Boston University
Electrical & Computer Engineering
EC463 Senior Design Project

First Semester Report

MuseumMate

Submitted to

Professor Thomas Little
8 Saint Mary's St.
Boston MA 02215
617-353-9877
tdcl@bu.edu

by

Team 7
AR Museum

Team Members

John Culley jculley@bu.edu
Kwadwo Osafo kosafo@bu.edu
Kai Imery kimery@bu.edu
Ananth Sanjay ananths@bu.edu
Yangyang Zhang yz21@bu.edu

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Table of Contents

(right click on Table of Contents to update fields and page numbers automatically)

Executive Summary

Museum Mate
Team 7 – AR Museum

MuseumMate is an advanced indoor navigation and exhibit interaction system, designed to enrich museum visits. Upon entering a museum, visitors receive a handheld device, the TourTag, which detects Bluetooth Low Energy (BLE) signals from beacons placed throughout the premises. This device transmits signal strengths to a server to pinpoint the visitor's location, facilitating precise navigation through a user-friendly web application. Additionally, RFID tags on exhibits interact with the TourTags, allowing visitors to automatically access rich multimedia content about the exhibits they are near, thus enhancing their educational and interactive experience in the museum. This system seamlessly integrates efficient navigation with engaging exhibit exploration, revolutionizing the traditional museum visit.

1.0 Introduction

Nowadays, museums have become not only the forerunner of history preservation, but also a key venue for enjoying art. Visiting museums has become a premier leisure activity and in regions with a plethora of museums, such as Boston, every individual, ranging from the casual first-time visitor to the museum aficionado, is able to find a museum that they deeply cherish. Museums are aware of their appeal and make great efforts to maintain their exhibits and develop new media to provide innovative experiences to their visitors. Nevertheless, much of this media is left unused since the average museum visitor does not come into contact with everything available. Furthermore, the unfamiliar layouts of museums can cause museum visitors to get overwhelmed by overcrowding and disoriented as they try to navigate to exhibits. MuseumMate will address these issues by providing precise navigation and a system to display multimedia to its users.

MuseumMate aims to improve efficiency in all museum visits by giving the visitors the ability to plan museum trips beforehand, or in real-time, and by allowing museums to maximize their informative capabilities by giving them new and effective ways to reach their visitors. The system will use Bluetooth Low Energy (BLE) beacons to obtain positioning data of each visitor. Real time navigation based on the collected information will then coordinate the flow of traffic in the museum on the fly, allowing users to maximize their time spent viewing what they came to the museum to see and minimizing bottlenecks created by congestion. The location information collected for every user can also be studied to allow museums to optimize their layout to avoid congestion based on the peak activity at various exhibits or rooms and at what time of the day this occurs.

MuseumMate will provide unique IDs to every exhibit through the use of RFID tags, which will allow museums to greatly enrich the experience of their visitors by giving them access to a vast store of multimedia that is currently underutilized through a combination of RFID technology and a web application. Furthermore, with RFID technology, users will be able to view information about any exhibit in various forms including text-to-speech and subtitled videos, making them accessible to all people, including those with physical impairments.

The dominant issue that our proposed system aims to tackle can be split into three subsections: congestion in museums due to irregular museum layouts and bottlenecks created by popular exhibits or sections, the lack of engaging and interactive media about exhibits, and the scarcity of tools that promote accessibility in museums.

Our proposed solution to tackle this issue involves designing portable user devices, dubbed TourTags, which incorporate BLE sensors to passively detect BLE signals from beacons, and RFID scanners to utilize RFID tags on exhibits for unique identification of individuals and accurate user location tracking. The information gathered will be sent to a server for processing and storage in a database. Finally, users will use a mobile application that communicates with the aforementioned server to retrieve data from the database to provide routing guidance within the museum and displays exhibit-related media obtained from the museum's collection of multimedia based on RFID scans.

2.0 Concept Development

2.1 Engineering Understanding of the Customer's Problem

In the realm of museum experiences, visitors often face challenges such as navigating through complex layouts, contending with crowded spaces, and accessing detailed information about exhibits. The current market solutions, like the Navigine indoor navigation system, provide basic directional assistance but fall short in offering a dynamic, crowd-aware, and informative experience. Our customer's problem, therefore, revolves around enhancing the museum visit by offering a smart, adaptive navigation system coupled with rich multimedia content delivery for each exhibit, thereby improving the overall visitor experience and accessibility.

2.2 Conceptual Approach

To transform this vision into reality, our engineering solution incorporates a blend of RFID (Radio Frequency Identification) and BLE (Bluetooth Low-Energy) technologies. This dual-technology approach is designed to cater to both precise exhibit identification and effective crowd management. The key components of our system include:

> **RFID for Exhibit Interaction:** RFID tags will be placed on exhibits, and visitors will be equipped with a User Device (UD) containing an RFID scanner. This setup allows for the precise identification of exhibits as visitors navigate the museum, triggering the app to provide relevant multimedia content.
>
> **BLE for Indoor Positioning and Crowd Management:** BLE beacons will be strategically placed throughout the museum. These beacons will communicate with the visitor's UD to facilitate indoor positioning. By analyzing the signal strength and the density of UDs in different areas, the system can map crowd concentrations and adjust visitor routes in real-time.
>
> **Comprehensive Database and User-Friendly Mobile Application:** A backend database will store and manage exhibit information and crowd data. The mobile application, designed for easy use and accessibility, will interact with this database to provide visitors with exhibit information and optimized routing based on current conditions.

2.3 Engineering Requirements (Appendix 1)

Mobile Navigation Application Requirements

Functional: The mobile navigation application is an essential component that provides multimedia content from URLs, enabling audio, video, and text information to be accessed within the museum. It supports navigation through comprehensive mapping of the museum, inclusive of all floor plans with clear turn-by-turn instructions or directional arrows. A key feature is the heat map visualization of current visitor traffic, assisting in avoiding congested areas. The application is designed to calculate the most direct route from the user's location to a chosen exhibit while considering the density of visitors in different rooms, ensuring a smooth visitor flow. Additionally, it graphically represents the user's instant location on the museum map for easy orientation. The app interface will be compatible with web browsers and as a standalone application, making it widely accessible. A diagnostic function is also included for system maintenance, though it is restricted to users with elevated access.

Performance: The application's performance is optimized for responsiveness, with route calculations and map displays completing in under three seconds. Navigation updates will also occur swiftly, taking less than two seconds to reflect any changes due to crowd movements or other factors.

Routing Algorithm / Server Specifications
Functional: The server's functionality is multi-faceted, including the collection of journey data from each user device (UD) and accurate positional data. It logs the time users spend at exhibits and manages route computation requests, aiding in personalized visitor experiences. Additionally, it generates traffic heat maps for dissemination to the mobile application and maintains a detailed record of UD interactions for system diagnostics. The server also allows for data extraction in .csv format for analytical purposes and responds to shortest path queries from the navigation application. It is designed to be hosted on local networks or cloud-based systems, ensuring scalability and reliability.

Performance: The system's robustness is demonstrated by its ability to support up to 512 UDs concurrently, which ensures that even at peak times, visitor experience and application performance remain uncompromised.

Indoor Positioning Functionality
Functional: The indoor positioning functionality is based on RFID technology for precise location estimation and BLE for supplementary positioning. The integration of these technologies ensures that visitors can navigate the museum with high accuracy and receive timely information about the exhibits.

Performance: The system provides frequent updates on user location, at least every ten seconds, with RFID ensuring accuracy within one meter. BLE technology complements by accurately identifying the room a visitor is in, maintaining a positioning accuracy within four meters for 90% of cases.

User Device Features
Functional: The user device is designed to integrate smoothly with the visitor's smartphone, enhancing the usability of the system. It effectively reads signals from BLE beacons and scans RFID tags at exhibits, contributing to the overall positioning and informational services. It uses BLE beacons for general and precise localization and facilitates the exchange of positioning and RFID data with the user's smartphone. The device is also rechargeable, which supports sustainability and ease of use.

Performance: The production of the devices is planned to be cost-effective, with costs kept below $50 per device in large-scale batches. Each device is expected to function for over 12 hours on a full charge, accommodating extensive use throughout museum operating hours.

2.4 Detailed Conceptual Approach

Our chosen solution leverages the precision of RFID for direct exhibit interaction and BLE's capability for broader area monitoring. RFID's role is crucial in providing detailed information about exhibits as visitors engage with them. Concurrently, BLE technology enables the system to understand and react to the spatial distribution of visitors, allowing for intelligent crowd management and personalized route guidance.

2.5 Alternative Solutions Considered

GPS-Based Navigation: Initially considered due to its widespread use and familiarity among users. However, the inherent limitations of GPS in indoor environments led us to discard this option.

Wi-Fi Positioning System (WPS): While Wi-Fi infrastructure is commonly available in museums, its accuracy for indoor positioning is variable. Additionally, concerns regarding visitor privacy and the complexity of integrating with various Wi-Fi networks rendered this option less favorable.

Camera-Based Monitoring Systems: These systems could potentially offer accurate crowd monitoring. However, concerns regarding privacy and the extensive installation and maintenance required made this option less viable.

2.6 Rationale for Chosen Concept

Our decision to utilize a combination of RFID and BLE technologies stems from their complementary strengths. RFID's ability to provide detailed, exhibit-specific information enhances the educational aspect of the museum visit. In contrast, BLE's efficacy in indoor positioning and crowd density mapping addresses the navigational and crowd management aspects. This synergy promises a holistic and enriched museum experience.

2.7 Conclusion

By integrating RFID and BLE technologies, our proposed solution aims to revolutionize the museum visiting experience. It addresses the core needs of efficient navigation, crowd management, and enhanced engagement with exhibits, setting a new benchmark in the domain of museum visitor services.

3.0 System Description

3.1 Hardware

3.1.1 Beacons

Beacons, key to the network, are distributed throughout the museum. These small devices continuously emit BLE signals with unique identifiers, vital for the system's operation. The network of Beacons underpins the system's ability to accurately track and guide users within the museum. By processing RSSI data from these Beacons, the system adeptly locates and navigates visitors.

BLE Signal Emission:
These Beacons emit BLE signals containing specific identifiers, captured by User Devices. The signal strength (RSSI) weakens with distance, providing a basis for assessing the proximity of the User Device to the Beacon.

3.1.2 User Devices

The User Device, central to our system, is a handheld, ergonomically designed tool, tailored for ease of use and interactivity during museum visits.

Connectivity and Data Transmission:
These devices securely connect to the museum's network using WPA2-PEAP, a key aspect of their reliable connection to eduroam. This connectivity is crucial for the consistent transmission of data between the device and the server.

RSSI Data Collection and Transmission:
Equipped with Bluetooth Low Energy (BLE) technology, the User Device continually scans for BLE signals from Beacons. It captures Signal Strength (RSSI) data, which, along with Beacon ID and User Device ID, is sent to the server through UDP Port 3333. This RSSI data is essential for the system's location tracking capabilities.

RFID Integration and Data Handling:
A standout feature of the User Device is its embedded RFID module, RC522. This module detects RFID TAG IDs placed near museum exhibits. Upon recognition of an RFID TAG, the device sends the scanned ID to the server via UDP Port 3334. This action facilitates the immediate display of relevant multimedia exhibit information.

3.2 Server

Our system is a robust and innovative solution designed to enhance the visitor experience within museum environments. At the core, it utilizes a Node.js server that acts as a central processing hub, receiving Radio Signal Strength Indicator (RSSI) and Radio-Frequency Identification (RFID) data via User Datagram Protocol (UDP) from an ESP32 module. This data is critical in providing real-time location services and interactive content to museum visitors.

RSSI and Location Processing:
The server employs a K-Nearest Neighbors (KNN) Machine Learning (ML) model to accurately determine the location of user devices based on RSSI data. The KNN model has been trained and optimized to interpret the RSSI inputs and map them to specific coordinates within the museum, ensuring visitors can navigate the space efficiently.

RFID Data Handling:
In parallel, the RFID information captured by the ESP32 is sent to the server, which then forwards it through a WebSocket connection to a front-end application built with React Native. This enables the app to provide visitors with immediate multimedia content relevant to their location and the exhibits they are engaging with.

REST API Gateway:
The server is equipped with a REST API gateway that exposes four distinct endpoints, each serving a unique function within the system's ecosystem:

- /location/:userID:
  - This API endpoint retrieves the location of a specific user device as calculated by the KNN model. It allows the system to track and display the real-time position of the user within the museum premises.
- /path/:userID:
  - Leveraging Dijkstra's algorithm, this endpoint calculates the shortest path for a user device from its current location to a designated room. This feature aids visitors in navigating the museum's layout without unnecessary detours, enhancing the overall visitor experience.
- /tsp-path:
  - Designed to accept an array of room locations, this API employs the Traveling Salesman Problem (TSP) algorithm to determine an optimal path that visits each room once. This is particularly useful for guided tours or exhibits that require visitors to follow a specific sequence.
- /rfid/:RFID:
  - Upon receiving an RFID tag number, this endpoint fetches and returns the corresponding multimedia content stored in MinIO, an object storage service. This allows for scalable and efficient retrieval of rich media resources, delivering a seamless content delivery network that enhances educational and interactive elements for visitors.

3.3 Front-End

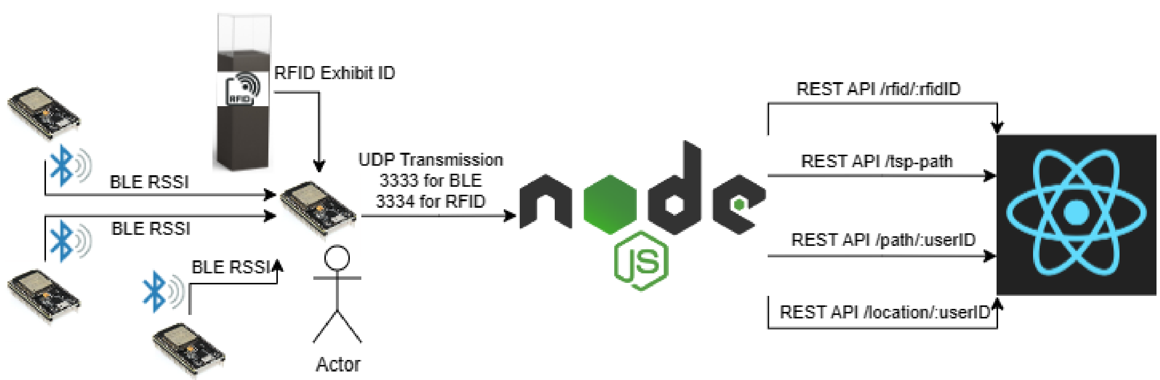
Upon entering the museum, visitors are greeted by the HomeScreen of the application, which presents a welcoming interface and initiates the engagement process. The user is prompted to scan their TourTag, linking it to the app and activating the navigation features. The BarcodeScanner component takes center stage here, providing a seamless start to the museum exploration.

MuseumMate's interface is meticulously crafted to cater to diverse preferences. Through the TourType screen, visitors can select from various guided tours—each carefully curated to cover specific themes or exhibits within a set timeframe. Alternatively, they can opt for an exploratory mode, enabling a more spontaneous journey through the museum.

For visitors embarking on a timed tour, the PreMade component presents a selection of tours with estimated durations, allowing them to manage their visit according to their schedule. As visitors embark on their chosen path, the CurrentLoc component actively updates their location in real-time, aided by the BLE beacons. The application guides them from one exhibit to the next, ensuring they remain on the most efficient route, all the while avoiding congestion and enhancing their overall experience.

Exhibit Interaction and Multimedia Content Delivery

Each exhibit is equipped with an RFID tag that the TourTag automatically scans when in proximity. This triggers the RFIDScreen component, which fetches and displays detailed multimedia content related to the exhibit. This could include audio guides, high-resolution images, videos, or textual histories, providing a rich, interactive learning experience. The content is dynamically loaded and designed to be engaging and accessible, catering to a broad demographic of museum visitors.



4.0 First Semester Progress

Indoor positioning using BLE beacons and TourTags:

One of the first microsystems we focused on was the localization of each user in the system, and we prioritized developing a working proof-of-concept for this feature as soon as we could since it serves as the backbone for the rest of our systems functionality. To do this, we designed a system capable of indoor positioning through the use of BLE technology and ESP32 microcontrollers. Each ESP32 in the system was designated to serve as either a beacon or a TourTag. The beacons were given fixed preset locations in a room and constantly (roughly every second) broadcast a BLE signal. Each TourTag was then programmed to regularly measure the RSSI of each BLE signal it could sense and report the measured data to a central server, which would be able to deduce the approximate location of the TourTag. We were able to successfully complete this task early on in the semester, although it required some calibration in order to understand the expected range of RSSI. Our key conclusion from this task was that although it was efficient and simple, using BLE beacons alone would not suffice since it could not pinpoint the exact location a user was in a room.
Additionally, we were able to figure out a stable method of connecting the ESP32 to a secure network in order to facilitate communication between the TourTags and the central server.

Front end:

- **(Identification of TourTag)**

Having a system track a TourTag will not be useful on its own, so we planned to develop a process that allows the system to match each user to a particular TourTag to allow for personalized suggestions and self-localization on the application. In order to accomplish this, we attached QR codes to each TourTag and added functionality on the frontend which prompted users to scan the QR code attached to their TourTag before using the system.

- **Museum map (localization and direction)**

Another addition made to the project this semester was the inclusion of a live map feature to the frontend. In order to accomplish this task, we decided to add a 2D image of the layout of the "museum", which in our case consisted of PHO 111 and PHO 113, and included an overlay, which was updated in real-time to indicate the room that the user is in. The app is able to query the backend using the ID of the TourTag linked to the user and generates the appropriate overlay corresponding to which room the user is in.

Back end

The backend consists predominantly of a Node.js server which serves as the central hub for the system. It played an important role in the integration of all developed parts of the system into a composite system to serve as a first prototype. It was developed in various stages, which are as follows:

- Development of base UDP server to receive RSSI values from the TourTags

- Development of base localization algorithm
- Integration of time-series database to store received data
- Integration of backend with frontend through the use of APIs
- Integration of machine learning model using KNN algorithm to make localization algorithm more robust
- Modification of UDP packet format in order to make localization algorithm more efficient (Inclusion of RFID field and “default” RSSI value representing when a beacon is out of range)
- Development of routing algorithm using Djisktra’s algorithm and weighted graphs with weights derived from room congestion data
- Integration of multimedia database
-

Improvements to TourTag

We made some further improvements to our TourTag design through the development of 3D printed enclosures for the TourTag, as well as the addition of an RFID scanner, which allows the TourTag to be used to trigger the display of specific multimedia corresponding to an exhibit.

First Deliverable Testing

We demonstrated an integrated prototype consisting of the aforementioned subsystems to our client and our supervisors. We used our allocated lab space to act as a representation of a museum in order to facilitate the demonstration. We set up beacons in fixed locations around the “museum” and collected training data using the TourTags and these beacons. This training data was then used to calibrate the machine learning model used in localization as we realized that the RSSI values recorded by the TourTag varied substantially based on congestion, and we wanted our localization algorithm to be more robust by identifying trends instead of using raw RSSI values as thresholds. Overall, the demonstration was a success as we were able to integrate all the subsystems effectively and demonstrate real-time transmission of information between all the parts.
One major discovery we had through this prototype was how using BLE and machine learning was not sufficient for our project, prompting us to begin researching into other technologies, such as UltraWide Bandwidth, which we believe could give us more precision and allow us to have a singular method of localization, rather than amalgamating multiple technologies to determine location.

5.0 Technical Plan

This section outlines the detailed plan for completing the proposed solution, with activities spanning from January 15, 2023, to April 10, 2023. It describes a series of tasks and milestones that culminate in the delivery of a fully functional project, with the final testing scheduled for the week of April 1, 2023.

Task 1: Transition to UWB Trilateration

- Objective: Replace the existing KNN ML learning models with a more accurate and efficient trilateration method using Ultra-Wideband (UWB) technology for location services.
- Action Items:
  - Research and Design Phase: Conduct a comparative analysis between KNN ML models and UWB trilateration (January 15-31).
  - Implementation Phase: Develop algorithms and integrate UWB trilateration into the existing system (February 1-28).
  - Optimization Phase: Fine-tune the system for optimal performance and accuracy (March 1-15).
- Deliverables:
  - Comparative analysis report
  - UWB trilateration integration documentation
  - Performance benchmarks report

Task 2: Finalize Front-End React Native UI

- Objective: Complete the development of the user interface using React Native to ensure a seamless and engaging user experience.
- Action Items:
  - Design Review Phase: Review the current UI design and gather feedback (January 15-22).
  - Development Phase: Implement the final design adjustments and integrate with backend services (January 23 - February 28).
  - User Testing Phase: Conduct user testing sessions to validate the design and gather user feedback (March 1-15).
- Deliverables:
  - Final UI design files
  - Integration report
  - User testing feedback summary

Task 3: Comprehensive System Testing

- Objective: Perform thorough testing on hardware, server, and front-end components to ensure system integrity and reliability.
- Action Items:

  - Test Plan Development: Develop a comprehensive test plan covering all system components (February 1-7).
  - Testing Execution: Execute test cases as per the test plan and document the findings (February 8 - March 15).
  - Issue Resolution: Address any identified issues and re-test to confirm resolution (March 16-31).
- Deliverables:
  - Test plan
  - Test reports
  - Issue resolution report

Task 4: Optimize Design

- Objective: Conduct a full review and optimization of all design facets to enhance system performance and efficiency.
- Action Items:
  - Review Phase: Analyze the current design for potential improvements (February 1-14).
  - Optimization Phase: Implement design changes and optimizations (February 15 - March 22).
  - Evaluation Phase: Evaluate the impact of optimizations on performance (March 23 - April 1).
- Deliverables:
  - Design optimization report
  - Performance improvement benchmarks
  - Final optimized design documentation

6.0 Budget Estimate

In this section you discuss WHAT ARE THE BUDGET IMPLICATIONS AND CONSTRAINTS for your effort.

Item	Description	Cost
1	12 ESP32 (10 for beacons and 2 for user devices)	$251.40
2	Corner BLE enclosures	$3.49
3	Wall BLE enclosures	$2.38
4	Handheld device enclosure	$2.89
	Total Cost	$257.78

The budget breakdown for the proposed system highlights a modest total cost of $257.78 for the necessary hardware components. The bulk of the expenditure is attributed to the purchase of 12 ESP32 microcontrollers, amounting to $251.40, which will serve both as beacons and as the core of user devices. Additionally, the budget accounts for the cost of BLE enclosures with corner units priced at $3.49 and wall units at $2.38, intended for optimal placement throughout the museum to ensure effective signal transmission and reception. Finally, the handheld device enclosure, which will secure the user device equipped with RFID scanning capabilities, is modestly priced at $2.89. This cost-effective allocation for hardware suggests a financially feasible approach to developing the museum's navigational and informational support system.

7.0 Attachments

7.1 Appendix 1 – Engineering Requirements

Team #7 Team Name: MuseumMate

Project Name:Mueseum Mate

Requirement	Value, range, tolerance, units
Route Determination Time	≤3 seconds
Map Display Time	≤3 seconds
Navigation Update Time	≤2 seconds
UD Support Capacity	Up to 512 user devices
Positional Update Frequency	Every ≤10 seconds
RFID Positioning Accuracy	Within ±1 meter
BLE Positional Accuracy	Within ±4 meters for 90% of cases
UD Production Quantity	Minimum of 4 user devices
Production Cost per Device	≤$50 for batches of 1000
UD Battery Life	>12 hours on a full charge

Mobile Navigation Application

Functional:

1. Multimedia content (audio, video, text) sourced from URLs. In this scenario, "multimedia" refers to audio-visual elements inclusive of text.
2. Enables navigation using a comprehensive museum map, which includes all floors, whether this be with distinct turn-by-turn indications or indicative arrows. "Navigation" in this context is providing a pathway guide to users.
3. Depicts current traffic through a potential heat map representation. Here, "Traffic, adjusting for room densities. Furthermore, it should provide consecutive directions to the next museum spot.
4. Graphically showcases the user's instantaneous location on the museum map.
5. Interface can be accessed through web browsers or as a standalone application.
6. Equipped with a diagnostic function, but exclusively in an elevated user mode.

Performance:

1. Time taken for route determination should not exceed 3s.
2. The map's display time must remain under 3s.
3. Any alterations in navigation should manifest in less than 2s.

Routing Algorithm / Server

Functional:

1. Amass the journey data for each unique device (UD).
2. Procure the positional data of every UD.
3. Record the duration each UD spends at particular exhibits.
4. Retain all route computation requests made by users.
5. Generate traffic heat maps intended for dissemination to smartphone apps.
6. Keep a detailed log of all UD interactions, meant for diagnostic and troubleshooting purposes.
7. Facilitate the extraction of collected data in .csv format for insightful analysis.
8. Respond to shortest path requests initiated by the mobile navigation application.
9. Host on either local networks or a cloud-based system.

Performance:

1. System should be capable of supporting as many as 512 UDs.

3.3 Indoor Positioning Function

Functional:

1. RFID is the source of positional estimation. Here, "RFID" pertains to Radio Frequency Identification.
2. BLE (Bluetooth Low Energy) also serves as a means of positional estimation.

Performance:

1. Positional updates on a UD should be made every 10s or faster.
2. RFID should offer positioning accuracy within 1m in all cases.
3. For BLE, the basic expectation is to pinpoint the encompassing room accurately in every scenario.
4. Typically, BLE's position accuracy should be within 4m for 90% of cases.

User Device

Functional:

1. Device interfaces seamlessly with the user's smartphone.
2. Efficiently reads signals emitted by BLE beacons.
3. Scans and identifies RFIDs present at exhibits.For localization, it relies on at least one BLE beacon for proximity and multiple beacons for precise positioning.
4. Facilitates communication between itself and the user's smartphone regarding positioning and RFID scans.
5. Can be recharged after usage.

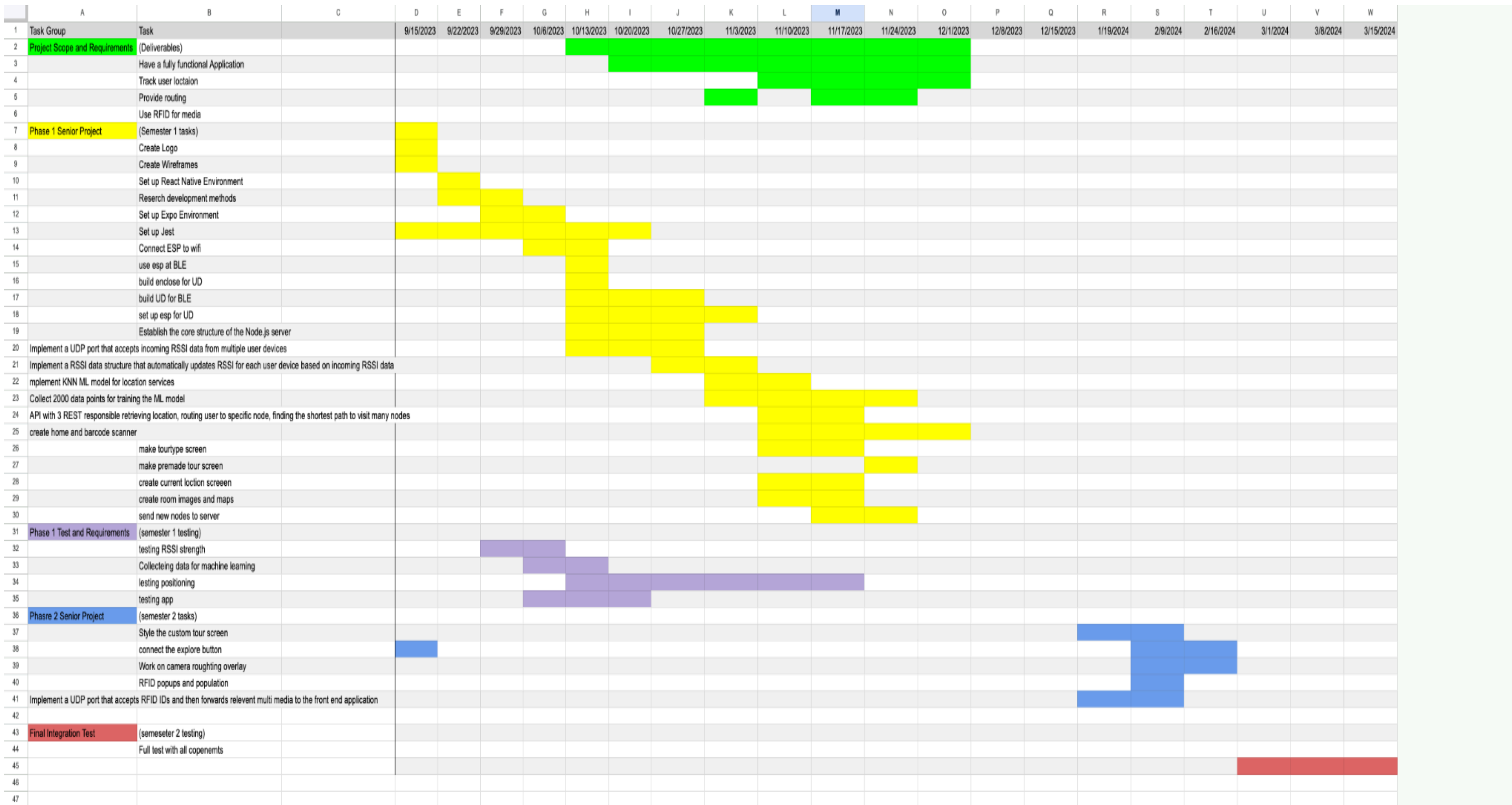
Performance:

8.0 A minimum of 4 UDs should be produced.

9.0 Production cost per device should remain below $50 when made in batches of 1000.

10.0 Should function continuously for over 12 hours post a full charge.

10.1 Appendix 2 – Gantt Chart



10.2 Appendix 3 – Other Appendices