dB	100%
25	-41 dBm	90%	60 dB	100%
20	-52 dBm	80%	43 dB	90%
21	-52 dBm	80%	40 dB	80%
15	-63 dBm	60%	33 dB	50%
10	-75 dBm	40%	25 dB	35%
5	-89 dBm	10%	10 dB	5%
0	-110 dBm	0%	0 dB	0%

Knowing that information presented can move from one layer to another sublayer (from PHY to MAC) is essential when working with devices that are not capable of multi-layer configurations.

2.6 Antenna Propagation and Distance Studies

Due to the multiple wireless applications and the evolution of wireless technologies, many types of different antennas have emerged over the years. Ultimately achieving the same goal, antennas vary greatly in design and performance. Used as an instrument to send and receive electromagnetic waves on certain frequencies, antennas can have different power levels and propagation. Different power levels in antennas are represented in decibels relative to an isotropic radiator (dBi). An isotropic radiator is an ideal source of the signal allowing for equal signal generation and radiation in all directions compared to the source (Coleman, 2009, p. 105). A unit of an antenna’s power is measured in the unit of a watt (W) or milliwatt (mW). Increasing antenna propagation is the ability of an antenna to direct a signal towards a certain direction or allows the signal to be spread evenly around. Various types of antennas include omnidirectional, directional, panel, highly directional antennas, etc. Knowing these variables is crucial when conducting tests utilizing wireless technologies and designing wireless networks. Most factory devices employing wireless networks come with a low-power omnidirectional antenna but is always advisable to double-check the manufacturer's manual.

In order to increase the power of an antenna, one can increase power at the source or direct the signal towards the device. When directing the electromagnetic waves of an antenna, the antenna is able to better hone into the targeted device for better transmission, while not produce more power. By manipulating the two variables different distances can be achieved by applying different power levels. The study conducted by Lauridsen et al. (2016) on *Coverage and Capacity Analysis of Sigfox, LoRa, GPRS, and NB-IoT* showed minimum link loss variation between NB-IoT and LoRA when using directional, omni-directional and sectorized antennas. More specifically, omni-directional antennas are capable of giving greater advantages over the other two types of antennas used. In another research study *Coverage comparison of GPRS, NB-IoT, LoRa, and SigFox in a 7800 km^2 area* by Lauridsen et al. (2017) in comparing indoor and outdoor devices, outdoor devices are known to have lower than 1% of outages while indoor devices approximately have 2% when associated with LoRa and lower than 1% when associated with NB-IoT, it appears to be greater benefits to NB-IoT as seen by this technology having a 3 dB average which is higher than LoRa and does not utilize omni-directional antennas.

2.7 Cloud RF

CloudRF™ is a web service that originated in the United Kingdom that allows users to model radio propagations (*CloudRF - Model The Future*, 2020). The application started as an Android launcher in 2011 helping people in the industry with a cheap solution compared to the military-grade equipment that is often proprietary and expensive to license. Now the application is capable of building 3D interfaces, legacy interfaces utilizing multiple antenna patterns and different models allowing to plan for various terrains and different receiver losses. Software's user interface is presented in Appendix G.

This software was utilized in the study *Performance Evaluation of LoRa Considering Scenario Conditions conducted by* Sanchez-Iborra et al. (2018) where researchers presented a study of LoRaWAN performance under multiple environmental circumstances. More about this study will be discussed in the related works section.

2.8 Related Work

The study *Performance Evaluation of LoRa Considering Scenario Conditions* presented by Sanchez-Iborra et al. (2018) illustrates methods and procedures used during testing performance evaluations. The research methodology was divided into two stages the (1) theoretical coverage study and the (2) experimental results. In the theoretical coverage study section, a radio planning tool was utilized to estimate and predict signal levels in the tested areas. The researchers were using the Okumura-Hata propagation model when demonstrating their coverage scenarios in theoretical analysis. Rural, suburban, and urban scenarios were tested and evaluated. In the experimental results section, the collected data was visualized and presented for comparison and analysis. The result found by testing researchers was the ability to have a baseline site survey for these three environments, which concluded the reach distance of LoRaWAN was the best in rural than in suburban and lastly in an urban area (Sanchez-Iborra et al., 2018). The study was performed under European standards which operate in lower frequency compared to North America's ISM band.

A site survey study conducted by Frank Wolf (2020) a senior system engineer at Purdue University's College of Agriculture shows different coverage maps of LoRaWAN implementation in West Lafayette and Lafayette area. Full coverage maps of site surveys with data collected can be seen in Appendix A. Data accumulated during the survey demonstrates different RSSI values measured in the pinned locations compared to distances from the LoRaWAN Gateway. Multiple maps allow for visualization of signal propagation throughout different terrains, landscapes, and elevations. Additionally, Figure 19 in Appendix A provides an urban area coverage of LoRaWAN where other figures provide more rural area coverage. Gateways and end nodes used in the study are MULTITECH's MTCDT gateways and MULTITECH's MultiConnect mDot Box are capable of sending various information such as coordinates, elevation, RSSI, etc. An important observation from the interview, Wolf (2020) was not utilizing any antennas other than those provided as the MULTITECH's defaults.

The results of the gathered information from Wolf (2020) presented in Appendix A show several different scenarios. In Figure 19, the gateway used was mounted between ten and fifteen meters in the air (Wolf, 2020). The distance covered from the "ACRE LoRa Gateway" to the "LoRa Test 37" point is approximately 11779 meters which is the furthest distance on the map from the gateway. Between these two points, there are no major obstructions such as forests or tall buildings. In Figure 20, Appendix A the maximum distance reached was 4189 meters with several groupings of trees obstructing the direct line of sight. Lastly, in Figure 21, Appendix A the maximum distance achieved was 487 meters in “Martel 21” point. The figure shows large bodies of trees which as stated by Wolf (2020) greatly impacted the signal propagation.

Lastly, in the paper on *A comparative study of LPWAN technologies for large-scale IoT deployment* by Mekki et al. (2019) multiple variables between LoRa and NB-IoT were shown (Figure 6) in a relationship and how they equate to each other.

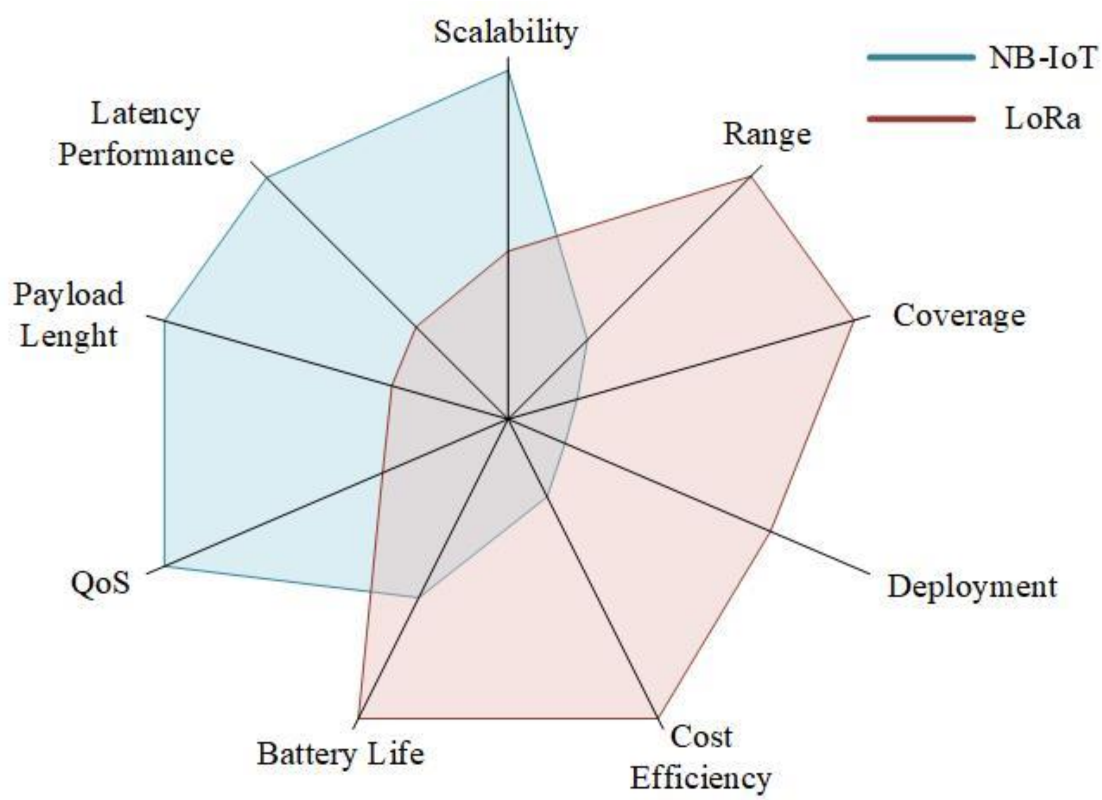

Figure 6. *LoRa and NB-IoT comparison*

2.9 Summary

In summary, the review of the literature section firstly introduced an area of study where this research will be performed. Secondly, the technologies used in the study were reviewed in order to gain a better knowledge of the systems, how they operate, and the reasons why they should be considered. Moreover, related information on dependent protocols, software, technologies, and necessary requirements on how to make the platforms operational and functional, was presented. Thirdly, related works, and previous studies were evaluated and the reasons why this study is significant for the research. The databases for literature review were carefully chosen to be of high quality and industry know sources such as IEEE Xplore, EBSCOhost Educational Source, ProQuest Technology Collection, and ERIC database allowed the study to ensure the high quality of materials reviewed. Discoveries relevant to the research showed a rough draft of a plan for the methodology of the study. Evidence such as instruments needed to complete the project, techniques of data collection, and procedures regarding methodology were evaluated, finding the optimal way to successfully address the research.

CHAPTER 3. METHODOLOGY

This section comprised of two subsections presents the methodology of the study. The first subsection is reiterating the problem, the purpose and the significance of the research which was stated in the first chapter of the document. The second portion presents methods and procedures that will be utilized during the design process and data gathering. Furthermore, the other subsections in the second portion will address reliability and statistical significance and the instrumentation of the data collected.

3.1 Introduction

Section 3.1 shows a summary of the problem statement, purpose of the study, significance of the problem, limitations, delimitations, and assumptions.

3.1.1 Problem

The problem addressed in this study is a lack of data on signal propagation utilizing low-power networks, NB-IoT and LoRaWAN in particular, regarding different environments such as rural and urban area. Furthermore, the study denotes the lack of comparison between existing software solutions to real signal propagation surveys. The following hypothesis derived from this problem are:

H_{10}: NB-IoT will perform better in urban vs. rural scenario.

H_{1a}: NB-IoT will not perform better in urban vs. rural scenario.

H_{20}: LoRaWAN will perform better in urban vs. rural scenario.

H_{2a}: LoRaWAN will not perform better in urban vs. rural scenario.

H_{30}: LoRaWAN will perform similarly to modeling radio propagation system.

H_{3a}: LoRaWAN will not perform similarly to modeling radio propagation system.

3.1.2 Purpose

The purpose of this research was to test and evaluate the two environments and the signal propagation by utilizing two low-power technologies. LoRaWAN was then compared to existing, available, wireless propagation modeling software.

3.1.3 Significance of the Problem & Purpose

As previously noted, the benefit of this study was to gain a better understanding of signal propagation of NB-IoT and LoRaWAN technologies in two different environments. The two environments chosen for this study were rural and urban, due to IoT systems being highly utilized in both. The additional benefit was to understand and visualize the comparison of gathered data and wireless propagation software modeling engines, allowing for future predictions, planning, and research expansion.

3.1.4 Assumptions, Limitations and Delimitations

The main assumption of this study was that the instruments used were reliable and produce accurate data for further analysis. The other assumptions were related to the testing methods. The biggest limiting factor for the NB-IoT system was that only one carrier was used and there was no available information of the exact location of cell towers utilized by NB-IoT. Lastly, the study was limited to the West Lafayette and New Richmond area which have unique parameters when compared to different environments.

For the full list of assumptions, limitations, and delimitations reference Chapter 1.

3.2 Methods and Procedures

This section shows the detailed methods and the procedures taken in an effort to answer the research questions of this study:

- What is the performance evaluation of NB-IoT in urban and rural scenarios?
- What is the performance evaluation of LoRaWAN in urban and rural scenarios?
- How does the performance evaluation of LoRaWAN in urban and rural scenarios translate to modeling radio propagation software?

3.2.1 Device Configuration

Requirements and device configurations were presented in this portion along with the manufacturer’s specifications required to make the two systems operational for field testing. The equipment was chosen based on recommendations from industry professionals, professors, literature and on how easily devices can be acquired.

LoRaWAN

For LoRaWAN setup MULTITECH’s IoT Starter Kit for LoRa Technology was selected following the recommendations of Smith (2020) and Wolf (2020). The kit came with MultiConnect Conduit, MultiConnect mDot Box, MultiConnect mDot, MultiConnect mDot Developer kit board, GPS antenna, two LoRa antennas and other miscellaneous parts. The devices used for this test consist of MultiConnect Conduit, MultiConnect mDot Box, two LoRa antennas, GPS antenna, power supply for Conduit and 9V battery to power mDot Box. A visual representation of the equipment is presented in Figure 7.

Figure 7. *MultiConnect Conduit and Multitech mDot Box*

The MultiConnect Conduit “is a programmable gateway using an open Linux development environment to enable M2M connectivity using various wireless interfaces” (*MultiConnect® Conduit Hardware Guide* ®, 2018, p. 4). The device allows for data to be pooled and stored locally or sent to the application server via RJ-45 port to the internet. Additionally, the device has the ability to connect other add-on cards that can be installed as a failover method or a primary method of communication with the internet. The internet connection was not needed for this study which eliminated any additional configurations. The specifications needed for the study, such as LoRa frequency in the US device specified from 923.3 MHz to 927.5 MHz with an RF power output of 25.1 dBm (*MultiConnect® Conduit Hardware Guide* ®, 2018, p. 20) was noted.

Multitech mDot box is site a survey device that is capable of sending sensor information to the gateway. The device can act as a proof-of-concept and end device with a combination of LoRa gateway. Additionally, sensors implemented into the device such as Global Positioning System (GPS), accelerometer, pressure, altimeter, temperature, and light sensor make Multitech mDot box a perfect device for this study (*MultiConnect® MDot Box Hardware Guide*, 2018). The site survey data extraction from the Multitech mDot box was performed using a Windows 10 laptop, Putty software (*PuTTY*, 2013), and mDot Micro Developer kit with ribbon cable included in the kit by running the AT+GSDF command. The command listed all site survey points previously taken with all information available in the console view which permitted the information to be copied and further examined and graphed.

The two antennas provided with the kit are AN868-915A-1HRA antennas. According to MULTITECH’s Accessories Ordering Guide (*Wireless Products Accessories*, 2017, p. 20) and Digi-Key Elctronic’s (*AN868-915A-1HRA Multi-Tech Systems Inc. | RF/IF and RFID | DigiKey*, n.d.) website, antenna specifications are as follow:

- Antenna type: Whip, Tilt
- Antenna Gain: 3dBi
- Number of Bands: 2
- Frequency Group: UHF (300MHz ~ 1GHz)
- Frequency Range: 868MHz ~ 915MHz
- Frequency (Center/Band): 868MHz, 915MHz

The antenna radiation pattern was not available on the internet but from the research conducted shows the antenna follows normal omnidirectional radiation patterns.

The system configuration on both devices was left on default settings allowing for ease of use and the replication of the study.

NB-IoT

The NB-IoT setup utilized BC66-TE-B-KIT developed by QUECTEL, consisted of BC66-TE-B board, antenna, and a USB cord for connecting the device to a laptop or a computer. The kit was chosen because of the ability to integrate with multiple interfaces allowing for versatility and flexibility of the system. The board supports Arduino interface design and STM32 Nucleo-64 development board (*BC66-TE-B User Guide*, 2019, p. 8). Unlike MULTITECH's IoT Starter Kit for LoRa Technology, the kit required some additional configuration to the board and

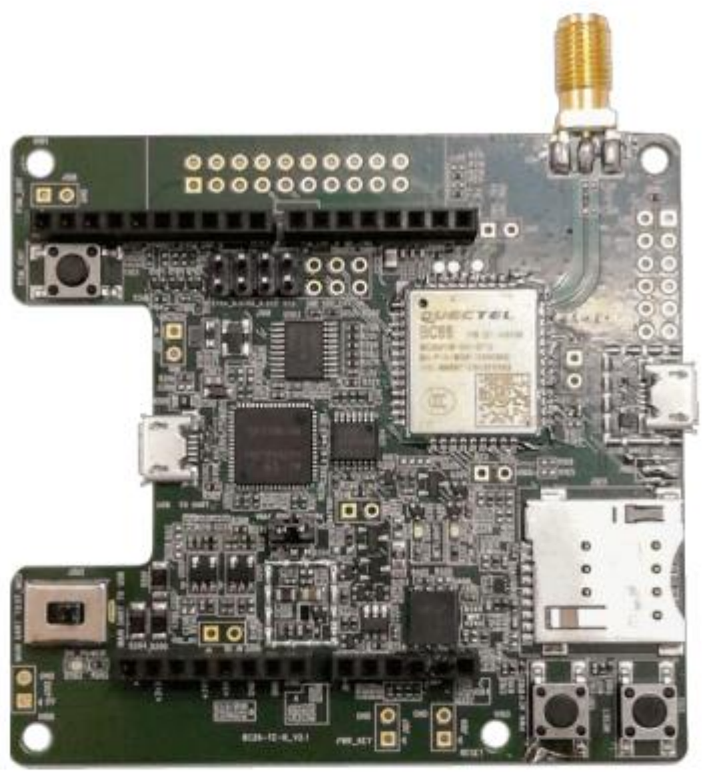

Figure 8. *BC66-TE-B (BC66-TE-B User Guide, 2019)*

purchasing AT&T’s NB-IoT plan including a SIM card. The top view of the board is presented in Figure 8.

AT&T’s NB-IoT One Rate Plan was chosen due to the chip on the BC66-TE-B board being certified with AT&T’s NB-IoT plan, removing any likelihood of incompatibility between the service provider and the device manufacturer. Additionally, AT&T’s NB-IoT One Rate Plan allows for one year of maximum throughput speed of 16kbps (*Products & Solutions - AT&T IoT Marketplace*, n.d.). The package only included one SIM card capable of standard, micro, and nano size implementation. Micro SIM card size was needed for the setup in this application.

In order to connect and configure the board, a laptop with 64bit Windows 10 (*Microsoft Windows 10 Pro*, 2020) operating system and Silicon Labs Virtual COM port Universal Driver for Windows 10 (CP210xVCPInstaller_x64 version 10.1.9) (*Silicon Labs Virtual COM Port (VCP) Universal Driver for Windows 10*, 2020) was installed. The software allowed for serial port connections to the board through QUECTEL’s QCOM_V1.6 software (*QCOM_V1.6*, 2014). QCOM_V1.6 software’s interface is designed for interaction between the user and the board via AT commands. These commands are used by modems in GSM, GPRS, and other wired and wireless systems giving them the ability to be configured. The required configuration essential to configure the board and commands used to collect RSSI and cell information needed for this research are presented in Table 3.

Table 3.

BC66-TE-B Configuration (Li et al., 2019)

Line No.	Command	Interpretation
1	AT+CPSMS=0	Disables power-saving mode
2	AT+QSCLK=0	Disables sleep mode
3	AT+QBAND=0	Search for all supported bands
4	AT+QCGDEFCONT="IP","APN"	Set PSD for PDN utilizing APN
5	AT+CGPADDR=1	Gives an IP address of the device
6	AT+QIDNSGIP=1,"www.google.com"	Gets IP address by the domain name
7	AT+CESQ	Gives extended signal quality

8	AT+QENG=0	Gives current modem status including cell serving the information
9	AT+QBAND?	Information on operating band

There was no specification for the antenna provided in the kit that could be used in this study, furthermore no information could be found in the official BC66-TE-B User Guide and no support was gained by contacting the support team of the product manufacturer.

3.2.2 Procedures

This section presents the location utilized in the study, how the data was collected, and which parameters were encountered when collecting the data for further analysis.

Locations

The first location representing an urban area was Purdue University's West Lafayette campus. The campus environment was characterized by a great diversity of building structures and building heights which are found in urban and suburban areas. Additionally, the variety of multiple story buildings, gyms, narrow spaces, garages, and stores add to the complexity of the urban area. As most communication methods in urban areas place systems and/or antennas on top of buildings, this study wanted to replicate those environments by placing a MultiConnect Conduit on top of a five-story building. A five-story building is a good model of building height for which most small and big urban areas would find applicable. A detailed map and the location of the building is presented in Figure 9. Location L00 represents the gateway's placement on top of the building. A more detailed placement position can be found in Appendix B, Figure 23.

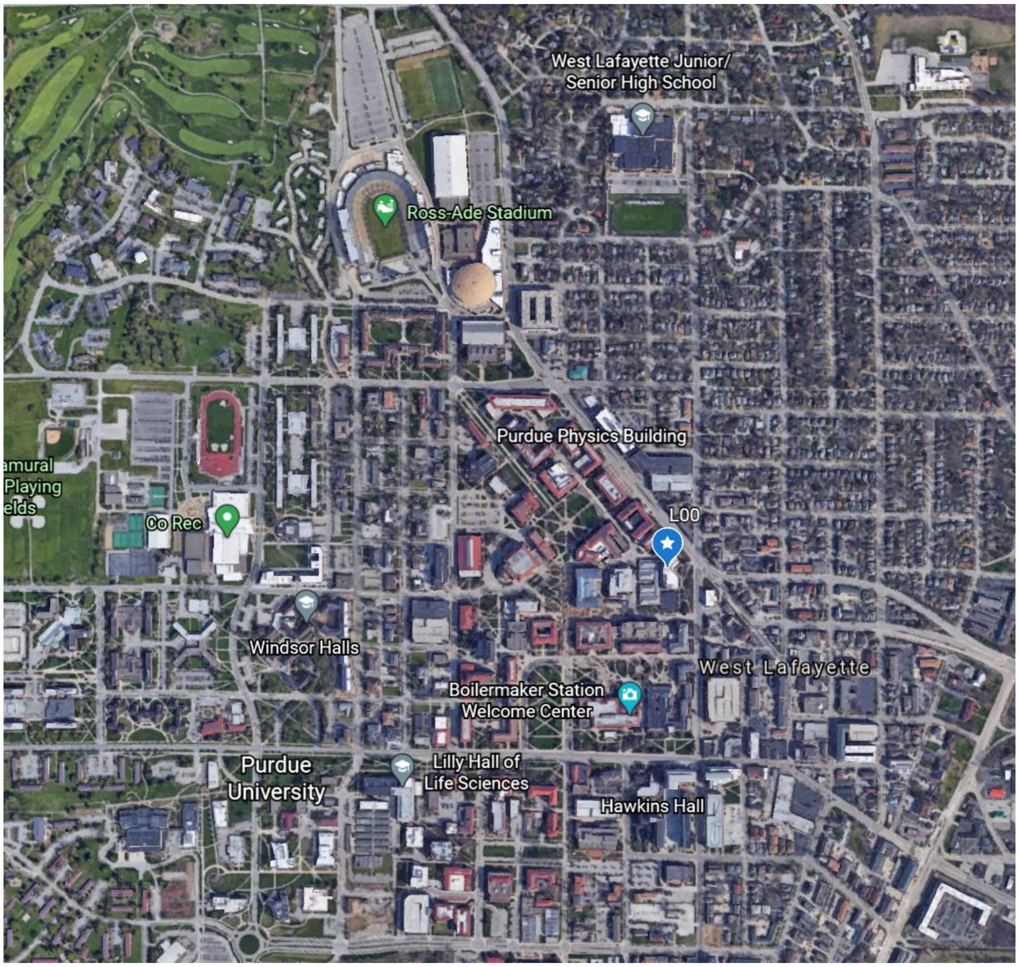

Figure 9. *Urban Location*

The second location for this study was a rural environment. For this location, multiple variables were taken into consideration. Rural areas often have a mixture of multiple fields, forests, farms, scattered objects, and elevation changes. The location that incorporated all the parameters was just south-west of West Lafayette shown in Figure 10 Location L00 represents the gateway's placement roughly 1m of the ground level. The detailed picture of the gateway's placement is presented in Figure 22 of Appendix B.

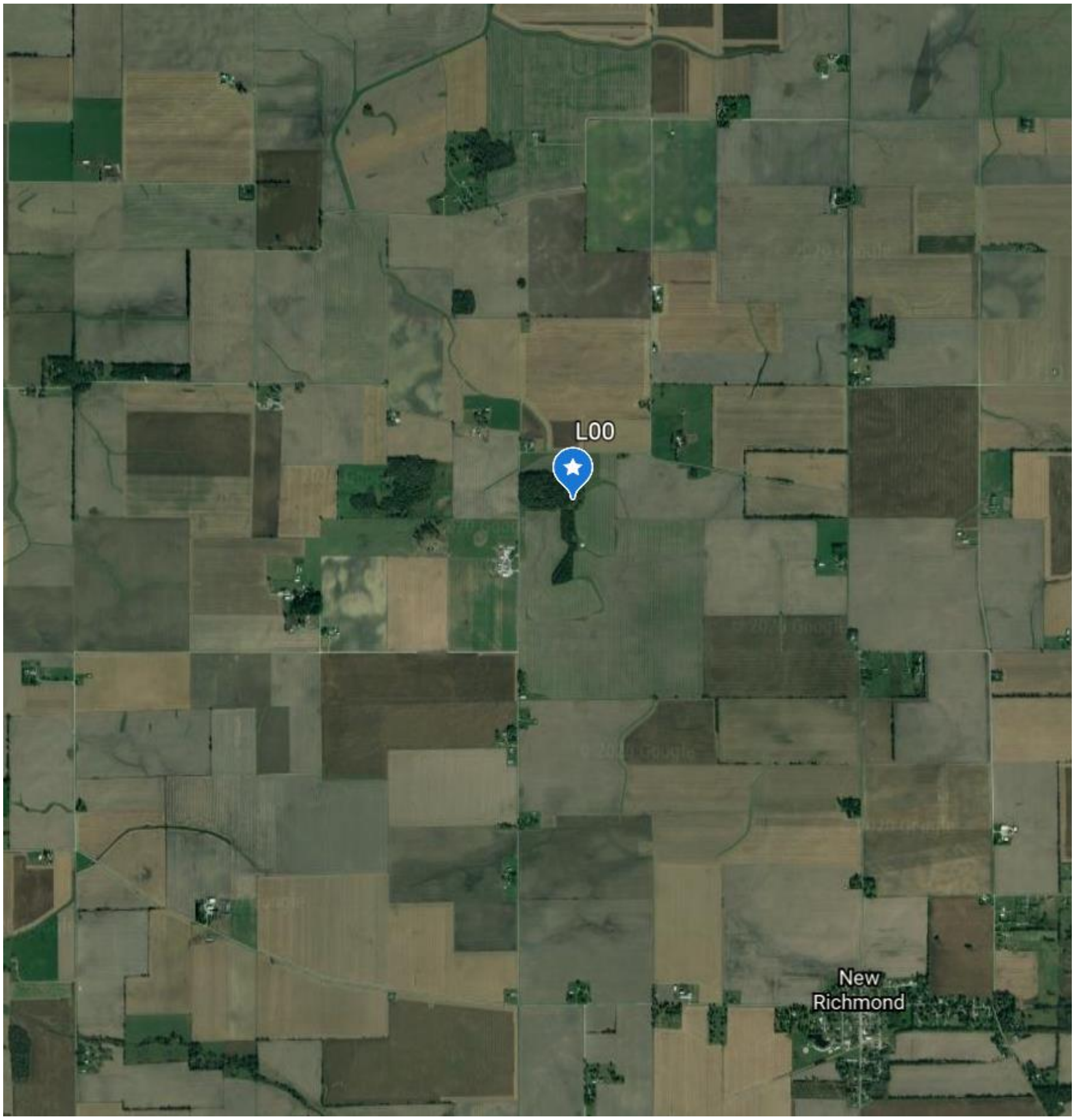

Figure 10. *Rural Location*

For the purpose of data collection locations selected, numbered between forty and forty-five points. This ensured optimal coverage of the terrain in all directions. Location points for LoRa and NB-IoT survey were chosen around the center of MultiConnect Conduit placement since LoRa required a fixed location from the gateway. To ensure exact locations for both systems, GPS coordinates were recorded by the Multitech mDot box. The showcase of the locations is presented in Figures 11 and 12 while GPS locations are recorded in Table 6 and

Table 7 in Appendix C. Blue placemarks with a dark blue dot inside represent survey locations where LoRa and NB-IoT were surveyed. Blue placemarks with a white star inside represent the placement of MultiConnect Conduit.

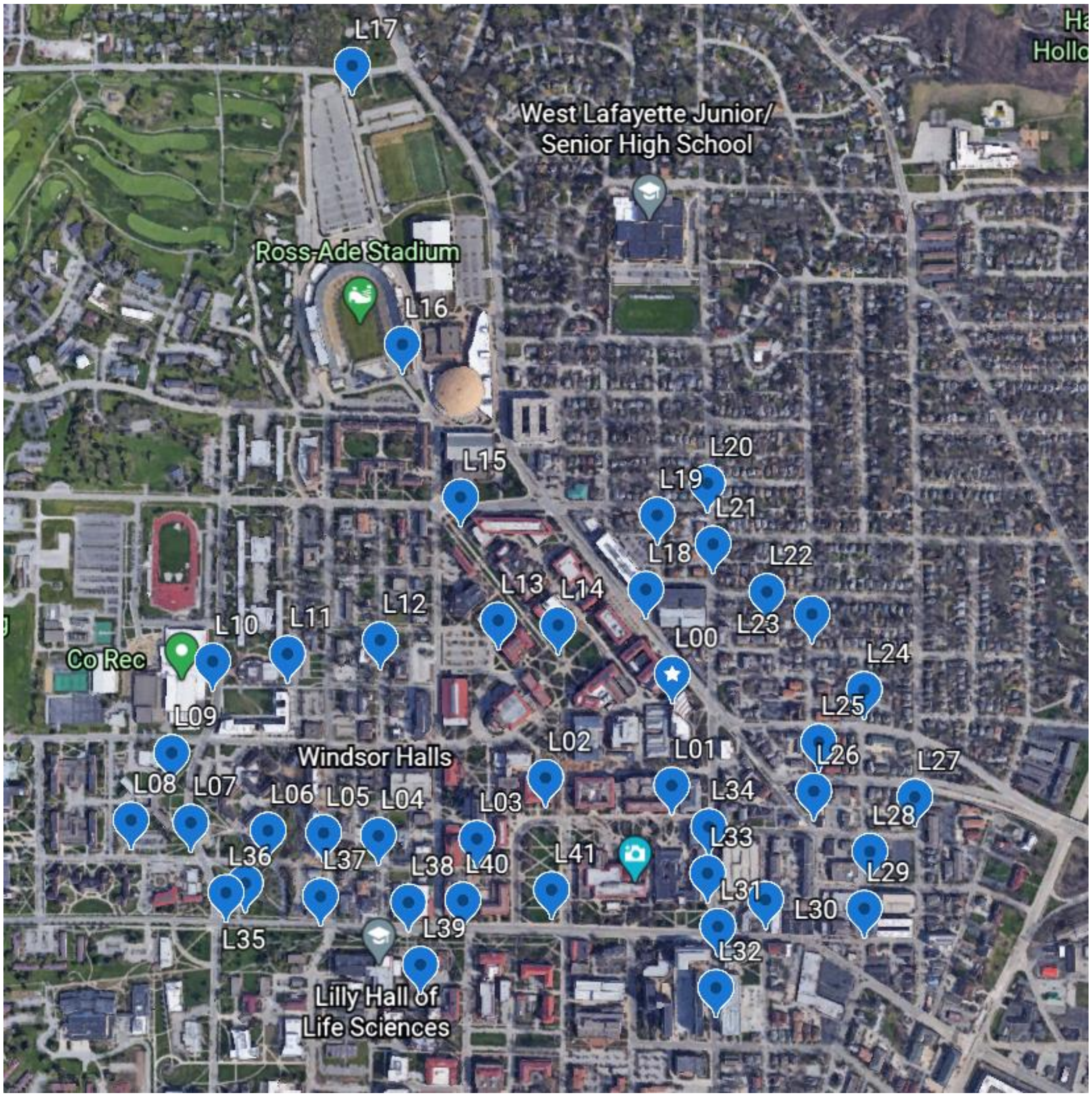

Figure 11. *Urban Location – Survey Points*

Survey points on Figure 12 are taken along the roadside due to the land belonging to private parties.

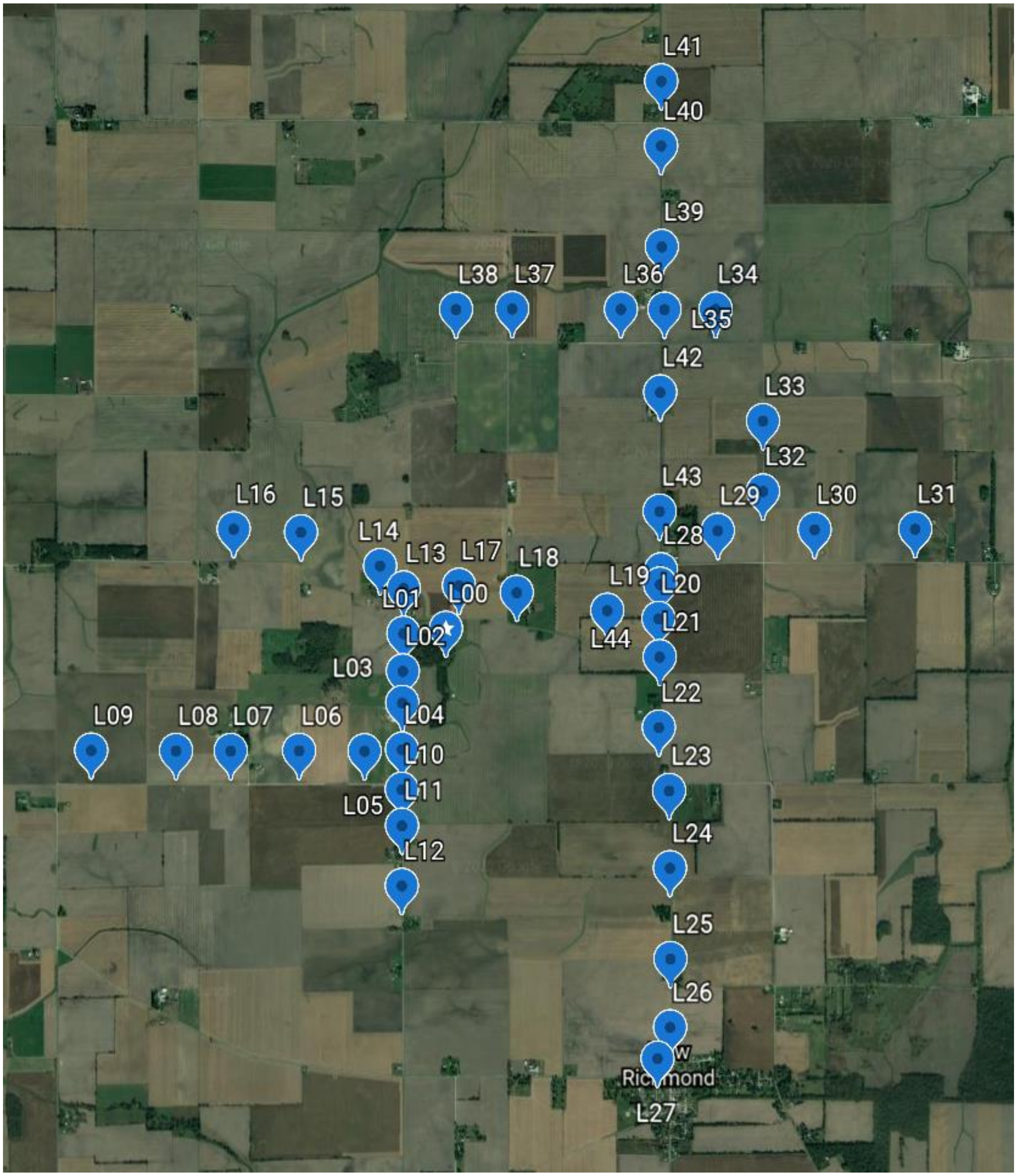

Figure 12. *Rural Location – Survey Points*

Note: *Every figure above is aligned where the top of the figure is pointed towards the north.*

Data Collection

The data collection process consisted of gathering data from two separate devices, Multitech's mDot box, and Qectel's BC66-TE-B board. The data in urban locations were gathered by a surveyor walking around and pausing for 3-5 minutes from around 0.9m above the ground level, ±0.2m difference, as shown in Figure 24 in Appendix D. For the rural environment site survey data, the devices were mounted to a car (height 1.5m, ±0.1m) which can be seen in Figure 25 in Appendix D. During the data collection in rural areas, the car was driven to the locations and set to rest for 3-5 minutes before the data was collected to ensure the static gathering of information. In addition, if there was no data collected at the first try the commands were reentered two more times to eliminate any potential device malfunctioning. As a final test and proof that the devices stayed calibrated during the survey, the last data gathering was at the initial location and was compared with the results of the first data gathering. If they were in the acceptable range the results were assumed to be valid, if not, the survey was repeated.

The data collected from Multitech's mDot box came in the format showing different values presented in Table 4 below (*MultiTech Developer Resources » Survey Data File*, n.d.). Data utilized in this study used ID for location information, latitude and longitude for accurate location position, and RSSI for measuring downlink signal strength.

Table 4.

Multitech's mDot Output Format

Variable	Interpretation
ID	Identifies the line as a single survey or part of a sweep and contains the corresponding index
Status	Specifies if the survey was a success or failure
Lock	GPS lock (# of satellites)
Lat	Latitude (recorded from GPS)
Long	Longitude (recorded from GPS)
Alt	Altitude (recorded from GPS)
Time	Time (recorded from GPS)
Gateway	How many gateways heard the link check request
Margin	Signal margin above the demodulation floor (in dBm)
RSSIdown	Downlink signal strength (RSSI)
SNRdown	Downlink signal-to-noise ratio (SNR)
DataRate	TX datarate used
Power	TX power used

If there was no connection the fields would be empty and the status indicator would show F (failed) as an indication of an unsuccessful survey.

The output information format from Qectel's BC66-TE-B board connected via QCOM_V1.6 software differed compared to Multitech's mDot box format. By running the command, *AT+QENG=0* would display necessary information for the study. If the mode of AT+QENG function was equal to zero a user would get the following response format (Li et al., 2019, p. 27):

+QENG:0,<sc_earfcn>,<sc_earfcn_offset>,<sc_pci>,<sc_cellid>,[<sc_rsrp>],[<sc_rsrq>],[<sc_rssi>],[<sc_sinr>], <sc_band>,<sc_tac>,[<sc_ecl>],[<sc_tx_pwr>],<operation_mode>

The information presented is interpreted in Table 5.

Table 5.

AT+QENG=0 Command Interpretation (Li et al., 2019, p. 27-30)

Variable	Interpretation
0	Display radio information for serving and neighbor cells
sc_earfcn	Integer type. The EARFCN for serving cell. Range: 0-262143
sc_earfcn_offset	Integer type. The EARFCN offset for serving cell
sc_pci	Integer type. Serving cell physical cell ID. Range: 0-503
sc_cellid	String type. Four-byte (28-bit) cell ID in hexadecimal format for serving cell
sc_rsrp	Signed integer. Serving cell RSRP value in dBm (can be negative value)
sc_rsrq	Signed integer. Serving cell RSRQ value in dB (can be negative value)
sc_rssi	Signed integer. Serving cell RSSI value in dBm (can be negative value)
sc_sinr	Signed integer. The last SINR value for serving cell in dB (can be negative value)
sc_band	Integer type. The current serving cell band
sc_tac	String type. Two-byte tracking area code (TAC) in hexadecimal format
sc_ecl	Integer type. The last Enhanced Coverage Level (ECL) value for serving cell
sc_tx_pwr	Signed integer. The current transmit power of UE
operation_mode	Integer type. Operation mode of the serving cell

Information collected from the *AT+QENG=0* command output was *sc_rssi* and *sc_cellid*. As stated in the previous table RSSI output will allow the display connection to the cell tower and show signal value. If the board was not connected to the cell tower the return command looked as follow:

AT+QENG=0

ERROR

Once the data was extracted throughout the methods explained in the device configuration section previously, the records were copied and sorted into separate CSV files.

Data Analysis

After extracting the data from the devices and storing the data in the four CSV files. One file per each location of the two systems. This section shows how the files were processed and analyzed.

Following the four files being created unnecessary information was removed from the files. For this step, Microsoft Excel (*Microsoft Excel*, 2016) was applied to remove columns and line up the data for further research. The columns left in the files included location ID, latitude, longitude and RSSI, cell_id information. The cell_id information column was left due to the attempt to locate the cell tower and measure the distance from the node.

With the information sorted in CSV files, Google Earth (*Google Earth*, 2020) web application was utilized to depict the locations where the connection was successful and where the connection failed to succeed. The maps were downloaded as .KML files for future analysis or for any additional improvements. Creating the files allowed for detailed analysis of data gathered and propagation of the signal in an urban and rural environment which will be further discussed in Chapter 4 Results. The final step in this process was calculating the distances from the L00 placemark to the remaining locations allowing for more detailed analysis and examination. The distances were rounded to the nearest whole number.

Lastly, CloudRF model propagation maps were created to be compared to LoRaWAN survey information created by this study. Survey information was given in .KML files allowing the interpretation through the Google Earth web application. A comparison of these two parameters depicted the differences between software model propagation and initial surveys. Parameters used for CloudRF model propagation listed below:

- Site/Tx – Latitude: latitude of the site used
- Site/Tx – Longitude: longitude of the site used

- Site/Tx – Height AGL: 21.5m (urban); 3m for the rest of the sites (minimum value)
- Signal – Frequency: 915 MHz
- Signal – RF power: 25.1 dBm
- Signal – Bandwidth: 1MHz
- Antenna – Pattern: RF Industries Pty Ltd COL2195.ADF (closest specifications to factory antenna
- Model – Model: Okumura-Hata (0.15-1.5GHz)

Representation of CloudRF's software user interface is represented in Appendix G.

3.3 Summary

Chapter 3 presented a detailed two-section methodology of the research. The first section reiterated the content provided in Chapter 1 to remind the reader of the problem, significance, and purpose of the research. The second section, methods, and procedures displayed the exact steps taken to complete the project starting with, what was needed to configure the devices and make them operational to how the locations were chosen, and methods on how the data was collected and analyzed.

CHAPTER 4. RESULTS

In this section of the document, gathered data was analyzed and interpreted. As presented in the previous chapter, four different files were created alongside two different Google Earth maps with survey locations representing urban and rural areas, respectively. This led to the chapter being divided into two major sections (1) Experimental Results, where LoRaWAN and NB-IoT coverage surveys were analyzed and (2) Theoretical Coverage Study of LoRaWAN where pre-build radio propagation modules were compared with existing site surveys of LoRaWAN.

4.1 Experimental Results

The experimental results section presents the plotted data gathered during the survey. The section is divided into two subsections based on the two different technologies used. Each subsection contains a detailed overview of the survey data and its analysis.

The coloration of placemarks is depicted as the blue placemark with the white star in it representing the starting location/ location of the LoRaWAN gateway. In all the following figures this place is marked as L00 where “L” represents the location chosen in the methodology chapter and corresponding coordinates to the map are referenced in Appendix C. The green placemarks with dark green dots inside of them represent a successful connection to the gateway or the cell tower. The red placemarks with dark red dots inside symbolize a failed connection to the gateway or the cell tower.

4.1.1 LoRaWAN

The following sections discuss LoRaWAN coverage in urban and rural environments conducted by this research.

Urban

The first site survey taken was in the urban area utilizing LoRaWAN. From Figure 13 below it can be seen that there are 12 locations where the survey was not able to be completed.

The shortest distance where the signal transmission was not successful was in L20 compared to L00 and is approximately 367 meters (Table 8 in Appendix E). In the direct line of sight between L00 and L20, there are large multi-story buildings. The structures like this can interfere with the signal propagation and have an impact on overall distance. Even though L20 (367m) and L26 (356m) had a similar distance from L00, a large building was in the way between L00 and L20

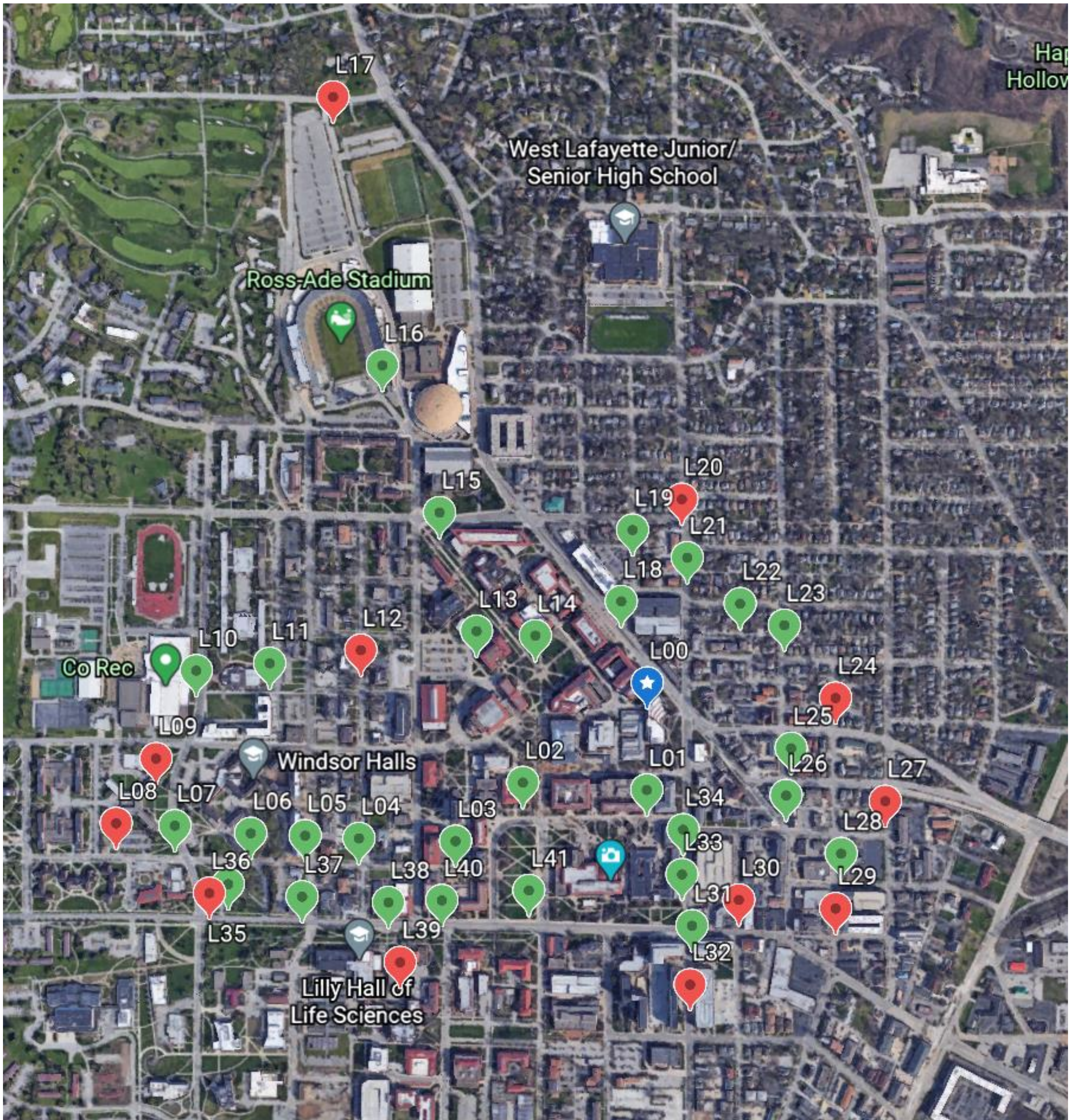

Figure 13. *LoRaWAN Coverage Map -Urban*

which caused an unsuccessful connection. Another representation of this situation is in L30 where there is a multi-store garage between the two locations. The failure in L24 was considered as out of the ordinary but the building right in front of the location could possibly be obstructing the signal.

On the contrary, the furthest distance reached was in L07 measuring approximately 974 meters. There are a few possible variables that could have played into the result obtained. In this instance, a clearer line of sight can be observed and there were not as many obstructions along the way.

Another observation worth mentioning was on the east side of the map in L24, L27, and L29 (Figure 13). These three locations are on downhill compared to the L00 and this could have influenced the failure of the connection. Due to the altimeter in Multitech mDot Box not gathering trustworthy values, the exact altitude difference in these three spots could not be determined but from the surveyor's perspective, the altitude was drastic.

Rural

The experimental study of LoRaWAN in the rural area gave contrasting results when compared to the urban testing environment. The reached distances were longer despite the gateway being placed closer to the ground (approximately 1m from the ground level). Additionally, in the rural compared to the urban area, there were fewer distortions of elevation. The longest distance of 3939 meters reached was at L40 with RSSI reading of -109 dBm (Table 9 in Appendix E). Despite the transmission working well in the noise floor, this was not the lowest number with a successful transmission. At the L25 (Figure 14) the RSSI value was -122 dBm which can be considered as the limit of the successful signal broadcast. The loss of the signal in L20 was not anticipated but can be associated to a hill that is blocking the direct line of sight between L00 and L20. The loss of the signal at L35 was tested three times and remained unsuccessful despite the almost clear line of sight and other locations around it having a successful broadcast.

In locations L13, L14, and L15 (Figure 14) the transmission had to go through roughly 350 meters of forest. The distance of L13 from L00 was measured to be 457 meters with -102 dBm RSSI. L02 had relatively the same distance measured 454 meters, minimal altitude difference, and RSSI of -84 dBm but mostly the transmission did not propagate through the forest. The difference of 18 dBm between these two locations with similar distances can be ascertained to be due to the forest. The study was performed in the fall when the amount of leaves in the forest was minimal to none. A difference in foliage can impact the outcome if the research if done during a different time of the year.

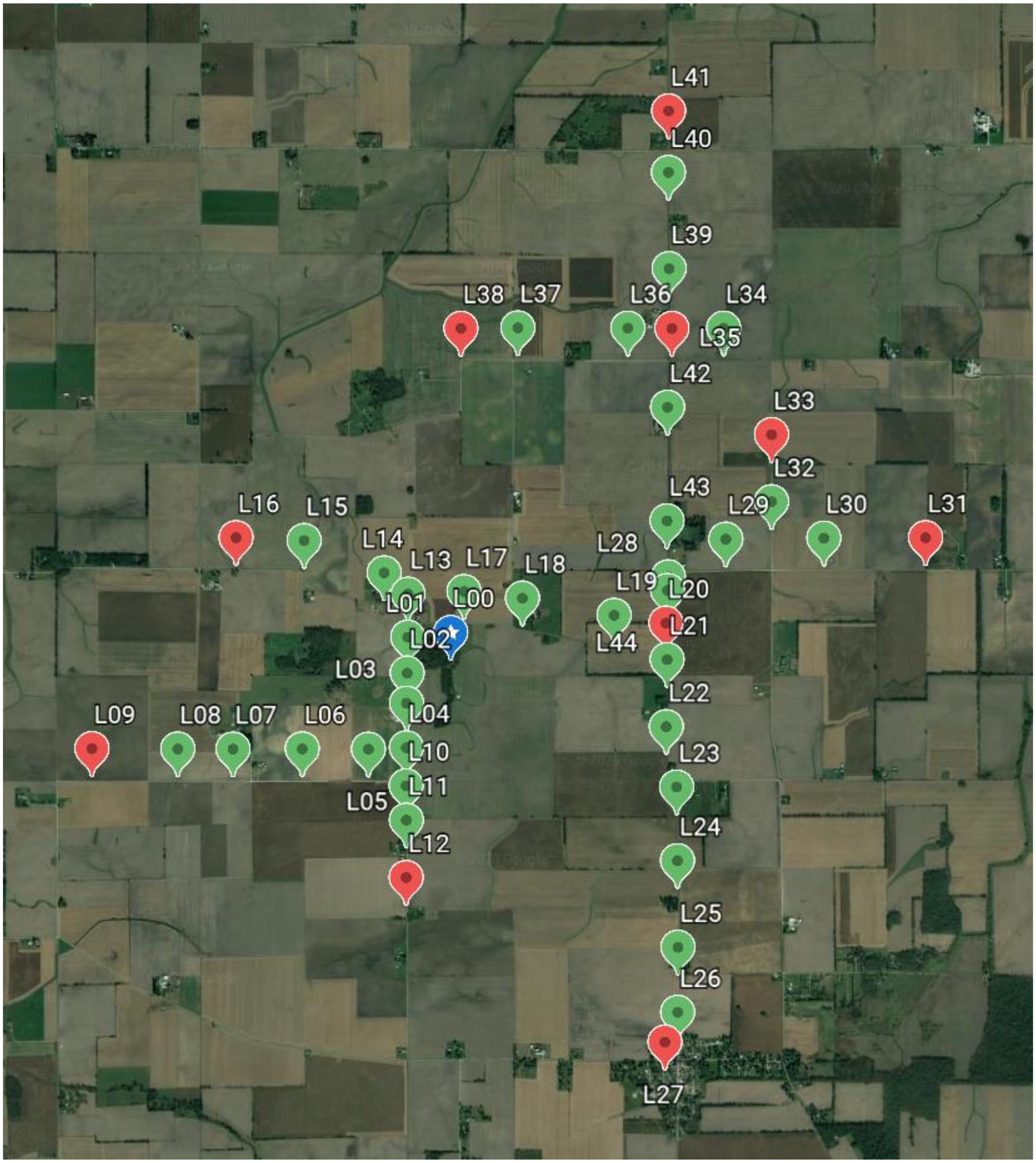

Figure 14. *LoRaWAN Coverage Map – Rural*

4.1.2 NB-IoT

The following sections discuss NB-IoT coverage utilizing AT&T's service in urban and rural environments.

The data interpretation of NB-IoT in urban and rural area differs from LoRaWAN's data interpretation. The difference in system architecture and the ability to collect accurate information on cell tower locations, which the NB-IoT device connects, is one of the limitations of this study. From the research conducted, the cell tower location and information are proprietary information to carrier and is not available to the public. Nevertheless, the information to which cell tower the NB-IoT device was connected is recorded for future studies in case that information ever becomes public. The cell identifier (*sc_cellid*) field (Table 10 and Table 11 in Appendix F) is a hexadecimal number that needs to be converted to decimal.

Urban

The overall performance of Qectel's BC66-TE-B board shown in Figure 15 had eight places where the signal was not received, predominately in the south-east region of the survey. Out of the eight locations with no signal received, L27, L28, L29, L31, L32, and L33 are located in the area where the building's infrastructure is denser and higher compared to the rest of the survey. L25 and L26 are in residential areas where buildings did not exceed three to four stories. The assumption could be given that the cause of this was due to the distance from the cell tower or other obstruction between the cell tower and the location being present. In L30 the connection process had to be performed three times before the connection was established.

The lowest RSSI received during the urban survey was in L13 (Table 10 Appendix F) with a value of -80 dBm. The best RSSI received was in L04 with a value of -43 dBm. The majority of the locations with the successful connection varied from -43 dBm to -64 dBm.

In the urban study, four different *sc_cellid*'s were recorded: 2EA3039, 2EA453B, 2EA303A, and 2EA1E3A.

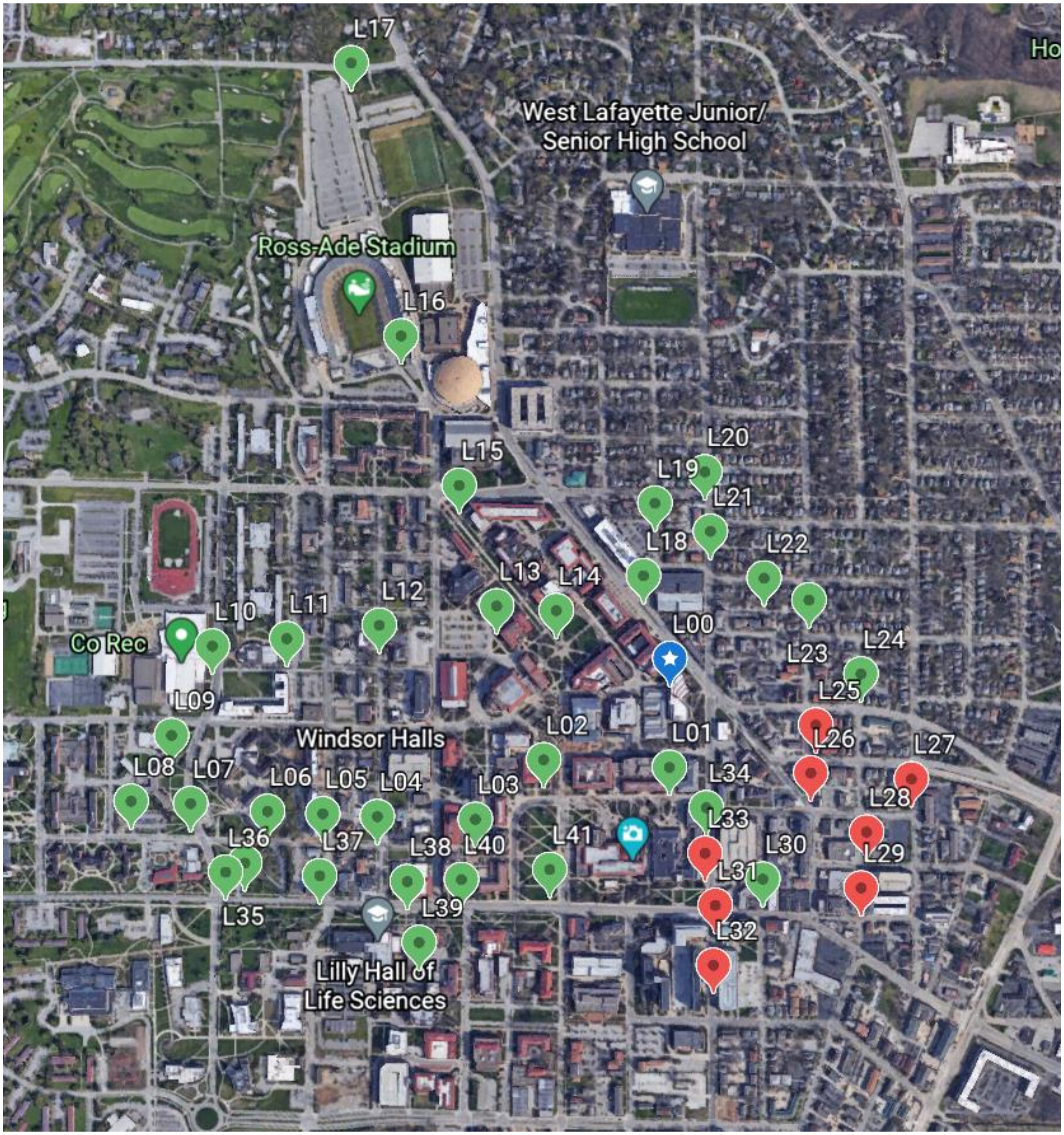

Figure 15. *NB-IoT Coverage Map - Urban*

Rural

Compared to the urban environment, the performance of Qectel's BC66-TE-B board utilizing AT&T's network in the rural environment did not receive any signal in only four locations (Figure 16). The strongest signal was in L28 with the RSSI value of -64 dBm. Moreover, the weakest signal that allowed the successful broadcast was in L27 with the RSSI value of -86 dBm (Table 11, Appendix F). There were only two locations where multiple

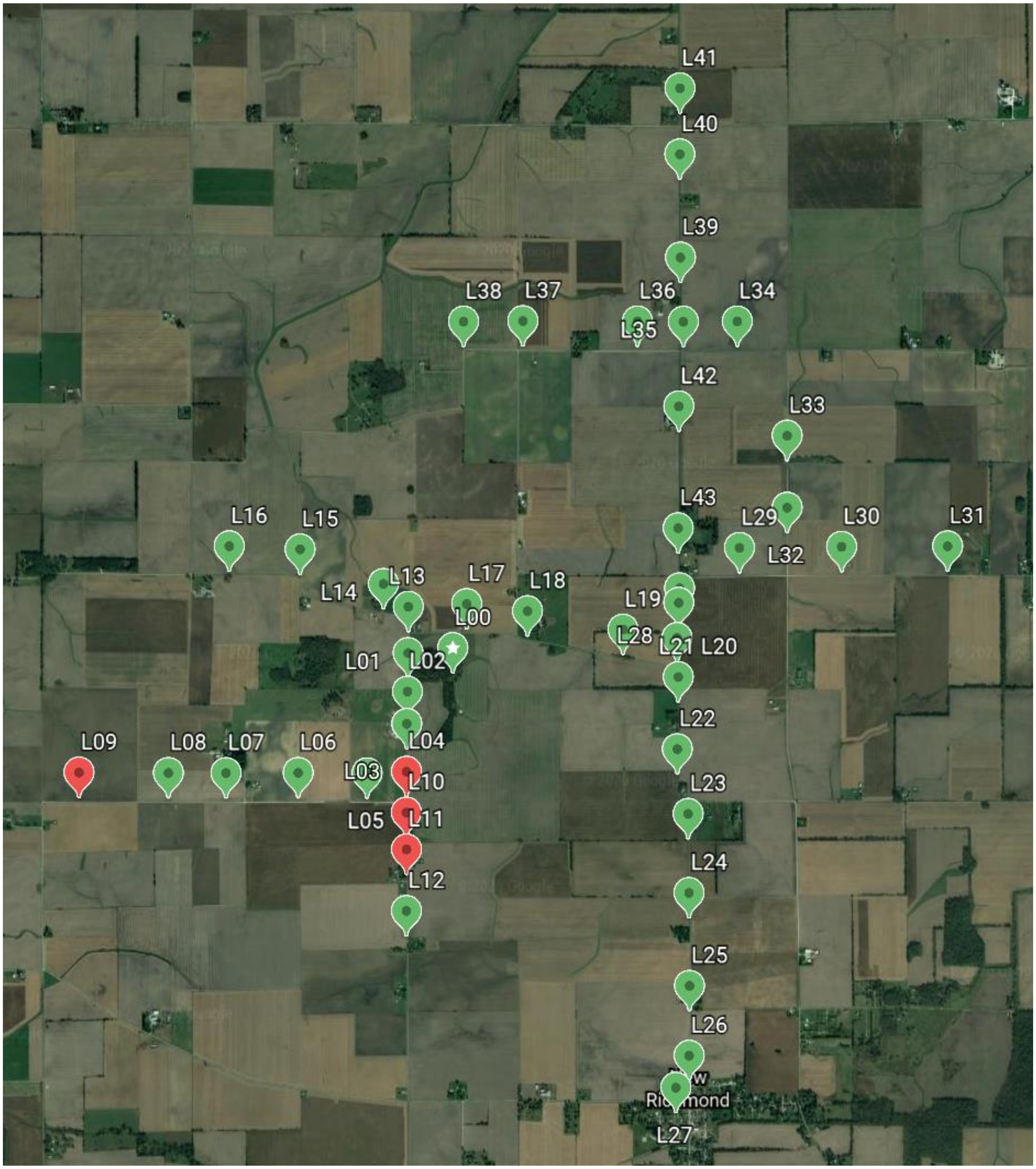

Figure 16. *NB-IoT Coverage Map – Rural*

reconnections tries were successful. In L05 where after two tries connection was reestablished with the final RSSI reading of -75 dBm and in L12 where three tries were enough to receive RSSI of -74 dBm.

In the rural survey study, three different *sc_cellid*'s were recorded: 2EA313B, 2F1F33B, and 2EA313A.

4.2 Theoretical Coverage Study LoRaWAN

After performing the experimental study, CloudRF (*CloudRF - Model The Future*, 2020) web service was utilized to analyze, compare and contrast the data gathered from the modeling radio propagation service and two LoRaWAN site surveys. CloudFR "employs topographic maps in order to consider the impact of the terrain elevations on the signal propagation and presents highly configurable options to precisely simulate the characteristics and conditions of the real equipment" (Sanchez-Iborra et al., 2018, p. 9). The two radio propagation models created by CloudRF were for the urban (Figure 17) and rural (Figure 18) environment. The Tx (the gateway's) location used the coordinates of L00 locations from Appendix C related to the LoRaWAN survey.

The NB-IoT system was not analyzed in this section due to the unconfirmed locations of cellular towers used by Qectel's BC66-TE-B board.

4.2.1 Urban

In the first radio propagation model presented in Figure 17, the radius was set to 1500 meters due to the location of the furthest measured point in the urban LoRaWAN survey. Additionally, the radius puts the distance perspective on Figure 17. On the right-hand side of Figure 17, the dBm chart with multiple colors represents the loss in a relation to the Tx point on the map. As can be seen from visual analysis most of the coverage radius is between -50 dBm and -78 dBm apart from several dead spots. When compared to the actual survey data performed for this research results vary greatly. As it can the referenced from Table 8 Appendix E the longest distance reached was at L07 measuring approximately 974 meters with RSSI reading of -111 dBm (marked with a red star in Figure 17.). The outcome produced for the theoretical coverage map in urban areas does not resemble similarities to the site survey recorded. Buildings and other obstacles in the area of the survey did not seem to affect signal propagation as expected. Around certain larger structures, there is a coverage loss but only to a degree.

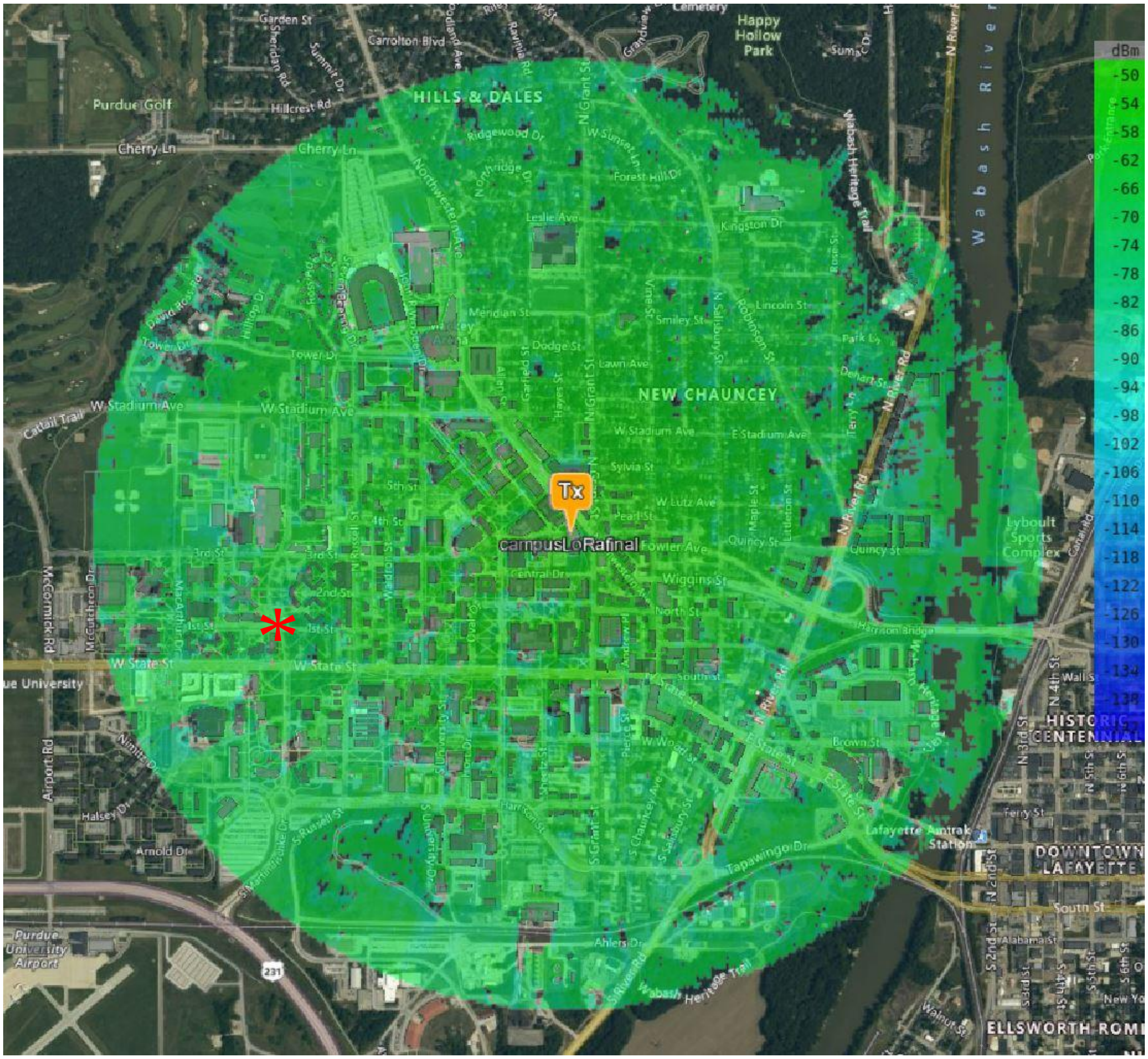

Figure 17. *LoRaWAN Theoretical Coverage Map – Urban*

4.2.2 Rural

In the second radio propagation model presented in Figure 18, the radius was set to 5000 meters. The height of the gateway in the propagation model needed to be set to 3 meters above the ground due to the minimum requirements of the Okumura-Hata (0.15-1.5GHz) model where the LoRaWAN gateway was located approximately 1 meter off the ground. The parameters of signal propagation stayed the same as in Figure 17 showing the coverage color scheme from green representing -50 dBm to dark blue representing -142 dBm value. Despite the difference between the base height of the gateway in the initial survey and the propagation model, the results were much more relatable to the survey conducted. Placemark L40 (marked with a red star in Figure 18) had the longest distance of 3939 meters with the RSSI reading of -109 dBm (Figure 9, Appendix E). Comparing that location to the theoretical coverage map in rural area location, where the dBm reading is around -98 dBm is a slight difference compared to what was seen in the previous section. Another example is L26 (marked with a white star in Figure 18) placemark near where the signal propagation on the theoretical coverage map intermittently showing an approximate reading between -102 dBm and -106 dBm. In the L26, RSSI reading is -120 dBm which is close to the difference in ratio from the previous example, with a consideration for the overall range.

The forest on the north-west did not appear to change propagation patterns much as compared to L00 placemark.

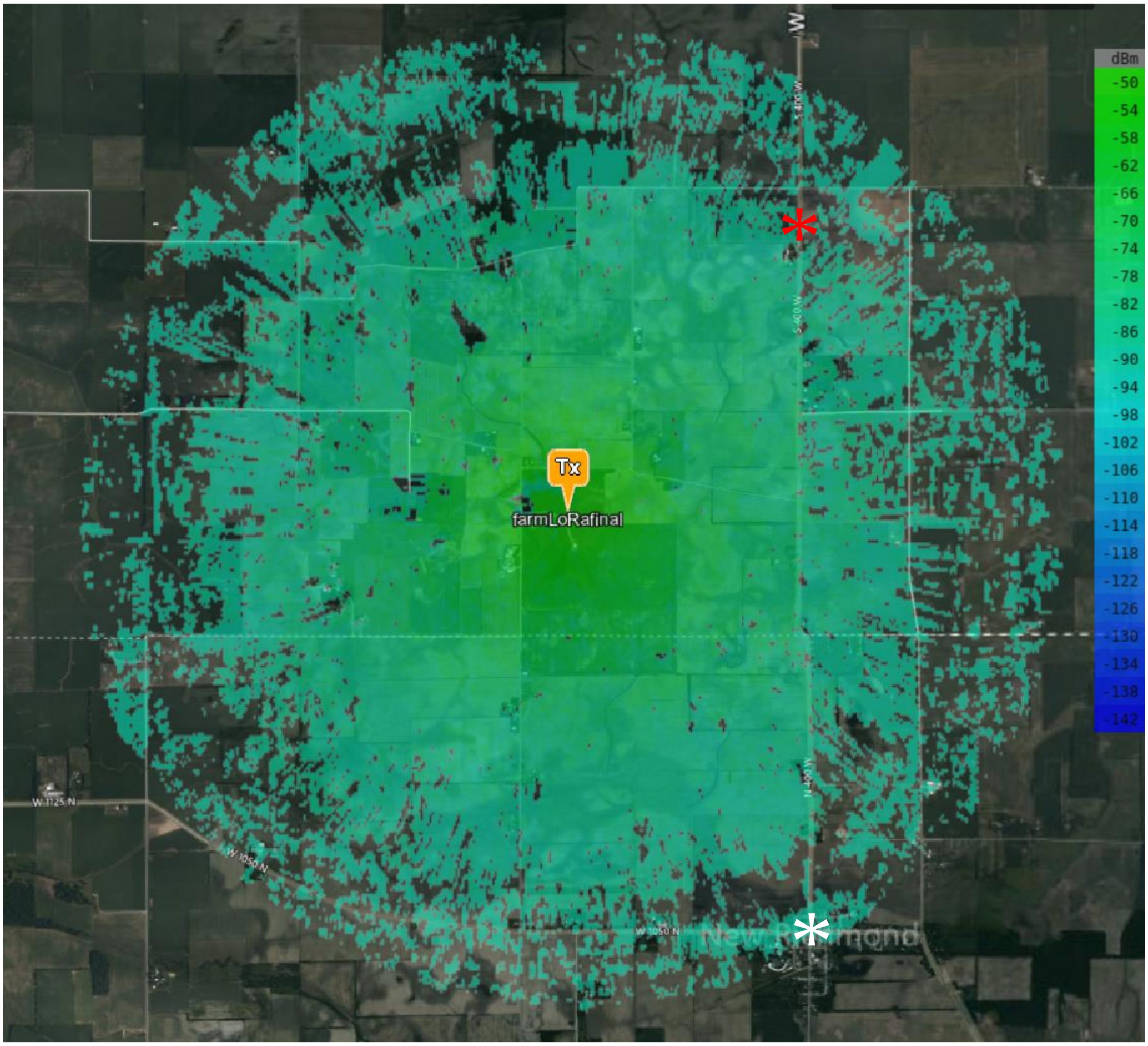

Figure 18. *LoRaWAN Theoretical Coverage Map – Rural*

4.3 Summary

Chapter 4 presented the performance evaluation results of the study from two drastically different locations properties incorporating two different systems, LoRaWAN and NB-IoT. The previously collected data was plotted into figures created in Chapter 3 and further analyzed by use of the theoretical coverage map to enhance understanding. As per hypothesis NB-IoT and LoRaWAN performed better in the rural scenario. The modeling software (CloudRF) was not comparable to LoRaWAN site survey propagation patterns conducted in an urban environment, whereas in the rural environment the propagation patterns were very close compared to the survey.

CHAPTER 5. CONCLUSION AND FUTURE WORKS

Chapter 5 concludes the research previously completed by interpreting the results analyzed in Chapter 4 and providing answers to the research questions asked in Chapter 1. Additionally, the limitations of the results are debated and finally, the possibilities of the future work of this study are introduced and discussed.

5.1 Conclusion

The purpose of this study was not to compare the NB-IoT system to the LoRaWAN system but, rather to gain a better understanding of the system's coverage and performance in two different environments. Furthermore, the research is just a first step, showing one of the multiple possibilities that can be taken into account when evaluating low-power networks. With LPWAN and IoT growing rapidly the variations of practices shown can be translated to future studies and the flexible nature of the results collected allows for an effortless continuation if and when necessary. Different variables used in this study such as RSSI, distance, infrastructure, lack of infrastructure, and the terrain properties showed how signals can be distorted to the original and expected propagation.

During the LoRaWAN testing, the furthest distance reached in the urban area was 974 meters with the gateway height of 21.5 meters above the ground level. The shortest distance in an urban area where the signal was not successfully propagating was 367 meters where multi-story infrastructures were obstructing the view. In the rural area, LoRaWAN performed better despite the gateway being placed only 1 meter above ground level. The longest distance reached was 3939 meters with RSSI reading of -109 dBm, receiving well in the noise floor. Some observations made were the influence of nearby forest on the signal propagation but overall, the LoRaWAN system had better coverage in the rural area.

Despite the challenges faced with the cellular towers not providing known locations, the study utilizing the NB-IoT system produced viable data. Overall, Qectel's BC66-TE-B NB-IoT board showed eight spots where the signal was not propagated in urban areas and four spots in rural areas, concluding again better performance in rural areas. The study's data is only applicable to AT&T's cellular network since the SIM card used was manufactured to serve only on the network. The coverage maps in the same areas could look different if another service provider is operated.

The CloudRF modeling radio propagation service created was compared to the site surveys taken for this study in rural and urban environments. The results showed vast differences in propagation patterns and distances in urban areas when compared to each other. In the rural environment, the difference between the modeling service and the actual survey maps was much closer when compared with RSSI parameters, even with the gateway elevation differing 2 meters.

In both systems, signal propagation was more consistent in rural areas. As seen from the results in the previous chapter neither of systems are 100% reliable in the areas tested.

5.2 Future Works

This research allows for an effortless expansion of the study and is just the first step and purposed starting point for future studies. The expansion of the study can be accomplished with the *sc_cellid* data collected, but due to the proprietary information of the network provided via a cellular tower, the researcher was not able to determine the exact locations resulting in the inability to analyze the data the same way as LoRaWAN site survey.

Within the study, only two communication methods were analyzed and portrayed limitations. To reduce those limitations, the future works for this study would be to create a platform or a testbed of multiple low-power communication methods with multiple different manufacturers. This will allow for better performance evaluation as well as side by side and one to one comparisons of the systems. The testbed will be modular by letting quick and easy incorporation of the new elements as well as the flexibility of easy location change. Additionally, designing, building, and validating the testing environment for low-power networks in IoT can be essential for teaching efficiency. Having a physical testing environment at the beginning of the courses will not only be beneficial to the students while learning the concepts but to the professors and teaching assistants in explaining them. This has been shown by Korwin and Jones (1990) in the study where hands-on learning had much better results compared to traditional lecturing. Another paper published by Kontra, Lyons, Fischer, and Ceilock (2015) explains the benefits to hands-on learning showing students in this environment have better test scores. Additional evidence according to Kontra et al. (2015) comes in the form of brain scans showing activation in parts of the brain associated with better test scores and activation when engaging in motor and sensory activities.

Furthermore, testing environments such as the one introduced in this research can be used for assessing compatible designs and evaluating new devices in an ever-growing market. Norton, an antivirus and security software company, predicts that by 2025 there will be over 21 billion IoT devices (Symanovich, 2020), with so many devices in demand within the industry this will create a lasting impact on information, technology, and security programs at colleges and universities.

The importance of the testing environment as presented in the paper published by Harvard University stating that “to support continued innovation in these areas, we believe that it is critical to develop large-scale testbeds and development environments” (Murty et al., 2007, p. 6). With these already developed testbeds students will have greater time to allocate to research that can be industry-specific, each industry can then utilize this information as a starting point to resolve issues, this will positively impact grades which are a reflection of the research work they complete.

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APPENDIX A. ADDITIONAL COVERAGE MAPS

Note: *All rights to the data in this Appendix are reserved to Frank Wolf. Used with permission.*

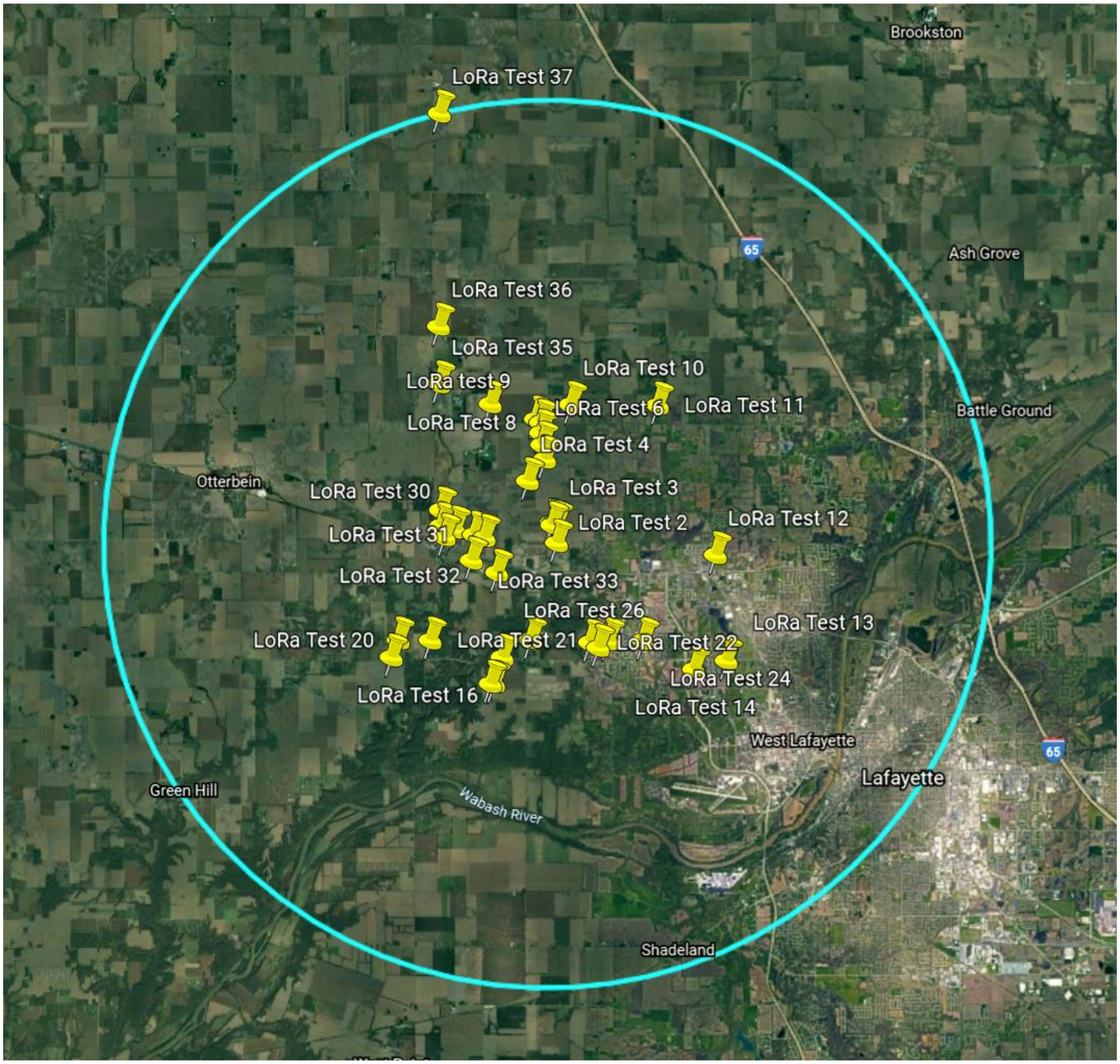

Figure 19. *ACRE Survey Map*

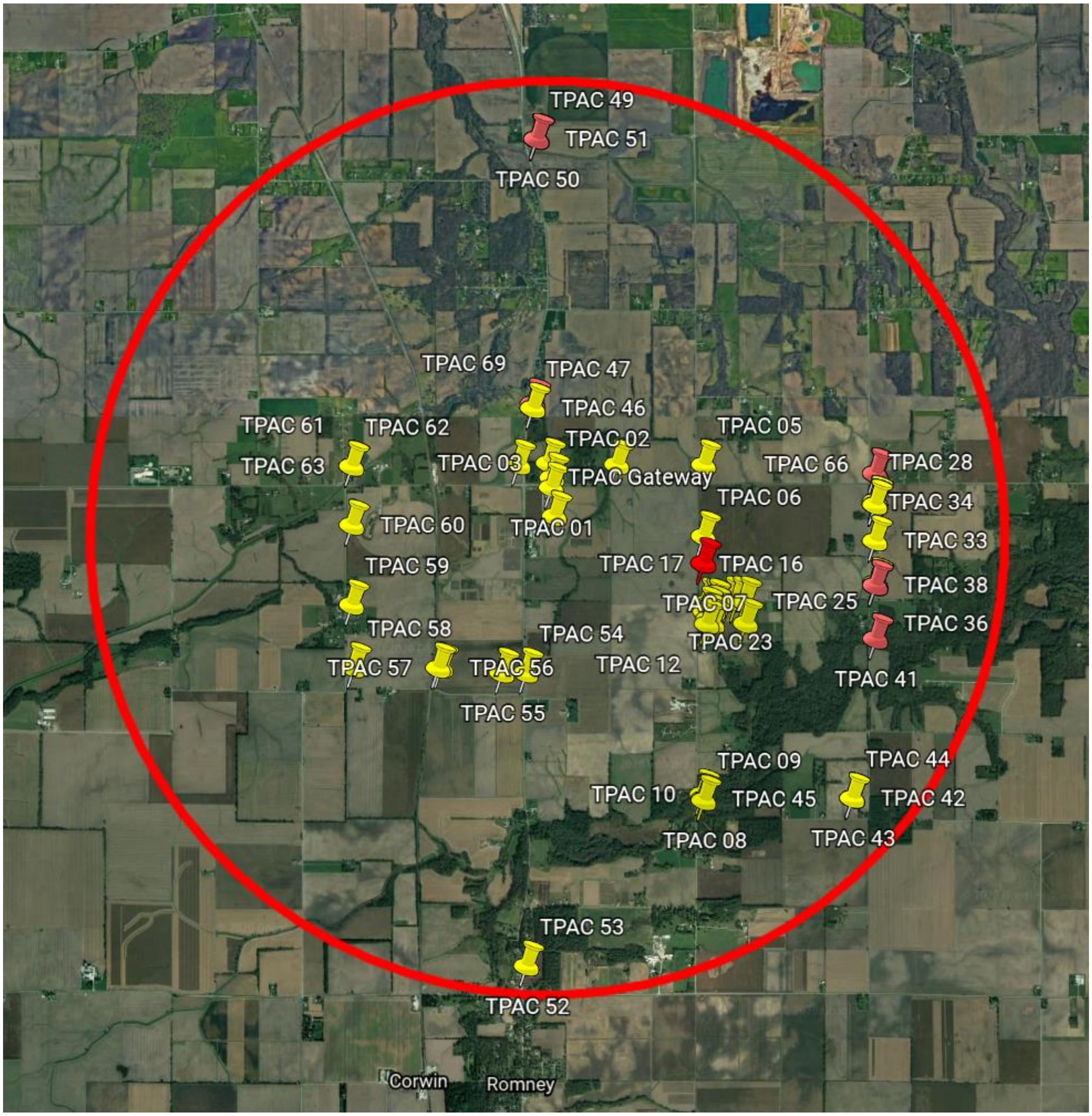

Figure 20. *TPAC Survey Map*

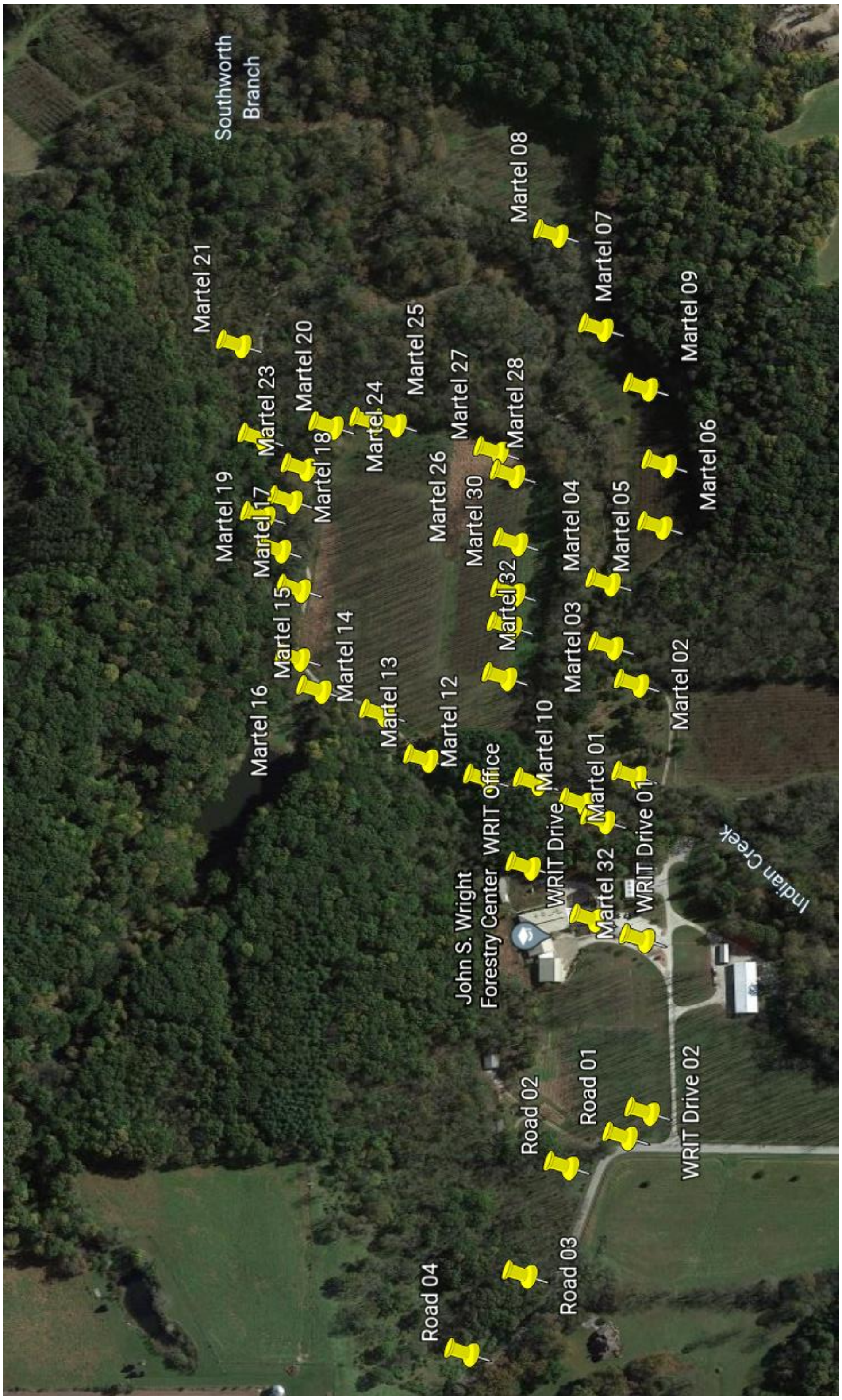

Figure 21. *WIRT Survey Map*

APPENDIX B. GATEWAY PLACEMENT

Figure 22. *Gateway Placement – Rural*

Figure 23. *Gateway Placement - Urban*

APPENDIX C. GPS SURVEY LOCATIONS

Table 6.

Urban Survey GPS Locations

Location ID	Latitude	Longitude
L0	40 25 34.164 N	86 54 40.458 W
L1	40 25 34.164 N	86 54 40.458 W
L2	40 25 34.074 N	86 54 51.066 W
L3	40 25 30.420 N	86 54 56.634 W
L4	40 25 30.498 N	86 55 4.806 W
L5	40 25 30.678 N	86 55 9.312 W
L6	40 25 30.924 N	86 55 13.794 W
L7	40 25 31.320 N	86 55 20.232 W
L8	40 25 31.470 N	86 55 25.146 W
L9	40 25 35.412 N	86 55 22.674 W
L10	40 25 41.226 N	86 55 18.444 W
L11	40 25 41.568 N	86 55 12.648 W
L12	40 25 42.534 N	86 55 4.650 W
L13	40 25 43.746 N	86 54 54.948 W
L14	40 25 43.452 N	86 54 50.928 W
L15	40 25 51.324 N	86 54 58.050 W
L16	40 26 1.332 N	86 55 1.356 W
L17	40 26 17.928 N	86 55 6.234 W
L18	40 25 45.648 N	86 54 42.822 W
L19	40 25 50.208 N	86 54 41.874 W
L20	40 25 51.714 N	86 54 38.544 W
L21	40 25 48.438 N	86 54 37.284 W
L22	40 25 45.498 N	86 54 32.832 W

L23	40 25 44.148 N	86 54 29.112 W
L24	40 25 39.462 N	86 54 24.810 W
L25	40 25 36.084 N	86 54 28.452 W
L26	40 25 33.288 N	86 54 29.166 W
L27	40 25 32.868 N	86 54 20.544 W
L28	40 25 29.502 N	86 54 24.336 W
L29	40 25 25.974 N	86 54 24.780 W
L30	40 25 26.358 N	86 54 33.078 W
L31	40 25 25.524 N	86 54 35.322 W
L32	40 25 25.194 N	86 54 34.872 W
L33	40 25 28.188 N	86 54 37.722 W
L34	40 25 31.050 N	86 54 37.620 W
L35	40 25 27.588 N	86 55 15.756 W
L36	40 25 26.988 N	86 55 17.346 W
L37	40 25 26.778 N	86 55 9.570 W
L38	40 25 26.412 N	86 55 2.334 W
L39	40 25 22.542 N	86 55 1.950 W
L40	40 25 26.544 N	86 54 57.858 W
L41	40 25 27.174 N	86 54 50.562 W

Table 7.

Rural Survey GPS Locations

Location ID	Latitude	Longitude
L0	40 13 23.364 N	86 59 58.758 W
L1	40 13 21.258 N	87 0 13.128 W
L2	40 13 12.396 N	87 0 13.422 W
L3	40 13 4.860 N	87 0 13.632 W

L4	40 12 53.712 N	87 0 13.716 W
L5	40 12 53.358 N	87 0 26.136 W
L6	40 12 53.412 N	87 0 47.844 W
L7	40 12 53.370 N	87 1 10.560 W
L8	40 12 53.496 N	87 1 28.626 W
L9	40 12 53.478 N	87 1 56.844 W
L10	40 12 44.178 N	87 0 13.788 W
L11	40 12 35.574 N	87 0 13.722 W
L12	40 12 21.192 N	87 0 13.770 W
L13	40 13 32.142 N	87 0 13.044 W
L14	40 13 37.518 N	87 0 20.988 W
L15	40 13 45.588 N	87 0 47.244 W
L16	40 13 46.350 N	87 1 9.648 W
L17	40 13 32.826 N	86 59 54.786 W
L18	40 13 31.170 N	86 59 35.634 W
L19	40 13 26.874 N	86 59 5.586 W
L20	40 13 24.918 N	86 58 48.570 W
L21	40 13 15.792 N	86 58 48.186 W
L22	40 12 58.968 N	86 58 48.486 W
L23	40 12 43.860 N	86 58 45.084 W
L24	40 12 25.422 N	86 58 44.826 W
L25	40 12 3.756 N	86 58 44.682 W
L26	40 11 47.430 N	86 58 44.778 W
L27	40 11 39.966 N	86 58 48.948 W
L28	40 13 36.504 N	86 58 47.766 W
L29	40 13 45.930 N	86 58 28.884 W
L30	40 13 46.164 N	86 57 56.706 W
L31	40 13 46.278 N	86 57 23.334 W
L32	40 13 55.284 N	86 58 13.848 W
L33	40 14 12.102 N	86 58 13.860 W
L34	40 14 38.796 N	86 58 29.538 W

L35	40 14 38.784 N	86 58 46.524 W
L36	40 14 38.808 N	86 59 0.984 W
L37	40 14 38.898 N	86 59 37.086 W
L38	40 14 38.940 N	86 59 55.446 W
L39	40 14 53.748 N	86 58 47.346 W
L40	40 15 17.826 N	86 58 47.634 W
L41	40 15 33.228 N	86 58 47.580 W
L42	40 14 18.972 N	86 58 47.964 W
L43	40 13 50.526 N	86 58 48.168 W
L44	40 13 33.108 N	86 58 48.030 W

APPENDIX D. SURVEY NODE HEIGHT

Figure 24. *Urban Survey Node Height LoRa and NB-IoT*

Figure 25. *Rural Survey Node Height NB-IoT*

APPENDIX E. LORAWAN SURVEY TABLES

Table 8.

LoRaWAN Urban Area Site Survey Data

Location ID	Status	Lock	Alt	RSSI down	Distance from L00 (m)	Elevation dif. from L00 (m)
L00	S	6	198	96	0	0
L01	S	6	198	96	212	0
L02	S	8	198	97	314	-1
L03	S	10	196	94	489	2
L04	S	10	192	97	647	-1
L05	S	11	195	107	739	-11
L06	S	10	196	102	837	-6
L07	S	10	190	111	974	-15
L08	F	10	213	n/a	1083	n/a
L09	F	11	154	n/a	982	n/a
L10	S	10	196	107	890	-11
L11	S	10	205	111	746	-15
L12	F	10	224	n/a	569	n/a
L13	S	11	209	92	315	4
L14	S	11	281	100	240	-4
L15	S	11	207	105	531	-9
L16	S	6	36	105	813	-9
L17	F	4	34	n/a	1299	n/a
L18	S	6	34	87	166	9
L19	S	7	80	100	299	-4
L20	F	10	85	n/a	367	n/a
L21	S	10	190	109	255	-13

L22	S	10	192	99	240	-3
L23	S	10	186	99	292	-3
L24	F	10	190	n/a	375	n/a
L25	S	11	201	88	314	8
L26	S	10	189	95	356	1
L27	F	10	187	n/a	528	n/a
L28	S	11	198	110	508	-14
L29	F	11	185	n/a	583	n/a
L30	F	11	199	n/a	463	n/a
L31	S	11	213	108	488	-12
L32	F	11	215	n/a	602	n/a
L33	S	11	305	112	386	-16
L34	S	11	313	87	296	9
L35	S	6	34	111	917	-15
L36	F	7	114	n/a	959	n/a
L37	S	8	201	102	802	-6
L38	S	9	201	103	669	-7
L39	F	10	216	n/a	732	n/a
L40	S	12	193	111	586	-15
L41	S	12	197	103	469	-7

Note: *The altitude difference does not seem to be accurate after further testing.*

Table 9.

LoRaWAN Rural Area Site Survey Data

Location ID	Status	Lock	Alt (m)	RSSI down	Distance from L00 (m)	Elevation diff. from L00 (m)
L00	S	9	181	8	0	0
L01	S	12	233	91	336	52
L02	S	12	234	84	454	53
L03	S	12	234	85	642	53
L04	S	12	233	105	954	52
L05	S	12	236	97	1107	55
L06	S	12	231	105	1459	50
L07	S	12	230	108	1911	49
L08	S	12	240	111	2298	59
L09	F	12	233	n/a	2920	52
L10	S	12	238	110	1231	57
L11	S	12	231	110	1486	50
L12	F	12	227	n/a	1922	46
L13	S	12	232	102	457	51
L14	S	12	230	97	689	49
L15	S	12	228	105	1345	47
L16	F	12	229	n/a	1816	48
L17	S	12	233	98	329	52
L18	S	12	236	80	610	55
L19	S	12	244	103	1285	63
L20	F	12	236	n/a	1669	55
L21	S	12	235	105	1692	54
L22	S	12	232	100	1826	51
L23	S	12	239	101	2123	58

L24	S	12	241	109	2490	60
L25	S	12	238	122	3005	57
L26	S	12	228	120	3427	47
L27	F	12	236	n/a	3571	55
L28	S	12	231	102	1745	50
L29	S	12	228	103	2253	47
L30	S	12	240	107	2988	59
L31	F	12	231	n/a	3757	50
L32	S	12	230	99	2692	49
L33	F	12	220	n/a	2920	39
L34	S	11	225	110	3160	44
L35	F	11	226	n/a	2911	45
L36	S	11	228	108	2720	47
L37	S	11	231	109	2400	50
L38	F	11	224	n/a	2358	43
L39	S	12	224	117	3276	43
L40	S	12	222	109	3939	41
L41	F	12	227	n/a	4366	46
L42	S	12	221	117	2419	40
L43	S	12	235	108	1889	54
L44	S	12	233	113	1710	52

Note: The a*ltitude difference does not seem to be accurate after further testing.*

APPENDIX F. NB-IOT SURVEY TABLES

Table 10.

NB-IoT Urban Area Site Survey Data

Location ID	Status	sc_cellid	sc_rssi	sc_band
L00	n/a	n/a	n/a	n/a
L01	S	2EA3039	-49	17
L02	S	2EA3039	-55	17
L03	S	2EA3039	-57	17
L04	S	2EA303A	-43	17
L05	S	2EA303A	-59	17
L06	S	2EA303A	-59	17
L07	S	2EA303A	-72	17
L08	S	2EA303A	-71	17
L09	S	2EA303A	-78	17
L10	S	2EA1E3A	-62	17
L11	S	2EA303A	-58	17
L12	S	2EA303A	-66	17
L13	S	2EA303A	-80	17
L14	S	2EA3039	-69	17
L15	S	2EA3039	-69	17
L16	S	2EA303A	-68	17
L17	S	2EA453B	-66	17
L18	S	2EA3039	-76	17
L19	S	2EA3039	-77	17
L20	S	2EA3039	-74	17
L21	S	2EA3039	-73	17
L22	S	2EA3039	-60	17

L23	S	2EA3039	-70	17
L24	S	2EA3039	-63	17
L25	F	n/a	n/a	n/a
L26	F	n/a	n/a	n/a
L27	F	n/a	n/a	n/a
L28	F	n/a	n/a	n/a
L29	F	n/a	n/a	n/a
L30	S/3	2EA433B	-64	17
L31	F	n/a	n/a	n/a
L32	F	n/a	n/a	n/a
L33	F	n/a	n/a	n/a
L34	S	2EA3039	-50	17
L35	S	2EA303A	-61	17
L36	S	2EA303A	-56	17
L37	S	2EA303A	-64	17
L38	S	2EA303A	-57	17
L39	S	2EA303A	-54	17
L40	S	2EA303A	-51	17
L41	S	2EA3039	-45	17

Note: *S/# means after how many tires the connection was successful.*
sc_cellid is a hexadecimal value field

Table 11.

NB-IoT Rural Area Site Survey Data

Location ID	Status	sc_cellid	sc_rssi	sc_band
L00	S	2EA313B	-81	17
L01	S	2EA313B	-78	17
L02	S	2F1F33B	-81	17
L03	S	2F1F33B	-81	17
L04	F	n/a	n/a	n/a
L05	S/2	2F1F33B	-75	17
L06	S	2F1F33B	-79	17
L07	S	2F1F33B	-80	17
L08	S	2F1F33B	-69	17
L09	F	n/a	n/a	n/a
L10	F	n/a	n/a	n/a
L11	F	n/a	n/a	n/a
L12	S/3	2EA313B	-74	17
L13	S	2EA313B	-71	17
L14	S	2EA313B	-64	17
L15	S	2EA313B	-69	17
L16	S	2F1F33B	-70	17
L17	S	2F1F33B	-74	17
L18	S	2EA313B	-78	17
L19	S	2EA313B	-71	17
L20	S	2EA313B	-65	17
L21	S	2EA313B	-68	17
L22	S	2EA313B	-70	17
L23	S	2EA313B	-76	17
L24	S	2EA313B	-79	17

L25	S	2EA313A	-80	17
L26	S	2EA313A	-82	17
L27	S	2EA313A	-86	17
L28	S	2EA313B	-64	17
L29	S	2EA313B	-74	17
L30	S	2EA313B	-76	17
L31	S	2EA313B	-74	17
L32	S	2F1F33B	-65	17
L33	S	2F1F33B	-67	17
L34	S	2F1F33B	-70	17
L35	S	2F1F33B	-70	17
L36	S	2F1F33B	-70	17
L37	S	2EA313B	-75	17
L38	S	2EA313B	-73	17
L39	S	2EA313B	-68	17
L40	S	2EA313B	-69	17
L41	S	2EA313B	-70	17
L42	S	2EA313B	-71	17
L43	S	2F1F33B	-71	17
L44	S	2F1F33B	-68	17

Note: *S/# means after how many tires the connection was successful.*
sc_cellid is a hexadecimal value field

APPENDIX G. CLOUDRF LAYOUT

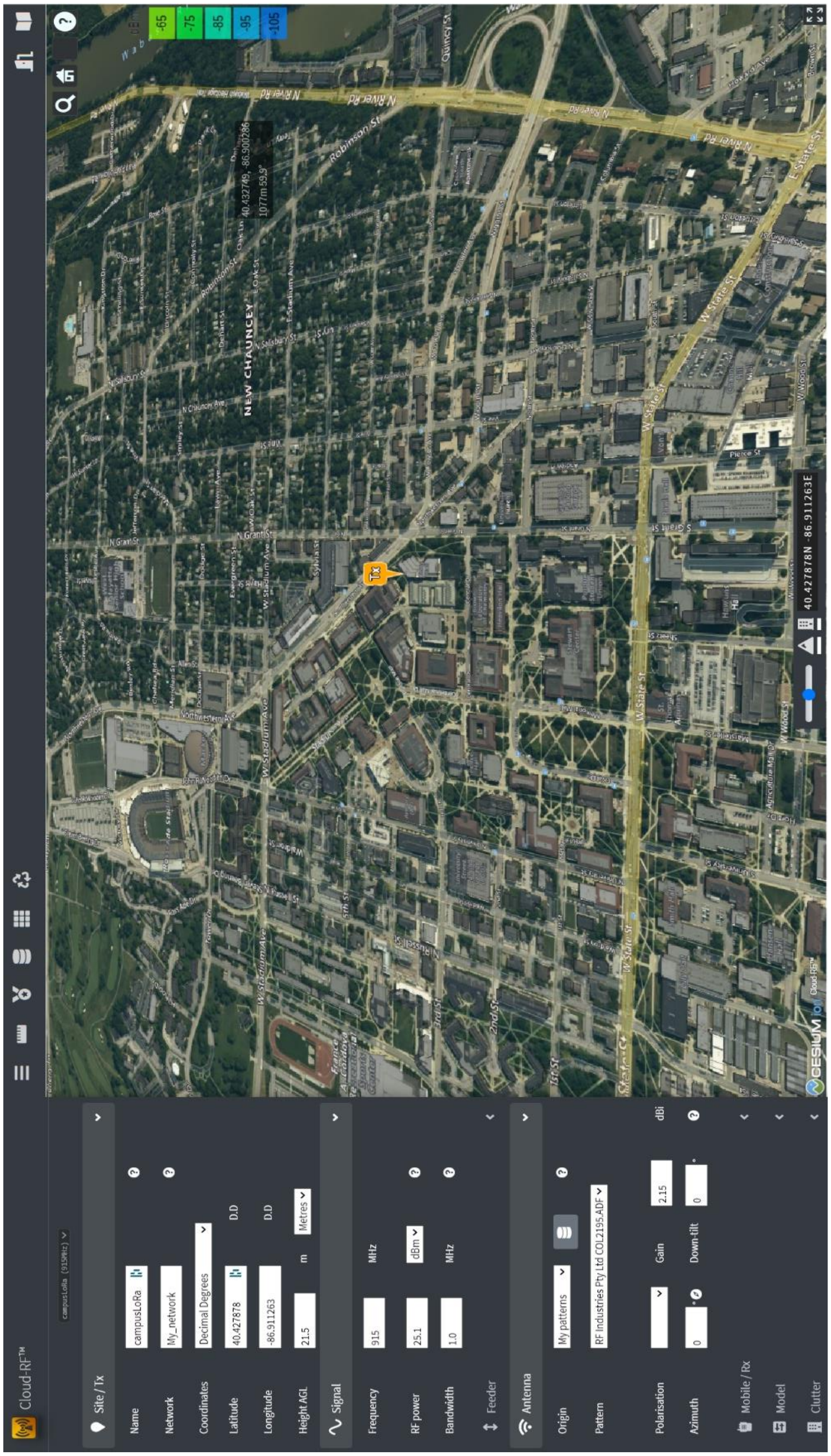

Figure 26. *CloudRF Software Layout*