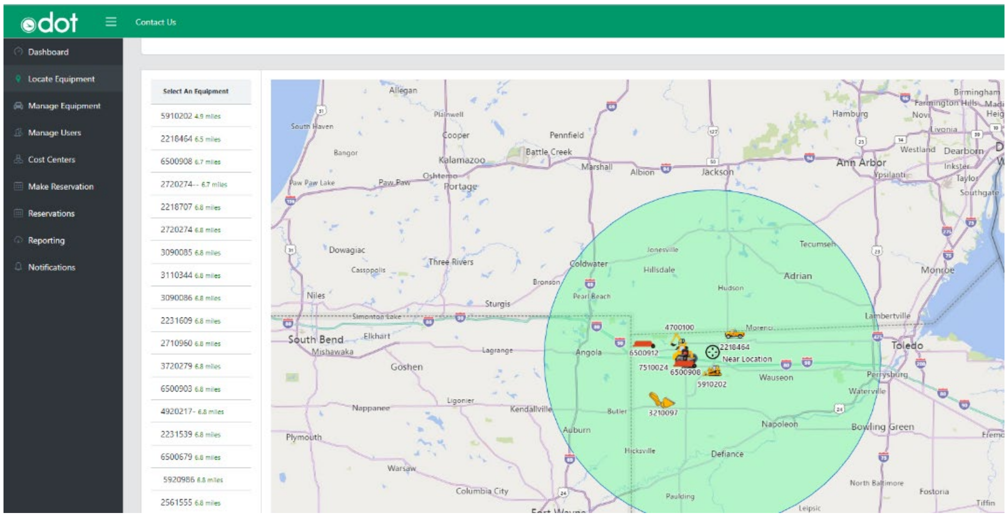
Optimizing Maintenance Equipment Tracking



Select An Equipment
5910202 4.9 miles
2218464 6.5 miles
6500908 6.7 miles
2720274-- 6.7 miles
2218707 6.8 miles
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3090085 6.8 miles
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2561555 6.8 miles

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16. Abstract

This report summarizes the results of a project that was completed to develop a system to allow multiple ODOT users with different administrative authority to locate and schedule different types of equipment in ODOT district and county garages. The project was divided into two phases. The results of Phase 1 indicated that the optimum tracking system should not consist of one type of tracking device, but rather a mix of Global Positioning System (GPS) and Bluetooth low energy (BLE) devices. In addition, the tracking software should be custom-made to integrate the various types of tracking devices into one system that is user-friendly for ODOT personnel. Phase 2 of this study included identifying and evaluating different types of BLE enabled GPS (GPS-BLE) devices, which can be used to track the various types of ODOT equipment and are able to detect BLE beacons. In addition, different types of BLE beacons were identified and their ability to track the different types of ODOT equipment was examined. Based on these evaluations, one GPS-BLE device and two types of BLE beacons were selected for further evaluation. A prototype of the system that can be used to track and schedule ODOT equipment was designed, developed and evaluated; referred to as ODOTMETS. The results obtained from the conducted field evaluation showed that the beacons can be reliably detected by the GPS-BLE devices. In addition, the results suggested that the system consisting of GPS-BLE and beacons can be used for tracking different types of equipment at ODOT district and county garages. The recommended tracking system consists of using few (minimum of three) GPS-BLE on certain equipment that are frequently used in the field operations of each ODOT district and county garages and using beacons on pieces of equipment that are typically needed and shared between by ODOT county garages. The results of the cost analysis indicated that the recommended system can be highly cost-effective with cost benefit ratio of more than 8 if it is efficiently used by ODOT district and county garages.

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Executive Summary

This report summarizes the results of a project that was completed to develop a system to allow multiple ODOT users with different administrative authority to locate and schedule different types of equipment in ODOT district and county garages. The project was divided into two phases. The results of Phase 1 indicated that the optimum tracking system should not consist of one type of tracking device, but rather a mix of Global Positioning System (GPS) and Bluetooth low energy (BLE) devices. In addition, the tracking software should be custom-made to integrate the various types of tracking devices into one system that is user-friendly for ODOT personnel.

Phase 2 of this study included identifying and evaluating different types of BLE enabled GPS (GPS-BLE) devices, which can be used to track the various types of ODOT equipment and are able to detect BLE beacons. In addition, various types of BLE beacons were identified and their ability to track the different types of ODOT equipment was examined. Based on these evaluations, one GPS-BLE device and two types of BLE beacons were selected for further evaluation. A prototype of the system that can be used to track and schedule ODOT equipment was designed, developed and evaluated; referred to as ODOTMETS. The results obtained from the conducted field evaluation showed that the beacons can be reliably detected by the GPS-BLE devices. In addition, the results suggested that the system consisting of GPS-BLE and beacons can be used for tracking different types of equipment at ODOT district and county garages. The recommended tracking system consists of using few (minimum of three) GPS-BLE on selected equipment that are frequently used in the field operations of each ODOT district and county garages and using beacons on pieces of equipment that are typically needed and shared between ODOT county garages. The developed tracking system has several benefits that include: reducing the time needed to locate equipment, optimizing the equipment scheduling and facilitating the equipment sharing between counties within the same district as well as in different districts, eliminating the need to rent equipment that is available in other counties and districts, maximizing the equipment fleet utilization based on obtained data, improve ODOT emergency response preparedness, and reducing the road user time. The results of the cost analysis conducted in this study indicated that the recommended system can be highly cost-effective with cost benefit ratio of more than 8 if it is efficiently used by ODOT district and county garages.

1. Project Background

The Ohio Department of Transportation (ODOT) districts and counties work together to provide the traveling public with a safe and reliable transportation system. An important responsibility of ODOT's eighty-eight counties is the maintenance of roads. Different types of equipment are used by ODOT counties for the road maintenance. Some of these pieces of equipment are expensive and are typically purchased in limited quantities by ODOT districts. Therefore, these pieces of equipment are shared between counties within a district and in some cases they are shared across the district lines. However, in order to share an equipment, the county owning this equipment should know the location of that equipment when it is needed. As the maintenance equipment are frequently used and moved between sites; therefore, the equipment owner might not know the exact location of these equipment at a given time. Therefore, when these pieces of equipment are needed by another county or district, the equipment owner will have to call around to locate the equipment. This results in considerable loss of time, which causes significant delays in the work to be performed. In addition, in certain times the requesting county will have to rent the needed equipment to avoid these delays, which results in additional cost to ODOT that can be saved if the equipment is quickly located.

ODOT initiated the project entitled "Optimizing Maintenance Equipment Tracking -Phase 1" (referred to as Phase 1 hereinafter) to evaluate ODOT's current process for tracking maintenance equipment, identify and evaluate technologies for tracking maintenance equipment, and provide recommendations for optimal tracking systems for ODOT. The results of Phase 1 indicated that ODOT districts have an issue in locating their equipment and considerable amount of time is wasted in finding maintenance equipment. The results of Phase 1 indicated that the optimum tracking system should not consist of one type of tracking device, but rather a mix of Global Positioning System (GPS) and Bluetooth low energy (BLE) devices. In addition, the tracking software should be custom-made to integrate the various types of tracking devices into one system that is user-friendly for ODOT personnel. Phase 1 indicated that the considered tracking systems have benefits that include: eliminating the time needed to locate equipment, eliminating the need of renting maintenance equipment, improving the annual equipment inventory process, improving ODOT emergency response preparedness, reducing the equipment theft, and reducing road user cost. In addition, the considered tracking systems were found to be cost effective with a cost benefit ratio ranging between 3.77 and 7.24.

Phase 2 determined the most reliable, cost-effective, and durable of the selected GPS-BLE and BLE beacon devices identified in Phase 1. It also validated the results of preliminary testing BLE beacons devices conducted in Phase 1, which indicated that a BLE beacon placed on an equipment left on the roadside can be detected by a smartphone in a car passing at or near highway speed. In this phase a prototype was developed of the tracking system proposed in phase 1. The prototype includes GPS-BLE, BLE beacons and OEM tracking devices to locate the different types of ODOT maintenance equipment. Finally, Phase 2 included conducting a pilot study in selected ODOT counties in Districts 2 and 10 to evaluate this system and determine its cost-effectiveness. The main outcome of this project is a cost-effective and efficient process to track the location of maintenance equipment and optimize their use.

2. Research Context

The overall goal of this project is to provide ODOT with a cost-effective method to track and schedule its different types of maintenance equipment. The tracking system should be developed for all maintenance equipment, easily implementable statewide and has the ability to allow multiple users with different administrative authority to locate and schedule maintenance equipment at any time. Specific objectives of Phase 2 include:

- Select the most reliable, cost-effective, and durable GPS-BLE to be used in ODOT maintenance equipment tracking system.
- Determine the most reliable, cost-effective, and durable BLE beacons that ODOT can use on their maintenance equipment to track them.
- Develop a prototype of the tracking system proposed to locate the different types of ODOT maintenance equipment. The system will include a custom-made software to identify the location of maintenance equipment and schedule the use of these equipment.
- Conduct a pilot study in selected ODOT counties in Districts 2 and 10 to evaluate this system.

3. Research Approach

3.1 Selection and Evaluation of BLE Beacons

Different types of BLE beacons were identified to be used for tracking non-powered ODOT equipment including towed equipment (e.g., trailers, arrow boards, hot boxes, attenuators, …), attachments (e.g., buckets, forks, berm boxes, …), and fixed assets (e.g., generators, pumps, hand tools, weed eaters, chain saws, power tools). Some of identified beacons were selected for testing. The following factors was considered in the selection process: battery lifetime, range of signal, ruggedness, waterproof IP ratings, additional features, and price. The selected beacons were acquired. Bench and lab testing of basic functionality was conducted on the obtained BLE beacons. In addition, the acquired BLE beacons ruggedness and durability under field environment was assessed. Based on the results of this task, the research team made recommendations to select Kontakt tough beacons and Xirgo XT1500 beacons to be used in the system prototype developed in this project for further evaluation in the field. Appendix A provides more details about the selection BLE beacons.

3.2 Selection and Evaluation of GPS-BLE

This task included the selection of GPS-BLE devices to be used for tracking different maintenance equipment. The GPS-BLE from two manufacturers was selected. The following was considered in this selection: battery lifetime, range of signal, ability to detect different types of BLE beacons, ruggedness, support, data network type, additional features, and price. The selected GPS-BLE devices were acquired. Bench and lab testing of basic functionality was conducted on the obtained GPS-BLE devices. In addition, preliminary assessment of the acquired devices' ruggedness and durability under field environment was conducted. Based on the results of this task, the research team made recommendations on which of the selected GPS-BLE devices to be used in the system prototype developed in this phase. Appendix A provides more details about the selection of GPS-BLE devices.

3.4 Developing System Hardware Prototype

This task involved designing and developing a prototype of the ODOT Maintenance Equipment Tracking system (ODOTMETS) system hardware. Figure 1 presents the designed system prototype. The system hardware included using GPS-BLE and BLE beacons to track various pieces of equipment. The following subsections provide a description of steps taken for evaluating this system. Appendix A provides more details about the ODOTMETS system hardware prototype development.

3.4.1. Selection of Optimum Configuration for GPS-BLE and BLE Beacon

Field experiments were conducted to determine the factors and parameters for ensuring GPS-BLE detection of beacons. The focus was on determining the settings of the GPS-BLE and beacon devices that should be used to optimize the beacons power consumption while ensuring their detection in different conditions. The effect of different factors on the beacon detection were determined including:

- Car Speed: different speeds ranging from 0-40 mph
- GPS BLE locations: experiments were conducted with and without obstruction between the GPS-BLE and beacons.
- GPS-BLE settings: Beacon reporting time, Beacon scanning time, Beacon scanning window (channel window)
- Beacon types: Kontakt tough beacons and Xirgo XT1500 beacons were used in these experiments.
- Beacon settings: Transmission power and advertising interval (reporting Interval). This was only evaluated for Kontakt tough beacons.

Appendix A provides more details about the conducted experiments and the results obtained from these experiments.

3.4.2. Evaluation of Beacon Detectability at High Driving Speed

The main principle of the developed tracking system is that maintenance equipment tracked using the GPS-BLE devices would be able to detect the location of the BLE-beacon tracked equipment while moving at different speeds close to each other. To evaluate the feasibility of the beacon detectability at highway speeds experiments were performed. The testing included placing the BLE beacons on the side of interstate highways and detecting them by a vehicle moving at highways speeds (up to 65 mph). The experiments were performed using the optimal beacon and GPS-BLE configurations determined based on the previous experiments. For each speed the experiment was performed three times to insure reliable detection of the beacons. The results of these experiments indicated the beacons were detected at highways speeds and consistently in all three trials.

3.5 Design and Develop A Prototype of the System Software

This task included the development of all software components of the ODOTMETS system prototype. The ODOTMETS system was developed using different technologies, these include:

- .Net Core 3.1
- Angular 14.2.3
- SQL Server 2017
- Message Queue

- Selenium
- Docker

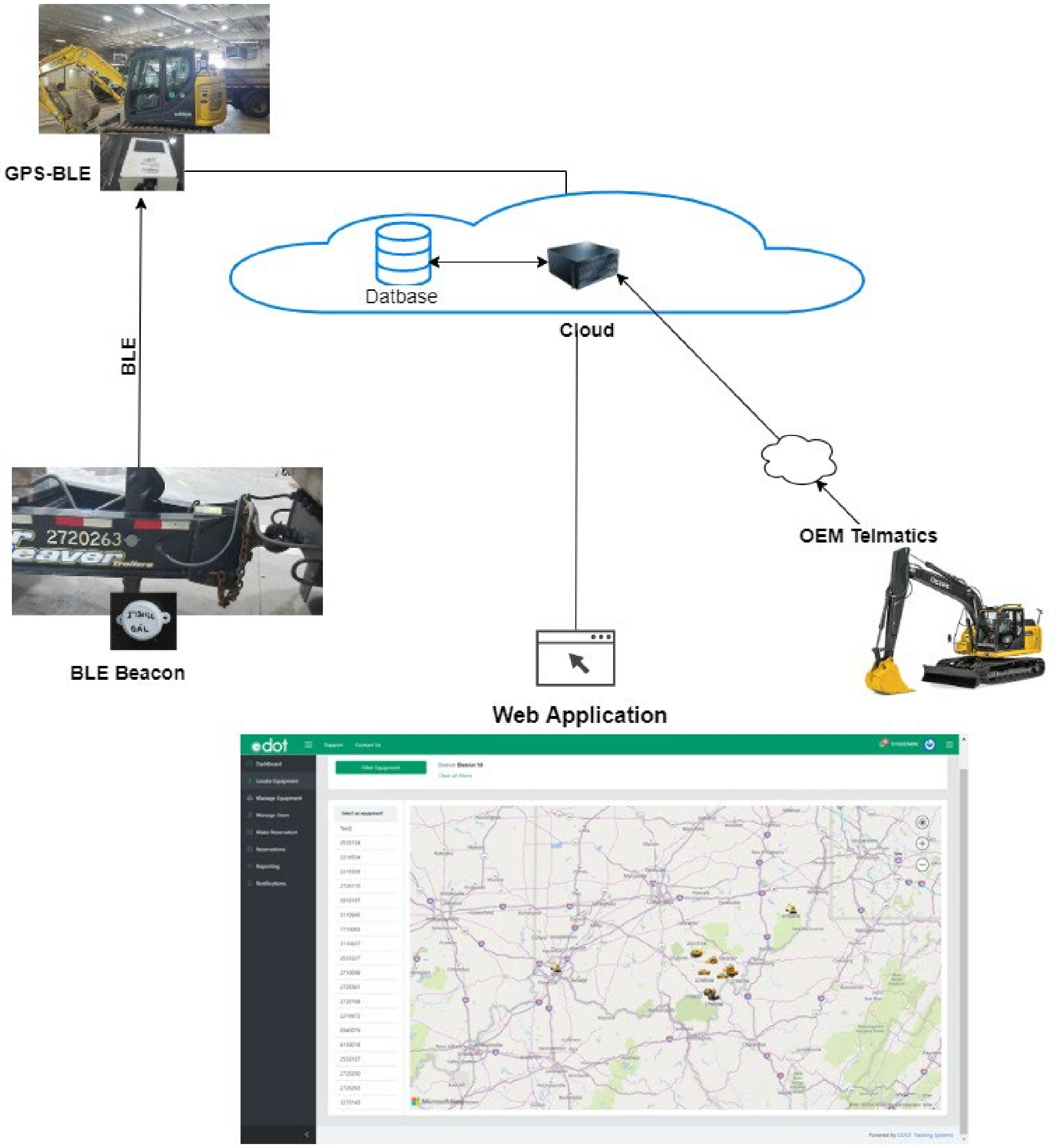


Figure 1: Developed System Prototype

The .Net Core 3.1 was used in the system to implement most of the logic, save the data into SQL server, and interacts with the system via a web Graphical User Interface (GUI). In addition, the GUI is built with angular. Selenium is used to obtain information for the equipment with John Deere OEM telematic devices from John Deere website. Finally, all application components were deployed using Docker.

Figure 2 presents the software architecture that was designed for ODOTMETS. It is noted that the software application has different components, which include: GPS Listener, Backend, Graphical User Interface (GUI), and SQL database.

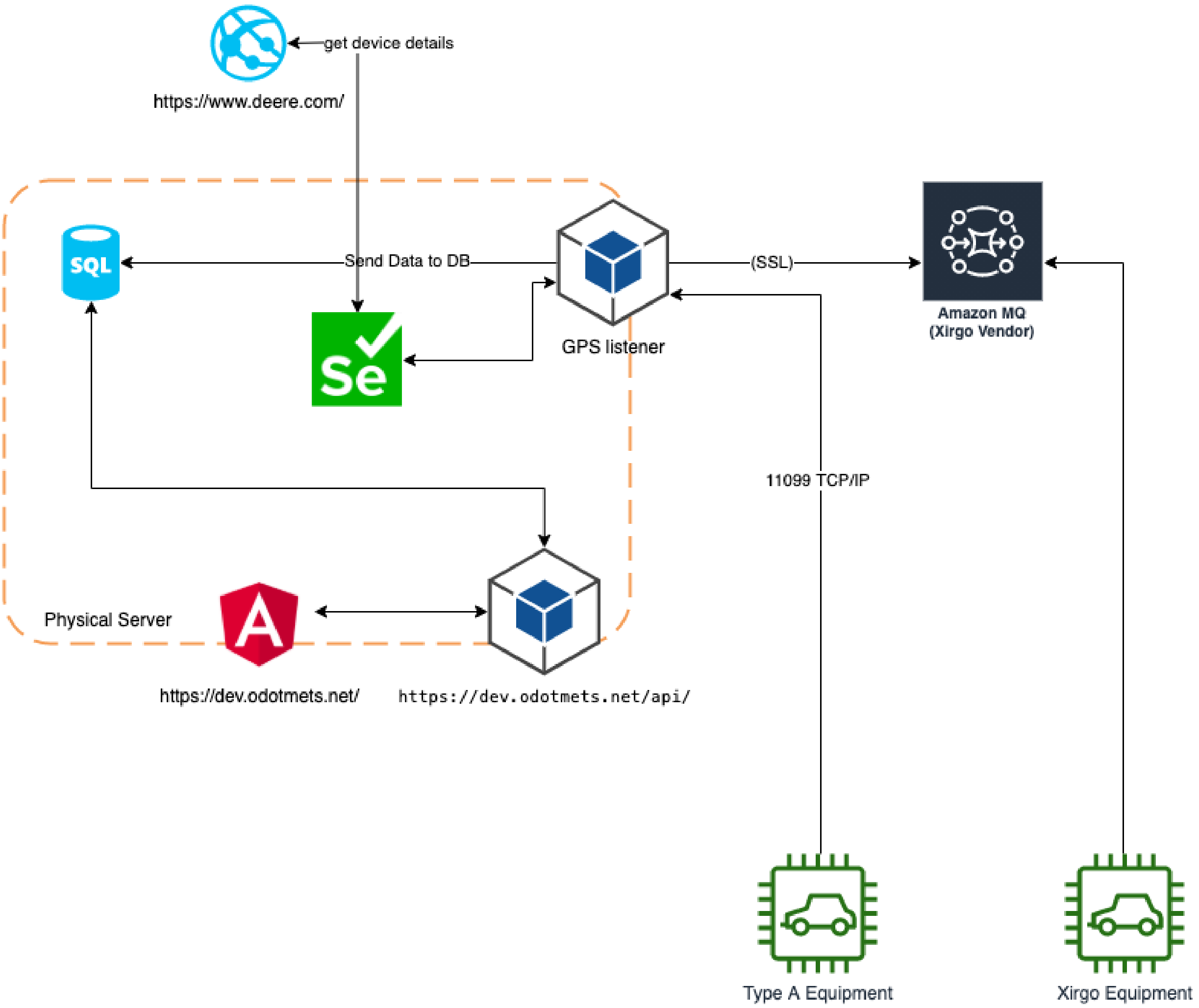


Figure 2: Software Application Architecture

GPS listener main function is to gather all the equipment locations and information from different types of tracking devices and save them into one database. The different types of tracking devices are: Type A GPS-BLE Devices, Xirgo GPS-BLE Devices, John Deere OEM telematic Devices. Figure 3 presents the sequence diagram that shows how the system interacts with each of these tracking devices vendors. The backend of the system consists of RESTful APIs developed using .Net core, and the APIs are documented using Swagger (Figure 4). The GUI is developed as a web application using Angular framework which interacts with the restful services from the backend. The authentication/authorization is based on JWT Tokens.

The ODOTMETS software was developed to easily track and schedule the different types of maintenance equipment in different ODOT cost centers. The software system (Figure 5) has different modules:

1- Locate Equipment: This module allows to locate tracked equipment
2- Manage Equipment: This module allows to add, edit and delete equipment

3- Manage User: This module allows to add, edit and delete user in the system
4- Cost Center: This module allows to add, edit and delete cost centers in the system
5- Make Reservation: This module allows to see the calendar for the equipment and make reservation for the needed equipment based on this calendar
6- Reservations: This module allows to see the reservation a user made as well as those requested for equipment owned by that user.
7- Reporting: This module allows to download the information for all equipment in the system including the latest recorded location.
8- Notifications: This module shows the messages sent from equipment requester that the user need to approve or decline.

Two types of user accounts are available: super admin and general user. The admin/administrative accounts give their holder a permission to add authorized users, manage their access, register newly purchased devices, and create an inventory of equipment in a county or district in addition to all other functionality available to general users. The general user account is given functionality such as searching, tracking, and scheduling maintenance equipment by number or by category in addition to features such as checking schedules and reserve equipment.

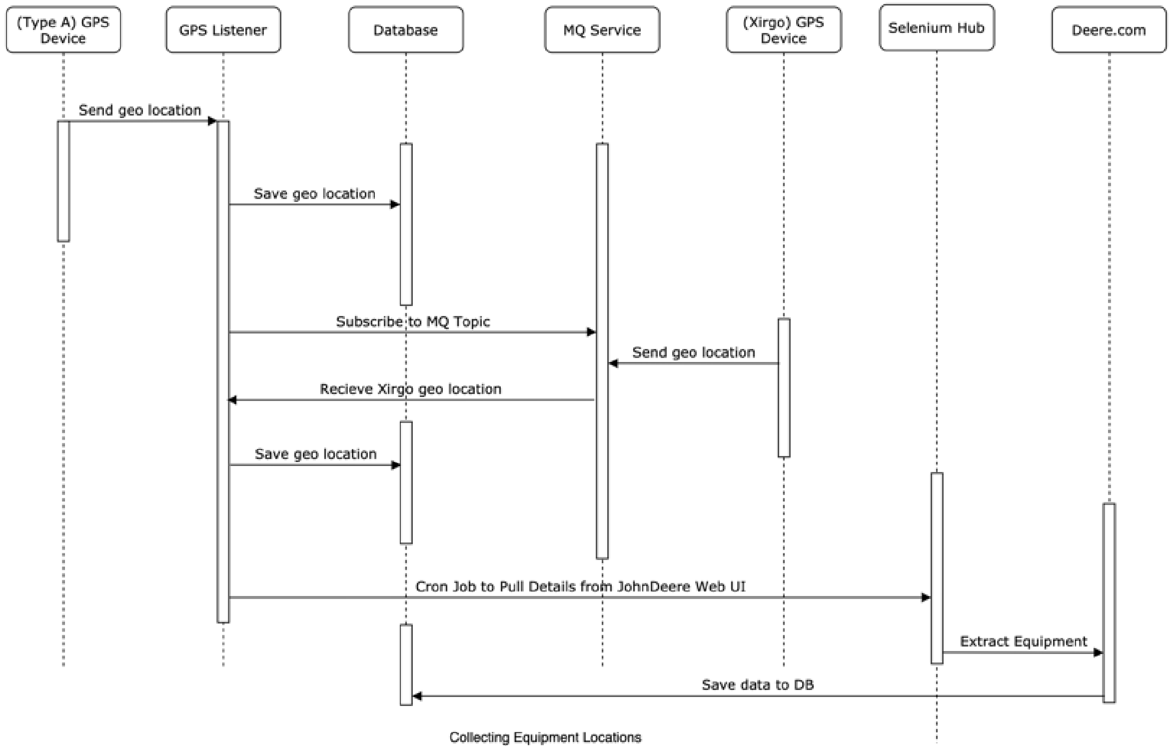


Figure 3: Sequence Diagram for System Interaction with The Tracking Devices

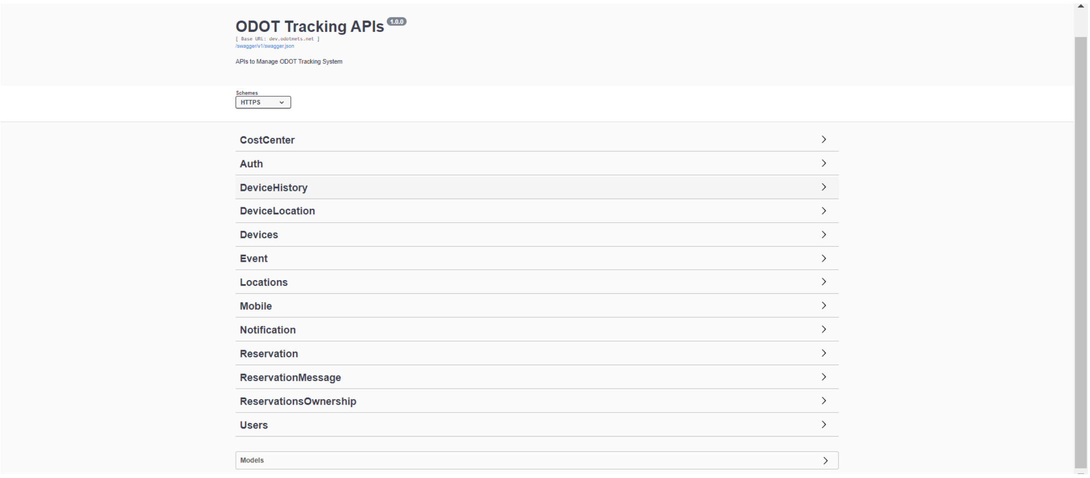


Figure 4: Swagger Documentation of APIs

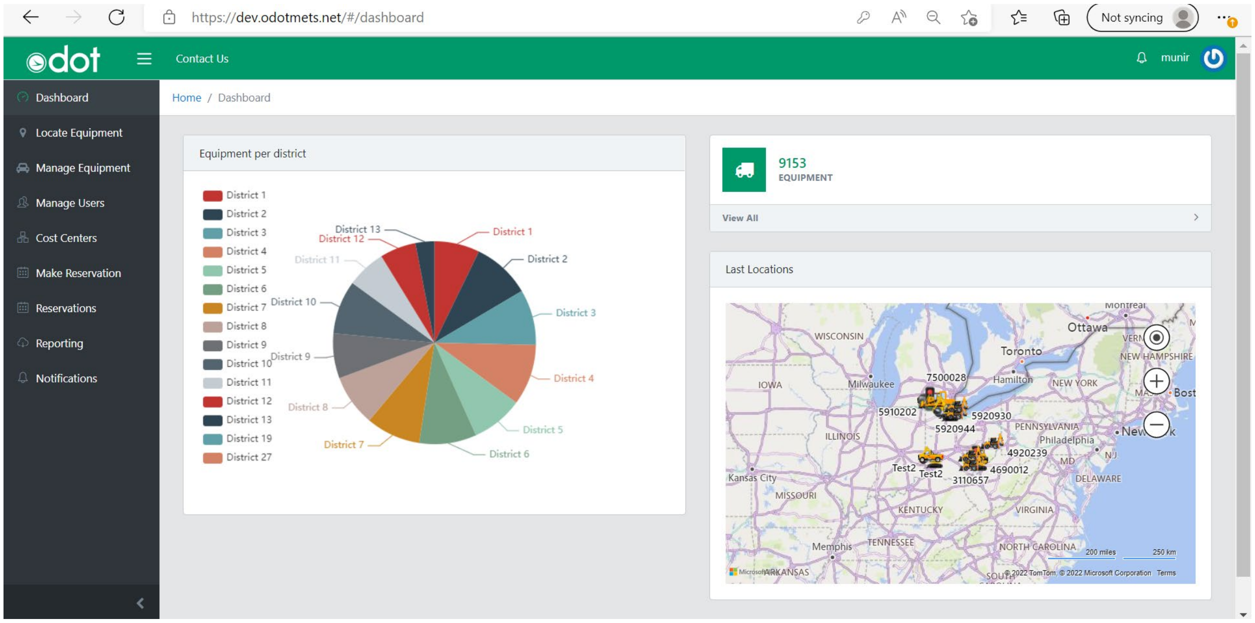


Figure 5: ODOTMETS Web Application

3.6 Field Evaluation of Developed System

Once a prototype of the system was designed and developed, it was evaluated in the field. To this end, GPS-BLE and BLE beacons were purchased and installed on different types of equipment in selected county and district garages to evaluate the reliability and accuracy of the developed system. The selected ODOT counties were Williams County garage (District 2), Henry County garage (District 2), Fulton County garage (District 2), Gallia County garage (District 10), Vinton County garage (District 10), Meigs County garage (District 10), and District 8 garage. GPS-BLE devices were installed on different types of powered equipment and the beacons on powered and non-powered equipment such as excavators, skid steers, trailers, attenuators, chippers, dump trucks, mowers, portable traffic signals, solar powered message centers, backhoes, and tractors. It was made sure that the GPS and beacons are installed properly. The GPS-BLE was configured to turn on when the equipment starts or move even when engine is turned off.

All the data reported by the GPS-BLE devices was sent to and recorded in the database of the developed ODOTMET application. An analysis program was developed to obtain the data directly from the database through a Python interface. Once the date is obtained, the analysis program parses the GPS-BLE messages to provide the location of beacon detection, time of beacon detection, GPS-BLE equipment number and its category, equipment with beacon number and its category, as well as the number of times the beacons were detected by the GPS-BLE equipment each month. The results from analysis conducted using the developed program was used to evaluate effectiveness of the developed system in tracking different types of equipment. In addition, the results of analysis conducted were used to optimize the developed system by identifying the best maintenance equipment that needs to be tracked using GPS-BLE devices to ensure the detection of other equipment. Similarly, the results were used to identify the equipment categories that should be tracked using BLE beacons.

3.7 Conduct Training for ODOT Maintenance Staff

Training sessions were held for ODOT maintenance staff in all participating counties in District 2 and 10 as well as equipment managers at Districts 2, 8 and 10. These sessions informed the attendees on using ODOTMETS system to locate and schedule. In addition, the research team discussed the factors and measures that should be taken to ensure successful and efficient usage of system.

3.8 Evaluate the Cost Benefits of Developed System

The data collected in previous tasks was used to conduct cost-benefit analysis to evaluate cost-effectiveness of using the developed tracking systems. This analysis included computing the total cost for ODOT counites to implement ODOTMETS statewide based on guidelines developed. The total costs include but are not limited to: initial cost of hardware, operation and maintenance cost of hardware, and cost of data subscription. In addition, the analysis also included computing the cost benefits. Based on that, the cost benefit ratio was calculated using Equations 1. The results of the cost-benefit analysis were used to determine if implementing the developed system to track ODOT maintenance equipment is cost-effective.

$$Cost\ Benefit\ Ratio = \frac{Cost\ Benefit}{Total\ Cost\ of\ tracking\ System} \tag{1}$$

3.9 Create A User’s Manual for the Developed System

Several user’s manuals were created for the developed system, which included:

- Software documentation: this manual included documenting the software architecture design, different software components, and the database schema.
- Software deployment instructions documentation: this document provided details about the deployment of the software in different environments.
- Detailed and quick reference user manuals: these manuals provided a step-by-step procedure for performing different tasks in ODOTMETS software; including: locating an equipment, reserving an equipment, managing a reservation, managing equipment users and cost centers.

- GPS-BLE installation guidelines: This user guide described the GPS-BLE device used in the system and the associated parts. In addition, it provided detailed description of GPS-BLE harness wiring process. Finally, this document provided guidelines for the GPS-BLE mounting and installation process.

4. Research Findings and Conclusions

Appendix A present a detailed summary of the system development and evaluation. In addition, a summary of the cost analysis of the developed system is provided in Appendix B. The main findings of this project are summarized below.

- A lower scanning window value of GPS-BLE improves the beacon detection performance. However, the channel window value does not seem to affect the beacon detection performance.
- Based on experiments conducted in this project, the recommended GPS-BLE beacon scanning setting are a beacon reporting time of 30 seconds, a scanning window of 10 seconds, and a channel window of 2000 milliseconds.
- Based on experiments conducted in this project, the recommended BLE beacon settings for reliable detection are a transmission power (Tx) range of 0 dBm to 4 dBm and an advertising interval close to 1000 milliseconds.
- The results obtained from experiments conducted showed that the beacons can be reliably detected when it is within 0.004 miles to 0.25 miles from the GPS-BLE devices, which depends on the beacon transmission power used and the field conditions.
- The results of geo-spatial analysis of the beacon detection indicated that the GPS-BLE tracked equipment can be used to accurately locate other beacon-tracked pieces of equipment at difference places.
- The results of the field evaluation suggested that the system consisting of GPS-BLE and beacons can be used for tracking different types of equipment at ODOT district and county garages.
- The recommended tracking system consists of using few (minimum of three) GPS-BLE on selected equipment that are frequently used in the field operations of each ODOT district and county garages and using beacons on pieces of equipment that are typically needed and shared between by ODOT county garages.
- The results of cost analysis indicated that the recommended system can be highly cost-effective with cost benefit ratio of more than 8 if it is efficiently used by ODOT district and county garages.
- The results of analysis suggested that there are discrepancies in the utilization data based on the ODOTMETS system John Deere OEM telematics and that of ODOT EIMS system.

5. Recommendations for Implementation

This study developed a system prototype (ODOTMETS) that can be used by ODOT district and county garages to schedule and locate their different types of equipment. The results of evaluations conducted in this study indicated that the system can be efficiently and accurately used to locate various types of equipment. In addition, the system was found to be highly cost effective. However, the effectiveness and benefits of ODOTMETS will highly depend on the level of usage by ODOT district and county garages staff for this system to optimize the utilization and sharing of different pieces of equipment. ODOTMETS uses GPS-BLE devices to detect beacons, further research is needed to examine the use of mobile application on cellphones that will be developed to detect beacons and can be utilized to track the location of equipment with beacons.

Appendix A: Development and Evaluation of Tracking System

A.1 Selection and Evaluation of Tracking Devices

A.1.1 Selection and Comparison of Bluetooth Low Energy (BLE) Beacons

BLE is a wireless network technology that was first introduced in the market in 2011. The main distinction of BLE over classical Bluetooth technology is its low power consumption at the expense of smaller amounts of data transferred, which makes it excellent for internet of things (IoT) applications that doesn't require large amounts of data exchange including asset tracking. All iPhone devices starting with iPhone 4 and newer, iPad mini and newer and all Android phones and tablets with Android 4.3 and newer are BLE compatible.

A BLE beacon is a transmitter that periodically broadcasts a unique identifier around itself in a range that may vary from sub-inch to more than 300 ft. A BLE compatible device such as a smartphone or a BLE enabled GPS device can scan a beacon when it is within it the broadcasting range. When an app preinstalled on a BLE compatible smartphone, GPS device or a BLE gateway receives the identifier, it can store the received signal or link it to a certain action such as sending information to a cloud server. Some construction equipment manufacturers (such as Caterpillar) have already started to install BLE beacons on its equipment attachments.

Different BLE beacons are currently available in market, which were identified in this study. The information of the identified devices was obtained by contacting the manufacturers or directly from their website. The collected information included prices as well as technical specifications. The obtained information was used to compare the different BLE beacons. Different factors were considered in this comparison, including battery lifetime, range of signal, ruggedness, and price. Table A.1 shows BLE beacons properties and their features and prices. One of the main features of BLE is its low energy consumption resulting in longer battery lifetime. However, this feature is heavily dependent on the manufacturer of the beacon. The battery lifetime and the signal range proclaimed on vendors websites were also used in the comparison.

Based on the properties discussed previously. BLE beacons from four different vendors were purchased and evaluated. The beacons selected for preliminary evaluation were from Confidex, ELA, Xirgo and Kontakt. The main factors that contributed to the selection of these beacons were: enclosure IP rating, range, battery life, price, vendor reputability, and recommendation of compatibility with certain GPS-BLE devices.

A.1.2 Selection and Comparison of BLE-Enabled GPS Trackers

GPS is a satellite navigation system that provides signals for location and time information for any vehicle or object that has a line of sight to four or more GPS satellites. Each GPS satellite transmits a unique signal that allow GPS devices to calculate the precise location of the satellite. GPS receivers use this information and trilateration to compute the exact location (Hoque 2016). A GPS device has also a transmitter to send the location information over a wireless network to a server.

The majority of equipment telematics systems currently uses GPS technology to track the location of the equipment.

Table A.1: BLE Beacons and Their Properties

Vendor	Model	Battery Life	Range	Protocol	Environment	BLE
Accent Systems	iBKS Plus	70 months	100 m	iBeacon and Eddystone	Waterproof	4.2
Accent Systems	iBKS 105	25 months	50 m	iBeacon and Eddystone	Not Waterproof	4.2
Accent Systems	iBKS USB	(USB)	100 m	iBeacon and Eddystone	Not Waterproof	4.2
BlueCats	AA Beacon (BC313)	36 months	100 m	iBeacon and Eddystone	water and dust resistant	4.0
BlueCats	Coin Beacon (BC413)	12 months	100 m	iBeacon and Eddystone	water and dust resistant	4.0
BlueCats	USB Beacon	(USB)	20 m	iBeacon and Eddystone	-	4.0
Estimote	Proximity Beacon	36 months	100 m	iBeacon and Eddystone	-	5.0
ELA	Blue Puck ID	Up to > 120 months	500 m	iBeacon and Eddystone	IP68	4.2
Xirgo	XT1500 Beacon	60 months	100 m	Eddystone	IP66	5.0
Gimbal (Qualcomm)	Series 22 Beacon	48 months	50 m	iBeacon	-	4.0
Gimbal (Qualcomm)	Series 21 Beacon	18 months	50 m	iBeacon	-	4.0
Gimbal (Qualcomm)	U-Series 5 Beacon	(USB)	33 m	iBeacon	-	4.0
Feasycom	FSC-BP104	60 months	500 m	iBeacon and Eddystone	IP40	5.0
Minew	Robust Beacon I3	60 months	100 m	iBeacon and Eddystone	IP65	5.0
Minew	Max Beacon	120 months	300 m	iBeacon and Eddystone	IP67	5.0
Minew	DearBeacon (E9)	36 months	100 m	iBeacon and Eddystone	IP68	5.0
Minew	USB Beacon	(USB)	60 m	iBeacon and Eddystone	-	5.0
Kontakt	Tough Beacon TB18-2	50 months	70 m	iBeacon and Eddystone	IP65	4.2
Kontakt	Heavy Duty HD18-3	168 months	70 m	iBeacon and Eddystone	IP65 NEMA 4	4.2
Kontakt	Smart Beacon SB18-3	50 months	70 m	iBeacon and Eddystone	IP50	4.2
SATECH Beacon	STiE2	60 months	300 m	iBeacon and Eddystone	IP66	4.0/5.0
SATECH Beacon	STiE4	36 months	150 m	iBeacon and Eddystone	IP67	4.0/5.0
Confidex	Viking here	60 months	200 m	Eddystone	IP68	4.2

GPS tracking available have different power supply, which decides the type of equipment it will be used on. Some GPS devices are directly connected to the equipment electronic control module (ECM) through the OBDII or JBUS 1939/1708 ports available in most on-road vehicles. Virtually, every car and small truck with a model year of 1996 and newer is required to be OBDII compatible by US legislation. Other GPS tracking devices are hardwired. These are used when there isn't an available ECM connection, or when a more permanent connection is needed. They are powered by the equipment itself, and typically can provide real-time location when the equipment is on. This type of GPS trackers is generally suitable for powered maintenance equipment with accessible power connection points. Some of the OBD and wired trackers are supplied with backup batteries for motor off times. Such that they provide real-time location when the equipment is turned on, but when the equipment is off, those devices are powered by a battery and send location information less frequently, once per day for example. Another category of tracking devices uses solar energy for power or a combination of wired, solar, and battery.

GPS devices uses different types of cellular networks. Classical cellular networks such as LTE and 4G are highly power consuming and are not efficient for cases where small volumes of data are transmitted periodically. LTE Cat 1 and LTE Cat M1 use less amounts of bandwidth and allow for higher traffic to fit in the same bandwidth with less power consumption. LTE Cat 1 is preferred when higher reporting rates are needed. On the other hand, LTE Cat M1 is more efficient when it comes to power. Which plays a significant role in lifetime of battery powered trackers and life span of backup batteries. Finally, NB-IoT is a newer type of network. It doesn't operate in the LTE band and supports very small data rates due to its very narrow bandwidth. Older types of wireless mobile telecommunications technology include 3G and 2G cellular networks.

There are currently several GPS trackers that are BLE enabled can track equipment and scan beacons that are in range. The different GPS-BLE devices available in the market were identified (Table A.2). The information of the identified devices was obtained by contacting the manufacturers or directly from their website. The collected information used to compare the devices included price as well as technical specifications.

Due to these factors, Xirgo and Kontakt beacons were the ones selected for next stages of evaluation and implementation in this phase of the project. The difference between Kontakt and Xirgo is that the configuration settings for Kontakt beacons such as TX Power, Advertising Interval, power saving based on working hours etc., can be changed as per the requirement of the user whereas Xirgo beacons function on the fixed settings of 4 dBm Transmission Power and 1000 ms Advertising Interval. We decided to perform testing with Kontakt as we can explore different parameters and find the optimal settings for the beacons and GPS to provide long-life, cost-effective tracking system.

The evaluation of the AX11 was discontinued due to multiple factors such as the limited range of beacon detection due to the typical location of OBD II connectors under the front panel, and the challenges in having multiple OBD II devices (other than the tracker) connected in ODOT vehicles. The evaluation revealed some durability concerns related to the Atrack AS11 tracking devices. Some of the AS11 devices were found to suffer from water infiltration and failing after a short service period, even though the devices are presumably IP68 rated. Another problem related to the AS11 tracking devices was the false reporting and detection of beacons. After a short period of service life some of the devices started reporting beacons that are not present in their surroundings. The tracking device would see a beacon at a certain time and keep reporting it continuously even when the beacons were completely outside the range of the AS11. The vendor was informed of the problem and explained the problem to be a glitch in the device software. However, the suggested software update did not solve the problem which persisted even after the update. The Xirgo 4900 series trackers had few devices failure after some period of service life. It was noticed that the Xirgo 4900 failures were typically related to devices attached to high vibration maintenance equipment or in a location on the equipment that is particularly prone to vibrations. Due to the reason discussed previously, the Xirgo 4900 series BLE-enabled tracking devices were the ones selected for further evaluation and testing. The evaluated BLE-enabled GPS devices are shown in Figure A.2.

Table A.2: BLE-Enabled GPS Devices and Their Properties

Company	**Product**	**Technology**	**Power Supply**	**Data**	**IP Rating**	**Shock and vibration**
CalAmp	LMU 3030	GPS, BLE	OBD II	LTE Cat 1	-	MIL-STD 202G and 810F, SAEJ1455
CalAmp	LMU 3640	GPS, BLE, Wi-Fi	Wired	LTE Cat 1	-	MIL-STD 202G, SAEJ1455
CalAmp	TTU 3640	GPS, BLE, Wi-Fi	Rechargeable Battery	LTE Cat 1	IP67	MIL-STD 202G, SAEJ1455
Xirgo	XT4971A	GPS, BLE pairing	Wired, Solar	LTE Cat 1	IP67	-
Xirgo	XT4569A	GPS, BLE, Wi-Fi	Wired	LTE Cat M1	IP66	-
Xirgo	XT4769A	GPS, BLE, Wi-Fi	Wired	LTE Cat M1	IP66	-
Atrack	AK11	GPS, BLE 4.1	Wired, OBD II	LTE Cat 1	-	MIL-STD 810G
Atrack	AX11	GPS, BLE	OBD II	LTE Cat M1	-	MIL-STD 810G, SAE J1455
Atrack	AS11	GPS, BLE	Wired, Battery	LTE Cat M1 /Cat 1	IP68	MIL-STD 810G, SAE J1455
MoreyCorp	MC4	GPS, BLE	Wired	LTE Cat 1	IP68	SAE J1455 Level 1
Teltonica	FM4001	GPS, BLE	OBD II, backup battery	3G, 2G	IP41	-
Teltonica	FMM130	GPS, BLE	Wired, backup battery	LTE Cat M1 /NB	IP41	-
Gosafe	GAT-1000	GPS, BLE 4.0	Wired, backup battery	LTE Cat 1	IP67	MIL-STD 202G, SAEJ1455
Gosafe	GAT-3000	GPS, BLE 4.0	Wired, solar, backup battery	LTE Cat 1	IP67	MIL-STD 202G, SAEJ1455
Gosafe	GTU-5000	GPS, BLE 4.0	Wired, backup battery	LTE Cat 1	-	MIL-STD 202G, SAEJ1455
Gosafe	G1RUS	GPS, BLE 4.0	replaceable batteries	LTE Cat 1	IP67	MIL-STD 202G and 810F, SAEJ1455
Queclink	GL501MG	GPS, BLE 4.2	Batteries (1 year)	LTE Cat M1/NB1	IP67	-
Queclink	GV600MA	GPS, BLE 4.2	Wired, backup battery	LTE Cat M1/NB	IP67	-
FANSTEL	BLG840F	BLE 5	USB charger	LTE M/NB	-	-
ACCENT	TRK230)	GPS, Wi-Fi, BLE	USB, rechargeable battery	LTE M/NB	-	-

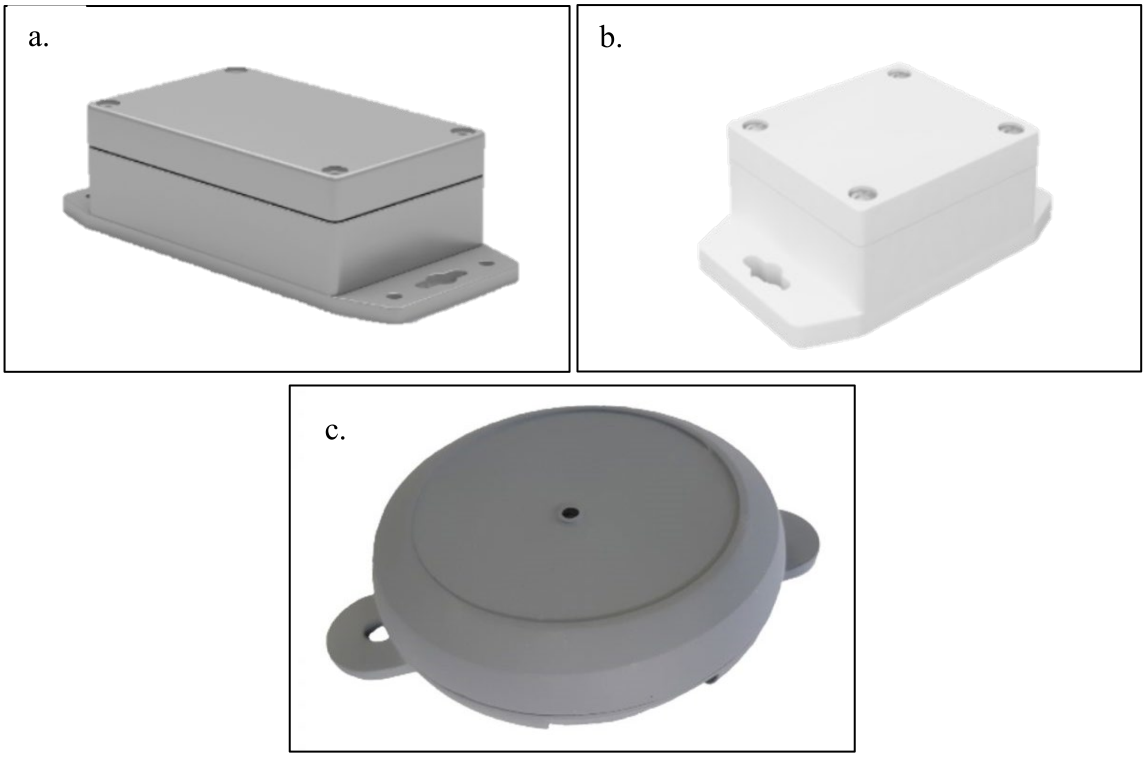


Figure A.1: a) Kontakt Heavy Duty Beacon, b) Kontakt Tough Beacon, and c) Xirgo XT1500 Beacon

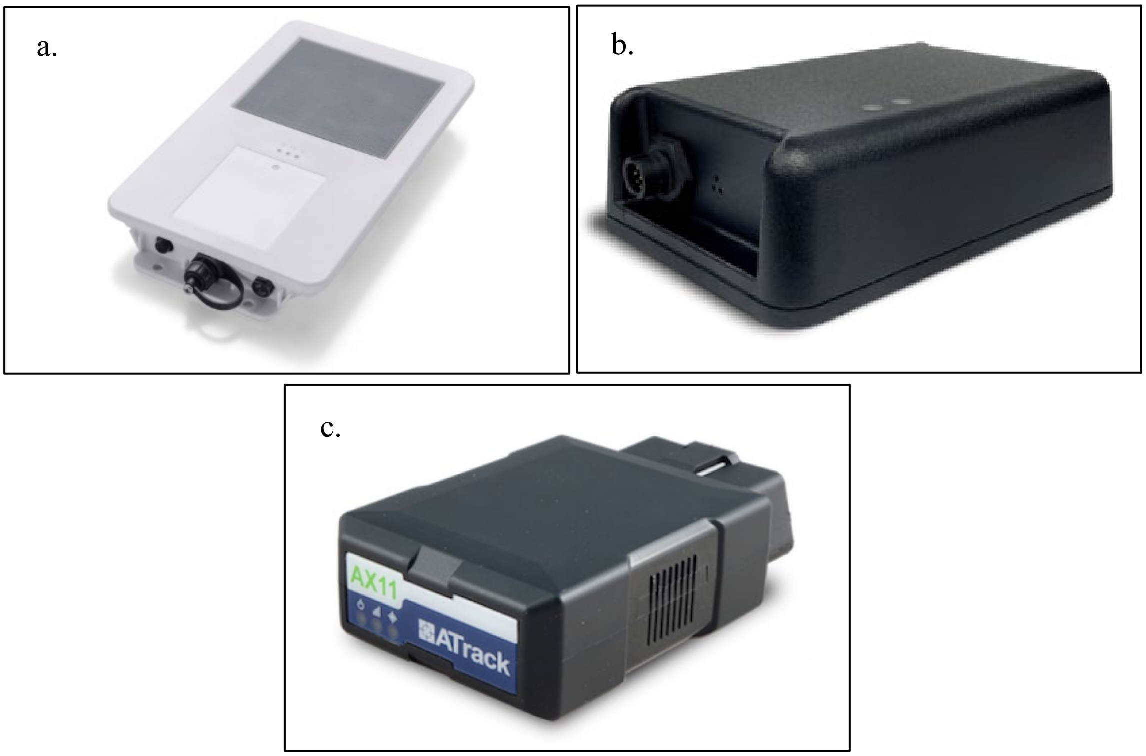


Figure A.2: GPS-BLE Devices Evaluated: a) Xirgo 4900 Series, b) Atrack AS11, and c) Atrack AX11

A.2 Optimizing System Configuration for Beacon Detection and Service Life

A.2.1 Experiment Setup and Description

A BLE-enabled GPS device was mounted on a moving vehicle and the beacons were kept stationary on the roadside at 50 ft apart from each other with the first one placed 22 ft from the centerline of the close driving lane. Figure A.3, obtained from Google Earth, gives an overview of the testing field such as width of the road, location, and distance of beacons from the edge of the road, and direction of traffic. The testing was conducted at the moving speeds of 20 mph and 40 mph, and 0 mph (15-30 seconds stop at the location of beacons) for varying settings. Each setting was experimented with two vehicle runs.

Figure A.3: Overview of the testing ground

Figure A.4 shows an example of the vehicles used in the testing as well as location where GPS were placed on the vehicles. The factor of obstruction in the way of GPS was also kept in mind and testing was done accordingly with blocked and unblocked scenarios. When the GPS is not facing the beacons directly, but rather is fixed on the other side of the vehicle, it is referred to as the blocked case.

Figure A.4: Testing vehicles with GPS mounted on top and side

The testing helped to identify the best GPS-BLE and beacon settings needed to optimize the beacon detection while maintaining a reasonable power consumption and expected service life. The messages were received on a cloud database and finally they were parsed using a python script. The GPS and beacons were identified using the MAC address labelled on the device. To observe where the GPS device detected the beacons and which setting was the most suitable for the beacons as well as the GPS, the tracking data obtained from the field testing was plotted on the Google Earth software. For this purpose, the tracking data from the field tests was arranged, organized, and labelled. Figure A.5 shows the plot of data collected from the field tests for multiple runs on Google Earth Pro. The yellow pins represent the beacons. The point where the GPS detected the beacons can be easily seen noted by the run code (e.g. R3fbs(i)-3).

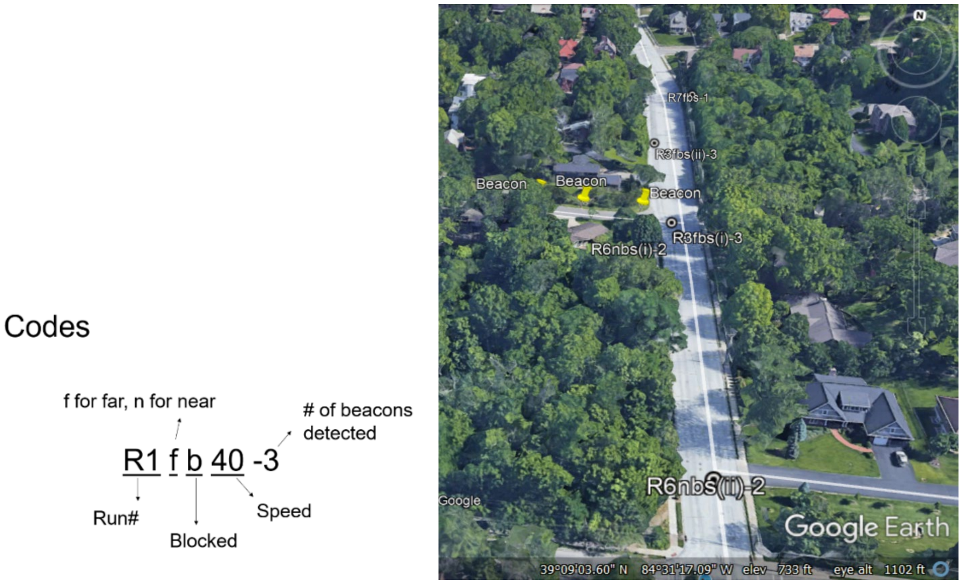


Figure A.5: Google Earth Overview

A.2.2 Factors Affecting the System Detection Efficiency and Service Life

A.2.2.1 Factors Related to BLE-enabled GPS Devices (GPS-BLE):

- Scanning Time:

The scanning time of the GPS-BLE device represents the time interval for each BLE signal receiving period. The BLE receiving interval will be restarted at the end of every scanning period.

- Reporting Time:

The device reporting interval represents the time rate at which the device will send the collected BLE data along with GPS information to the server. Other than beacon detection, the importance of the reporting period lies in the amount of data required for each report to be send. The amount of data sent per month can translate into an increase in the monthly cost of the system.

- Channel Window:

The maximum window period for a BLE signal to be received.

A.2.2.2 Factors Related to BLE Beacons:

- Beacon Type:

The two types evaluated based on the previously discussed selection process are Xirgo and Kontakt beacons.

- Transmission Power (Tx Power):

Transmission power (also known as TX power) is an indicator of the worst-case transmission power of a device i.e., a beacon will transmit at least that much power. This setting affects the factors such as signal range, signal stability and battery life. It defines the strength of signal transmitted from the beacon measured in dbm (Decibel-milliwatts) corresponding to a number rating of 0 to 7. As the transmission power increases, the range of signal increases which leads to bigger energy drain and shorter battery life. Table A.3 shows the approximate range and received signal strength for different levels of transmission power. As the transmission power increases, the range increases as well.

Table A.3: Transmission Power, Range & RSSI

TX Power Level	Transmission Power (dBm)	RSSI @ 1 meter	Approximate Range (m)
0	-30	-115	2
1	-20	-84	4
2	-16	-81	10
3	-12	-77	20
4	-8	-72	30
5	-4	-69	40
6	0	-65	60
7	4	-59	70

- Advertising Interval:

It is the time between each advertising event. A beacon device sends three advertise packets in each event on channels 37, 38 and 39. If the interval is set to be 1 second, the packets will be sent every second. (https://devzone.nordicsemi.com/f/nordic-q-a/9602/advertising-interval-and-advertising-timeout). It is measured in milliseconds (ms). Higher interval settings (over 700 ms) cause disturbance in signal stability whereas low setting leads to shorter battery life. (https://support.kontakt.io/hc/en-gb/articles/201567802-Advertising-Interval-best-practise).
An Excel sheet was created using interpolation, estimating battery life for different settings of transmission power and advertising interval as shown in Table A.4. Table A.4 is an excel sheet that shows the effect of advertising interval on battery life in months and years. Using this table, we can estimate the battery life for different configuration settings of TX power and advertising interval used in the field testing. It is a vital factor in the process of optimizing beacon detection.

- Battery Life:
  The factors that affect the battery life of a beacon are TX Power, Advertising Interval, and working hours. A higher advertising interval and a low transmission power result in battery life saving.

Table A.4: Battery life with varying settings

Interval (ms)	Transmission Power (dBm)	Battery life (months)	Battery life (years)
350	-12	50	4.2
800	-12	76	6.3
1000	-12	78	6.5
2000	-12	86	7.1
2500	-12	90	7.5
3000	-12	94	7.8
350	-4	47	3.9
800	-4	70	5.8
1000	-4	72	6
2000	-4	79	6.6
2500	-4	83	6.9
3000	-4	87	7.2
350	0	43	3.6
800	0	63	5.3
1000	0	65	5.4
2000	0	71	5.9
2500	0	75	6.2
3000	0	78	6.5
350	4	39	3.3
800	4	54	4.5
1000	4	56	4.7
2000	4	57.1	4.8
2500	4	64.1	5.3
3000	4	58.2	4.8

A.2.3 Evaluating Optimal GPS-BLE Device Settings

First, experiments were conducted to evaluate the optimal GPS-BLE device settings for beacon detection reliability. Three Kontakt and Xirgo beacons were placed together on the roadside at a distance and the GPS was mounted on top of the vehicle. As discussed in previous sections the GPS-BLE settings related to beacon detection are:

- BLE Reporting Time
- BLE Scanning Time
- BLE Scanning Window (Channel Window)

Table A.5 summarizes the settings tested in the field to determine the optimum GPS-BLE settings to be used in the system and in further tests.

Table A.5: Settings for optimal GPS-BLE configuration testing

Config. Number	TX Power (dBm)	Adv. Interval (ms)	Scanning Time (s)	Reporting Time (s)	Channel Window (ms)	Vehicle Speed (mph)
1	0	1000	30	10	2000	30, 40
2	0	1000	10	10	2000	40
3	0	1000	5	10	2000	40
4	0	1000	10	10	1000	40
5	0	1000	20	20	10000	40
6	+4	1000	20	20	10000	40
7	+4	800	20	20	10000	40
8	-12	800	20	20	10000	40
9	0	800	20	20	10000	40
10	0	800	10	10	2000	40
11	+4	2000	30	10	2000	20, 40
12	-12	2000	30	10	2000	[30 sec stop], 20, 40
13	0	2000	5	10	2000	[30 sec stop], 20, 40
14	+4	3000	30	10	2000	20, 40
15	+4	2500	30	10	2000	40
16	+4	2000	30	10	2000	40
17	+4	3000	10	10	2000	40
18	0	3000	10	10	2000	40

It can be concluded from the results that increasing the GPS reporting time improves the detection performance whereas lowering the scanning window improves the GPS's ability to detect. A higher scanning window causes difficulty in detection when the vehicle is moving at higher speed. However, a higher or lower channel window does not improve the results. The results were looked at by changing beacon configurations and observing the improvement in the results for a higher GPS configuration setting. The optimal GPS-BLE device settings determined from this experiment was 30 second scanning time, 10 second reporting time, and 2000 ms reporting interval.

A.2.4 Evaluating Optimal BLE Beacons Settings

A.2.4.1 Kontakt Beacons: Evaluated Configurations

After finding the optimal settings for the GPS-BLE and keeping that constant, we evaluated the effect of following factors on the beacon detection:

- Vehicle Passing Speed: 40 mph, 20mph, Stop & Go
- GPS-BLE location: Blocked and unblocked cases
- Beacon related factors such as
    - Beacon Type: Kontakt
    - Tx Power: Signal transmission power
    - Advertising Interval

The details of the evaluated settings and configurations are displayed in Table A.6.

Table A.6: Settings for optimal Kontakt beacons configuration testing

Config. Number	TX Power (dBm)	Adv. Interval (ms)	Scanning Time (s)	Reporting Time (s)	Channel Window (ms)	Vehicle Speed (mph)	Distances (ft)
1	0	1000	30	10	2000	[30 sec stop], 20, 40	0, 50, 100
2	+4	800	30	10	2000	[30 sec stop], 20, 40	0, 50, 100
3	+4	2000	30	10	2000	[30 sec stop], 20, 40	0, 50, 100
4	-8	1000	30	10	2000	[30 sec stop], 20, 40	0, 50, 100
5	-12	1000	30	10	2000	[30 sec stop], 20, 40	0, 50, 100
6	-4	1000	30	10	2000	[30 sec stop], 20, 40	0, 50, 100
7	0	1000	30	10	2000	[30 sec stop], 20, 40	0, 50, 100
8	+4	1000	30	10	2000	[30 sec stop], 20, 40	0, 50, 100

A.2.4.2 Kontakt Beacons: Results and Discussion

The GPS Signal can get blocked by either objects or the location where it is attached to the vehicle. The results have been better explained by the discussion in the following section. Based on the results obtained from the initial seventy field tests for optimizing Kontakt BLE configuration, the cases with most optimal settings have been selected and the results have been analyzed and summarized below, with respect to detection range, battery life, and optimal settings, by plotting the latitudes and longitudes obtained through the field experiments in Google Earth software. Moreover, the effect of vehicle speed on beacon detection has been discussed. It was observed that sometimes the GPS-BLE is unable to detect the beacons at higher speeds either because of a higher GPS-BLE scanning window or a higher beacon advertising interval. For example, 20 ms means a signal is broadcasted 5 times in a second, whereas it could also be broadcasted every second or two seconds. At lower speed, or stop and go, the GPS-BLE scanning interval gets enough time to detect the beacon as the cycle repeats, and sometimes the reason could be signal blockage or low beacon TX power. For this research, it is important to find a setting that enables beacon detection for vehicles moving at higher speeds as well as at lower speeds.

Some of the terminologies have been explained to better understand the figures. When the GPS is placed such that, it is attached to the side of vehicle facing the direction opposite to that of beacons or something is blocking its path, we refer to it as a block case represented by ‘b’ in the Run ID, otherwise its unblocked. The lane closer to beacons is referred to as near lane and the other lane is referred to as the far lane.

Case-I

In this case, the beacon reporting and scanning time for GPS-BLE were set at 10 seconds and beacon scanning window or channel window was set at a value of 2000 milliseconds. The Tx power for Kontakt beacons was set at 0 dbm and advertising interval at 1000 milliseconds. As shown in Figure 6, the GPS-BLE was able to detect all beacons within a 100 ft radius. The estimated beacon battery life that can be achieved for this setting is 6 years. All beacons were detected within a 100 ft radius.

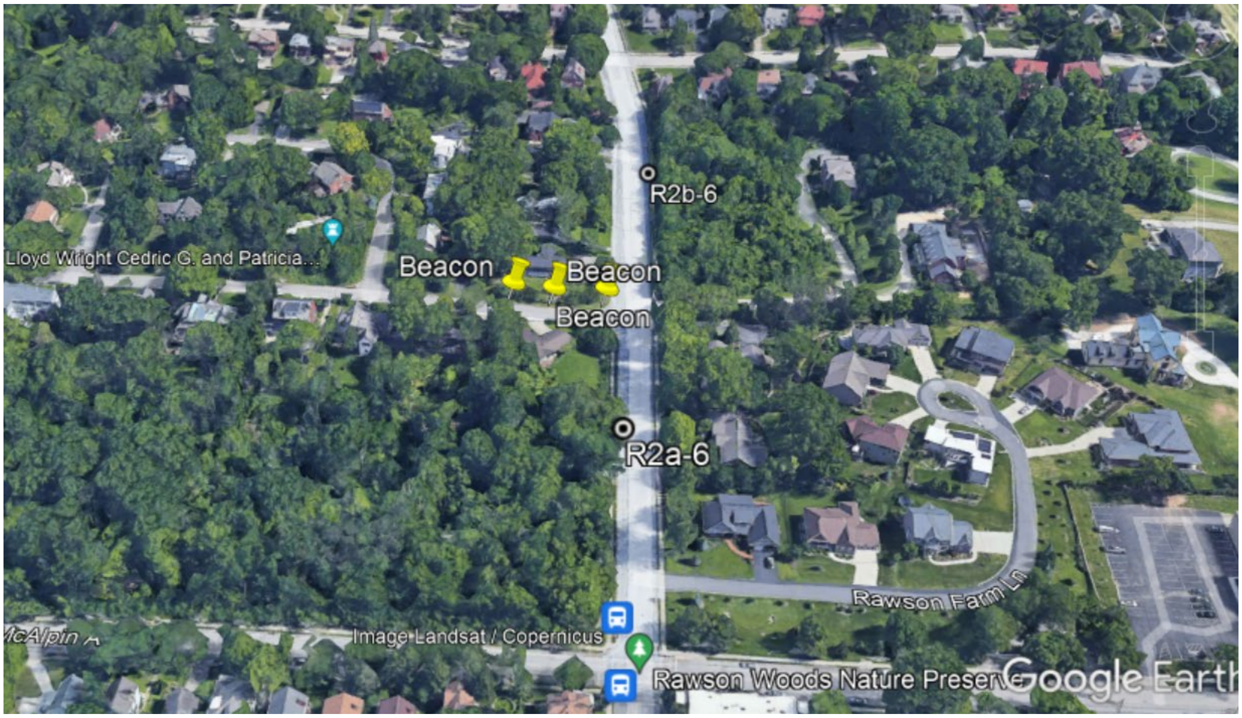


Figure A.6: Case-I Google Earth Analysis

Case-II

In this case, the results were looked at by increasing the Tx Power and decreasing the Advertising Interval. As a result, the battery life also decreased because of smaller advertising intervals. The Tx power for Kontakt beacons was set at +4 dbm and advertising interval at 800 milliseconds. As shown in Figure A.7, the GPS-BLE was able to detect all beacons within 100 ft. radius. The estimated beacon battery life that can be achieved for this setting is 5.1 years.

Case-III

In this case, when driving at the speed of 40 mph, the GPS was able to detect all beacons as can be seen in Figure A.8 and the battery life also increased by making advertising intervals larger. Only the Kontakt beacons were used and the Tx power for beacons was set at +4 dbm and advertising interval at 2000 milliseconds. The estimated beacon battery life for this setting that can be achieved is 8.8 years. The GPS-BLE was able to detect all Kontakt beacons within 100 ft radius.

Case-IV

In this case, by decreasing the Tx Power and increasing the advertising interval, the battery life is increased to 9.2 years. When blocked, the detection rate is affected. However, all beacons were detected when unblocked at the speed of 40 mph as can be seen in Figure A.9. The beacon detection test was done at varying speeds of 40 and 15 mph and 30 seconds stop. For this test, only the Kontakt beacons were used and the Tx power for Kontakt beacons was set at 0 dbm and advertising interval at 2000 milliseconds.

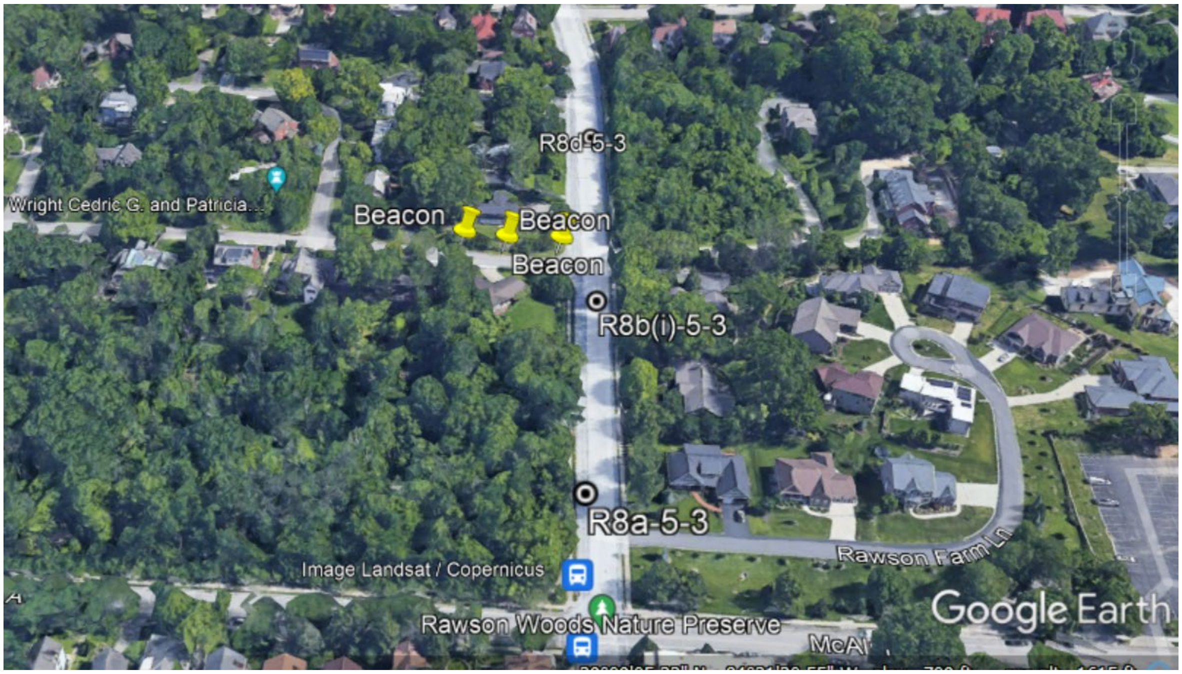


Figure A.7: Case-II Google Earth Analysis

Case-V

In this case, the TX power was lowered to -12 dbm, however, lower Tx Power affects the detection success rate and does not guarantee higher battery life every time. As can be seen in Figure A.10, the beacon detection was affected in the blocked case. The GPS-BLE was able to detect all Kontakt beacons within 100 ft. radius. The Tx Power for Kontakt beacons was set at -12 dbm and advertising interval at 1000 milliseconds. The estimated beacon battery life for this setting is 7.2 years.

Case-VI

In this case, a lower Tx Power with a larger advertising interval was used. Although, the GPS-BLE was able to detect all beacons in unblocked case as shown in Figure A.11, the estimated battery life does not increase significantly for this setting. For this test, only the Kontakt beacons were used and the Tx Power for Kontakt beacons was set at -4 dbm and advertising interval at 1000 milliseconds. The estimated beacon battery life for this setting is 6.7 years. The GPS-BLE was able to detect all Kontakt beacons within 100 ft. radius.

Case-VII

In this case, by increasing the TX power and keeping the Advertising Interval constant as in the previous case, the estimated battery life gets reduced to 6 years. The beacon detection rate is affected as well in the blocked case. However, all beacons were easily detected in unblocked case at the speeds of 40 mph and 20 mph as shown in Figure A.12. For this test, only the Kontakt beacons were used and the Tx Power for Kontakt beacons was set at 0 dbm and advertising interval at 1000 milliseconds. The GPS-BLE was able to detect all Kontakt beacons within 100 ft. radius.

Case-VIII

By increasing the Tx Power to +4 dbm, good detection rate was achieved as well as battery life of 7.2 years can be estimated. As shown in Figure A.13, the GPS-BLE was able to detect all beacons in both blocked and unblocked cases within 100 ft radius. For this test, only the Kontakt beacons were used and the Tx power for Kontakt beacons was set at +4 dbm and advertising interval at 1000 milliseconds.

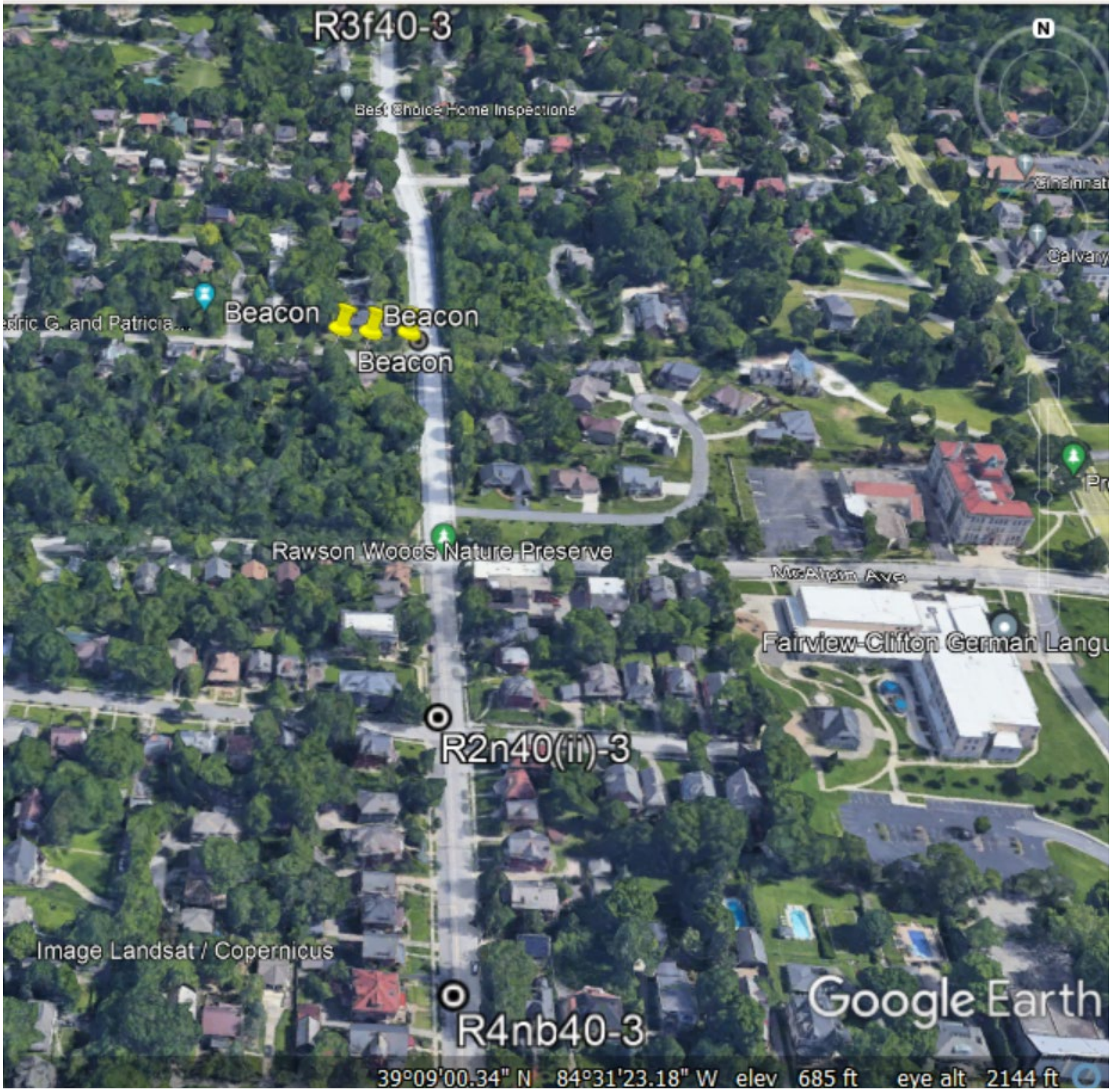


Figure A.8: Case-III Google Earth Analysis

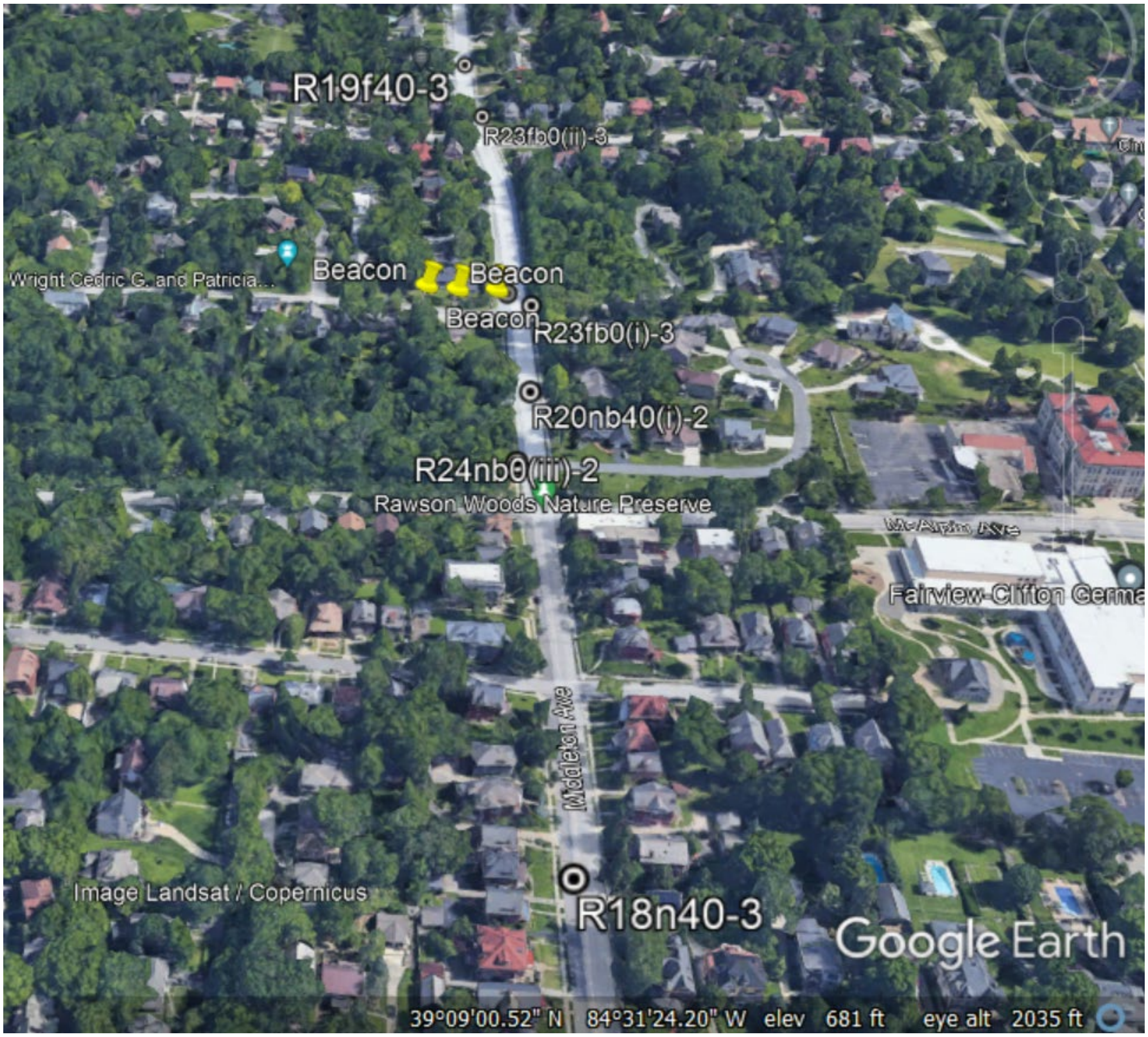


Figure A.91: Case-IV Google Earth Analysis

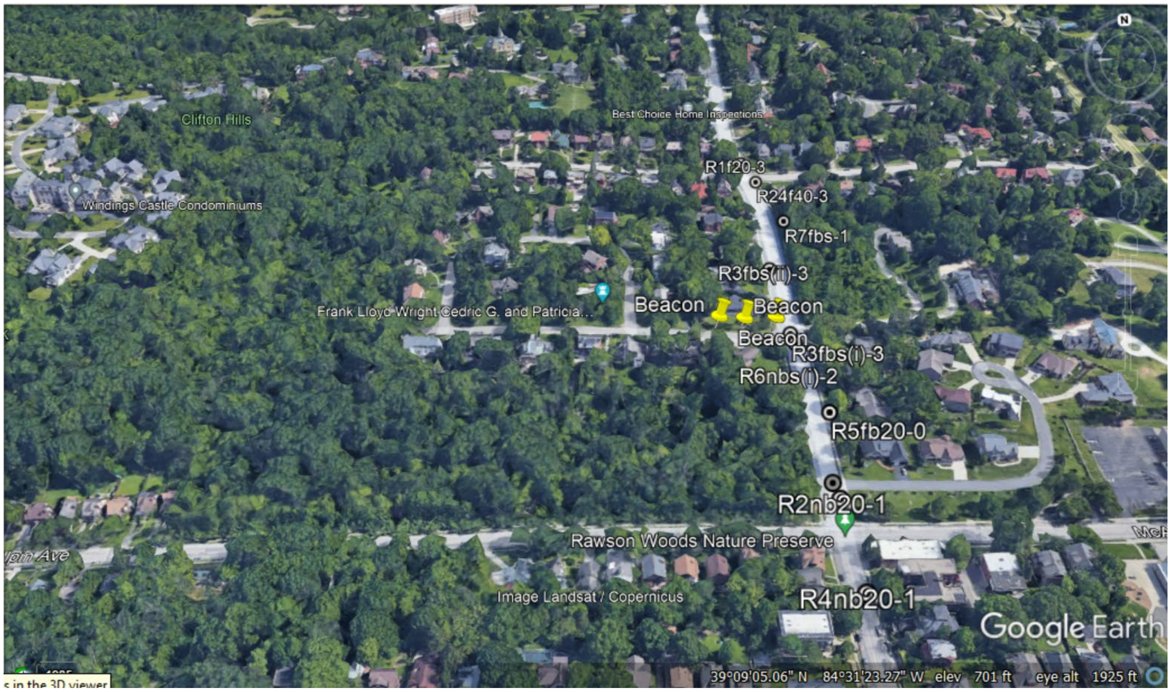


Figure 10: Kontakt BLE Case-V Analysis

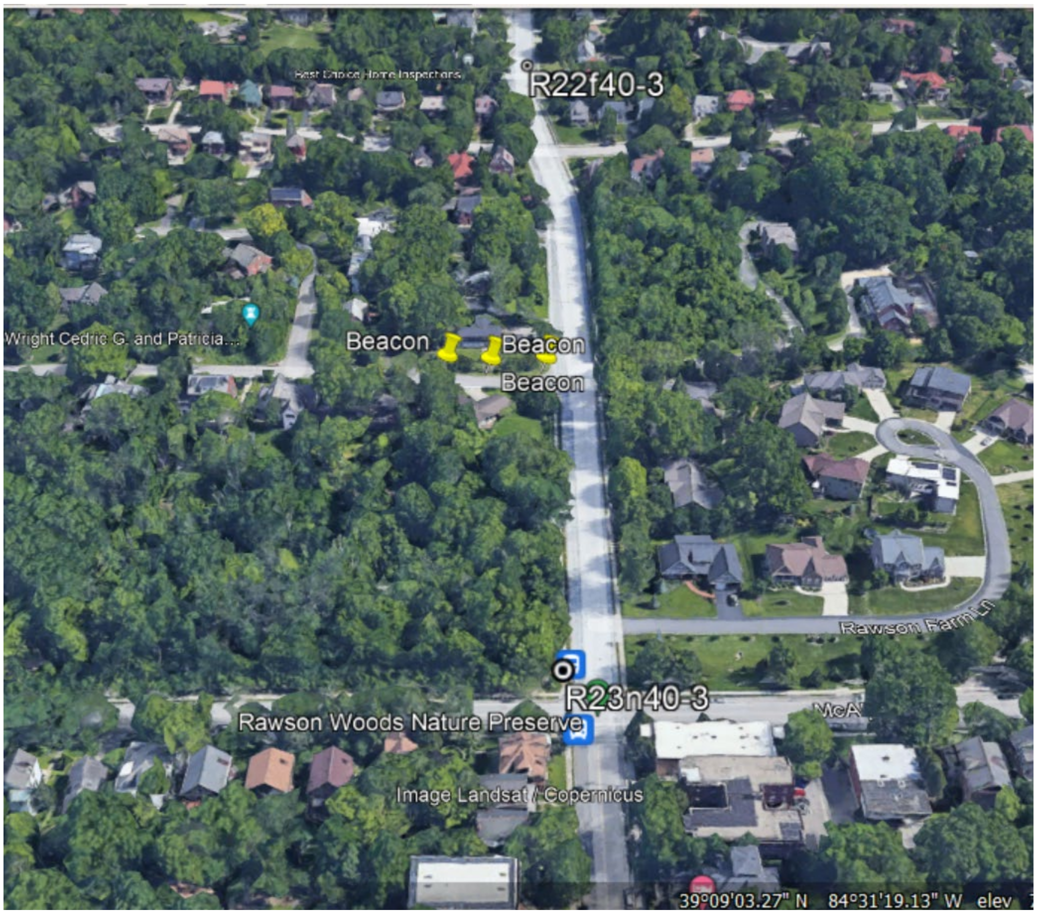


Figure A.11: Kontakt BLE Case-VI Analysis

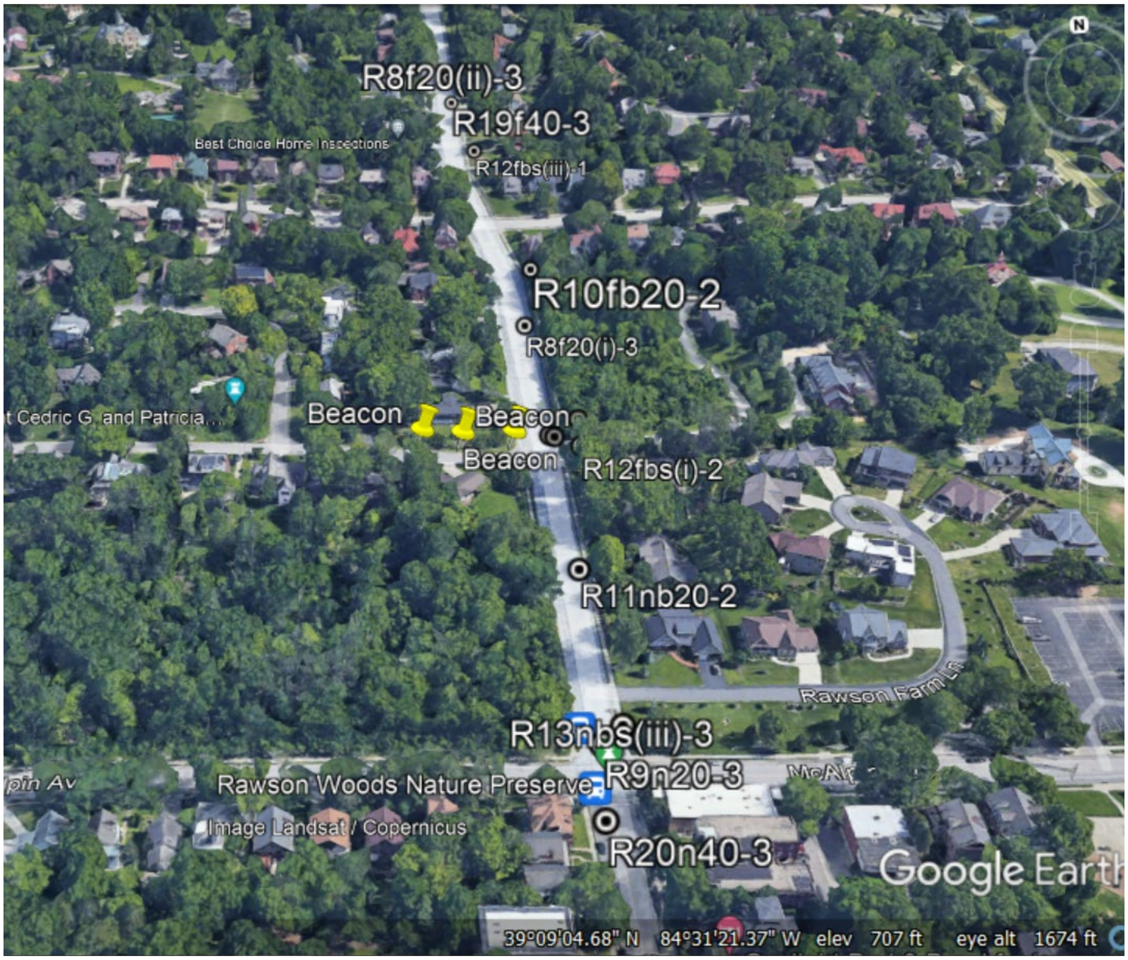


Figure A.12: Kontakt BLE Case-VII Analysis

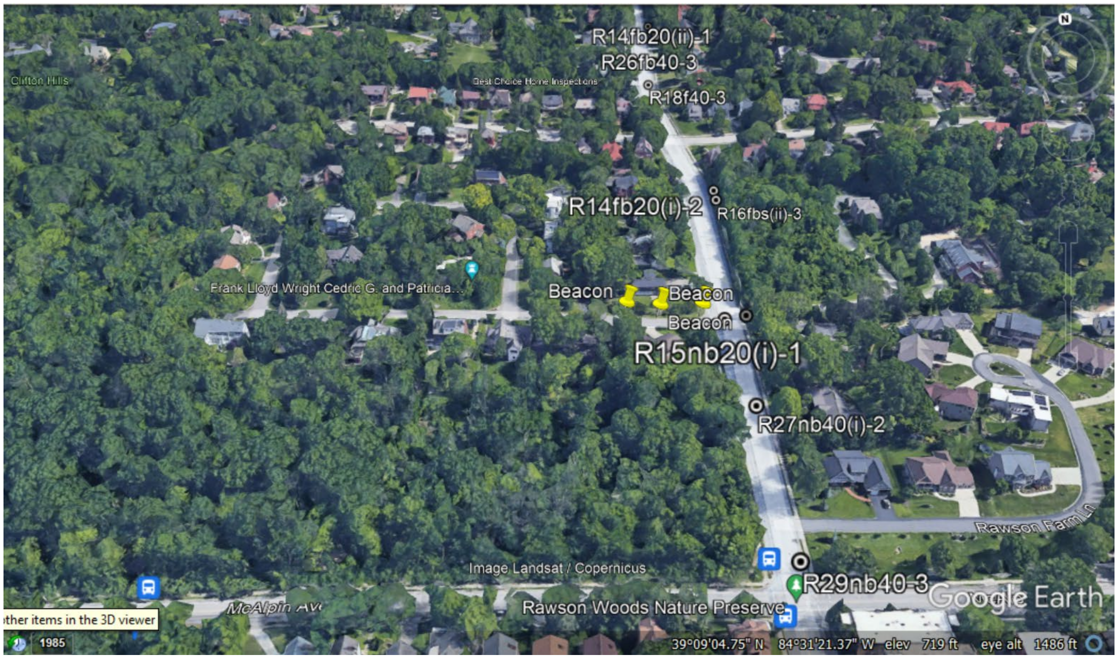


Figure A.13: Kontakt BLE Case-VIII Analysis

A.2.4.3 Xirgo Beacons: Evaluated Configurations

In this test, we evaluated the effect of the following factors on the beacon detection:

- Vehicle Passing Speed: 40 mph
- Beacon distance from the vehicle
- GPS-BLE location: Blocked and unblocked cases

Note: Xirgo beacons have fixed configuration settings and thus cannot be changed. The details of the evaluated test configurations are displayed in Table A.7.

Table A.7: Test settings for Xirgo beacons

Config. Number	TX Power (dBm)	Adv. Interval (ms)	Scanning Time (s)	Reporting Time (s)	Channel Window (ms)	Vehicle Speed (mph)	Distances (ft)
1	+4	1000	30	10	2000	40	0, 50, 100
2	+4	1000	30	10	2000	40	125, 175, 225

A.2.4.4 Xirgo Beacons: Results and Discussion

Xirgo comes with default configuration settings, and we identified the detected beacons using their MAC Address through the data obtained from the Python program. The results have been explained in the following case discussions.

Case-IX

The Xirgo beacons were tested in this case, and they were placed at up to 100 ft from the edge of road. The beacon reporting for GPS-BLE was set at 30 seconds and scanning time was set at 10 seconds. The beacon scanning window or channel window was set at a value of 2000 milliseconds. Xirgo beacons were used with the TX power of +4 dbm and advertising interval at 1000 milliseconds. The GPS-BLE was able to detect all Xirgo beacons within 100 ft radius as shown in Figure A.14.

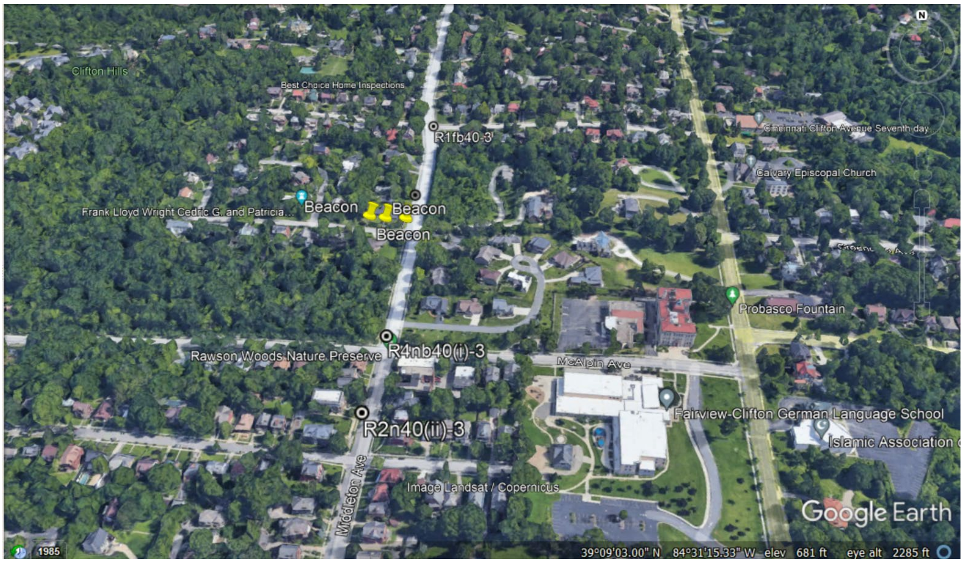


Figure A.14: Xirgo BLE Case-IX Analysis

Case-X

The beacons were placed up to 225 ft. from the edge of the road. The beacon reporting for GPS-BLE was set at 30 seconds and scanning time was set at 10 seconds. The beacon scanning window or channel window was set at a value of 2000 milliseconds. For this test, only the Xirgo beacons were used with the Tx power of +4 dbm and advertising interval at 1000 milliseconds. The GPS-BLE, when unblocked, was able to easily detect the beacons within 225 ft radius (Figure A.15).

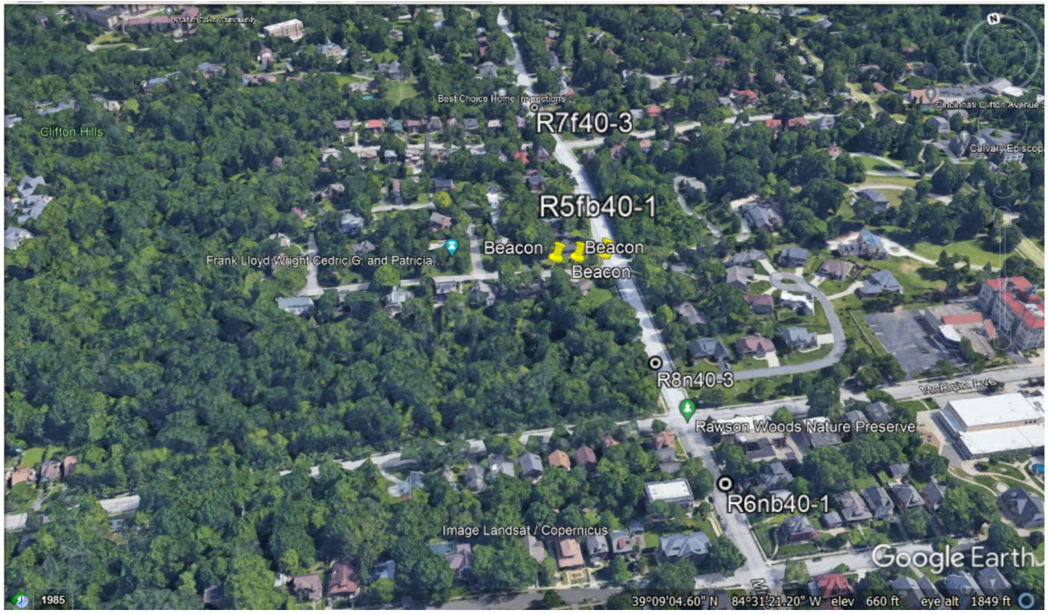


Figure A.15: Xirgo BLE Case-X Analysis

A.2.4.5 Test Cases Conclusion

It can be concluded from the conducted experiments that the most optimal setting for the Kontakt beacons in terms of beacon detection range, detection success rate, and beacon battery life can be seen in cases where the Tx Power is at least 0 dBm and the advertising interval is around 1000 ms. In these cases, the beacons were consistently detected, typically both in the covered and in the uncovered cases. At the same time the predicted battery life was acceptable. When it comes to the Xirgo beacons the default settings cannot be changed. At the default settings, the Xirgo beacons were able to detect beacons with consistency.

A.2.5 Evaluation of Beacon Detectability at High Driving Speed

The main principle of the developed tracking system is that maintenance equipment tracked using the GPS-BLE devices would be able to detect the location of the BLE-beacon tracked equipment while moving at different speeds close to each other. To evaluate the feasibility of the beacon detectability at highway speeds experiments were performed. The testing included placing the BLE beacons on the side of interstate highways and detecting them by a vehicle moving at highways speeds (up to 65 mph). The experiments were performed using the optimal beacon and GPS-BLE configurations determined based on the previous experiments. For each speed the experiment was performed three times to insure reliable detection of the beacons. The results of these experiments indicated the beacons were detected at highways speeds and consistently in all three trials.

A.3 Field Evaluation of Tracking System Prototype

A.3.1 Installation of GPS-BLE & Beacons on ODOT Construction Equipment

The following ODOT counties were selected: Williams (District 2), Henry (District 2), Fulton (District 2), Gallia (District 10), , Vinton (District 10), Meigs (District 10), and District 8 garage. GPS-BLE devices were installed on different types of powered equipment and the beacons on powered and non-powered equipment such as excavators, skid steers, trailers, attenuators, chippers, dump trucks, mowers, portable traffic signals, solar powered message centers, backhoes, and tractors. It was made sure that the GPS and beacons are installed properly and in an open place to avoid any signal obstruction. Figures A.16 and A.17 shows several types of equipment like trucks, excavators, traffic lights, mowers, and tractor with GPS-BLE, and beacons mounted using cradles with magnetic as well as epoxy, respectively. The GPS-BLE was configured to turn on when the equipment starts or move even when engine is turned off.

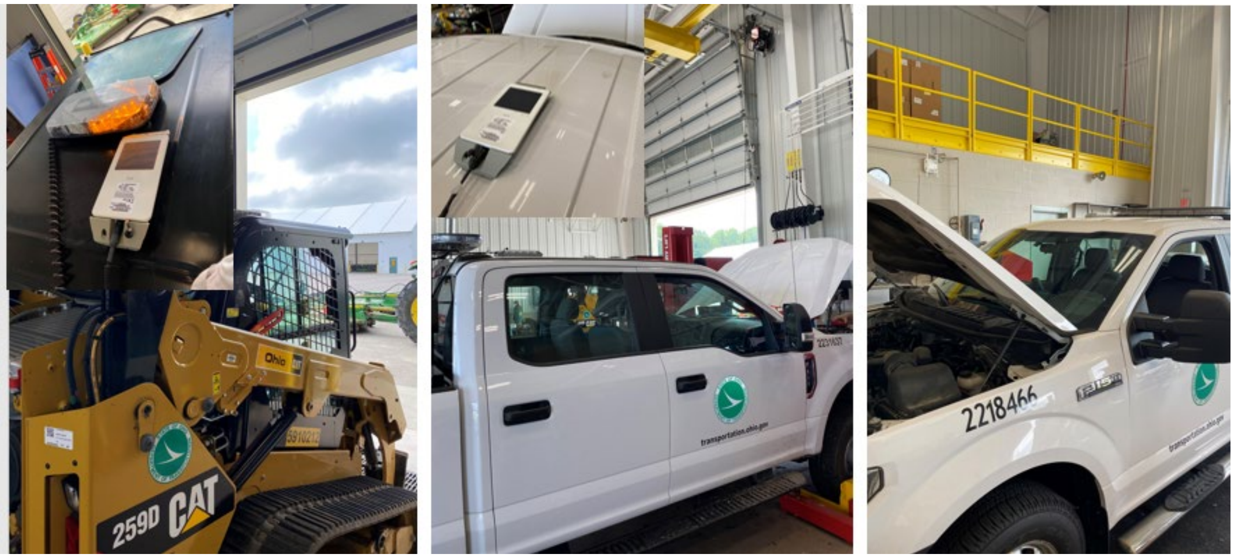


Figure A.16: GPS installed on ODOT's equipment

A.3.2 Analysis Program

All the data reported by the GPS-BLE devices is sent to and recorded in the database developed for the ODOTMETS application. The developed user web-application discussed in other sections of this report (Figure A.18) gets its data from the database using the .NET Framework based API. An analysis program was developed in Python to obtain the data directly from the database. It collects all required information from the database through a Python interface. The analysis program gets the data from the database, parses the GPS-BLE messages, and performs analysis on the data based on the information needed. The analysis can be performed on a GPS-BLE event scale or on beacon detection scale. A user interface was built for the analysis program to simplify the analysis process. Figure A.19 shows some components of the user interface. Most importantly, selection of the start and end dates are used to select the time frame within which the analysis will be performed. Other options can be specified if information such as the maintenance equipment usage data is needed.

Figure A.17: Beacon devices installed on ODOT's equipment

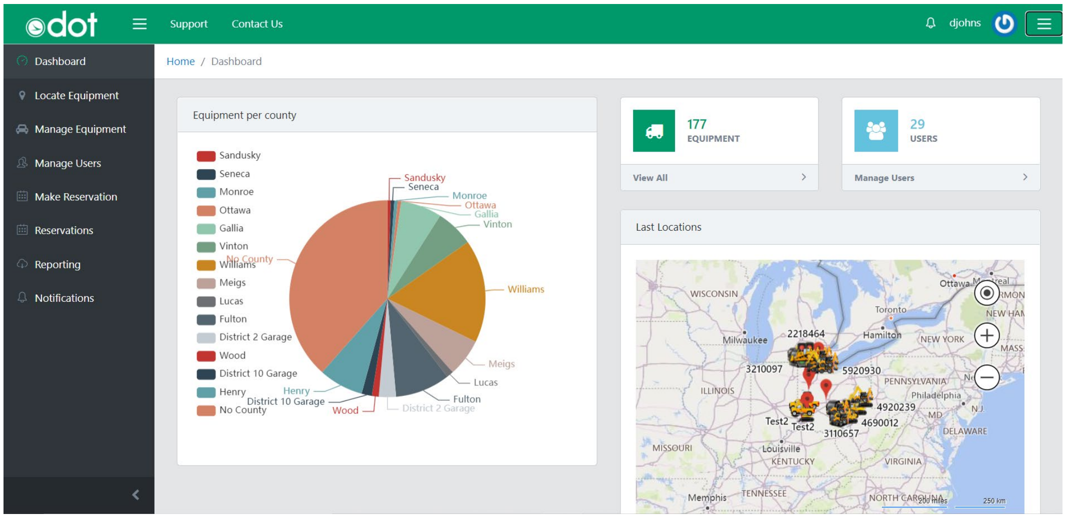
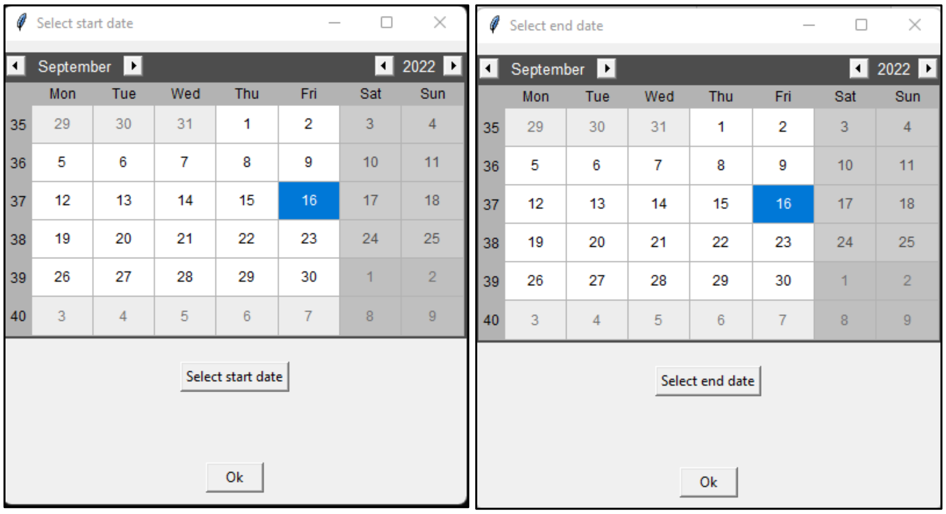


Figure A.18: Interface of User Web Application

A.3.3 Effectiveness of the Developed System in the Field

This section discusses the results obtained from the GPS-BLE beacon detection after they were installed on the ODOT's equipment. The data obtained included the location of detection, time of detection, GPS-BLE equipment number and its category, equipment with beacon number and its category, as well as the number of times the beacons were detected by the GPS-BLE equipment each month. Table A.8 gives a summary of the total number of times the GPS-BLE detected beacons between December 2020 and May 2021. In general, the results suggest that GPS-BLE consistently had high number of beacon detection and thus tracking the pieces tracked using the beacons. It is noted the number GPS-BLE increased after March due to increasing the number devices used. The results suggest that the system consisting of GPS-BLE and beacons can be used for tracking equipment at ODOT district and county garages.



	Mon	Tue	Wed	Thu	Fri	Sat	Sun
35	29	30	31	1	2	3	4
36	5	6	7	8	9	10	11
37	12	13	14	15	16	17	18
38	19	20	21	22	23	24	25
39	26	27	28	29	30	1	2
40	3	4	5	6	7	8	9

Figure A.19: Analysis Software User Interface Option Forms

Table A.8: GPS-BLE Detection of beacons Count

	BLE Detection Count				
GPS-BLE Type	**Dec-Jan**	**Jan-Feb**	**Feb-March**	**March-April**	**April-May**
XIRGO	58,214	57,658	63,833	179,868	287,397

Table A.9 shows the total beacon detection count of each pieces GPS-BLE equipment in different county garages for the period between May 2021 and October 2021. It is note that the GPS-BLE on some types of equipment was able to detect beacons on other pieces of equipment more frequently than other as indicated by BLE beacon detection counts. This suggests that some equipment with GPS-BLE is being used more than others or are more frequently located in the proximity of other equipment with beacons than other equipment.

Table A.9: GPS-BLE Track Count

County	**Equipment No.**	**BLE Detection Count**
	Month; May	
Henry	4700129	11847
	2231489	7767
	5910203	5904
Gallia	2130604	30140
	2130568	4980
Fulton	5910212	6397
	2218466	5223
	2231637	2939

Vinton	2130594	2733
	2130560	1801
	2218669	2364
Meigs	4690012	7482
	2533137	5924
Williams	5910202	27616
	2231539	7707
	4920217	961
Month: June		
Henry	2231489	14344
	4700129	4222
	5910203	4044
Gallia	2130604	18581
	2130568	9974
Williams	5910202	33245
Month: September		
Gallia	2130604	30169
	2130568	5028
Williams	5910202	28777
	2231539	7903
	4920217	961
Henry	4700129	11847
	2231489	7767
	5910203	5904
Meigs	4690012	7665
	2533137	6102
Fulton	5910212	6397
	2218466	5223
	2231637	2939
Vinton	2130594	2785
	2130560	1813
	2218669	2381
Month: October		
District 2 Garage	3300279	18443
Williams	5910202	12123
	2231539	11237
	4700100	2836
	4920217	1911
Gallia	2130604	8674
	2533137	5537
Henry	2231489	8482
	5910203	3871
Vinton	2130560	3577
	2218669	2873
Meigs	4690012	3424

	2130604	1754
Fulton	5910212	4364
	2218466	2125
	4700129	2088
	2231637	1948

The data obtained can be used to determine how many times a single equipment with beacon is detected by different GPS-BLE equipment. Table A.10 shows an example for pieces of equipment tracked using beacons along with the total number of times it was detected by different GPS-BLE equipment categories within a period from May 2021 to November 2021 in one county. It is noted that some of the equipment was detected more than other; however, the equipment was detected at least 1200 times. This also confirms that beacons can be used different types of equipment in ODOT district and county garages.

Table A.10: Sample Number of Detections of Beacon-Equipped Equipment (6-month period)

Equipment Number	Detection Count
3080197	5584
3080273	4239
8932192	6957
8932279	10341
2710961	6086
3090079	1228
3080273	2054

A.3.4 Effect of Equipment Category on the Detection of BLE Beacons Using GPS-BLE

One of the main steps to optimize the developed system was to identify best maintenance equipment that needs to be tracked using GPS-BLE devices to ensure the detection of other equipment. Similarly, the equipment categories that should be tracked with BLE beacons needs to be determined. To achieve that, analysis was conducted to evaluate the detection of beacons with GPS-BLE installed on different types of equipment in various participating counties in District 2 and District 10. To this end, the number of times each GPS-BLE tracked equipment detected other equipment with beacons was determined. In addition, for each GPS-BLE tracked equipment, the number of times each type of beacon-tracked equipment was detected was obtained.

Table A.11 shows the highest reporting equipment for the month of November 2021. The table presents the number of beacons detections received for the different GPS-BLE tracked equipment in various county garages. It is noted that the three equipment categories that had highest number of beacon detection from the various count garages were utility pickup trucks, skid steers, and excavators. These types of equipment are frequently located in the proximity of other pieces of equipment and therefore can be used to detect equipment tracked with beacons. The data for GPS-BLE tracked equipment with highest beacon detection count were analyzed to identify the types of beacon-tracked equipment that was detected and number of times it was detected. Tables A.12 through A.14 provides obtained information for 4700129, 2231489, and 5910202, respectively. It is noted that the GPS-BLE tracked equipment detected different types of beacons tracked equipment. The 4700129 had the detected more types of equipment than the other types of equipment.

A.3.5 Geo-spatial Analysis of Beacon Detection

Excel 3D-Maps tool was used to analyze the time-series and geo-spatial data for the beacon detection through different devices. This was done to obtain the locations where the beacon-tracked equipment was detected by GPS-BLE tracked equipment. Figure A.20 shows the map with locations where two beacon-tracked equipment (893 tractor and 308 messaging board) were detected on by equipment No. 4700129. It is noted that the beacon-tracked pieces of equipment were detected by the GPS-BLE tracked equipment at different locations including county garage and job sites. Figure A.21 shows the location for the detection for a beacon-tracked equipment (893 tractor) in Henry County by equipment No. 2231489. The tractor was located at the county garage, while it was in route to job sites, and at job sites. Similarly, Figure A.22 shows the detection of equipment No. 2130604 to a trailer mounted attenuator in the Gallia County. Finally, Figure A.23 the location where equipment # 5910212 detected a 7-10 ton trailer tracked with beacons. The results of geo-special analysis of the beacon detection indicate that the GPS-BLE tracked equipment can be used to accurately locate other beacon-tracked pieces of equipment at difference places.

Table A.11: GPS-BLE Detection of Beacons

County	Equipment #	Equipment Category	Detection Times
Gallia	2130604	213 - UTILITY TRUCK	30169
Williams	5910202	591 - LOADER, SKID STEER	28777
Henry	4700129	470 - EXCAVATOR, TRACKED	11847
Williams	2231539	223 - PICKUP, 1 TON	7903
Henry	2231489	223 - PICKUP, 1 TON	7767
Meigs	4690012	469 - EXCAVATOR, TRACKED	7665
Fulton	5910212	591 - LOADER, SKID STEER	6397
Meigs	2533137	253 - DUMP TRUCK	6102
Henry	5910203	591 - LOADER, SKID STEER	5904
Fulton	2218466	221 - PICKUP, 1/2 TON	5223
Gallia	2130568	213 - UTILITY TRUCK	5028
Fulton	2231637	223 - PICKUP, 1 TON	2939
Vinton	2130594	213 - UTILITY TRUCK	2785
Vinton	2218669	221 - PICKUP, 1/2 TON	2381
Vinton	2130560	213 - UTILITY TRUCK	1813
Williams	4920217	492 - GRADER, OVER 23000LBS	961

Table A.12: Evaluation of Beacons Detection Equipment # 4700129

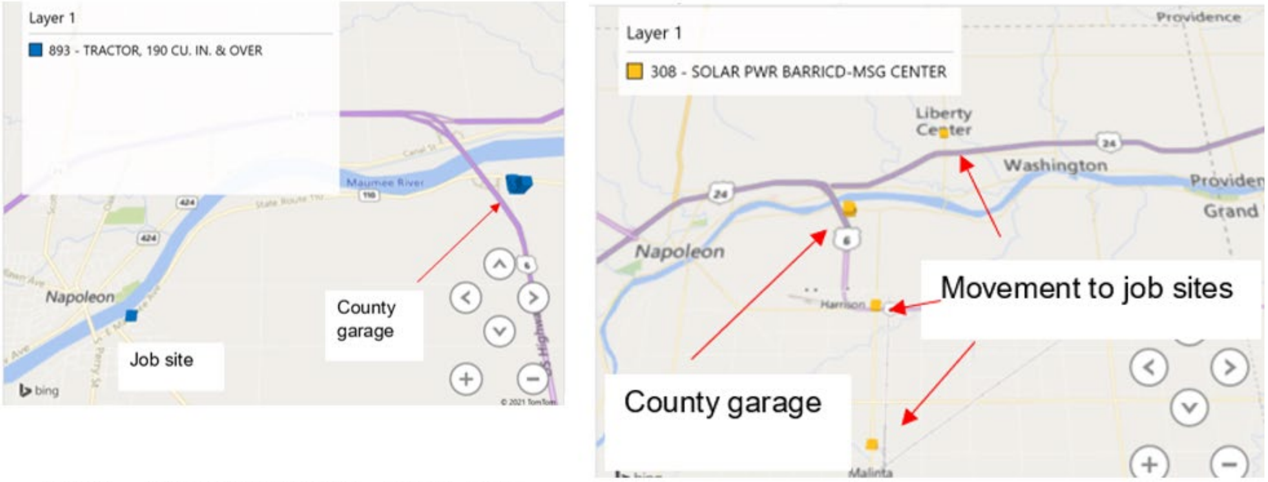
Beacon Equipment Category	**Count**
254 - DUMP TRUCK, S&I, SINGLE AXLE, GVWR > 26000 LB	253
256 - DUMP TRUCK, S&I. TANDEM AXLE, ALL GVWR	179
271 - TRAILER 7 TO 10 TON	889
272 - TRAILER, OVER 10 TON	1060
305 - PLANER, COLD, MNT	49
308 - SOLAR PWR BARRICD-MSG CENTER	155
309 - TRAFFIC SIGNAL, PORTABLE	2
311 - BACKHOE,TRACTOR W/LOADER	131
320 - BROOM, TOWED & PUSHED TYPE	2016
372 - COMPRESSOR OVER 125CFM	276
650 - MOWER,ROTARY,OVER 60IN.	688
751 - ROLLER, 1-3 TON	843
893 - TRACTOR, 190 CU. IN. & OVER	100
Grand Total	**11847**

Table A.13: Evaluation of Beacons Detection Equipment # 2231489

Beacon Equipment Category	**Count**
271 - TRAILER 7 TO 10 TON	1194
272 - TRAILER, OVER 10 TON	344
305 - PLANER, COLD, MNT	27
308 - SOLAR PWR BARRICD-MSG CENTER	1719
309 - TRAFFIC SIGNAL, PORTABLE	606
320 - BROOM, TOWED & PUSHED TYPE	313
893 - TRACTOR, 190 CU. IN. & OVER	3564
Grand Total	**7767**

Table A.14: Evaluation of Beacons Detection Equipment # 5910203

Beacon Equipment Category	**Count**
271 - TRAILER 7 TO 10 TON	909
272 - TRAILER, OVER 10 TON	715
305 - PLANER, COLD, MNT	264
308 - SOLAR PWR BARRICD-MSG CENTER	662
309 - TRAFFIC SIGNAL, PORTABLE	501
320 - BROOM, TOWED & PUSHED TYPE	1245
893 - TRACTOR, 190 CU. IN. & OVER	1608
Grand Total	**5904**



893 - TRACTOR, 190 CU. IN. & OVER

308 - SOLAR PWR BARRICD-MSG CENTER

Figure A.20: Geo-Spatial Analysis of GPS-BLE Beacon Detection- Equipment No. 4700129

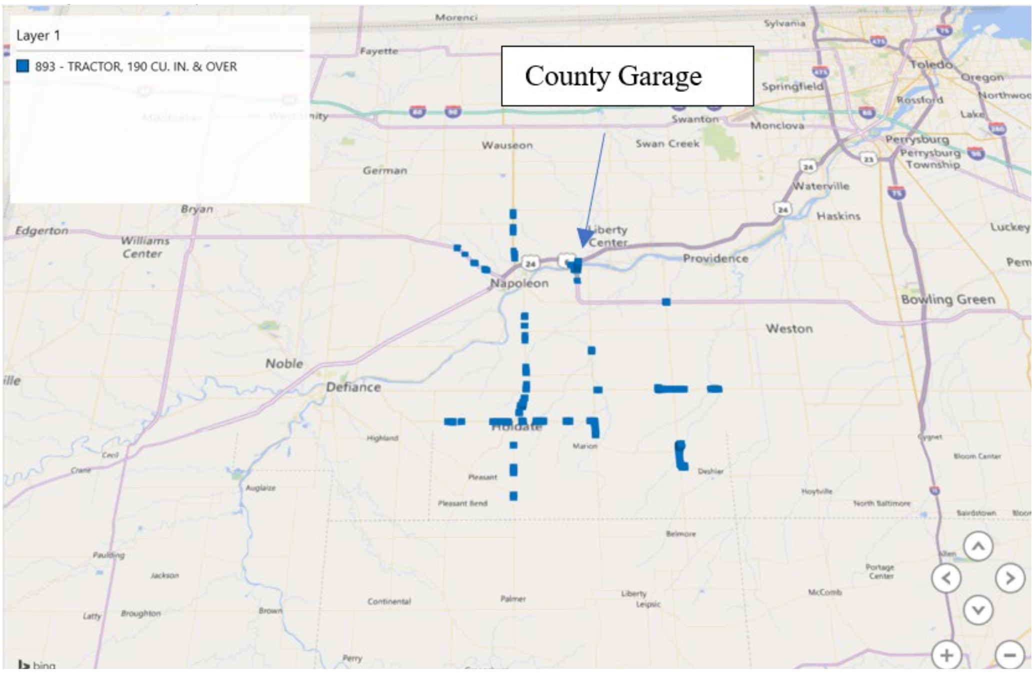


Figure A.21: Geo-Spatial Analysis of GPS-BLE Beacon Detection- Equipment No. 2231489

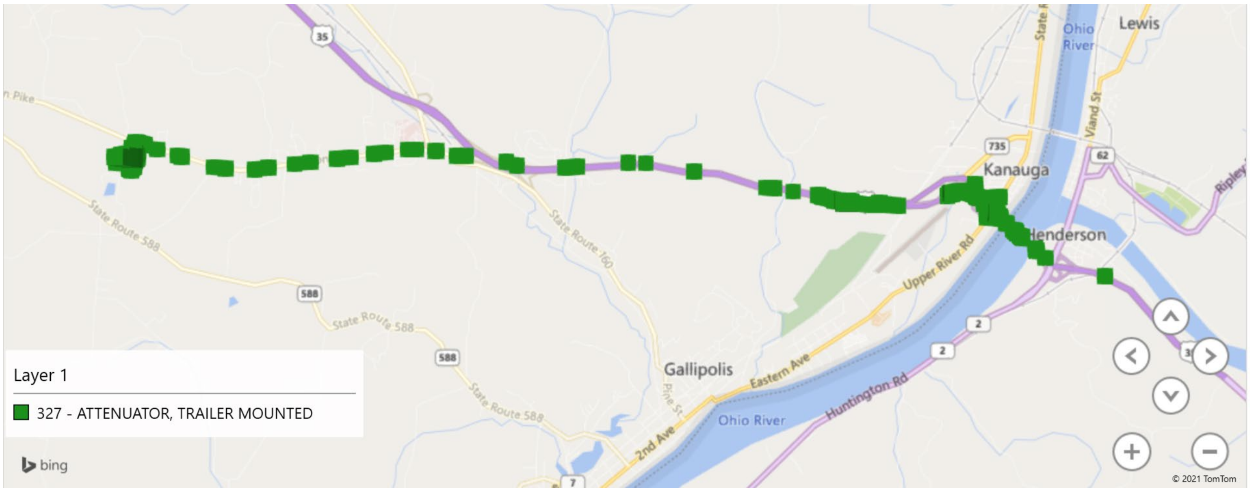


Figure A.22: Geo-Spatial Analysis of GPS-BLE Beacon Detection- Equipment No. 2130604

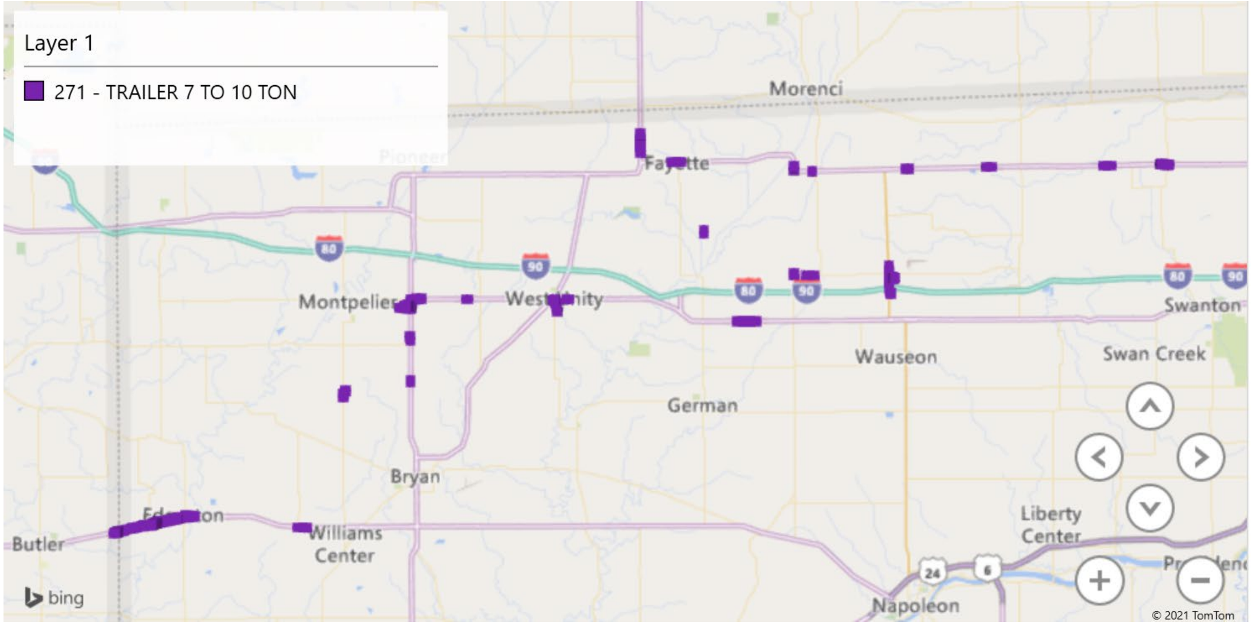


Figure A.23: Geo-Spatial Analysis of GPS-BLE Beacon Detection- Equipment No. 5910212

A.3.6 Developing Guidelines for Selecting Equipment to Be Tracked

The most cost-effective tracking system for ODOT will be a system that consists of using few GPS-BLE on certain equipment to track BLE beacons placed on other important equipment that are typically used by ODOT county garages. The GPS-BLE devices should be used on equipment that are typically used to travel around the county/district for bi-weekly inventory as well as are used at job sites. This will allow the equipment with GPS-BLE to pass by and cross paths with equipment tracked with beacons. The BLE beacons should be used to track equipment that are:

- Shared among counties
- Frequently used by ODOT county garages in different maintenance activities
- Harder to be locate

- Limited in number in a District or County.

Based on the results from the performed analysis and discussions with ODOT personnel it was estimated that on a minimum of pieces of equipment will need to be tracked by GPS-BLE devices in each district and county garages. The following devices should be considered for tracking by GPS-BLE devices:

- County Transportation Administrator and Transportation Manager pick-up trucks. It is noted that the transportation mangers might be better used particularly if they are used for the county bi-weekly inventory.
- Crew pick-up trucks that are used to transport ODOT crew to the job sites.
- Fuel pick-up trucks that are used to fuel maintenance equipment in the field.
- Utility pick-up trucks. Choose the truck that will by frequently used on job sites.
- Skid Steer: this equipment is frequently used by ODOT in different maintenance activities.
- Excavators: some counties seem to frequently use excavators, so this equipment might be good for detection beacons.
- District Bucket trucks. The two main trucks in the district that driven all around the counties. We will be testing this in District 8 to get more data to support this selection.

The following devices should be considered for tracking by beacons:

- 309 - Portable traffic signal
- 308 - SOLAR PWR BARRICD-MSG CENTER
- 311 - BACKHOE, TRACTOR W/LOADER
- 893 - TRACTOR, 190 CU. IN. & OVER
- 469 – EXCAVATOR (if not tracked by GPS-BLE or has OEM telematics)
- 320 - BROOM, TOWED & PUSHED TYPE (Depends on county)

A.4 Evaluation of BLE Beacons Durabiltiy and Service Life

The service life of both the Xirgo and the Kontakt beacons was evaluated. For this purpose, the reporting activity of 18 beacons that were installed on different types of equipment was obtained using ODOTMETS. The selected beacons consisted of 10 Xirgo and 8 Kontakt beacons. The beacons were installed on maintenance equipment of different categories, including but not limited to trailer, dump truck, mower, compressor, and tractor. The selected pieces equipment were in ODOT District 2 and District 10. The types and location of equipment tracked by the considered beacons allowed to examine the durability of the two types of beacons under various field operation, vibrations, moisture exposure, and weather conditions. The beacon data was tracked September 2020 to August 2022, which represented approximately two years of service life. It is noted that the selected timeframe does not represent the end of life for all beacons but is limited by the time of this project. Thus, the beacons that survived the evaluation period is expected to have a much longer service life.

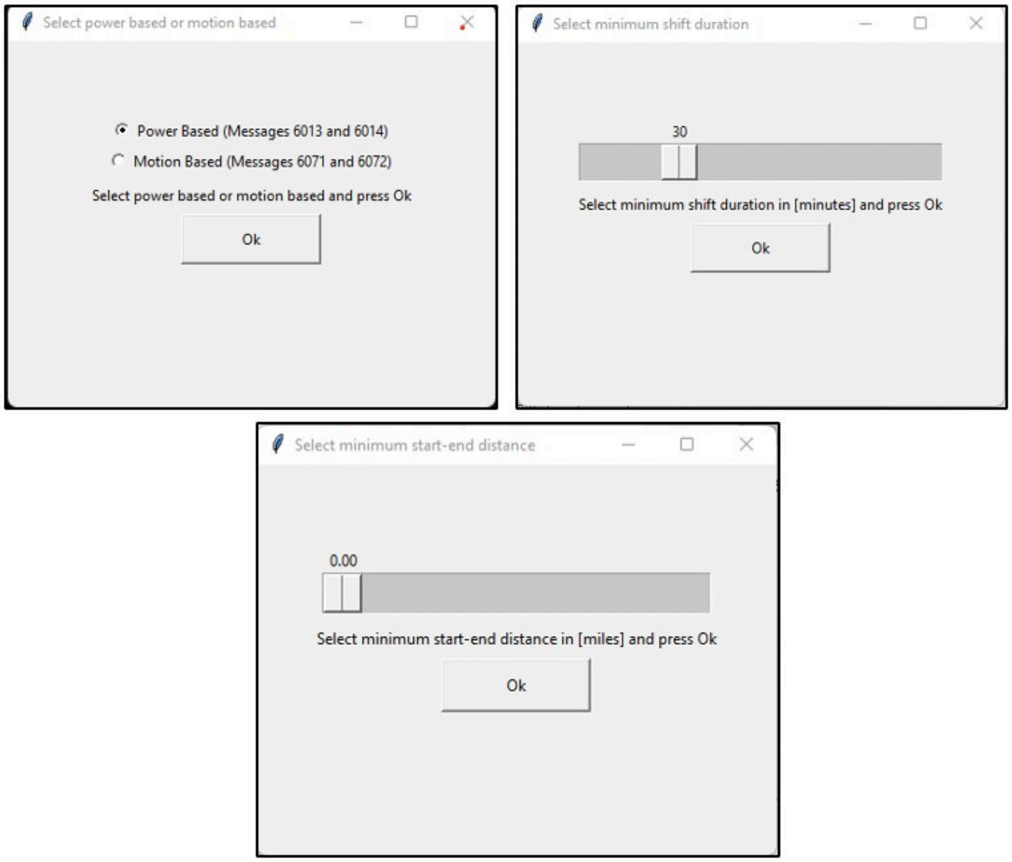
Out of the 10 observed Xirgo beacons, only three beacons continued reporting until the month of August 2022, and thus have a service life longer than 660 days or 22 months. The other 70% of the Xirgo beacons stopped reporting prior to the end on the evaluation period. The average service life of the failed beacons was 250 days, with great variability ranging from 44 days for the shortest and 493 days for the longest days of service. The failure of the devices can be attributed to multiple factors such as failure of internal connection between the battery and the BLE beacon chip, water intrusion, vibration conditions, or beacon being detached from the equipment. It is very important to note that the Xirgo beacons used in this project were development grade not production grade beacons, which might explain durability issues found under harsh operating conditions. It is noted that few production-grade Xirgo beacons were obtained closer on November 2021 but were not included in this evaluation due to limited time of testing.

For the Kontakt beacons, 6 out of the 8 evaluated beacons were still reporting by the end of the evaluation period, which suggests that they have a service life longer than 22 months (660 days). One out of the two beacons that stopped reporting was removed in June 2022 as the equipment it was installed on (311-backhoe tractor in District 2) was traded. It is noted that the beacons continued to report till June 2022. Thus, the beacon service life is expected to be much longer than the 600 days evaluation period for this beacon. The only beacon that has stopped before the end of the evaluation period was placed on snow removal vehicle (256-dump truck). Thus, the beacon was exposed to very harsh field operation condition as well as extreme and cold weather conditions. The beacon might be failed due to different reasons and their combination, but further investigation is needed to understand the reasons for failure particular for these two beacons. The results of the conducted evaluation suggest that the evaluated Kontakt beacons has good service life, which is better than that of Xirgo beacons examined.

A.5 Evaluation of Use of ODOTMETS System Data for Assessing Equipment Utilization

Daily utilization data was extracted for several equipment from ODOT's Equipment & Inventory Management System (EIMS) database (Figure A.25). It is noted that the EIMS daily utilization data is based on workorders information based on daily cards entered by ODOT employees. The data were obtained from the database for the period between 04/01/2021 and 04/01/2022 for three different pieces of equipment in District 2, the numbers for these pieces of equipment are: 5910202(Williams County Garage), 5910212(Fulton County Garage), and 4700129 (Henry County Garage).

The data collected by GPS-BLE also can be used to determine the usage of the different considered pieces of equipment. Every time the equipment engine is turned on (based on battery volts) a message is sent by GPS-BLE. It is followed by another message once the engine has been turned off. The data in the ODOTMETS system database was used to evaluate the usage of some devices. It is noted that ODOTMETS data was used to determine when and where the equipment was used. The Python program shown in Figure A.24 was developed to analyze the ODOTMETS system data to obtain the utilization for the equipment tracked with a GPS-BLE device. The goal is to compare the usage information obtained by analyzing the system's data and the data available in the Equipment & Inventory Management System (EIMS) system which are based on the daily card and inputted manually by ODOT employees (Figure A.25). This comparison is performed to evaluate the accuracy of both methods and compare the results of the system to the currently used methods of tracking equipment utilization. Furthermore, the EIMS data was also compared to the data obtained through OEM tracking systems of some equipment particularly John Deere.



Select power based or motion based

● Power Based (Messages 6013 and 6014)

○ Motion Based (Messages 6071 and 6072)

Select power based or motion based and press Ok

Select minimum shift duration

30

Select minimum shift duration in [minutes] and press Ok

Select minimum start-end distance

0.00

Select minimum start-end distance in [miles] and press Ok

Figure A.24: Python Program for Obtaining Utilization data from ODOTMETS

Figure A.25: EIMS System and Data Input

A.5.1 Evaluation of Equipment Utilization Based ODOTMETS And EIMS Data

The utilization data was obtained from ODOTMETS and EIMS system for two skid steers and an excavator in District 2 for the period between 04/01/2021 and 04/01/2022 and was compared. Table A.15 below presents an example of the dates when both the ODOTMETS and EIMS system reported that the equipment was utilized (on the left) and all the dates that were reported in the ODOTMETS system but were not included in the EIMS (on the right). Table A.16 shows the summary of utilization comparison between the ODOTMETS and the EIMS systems data for the different pieces of equipment. The results showed that both the EIMS and the ODOTMETS system data matched on at least 17 days; where both systems reported that the equipment was utilized. On the other hand, it was found that there least 20 days where the equipment was utilized according to the analyzed ODOTMETS system data but was not reported in the EIMS system. Upon analyzing the location of the reported utilization instances, it was found that for the days that utilization information from ODOTMETS system matched that of EIMS the pieces of equipment were mainly used outside its designated county garage. Furthermore, for the days that ODOTMETS reported usage but not the EIMS, there several days the equipment was used outside the designated county garage boundaries. The results suggests that there are discrepancies in the utilization data based on the ODOTMETS system and that of EIMS.

Table A.15: GPS and EIMS utilization dates comparison

Dates that matched	**Dates reported by GPS but not EIMS**
7/19/2021	6/30/2021
7/22/2021	7/15/2021
7/27/2021	7/20/2021
8/5/2021	7/21/2021
8/10/2021	7/25/2021
8/24/2021	7/26/2021
9/2/2021	7/28/2021
9/14/2021	8/4/2021
10/18/2021	8/20/2021
10/19/2021	9/1/2021
11/22/2021	9/17/2021
11/23/2021	9/21/2021
2/24/2022	9/23/2021
3/3/2022	9/24/2021
3/4/2022	10/5/2021
3/31/2022	10/7/2021
4/8/2022	10/13/2021
	10/28/2021
	11/1/2021
	11/16/2021
	12/1/2021
	12/7/2021
	12/9/2021
	12/14/2021
	1/13/2022
	2/7/2022
	2/22/2022
	3/8/2022
	3/14/2022
17	**29**

Table A.16: GPS and EIMS utilization comparison summary

Equipment Type	Days Matched		Days GPS Reported NOT EIMS	
	Total	Outside County garage	Total	Outside County garage
591	17	15	29	12
591	20	15	20	0
470	38	33	44	18

A.5.2 Evaluation of John Deere OEM data for assessing utilization data Compared to EIMS

Daily utilization for several equipment was extracted from EIMS database. The data were obtained from database 04/06/2021 to 06/06/2022 for three different pieces of equipment in Districts 2 and 10, the numbers for the equipment are: a grader in district, and two skid steers in District 2. The OEM Telematics for John Deere provides the hours of operation, which can be used to determine the usage of these pieces of equipment. The data from John Deere OEM Telematics were obtained through John Deere website to determine the workdays for different equipment. The EIMS data were compared to the analyzed data from John Deere database. The dates that matched and did not match between the EIMS and the system database were identified.

The results showed that both the EIMS and the OEM telematics data matched on at least 27 days where both the data from both sources reported that the equipment was utilized. On the other hand, it was found that there were up to 86 days where the equipment was utilized according to the analyzed OEM data but was not reported in the EIMS system. Table A.17 below displays an example for one of the equipment for dates when both the analyzed OEM telematics data and the EIMS showed that the equipment was utilized (on the left) and all the dates that were reported from the OEM utilization results but were not included in the EIMS database (on the right). Table A.18 shows the summary of utilization comparison between the analyzed OEM telematics data and the EIMS data. The results suggest that there are discrepancies in the utilization data based on the John Deere OEM data and that of EIMS database.

Table A.17: OEM and EIMS utilization dates comparison

Dates Matched	**OEM telematics reported but not EIMS**
5/17/2021	4/23/2021
5/18/2021	9/23/2021
5/19/2021	10/20/2021
5/20/2021	11/23/2021
5/21/2021	12/2/2021
5/24/2021	2/2/2022
5/25/2021	
5/26/2021	
6/7/2021	
6/8/2021	
6/9/2021	
6/10/2021	
6/11/2021	
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6/30/2021	
7/6/2021	
7/7/2021	
7/16/2021	
7/19/2021	
7/20/2021	
7/21/2021	
11/9/2021	
11/9/2021	
11/22/2021	
3/28/2022	
3/29/2022	
3/30/2022	
4/1/2022	
31	**6**

Table A.18: OEM and EIMS utilization comparison summary

Equipment No.	**EIMS reported Days**		**Days OEM Telematics Reported but NOT EIMS**
	Reported	Matched	Total
4920239	31	31	6
5910321	27	27	39
5920985	55	55	86

Appendix B: Cost Benefit Analysis

Cost-benefit analysis was conducted to evaluate the cost-effectiveness of using the developed systems. The analysis includes computing the cost benefits resulting in tracking and scheduling of the maintenance equipment in different ODOT cost centers. In addition, this analysis aims to calculate the total cost for DOTs to implement and maintain the developed system. The following section evaluates the benefits achieved from the proposed tracking system. While some of the cost savings from these benefits can be quantified, others are less tangible and harder to quantify.

B.1. Tracking System Cost

The most cost-effective tracking system for ODOT will be a system that consists of using few GPS-BLE on certain equipment to track BLE beacons placed on other important equipment that are typically used by ODOT county garages. The GPS-BLE devices should be used on equipment that are typically used to travel around the county/district for bi-weekly inventory as well as to job sites. This will allow the equipment with GPS-BLE to pass by and cross paths with other pieces of equipment that are tracked with beacons. It is recommended that each county garage and district garage select three pieces equipment/vehicles that from the following list:

- Transportation mangers pick-up trucks.
- Crew pick-up trucks that are used to transport ODOT crew to the job sites.
- Fuel pick-up trucks
- Utility pick-up trucks that will be frequently used on job sites.
- Skid Steer
- Excavators
- District Bucket trucks.

Assuming that each county and district garage will have three pieces equipment tracked with GPS-BLE, the total number of GPS-BLE needed statewide will 300.

The pieces of equipment that should be tracked by beacons are those are ones that are typically shared between counties and are harder to find. Based on discussion with ODOT Ditrict 10 and 8 equipment managers, the following equipment categories should be considered for beacons

- 271 - Trailer 7 To 10 Ton
- 272 - Trailer, Over 10 Ton
- 308 - Solar Pwr Barricd-Msg Center
- 309 - Traffic Signal, Portable
- 311 - Backhoe, Tractor W/Loader
- 314 - Arrow Board Portable
- 316 - Arrow Board Mounted
- 320 - Broom, Towed & Pushed Type
- 322 - Attenuator, Truck Mounted
- 469 - Excavator, Tracked, Operating Weight < 19999 Lbs
- 893 - Tractor, 190 Cu. In. & Over

ODOT equipment inventory was obtained from the ODOT Office of Facilities & Equipment Management. Table B.1 presents the number of pieces of equipment in the categories in the above list. It is noted that a total of 1704 pieces equipment fall under the categories in the list that should have BLE beacons.

Table B.1: Number of Pieces of in each of the equipment categories to be tracked with BLE Beacons

Equipment Category	Count of Equipment Category
271 - TRAILER 7 TO 10 TON	113
272 - TRAILER, OVER 10 TON	239
308 - SOLAR PWR BARRICD-MSG CENTER	187
309 - TRAFFIC SIGNAL, PORTABLE	131
311 - BACKHOE,TRACTOR W/LOADER	56
314 - ARROW BOARD PORTABLE	216
316 - ARROW BOARD MOUNTED	133
320 - BROOM, TOWED & PUSHED TYPE	202
322 - ATTENUATOR,TRUCK MOUNTED	42
469 - EXCAVATOR, TRACKED, OPERATING WEIGHT < 19999 LBS	22
893 - TRACTOR, 190 CU. IN. & OVER	363
Total	**1704**

The total costs for DOT to implement the developed system includes the following:

1- Initial and maintenance cost of GPS-BLE
2- Costs of data plans for GPS-BLE
3- Initial and maintenance cost of BLE beacons
4- Cost of software hosting and maintenance

To compute the annual cost of system, the Equivalent annual cost (EAC) was computed for the GPS-BLE and BLE beacons according to Equation 1. EAC was selected as BLE beacons lifespan depends on type and setting used. EAC is used most often to analyze system with with different lifespans, where costs are the most relevant variable.

$$EAC = \frac{Device\ Initial\ Price \times i}{1-(1+i)^{-N}} + AMC \quad \text{(B.1)}$$

N: Service life of the equipment
i: Interest rate
AMC: annual maintenance cost

An interest rate of 4% was used in the analysis. The service life of GPS-BLE was estimated to be 10 years. In addtion, GPS-BLE annual maintenace cost was estimated to 10% of the intial cost service life. In addtion, for the service life of beacons was estimated based on battery life as well testing in the field. The maintenance cost for the BLE beacons was estimated by computing the the number of times it is needed to replace the beacons within an analysis period of 10 years. As two types of beacons (Xirgo and Kontakt) were evaluated in this study. The cost of systems using those two different types of bacons was evaluated. The sections provides detials about this evaluation.

B.1.1 Xirgo Beacons Systems

The costs of system that has Xirgo GPS-BLE and Xirgo beacons was computed. Table B.2 presents the computed cost. It is noted that the software maintenance cost is considered to negligible as it is assumed that ODOT Office of Information Technolgy will be hosting and maintiannig the software. The total cost of the system is esitmated to be less than $48,484. It is noted that about 60% of the total cost covers the expenses for GPS-BLE purchasing, maintenance, and data plan.

B.1.2 Kontakt Beacons Systems

As indicated in previous chapter the Kontakt beacons service life depends on battery life, which in turn depends on the settings of the beacon used. Costs of the system that has Kotakt beacons was evaluated for different beacon working hours, reporting interact, beacon transmission power, and their combinations. To this end, two different hours of operation cases were investigated: all the time, and 10 hours every day. In addition, beacon transmission power (Tx) of -12, -4, 0, 4 dbm were considered. Finally, beacons reporting intervals of 350 ms, 800 ms, 1000 ms, and 2000 ms was investigated. It is noted that the settings were used to determine the battery life. The Kontakt beacons service life was assumed to be the battery life but did not exceed 10 years. Table B.3 presents the annual cost of the system for different beacons setting when the Kontakt beacons are in operation all day long. It is noted that optimal settings (reporting interval of 800 ms or 1000ms and/or Tx power of 0 or 4 dbm) the cost of the system is estimated to be between $44,141 and $48,425. This suggest that the system with Kontakt beacon is more cost-effective than that with Xirgo beacons despite the fact the that Xirgo beacons has lower initial price. The main reason for that is that Kontakt beacon was more durable in the field and had much more power saving settings that allows to increase the service life of the beacon battery.

Table B.2: Annual cost of the system with Xirgo beacons

Tracking Device	**Unit Cost**	**Number of Units/County**	**Cost**
Xirgo Beacon Cost			
Xirgo Beacon Initial Cost	$12	1704	$20,448
Xirgo Beacon Annual Maintenance Cost	$5.53	1704	$ 9,426
Xirgo Beacon EAC Cost		**1704**	**$20,267**
GPS-BLE Cost			
GPS-BLE Initial Cost	$ 260	300	$78,000
GPS-BLE Annual Maintenance Cost	$26	300	$7,800
GPS-BLE EAC Cost		300	$17,417
Data Plan Annual Cost	$36	300	$10,800
Total Annual GPS-BLE Cost			$28,217
Software Annual Cost			
		Total Cost	**$48,484**

Table B.4 presents the annual cost of the system for different beacons setting when the Kontakt beacons are set to operate 10 hours every day. When the Kontakt beacons are set to operate for 10 hours/day will result in increasing the battery life by at least 40% for all reporting intervals and Tx power settings. The total annual cost of the system for optimal beacons setting in this case ranges between $40,601 and $36,358. It is noted that setting the beacons to operate for 10 hours a day can reduce the cost by about 15% for optimal settings (reporting interval of 800 ms or 1000ms and/or Tx power of 0 or 4 dbm) are used. This suggest that the system with Kontakt beacon will more cost-effective than that with Xirgo beacons when setting it to operate for 10 hours every day. It is noted that Xirgo beacons do not have the option for setting the hours of operation.

Table B.3:1 Annual cost for system with Kontakt when operating all the time

Interval (ms)	Transmission Power(dbm)	Working hours	Battery life (months)	Battery life (years)	Annual Cost- BLE Beacons	Total Annual Cost
350	-12	24	50	4.2	$22,017	$50,234
800	-12	24	76	6.3	$12,978	$41,194
1000	-12	24	78	6.5	$12,422	$40,639
2000	-12	24	86	7.1	$10,866	$39,083
2500	-12	24	90	7.5	$10,125	$38,341
3000	-12	24	94	7.8	$9,449	$37,666
350	-4	24	47	3.9	$24,105	$52,321
800	-4	24	70	5.8	$14,535	$42,752
1000	-4	24	72	6	$13,881	$42,098
2000	-4	24	79	6.6	$12,195	$40,412
2500	-4	24	83	6.9	$11,391	$39,608
3000	-4	24	87	7.2	$10,659	$38,876
350	0	24	43	3.6	$26,687	$54,904
800	0	24	63	5.3	$16,592	$44,809
1000	0	24	65	5.4	$15,925	$44,141
2000	0	24	71	5.9	$14,056	$42,273
2500	0	24	75	6.2	$13,166	$41,382
3000	0	24	78	6.5	$12,354	$40,571
350	4	24	39	3.3	$29,950	$58,167
800	4	24	54	4.5	$20,209	$48,425
1000	4	24	56	4.7	$19,304	$47,521
2000	4	24	57.1	4.8	$18,835	$47,052
2500	4	24	64.1	5.3	$16,209	$44,426
3000	4	24	58.2	4.8	$18,384	$46,600

Table B.4:2 Annual cost for system with Kontak when operating 10 hours every day

Interval (ms)	Transmission Power(dbm)	Working hours	Battery life (months)	Battery life (years)	Annual Cost- BLE Beacons	Annual Cost
350	-12	10	72.4	6.0	$13,782	$41,999
800	-12	10	109.4	9.1	$7,398	$35,615
1000	-12	10	112.9	9.4	$7,015	$35,232
2000	-12	10	123.9	10.3	$6,303	$34,519
2500	-12	10	130.0	10.8	$6,303	$34,519
3000	-12	10	136.0	11.3	$6,303	$34,519
350	-4	10	68.0	5.7	$14,987	$43,204
800	-4	10	100.7	8.4	$8,472	$36,689
1000	-4	10	104.2	8.7	$8,021	$36,238
2000	-4	10	114.4	9.5	$6,859	$35,076
2500	-4	10	120.0	10.0	$6,305	$34,522
3000	-4	10	125.5	10.5	$6,303	$34,519
350	0	10	62.2	5.2	$16,856	$45,072
800	0	10	91.2	7.6	$9,890	$38,107
1000	0	10	94.1	7.8	$9,430	$37,646
2000	0	10	103.3	8.6	$8,142	$36,358
2500	0	10	108.3	9.0	$7,528	$35,745
3000	0	10	113.3	9.4	$6,969	$35,186
350	4	10	56.5	4.7	$19,108	$47,325
800	4	10	78.2	6.5	$12,385	$40,601
1000	4	10	81.1	6.8	$11,761	$39,977
2000	4	10	82.7	6.9	$11,437	$39,654
2500	4	10	92.8	7.7	$9,626	$37,842
3000	4	10	84.2	7.0	$11,126	$39,342

B.2. Benefits of Efficient Tracking System

The developed system will help ODOT in better scheduling and locating the different maintenance equipment in ODOT county and district garages as well as other cost centers. This will result in several benefits that can be achieved from:

- Reducing the time needed to locate equipment by ODOT counties for daily operation.
- Reducing the time needed by ODOT districts and counties for locating the equipment during the annual inventory.
- Optimizing the equipment scheduling and facilitating the equipment sharing between counties within the same district as well as in different districts.
- Eliminating the need to rent equipment that is available in other counties and districts.
- Enhancing the equipment maintenance management.

- Reducing the cost resulting from delayed equipment maintenance.
- Maximizing equipment fleet utilization based on obtained data.
- Reducing the road user time during closures when an emergency or an unexpected incident occurs requiring certain maintenance equipment.
- Improve ODOT emergency response preparedness.
- Enhancing the efficiency of ODOT operations.

The following subsections evaluate the issues faced by the DOT counties and districts which can be addressed or eliminated by the proposed system. The total amount of savings will be estimated resulting from eliminating the problems and conducting cost-analysis.

B.2.1 Saving Due to Reducing the Time Needed to Locate Equipment

Several DOT districts and counties face issues in locating their equipment frequently, ranging between once a week to every day. Williams county indicated facing the issue with locating their equipment two to three days a week depending on the season (winter or summer). District 10 indicated similar problem occurs at least once a week. Based on that, an average value of 2 days a week was selected for the frequency of not locating. A considerable amount of time, ranging from 15 minutes to several days, is lost by the staff in county garages trying to find the equipment. Based on that an average value of 30 minutes was selected for the time wasted when an equipment is not located. Thus, if two staff members typically are involved in finding the equipment the total amount of savings that results from eliminating the time locating maintenance equipment by ODOT counties was estimated to be $621,970 annually. As the developed system will only track the pieces of equipment that are ODOT district and county garages are frequently trying to locate, the estimated savings will be at least 30% of total amount that can be saved by accurately locating and scheduling ($186,591).

B.1.2. Saving from Reducing the Need for Renting Equipment

The DOT counties typically rent the equipment when not located to complete task on time. Therefore, if equipment is found when needed the cost of renting maintenance equipment encountered in these cases could be saved. The system will also facilitate the sharing of the equipment between different counties in the same district and different districts to share Based on the discussions with Williams County and District 10, it was estimated that ODOT counties typically will save at least 21 days (about 3 weeks) of an equipment rental every year. This corresponds to an average saving of $665,280 annually for ODOT. As the developed system will only track the pieces of equipment that are frequently shared between ODOT district and county garages, the estimated savings will be at least 30% of total amount that can be saved by eliminating the need for renting ($199,584).

B.1.3 Road User Cost Saving

In some cases, the equipment is needed for addressing unexpected or urgent road related issues, which is causing full or partial road closure. The longer it takes to locate the equipment, the greater the road user delays. Several steps were followed to estimate the road user cost due to delays for not locating the equipment. The first step was to estimate the average road user cost for closure on roads in Ohio. To achieve that, data was obtained from DOT Traffic Survey Reports to estimate the average AADT on roadways on priority and general systems in Ohio. Based on that, the hourly cost for trucks and cars due to road closure was computed, Table B.1. DOT road user cost for road closure of $21.13 for cars and $57.04 for trucks, was used in this calculation. For being unable to locate the equipment when unexpected issues arise, a total of 10 hours in delays is estimated in a year, and the road user cost is estimated to be on average $495,255 annually. It is noted that 10 hours assumption is equivalent based on a 2/1000 probability for not locating maintenance equipment when needed for an unexpected or urgent road repair equipment.

Table B.43 Road user cost due an hour of road closure

Road	**Car Cost**	**Truck Cost**	**Total Cost**
Priority	$ 64,295.31	$ 19,284.88	$ 83,580.19
General	$ 13,546.13	$ 1,924.60	$ 15,470.73

B.3. Cost Benefit Analysis

The cost benefit ratio was calculated using Equations 1. The cost benefits are estimated to be $386,175, which is the sum of the savings from only reducing the time needed to locate equipment and eliminating the need for renting pieces equipment that are available in ODOT county garages. Table B.5 presents the calculated cost benefit ratio. It is noted that the recommended tracking system is cost effective with cost benefit ratio ranging between 8 and 10, depending on type of beacon and the settings used for beacons. Thus, ODOTMETS is highly cost-effective.

$$\text{Cost Benefit Ratio} = \frac{\text{Cost Benefits}}{\text{Total } Cost\ of\ tracking\ System} \tag{B.2}$$

Table B.54 Cost-Benefit-Ratio Bar Chart

Beacon Type	Interval (ms)	Transmission Power(dbm)	Working hours	Total Annual Cost	Savings	Cost Benefit Ratio
Xirgo	1000	4	24	$ 48,484	$386,175	8.0
Kontakt	800	0	24	$44,809	$386,175	8.6
Kontakt	1000	0	24	$44,141	$386,175	8.7
Kontakt	800	4	24	$48,425	$386,175	8.0
Kontakt	1000	4	24	$47,521	$386,175	8.1
Kontakt	800	0	10	$38,107	$386,175	10.1
Kontakt	1000	0	10	$37,646	$386,175	10.3
Kontakt	800	4	10	$40,601	$386,175	9.5
Kontakt	1000	4	10	$9,977	$386,175	9.7