UNIVERSITY of SOUTH FLORIDA
College of Engineering
Department of Electrical Engineering

EEL4914 Fall 2024

Development of a multi sensor logger and a gateway using Bluetooth Low Energy (BLE)

FINAL REPORT

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TABLE OF CONTENTS

1. EXECUTIVE SUMMARY 4
  1.1 PROJECT OVERVIEW 4
  1.2 PURPOSE AND SCOPE OF THIS SYSTEM REQUIREMENTS DOCUMENT 4
  1.3 DEFINITIONS, ACRONYMS, AND ABBREVIATIONS 4
  1.4 REFERENCES 5
    1.4.1 Hardware 5
    1.4.2 Software 5
    1.4.3 IDEs and Development Tools 5
    1.4.4 Standards 5
    1.4.5 General References 5
2. PRODUCT/SERVICE DESCRIPTION 6
  2.1 PRODUCT CONTEXT 6
  2.2 ASSUMPTIONS 6
  2.3 CONSTRAINTS 6
  2.4 DEPENDENCIES 6
3. SYSTEM REQUIREMENTS 7
  3.1 FUNCTIONAL REQUIREMENTS 7
    3.1.1 USER INTERFACE REQUIREMENTS 7
    3.1.2 PERFORMANCE 7
    3.1.3 CAPACITY 7
    3.1.4 AVAILABILITY 7
    3.1.5 LATENCY 7
    3.1.6 MANAGEABILITY/MAINTAINABILITY 7
    3.1.7 MONITORING 7
    3.1.8 MAINTENANCE 7
    3.1.9 SYSTEMS INTERFACES 7
  3.2 SYSTEM REQUIREMENTS MATRIX 8
  3.3 DATA LOW-POWER OPERATION 9
  3.4 MULTI-SENSOR DATA ACQUISITION 9
  3.5 DATA TRANSFER 9
  3.6 PROCESSING 9
  3.7 MQTT BROKER 10
  3.8 USER INTERFACE DEVELOPMENT 10
4. USER SCENARIOS/USE CASES 11
  4.1 Environmental Monitoring in Smart Agriculture 11
  4.2 Industrial Equipment Health Monitoring 11

4.3 Smart Building Energy Management ... 11
4.4 Disaster Recovery ... 11
5. ANALYSIS MODELS ... 12
5.1 SEQUENCE DIAGRAMS ... 12
5.2 DATA FLOW DIAGRAMS ... 12
5.3 STATE-TRANSITION DIAGRAMS ... 13
5.4 SWAP ... 13
5.4.1 Size ... 13
5.4.2 Weight ... 14
5.4.3 Power ... 15
5.5 SYSTEM PERFORMANCE ... 15
6. PROJECT RISK ... 16
6.1 Technical ... 16
6.2 Operational ... 16
6.3 Environmental ... 16
6.4 Resource ... 16
6.5 Maintenance ... 16
7. STANDARDS ... 17
8. ENGINEERING ETHICAL RESPONSIBILITY ... 17
8.1 PUBLIC HEALTH ... 17
8.2 SAFETY ... 17
8.3 GLOBAL, SOCIAL, & CULTURAL FACTORS ... 17
8.4 ECONOMIC FACTORS ... 17
8.5 ENVIRONMENTAL FACTORS ... 18
9. SAFETY ... 18
10. CONCLUSION ... 18
11. WORK DIVISION ... 19

1. EXECUTIVE SUMMARY

This document outlines the system requirements and design considerations for the development of a multi-sensor logger and a gateway leveraging Bluetooth Low Energy (BLE). It details the purpose, scope, assumptions, constraints, and dependencies that guided the design and implementation of the system. Additionally, this report provides insight into the system's operational context, ensuring clarity and alignment for all stakeholders while emphasizing the project's goal of delivering a scalable, low-power monitoring solution.

1.1 PROJECT OVERVIEW

The **Development of a Multi-Sensor Logger and a Gateway Using Bluetooth Low Energy (BLE)** project aims to design a low-power, real-time environmental monitoring system. The system comprises two key components: sensor loggers for data acquisition and a gateway for data aggregation and transmission. The primary objective is to provide a scalable solution for collecting, transmitting, and visualizing environmental data, catering to diverse applications such as agriculture, industrial monitoring, and smart building management.

The sensor loggers use BLE to collect data on parameters such as temperature, humidity, ambient light, UV-index, magnetic field and motion. These data packets are transmitted to a gateway, which processes the data and forwards it to an MQTT broker via Wi-Fi. A web-based graphical dashboard is used for real-time visualization and analysis, offering users an intuitive interface to monitor and manage the system.

Originally sponsored by *ZTHRU*, the project adapted to significant changes following the company's closure. Despite these challenges, the team successfully delivered a robust system by overcoming hardware and software compatibility issues, particularly between the Silabs Thunderboard sensor platform and the ESP32 gateway.

1.2 PURPOSE AND SCOPE OF THIS SYSTEM REQUIREMENTS DOCUMENT

This System Requirements Document (SRD) serves to provide a complete set of requirements for the development of the "Development of a multi sensor logger and a gateway using Bluetooth Low Energy (BLE)". It outlines all key functionalities, technical details, and interfaces that define the scope of this project. The SRD is intended to guide stakeholders through the requirements necessary for the successful completion of the project, ensuring alignment with the desired outcomes and performance standards.

1.3 DEFINITIONS, ACRONYMS, AND ABBREVIATIONS

- **BLE**: Bluetooth Low Energy – A wireless communication protocol designed for low-power devices.
- **ESP32**: A low-cost, low-power system on a chip (SoC) with integrated Wi-Fi and Bluetooth capabilities, used as a gateway device.
- **EFR32BG22**: Silicon Labs' Bluetooth Low Energy System-on-Chip (SoC) used for sensor loggers.
- **MQTT**: Message Queuing Telemetry Transport – A lightweight messaging protocol for IoT systems.
- **GATT**: Generic Attribute Profile – A BLE protocol defining how devices exchange data.
- **SDK**: Software Development Kit – A set of tools and libraries for software development.
- **IDE**: Integrated Development Environment – A software suite for writing, testing, and debugging code (e.g., Simplicity Studio).
- **IoT**: Internet of Things – A network of devices that communicate and share data over the internet.
- **Wi-Fi**: Wireless Fidelity – A wireless networking technology for data transfer.

- **Grafana**: A visualization platform used to create real-time dashboards for data analysis.
- **EEPROM**: Electrically Erasable Programmable Read-Only Memory – A type of memory used for storing data persistently.
- **PCB**: Printed Circuit Board – The physical platform for mounting and connecting electronic components.

1.4 REFERENCES

1.4.1 Hardware

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- Bluetooth Special Interest Group (SIG). (2023). Generic Attribute Profile (GATT) Overview. Retrieved from https://www.bluetooth.com/specifications/gatt/

2. PRODUCT/SERVICE DESCRIPTION

The product is a multi-sensor logger system designed to collect and transmit environmental data for real-time analysis. Using Bluetooth Low Energy (BLE) and Wi-Fi, the system ensures reliable data acquisition and visualization for monitoring applications.

2.1 PRODUCT CONTEXT

Operating within the Internet of Things (IoT) framework, this system integrates BLE sensor loggers and a Wi-Fi-enabled gateway to provide scalable, energy-efficient monitoring. It is designed for deployment in scenarios requiring precise and continuous data tracking, such as industrial facilities or environmental research stations.

2.2 ASSUMPTIONS

- The system will be deployed in areas with reliable Wi-Fi connectivity to ensure seamless data transmission.
- Users will have access to interfaces, such as web browsers, for data visualization and configuration.
- Sensors will operate under standard environmental conditions as specified in the system requirements.

2.3 CONSTRAINTS

- Battery life constraints for sensor loggers necessitate power-efficient operation.
- Stable connectivity is required for reliable data transmission using the MQTT protocol.
- Physical space limitations may restrict the positioning and deployment of sensors.

2.4 DEPENDENCIES

- A stable Wi-Fi connection is essential for data transmission between the gateway and external systems.
- The Grafana platform is a critical component for data visualization, and its availability and compatibility must be ensured.
- Effective synchronization between the gateway and sensor loggers is vital for maintaining real-time monitoring capabilities.

3. SYSTEM REQUIREMENTS

3.1 FUNCTIONAL REQUIREMENTS

3.1.1 USER INTERFACE REQUIREMENTS

- The user interface shall provide an intuitive and user-friendly experience, enabling real-time data visualization and configuration of sensor settings through a web application.

3.1.2 PERFORMANCE

- The system should maintain reliable performance, without data transmission and processing delays under standard operating conditions.

3.1.3 CAPACITY

- The system shall support multiple sensor loggers simultaneously, with scalability for additional devices as needed.

3.1.4 AVAILABILITY

- The system shall operate continuously, ensuring minimal downtime and uninterrupted monitoring.

3.1.5 LATENCY

- Data transmission from sensors to the gateway and ultimately to the user interface should occur with minimal latency to enable real-time monitoring.

3.1.6 MANAGEABILITY/MAINTAINABILITY

- The system should be easy to manage, with tools provided for maintaining and updating sensor firmware and software components.

3.1.7 MONITORING

- The system should provide real-time monitoring features, including status indicators for sensors, battery levels, and data transmission health.

3.1.8 MAINTENANCE

- Regular maintenance schedules shall include sensor calibration and software updates, ensuring optimal system performance and accuracy.

3.1.9 SYSTEMS INTERFACES

- The system shall interface seamlessly with third-party platforms, such as cloud services for data storage and analysis, using standard communication protocols like MQTT.

3.2 SYSTEM REQUIREMENTS MATRIX

Requirement #	Function	Requirement Description	Comments	Date Reviewed	Faculty Approval
1	User Interface Requirements	The user interface shall provide an intuitive and user-friendly experience, enabling real-time data visualization and configuration of sensor settings through a web application.	Ensure simplicity and usability for all users.	11/8/24	JCl
2	Performance	The system should maintain reliable performance, without data transmission and processing delays under standard operating conditions.	Focus on reliability and stability under standard workloads.	11/8/24	JCl
3	Capacity	The system shall support multiple sensor loggers simultaneously, with scalability for additional devices as needed.	Scalability is critical for future expansion.	11/8/24	JCl
4	Availability	The system shall operate continuously, ensuring minimal downtime and uninterrupted monitoring.	Target 99.9% uptime.	10/20/24	JCl
5	Latency	Data transmission from sensors to the gateway and ultimately to the user interface should occur with minimal latency to enable real-time monitoring.	Ensure latency remains below 200ms on average.	10/20/24	JCl
6	Manageability/ Maintainability	The system should be easy to manage, with tools provided for maintaining and updating sensor firmware and software components.	Include a streamlined process for updates.	10/20/24	JCl
7	Monitoring	The system should provide real-time monitoring features, including status indicators for sensors, battery levels, and data transmission health.	Enable alerts for critical statuses.	11/8/24	JCl
8	Maintenance	Regular maintenance schedules shall include sensor calibration and software updates, ensuring optimal system performance and accuracy.	Define clear maintenance protocols.	11/27/24	JCl
9	Systems Interfaces	The system shall interface seamlessly with third-party platforms, such as cloud services for data storage and analysis, using standard communication protocols like MQTT.	Ensure compatibility with major platforms.	11/8/24	JCl

3.3 DATA LOW-POWER OPERATION

- All components, including sensor loggers and the gateway, shall optimize battery power consumption to extend operational lifespan, achieving a maximum battery life for the loggers under typical use.

3.4 MULTI-SENSOR DATA ACQUISITION

- Sensor loggers should collect temperature, humidity, ambient light, and UV data at configurable intervals.

3.5 DATA TRANSFER

- Bluetooth sensor boards shall transmit data packets securely to the gateway upon receiving the correct handshake request.

```
VCOM Console

[I] UV Index = 0
[I] Ambient light = 4.497070 lux
[I] UV Index = 0
[I] Humidity = 56.19 %RH
[I] Temperature = 26.93 C

[I] Humidity = 56.20 %RH
[I] Temperature = 26.93 C
[I] Battery level = 100 %
[I] Ambient light = 4.622803 lux
[I] UV Index = 0
```

Figure 1: Thunderboard debug console showing advertised sensor data following handshake from ESP32

3.6 PROCESSING

- The ESP32 gateway shall categorize incoming data from Bluetooth sensor boards before transmitting it to the MQTT broker for storage and analysis.

```
=== Starting BLE and MQTT Client ===
Connecting to NETGEAR65
..............
[INFO] Connected to Wi-Fi.
[INFO] Found and assigned Thunderboard #28685 to slot 1.
[INFO] Found and assigned Thunderboard #37310 to slot 2.
[INFO] Found and assigned Thunderboard #37324 to slot 3.

+---------+-----------------------+------------+-----------+---------+--------+------------+---------------+
| Slot No | Device Name           |Temperature | Humidity  | Battery | UV     | Light (lux)| Connected     |
+---------+-----------------------+------------+-----------+---------+--------+------------+---------------+
| 1       | Thunderboard #28685   | N/A        | N/A       | N/A     | N/A    | N/A        | NO            |
| 2       | Thunderboard #37310   | N/A        | N/A       | N/A     | N/A    | N/A        | NO            |
| 3       | Thunderboard #37324   | N/A        | N/A       | N/A     | N/A    | N/A        | NO            |
| 4       | N/A                   | N/A        | N/A       | N/A     | N/A    | N/A        | NO            |
| 5       | N/A                   | N/A        | N/A       | N/A     | N/A    | N/A        | NO            |
| 6       | N/A                   | N/A        | N/A       | N/A     | N/A    | N/A        | NO            |
| 7       | N/A                   | N/A        | N/A       | N/A     | N/A    | N/A        | NO            |
| 8       | N/A                   | N/A        | N/A       | N/A     | N/A    | N/A        | NO            |
+---------+-----------------------+------------+-----------+---------+--------+------------+---------------+
```

Figure 2: ESP32 debug log showing boot sequence

```
+---------+----------------------+------------+-----------+----------+--------+------------+---------------+
| Slot No | Device Name          |Temperature | Humidity  | Battery  | UV     | Light (lux)| Connected     |
+---------+----------------------+------------+-----------+----------+--------+------------+---------------+
| 1       | Thunderboard #28685  | 24.07      | 63.61     | 99       | 0      | 398.94     | YES           |
| 2       | Thunderboard #37310  | 26.46      | 55.43     | 100      | 0      | 14.44      | YES           |
| 3       | Thunderboard #37324  | 25.45      | 58.87     | 100      | 0      | 10.83      | YES           |
| 4       | Thunderboard #37153  | N/A        | N/A       | N/A      | N/A    | N/A        | NO            |
| 5       | Thunderboard #33078  | N/A        | N/A       | N/A      | N/A    | N/A        | NO            |
| 6       | N/A                  | N/A        | N/A       | N/A      | N/A    | N/A        | NO            |
| 7       | N/A                  | N/A        | N/A       | N/A      | N/A    | N/A        | NO            |
| 8       | N/A                  | N/A        | N/A       | N/A      | N/A    | N/A        | NO            |
+---------+----------------------+------------+-----------+----------+--------+------------+---------------+

[DEBUG] Restarting BLE scan...
[DEBUG] Disconnected device in slot 1: Thunderboard #28685
[DEBUG] Creating new BLE client...
[DEBUG] Attempting to connect to BLE server for device: Thunderboard #37153
[SUCCESS] Connected to BLE server for device: Thunderboard #37153

+---------+----------------------+------------+-----------+----------+--------+------------+---------------+
| Slot No | Device Name          |Temperature | Humidity  | Battery  | UV     | Light (lux)| Connected     |
+---------+----------------------+------------+-----------+----------+--------+------------+---------------+
| 1       | Thunderboard #28685  | 24.07      | 63.61     | 99       | 0      | 398.94     | NO            |
| 2       | Thunderboard #37310  | 26.47      | 55.40     | 100      | 0      | 12.88      | YES           |
| 3       | Thunderboard #37324  | 25.45      | 58.55     | 100      | 0      | 11.42      | YES           |
| 4       | Thunderboard #37153  | 26.88      | 55.93     | 100      | 0      | 19.54      | YES           |
| 5       | Thunderboard #33078  | N/A        | N/A       | N/A      | N/A    | N/A        | NO            |
| 6       | N/A                  | N/A        | N/A       | N/A      | N/A    | N/A        | NO            |
| 7       | N/A                  | N/A        | N/A       | N/A      | N/A    | N/A        | NO            |
| 8       | N/A                  | N/A        | N/A       | N/A      | N/A    | N/A        | NO            |
+---------+----------------------+------------+-----------+----------+--------+------------+---------------+
```

Figure 3: ESP32 debug log showing how the gateway handles more than 3 connected BLE devices

3.7 MQTT BROKER

- The MQTT broker (EMQX) shall handle the secure transfer of sorted data from the gateway to a web server for long-term storage and user access.

3.8 USER INTERFACE DEVELOPMENT

- A web-based user interface, implemented with Grafana, shall subscribe to the gateway and display real-time data received from sensor loggers.

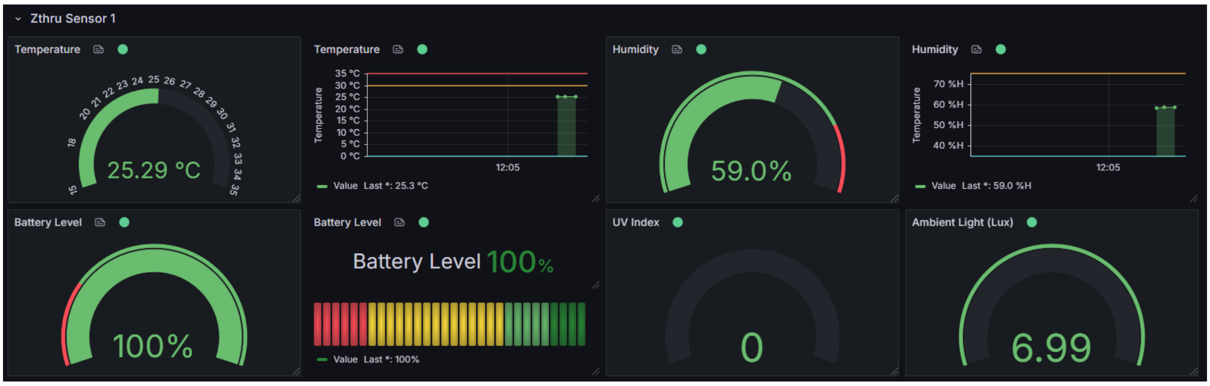


Figure 4: Grafana web user interface

4. USER SCENARIOS/USE CASES

4.1 Environmental Monitoring in Smart Agriculture

- Sensors monitor temperature, humidity, and soil moisture levels across large fields.
- Data is collected and transmitted to a central gateway for real-time analysis, enabling automated irrigation based on environmental conditions.

4.2 Industrial Equipment Health Monitoring

- Sensors are attached to machinery to track vibrations and noise levels.
- Sudden deviations trigger alerts through the MQTT broker to Grafana, helping to prevent breakdowns or unsafe conditions.

4.3 Smart Building Energy Management

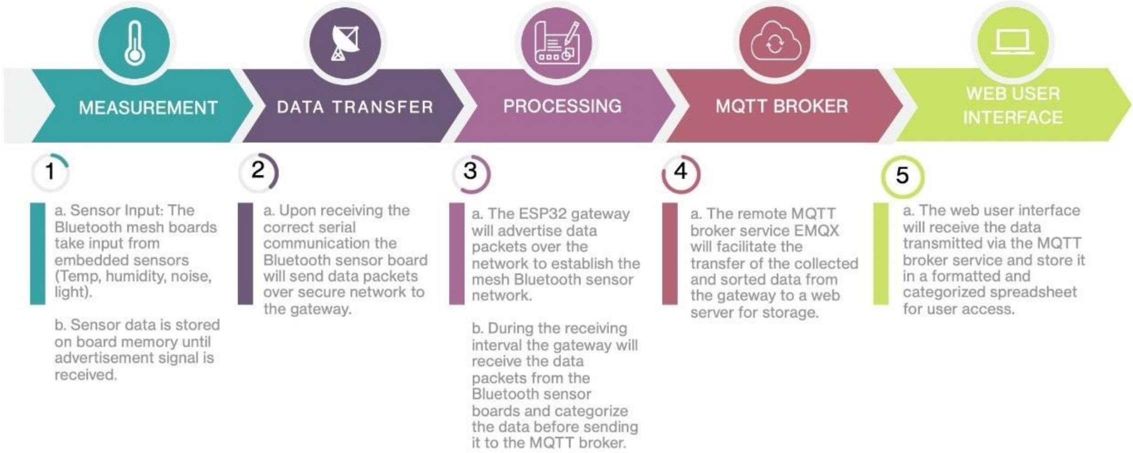
- Sensors track ambient conditions in different rooms, logging temperature and occupancy data.
- Data is used to optimize HVAC systems, reducing energy consumption while maintaining comfort.

4.4 Disaster Recovery

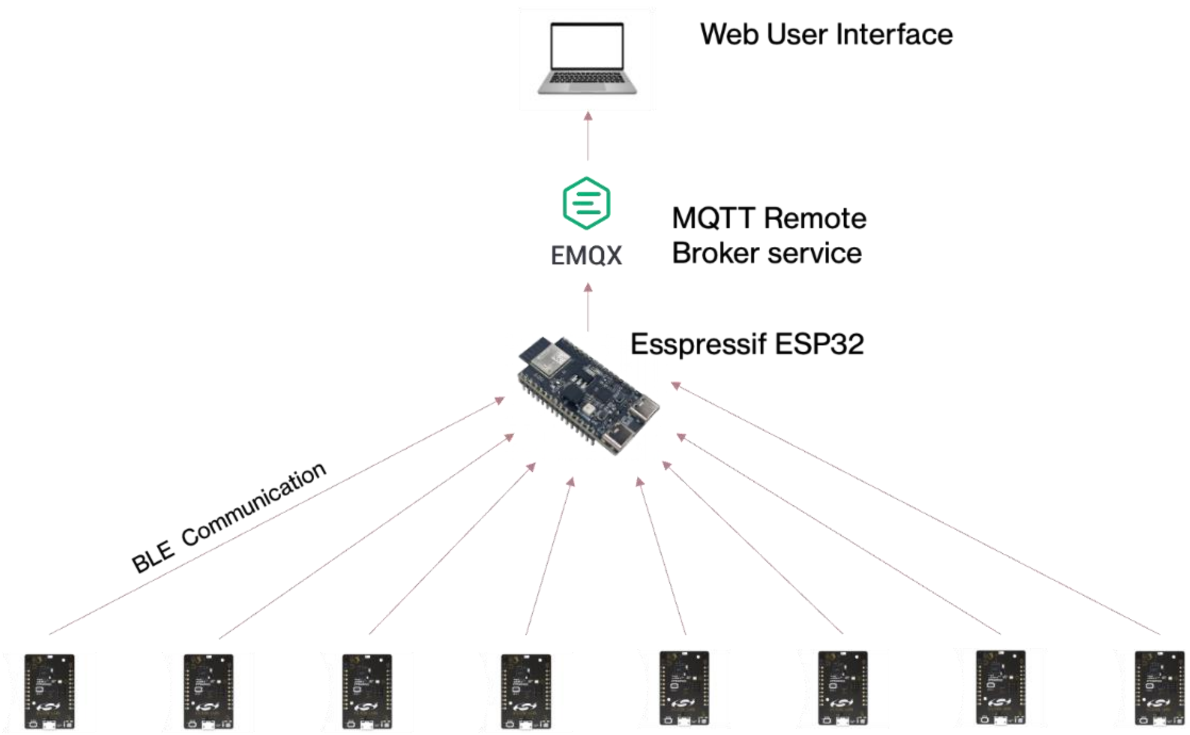
- A network of sensors is deployed in a remote area to monitor environmental changes after a natural disaster.
- The gateway relays data to emergency response teams to assess air quality and structural stability, ensuring safety for responders.

5. ANALYSIS MODELS

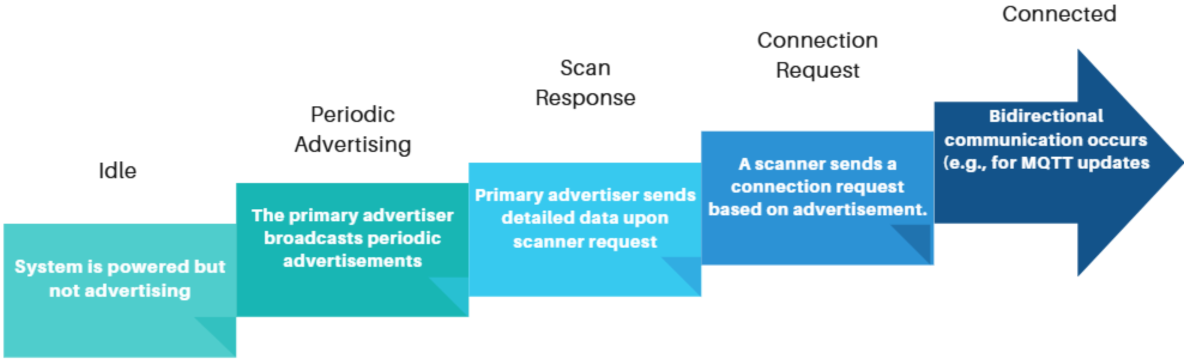
5.1 SEQUENCE DIAGRAMS



5.2 DATA FLOW DIAGRAMS



5.3 STATE-TRANSITION DIAGRAMS



5.4 SWAP

5.4.1 Size

- *ESP32*

- Development Board Dimensions: Typically, around 25 mm x 50 mm, depending on the model (e.g., ESP32-DevKitC or ESP32-WROOM).
- Chip Package: ESP32-WROOM modules are about 18 mm x 25.5 mm.

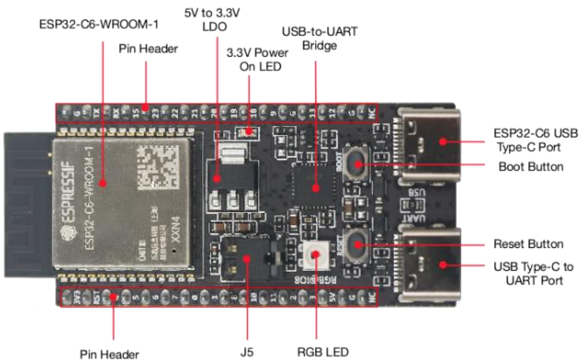


Figure 5: esp32-c6-devkitc-1

- *"Thunderboard" (EFR32BG22)*

- Thunderboard Development Kit Dimensions: 45.4 mm x 30.4 mm.
- EFR32BG22 Chip package size: 4 mm x 4 mm (QFN32 package).

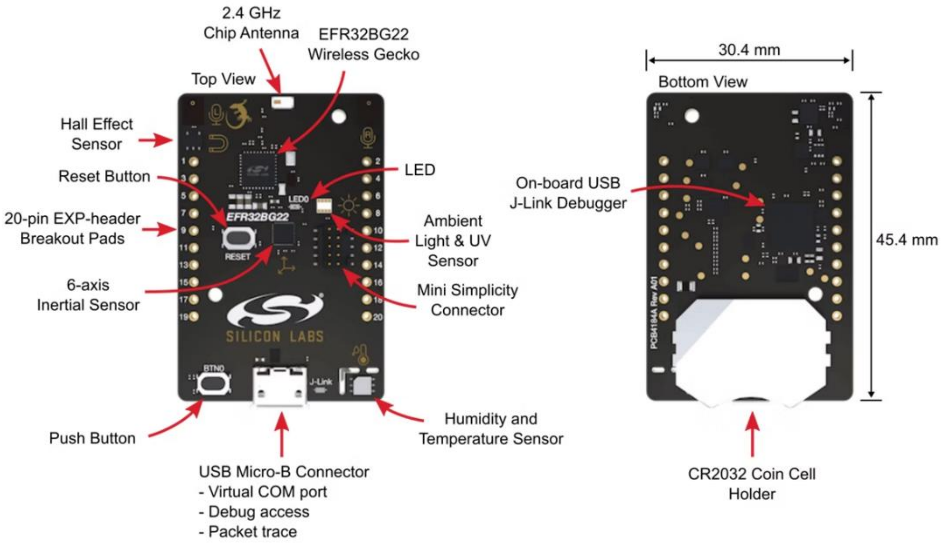


Figure 6: Silabs Thunderboard

5.4.2 Weight

- *ESP32*

- Weighs approximately 7-10 grams

- *EFR32BG22*

- Thunderboard: Weighs around 20-25 grams, including onboard components and casing.
- Bare EFR32BG22 Chip: Negligible weight (~0.1-0.5 grams)

5.4.3 Power

- *ESP32*

- Active Mode (Wi-Fi + BLE):
- Average current: ~200-300 mA at 3.3V.
- Peak: Up to 400 mA during transmission bursts.
- Sleep Mode (Deep Sleep):
- Average current: ~10 µA - 6 mA, depending on peripherals.
- Power Supply: Operates at 3.0V to 3.6V. A Li-ion battery (e.g., 3.7V) is commonly used.

- *EFR32BG22*

- Active Mode (TX at 0 dBm):
- Current consumption: ~3.6 mA at 3.3V.
- Sleep Mode (Deep Sleep):
- Current consumption: ~1.3 µA.
- Power Supply: Operates at 1.8V to 3.8V.
- Battery Life: Depending on configuration, a coin cell battery (CR2032) can last several months.

5.5 SYSTEM PERFORMANCE

The BLE system integrates EFR32BG22 sensor nodes and ESP32 gateways to deliver an efficient multi-sensor logging solution. The EFR32BG22 sensor nodes operate with low-power efficiency, periodically broadcasting data via BLE to optimize battery life. The ESP32 gateway aggregates sensor data reliably and transmits it to an MQTT broker over Wi-Fi, ensuring seamless delivery to a Grafana-based visualization platform.

The system has been designed to meet IoT application requirements, achieving reliable communication and scalable performance. It supports simultaneous operation of multiple sensors with minimal latency, ensuring real-time monitoring and data accessibility. This robust performance highlights its suitability for diverse applications such as environmental monitoring, industrial automation, and smart infrastructure systems.

6. PROJECT RISK

6.1 Technical

- *Risk*

Potential challenges related to the integration of hardware components and compatibility with the chosen software platforms.

- *Mitigation*

Modular testing of each hardware and software component before integration to identify compatibility issues early.

Maintain backup versions of firmware and software to revert quickly in case of errors.

6.2 Operational

- *Risk*

Issues that may arise during the deployment of the system, including connectivity interruptions or physical damage to sensor components.

- *Mitigation*

Include redundancy in communication paths to minimize connectivity interruptions.

Develop a step-by-step deployment manual to avoid mishandling during setup.

6.3 Environmental

- *Risk*

External environmental factors, such as extreme weather conditions, may affect sensor accuracy and system functionality.

- *Mitigation*

Use weatherproof enclosures for sensors and gateways to protect against environmental factors.

Perform simulations under extreme conditions to ensure system reliability.

6.4 Resource

- *Risk*

Risks related to the availability of key components, including sensors and microcontrollers, and potential delays in procurement.

- *Mitigation*

Identify alternate suppliers for key components to minimize procurement delays.

Order critical components in advance and maintain a buffer stock for replacements.

6.5 Maintenance

- *Risk*

The possibility of unexpected maintenance needs due to hardware malfunctions or software bugs that impact system performance.

- *Mitigation*

Develop a proactive maintenance schedule that includes periodic firmware updates and hardware checks.

Train end users or clients on basic troubleshooting techniques to address minor issues.

7. STANDARDS

- **IEEE 802.11**: Ensures consistent and reliable wireless communication between the sensor nodes and the gateway over Wi-Fi.
- **IEEE 802.15.1**: Establishes the standard for Bluetooth communication, enabling reliable operation and interoperability of BLE devices like the EFR32BG22.
- **MQTT Protocol**: A lightweight messaging standard critical for efficient and secure data transfer between the sensor network and the MQTT broker, enabling real-time data exchange.
- **IEEE 1451**: Ensures compatibility and interoperability among sensors and microcontrollers by standardizing transducer interfaces, essential for seamless integration of system components.
- **ISO 27001**: An information security standard implemented to safeguard data handling and transmission, ensuring the system adheres to best practices in cybersecurity.
- **NIST Cybersecurity Framework (CSF)**: Provides guidelines for securing IoT systems, addressing risks associated with wireless communication and data storage.
- **RoHS**: Ensures that hardware components comply with environmental regulations by restricting the use of hazardous materials.
- **ISO 9001**: Indicates adherence to quality management practices, ensuring high-quality design and implementation.
- **ISO/IEC 29182**: A framework for sensor networks, aligning the system design with established IoT best practices.
- **W3C Standards**: Web standards for user interface development ensure cross-browser compatibility and accessibility, enhancing user experience on the Grafana-based visualization platform.

8. ENGINEERING ETHICAL RESPONSIBILITY

8.1 PUBLIC HEALTH

- The system should be designed and implemented with consideration for public health impacts, ensuring data accuracy and reliability to inform environmental conditions that could affect human health.

8.2 SAFETY

- Adherence to safety standards shall be ensured during all phases of the project to prevent physical hazards to users or the environment. Rigorous testing protocols will be implemented to identify and mitigate potential risks associated with system deployment.

8.3 GLOBAL, SOCIAL, & CULTURAL FACTORS

- The system shall be developed with a focus on inclusivity, ensuring that it is accessible and usable in diverse cultural and socioeconomic contexts. This includes providing user interfaces in multiple languages and accommodating varying levels of technological literacy.

8.4 ECONOMIC FACTORS

- Cost-effectiveness shall be prioritized by optimizing manufacturing, deployment, and maintenance expenses, making the system affordable and scalable for both small-scale and large-scale applications.

8.5 ENVIRONMENTAL FACTORS

- Sustainability shall be integral to the system design, emphasizing low-power operation, the use of recyclable and eco-friendly materials, and minimizing electronic waste throughout the product lifecycle.

9. SAFETY

- The system shall comply with industry-recognized safety standards to mitigate risks associated with electrical malfunctions or component failures, ensuring the protection of both personnel and equipment.
- Comprehensive testing shall be conducted to verify the safe operation of all components under a range of environmental conditions, including extreme temperatures, humidity, and vibration.
- Emergency protocols shall be defined and implemented to address unexpected system behavior, including steps for isolating faulty components, alerting users, and initiating system recovery to maintain operational safety.

10. CONCLUSION

Despite the inherent challenges of working with commercial off-the-shelf (COTS) devices, this project successfully bridged the gap between the Silabs Thunderboard and the ESP32 gateway, which were not designed to communicate out of the box. The Thunderboard, intended as a demonstration platform for Silabs' BLE capabilities, was adapted for full-system integration through custom firmware modifications. Without official documentation or external support, the team leveraged engineering ingenuity to create a fully functional BLE sensor network, demonstrating adaptability and technical proficiency. By integrating various technologies such as Bluetooth, MQTT, and Grafana, the system ensures efficient data collection, processing, and visualization. The implementation of this system will lead to improved monitoring capabilities for diverse applications, providing valuable insights for users while ensuring public health and safety.

11. WORK DIVISION

Dillon M.:

- Designed and implemented the system's end-to-end software architecture, including the Bluetooth Low Energy (BLE) communication protocols, gateway programming, and MQTT broker integration.
- Developed custom firmware for the Silabs Thunderboard, adapting factory-loaded example programs through advanced debugging and code modification techniques to achieve seamless communication with the ESP32 gateway.
- Conducted extensive research into BLE communication standards and protocols, ensuring the system adhered to best practices for low-power operation and reliable data transmission.
- Led the integration of all system components, including the sensor loggers, gateway, MQTT broker, and Grafana visualization platform, ensuring data flowed seamlessly from collection to visualization.
- Troubleshot and resolved complex hardware-software compatibility issues, employing innovative problem-solving techniques to overcome the lack of official documentation and external support.
- Validated system performance through rigorous testing of BLE connections, data reliability, latency, and gateway-to-cloud communication, optimizing real-world deployment scenarios.

Yowhannes D.:

- Developed the web-based data visualization platform using Grafana, focusing on intuitive user experience and real-time monitoring capabilities.
- Configured MQTT subscriptions and validated data streams from the gateway to the Grafana dashboard to ensure proper data flow and visualization.
- Assisted with debugging data formatting issues to ensure sensor data was displayed accurately in the user interface.

Ngan D.:

- Supported the configuration and testing of the Bluetooth sensor loggers, assisting in validating temperature and humidity data accuracy.
- Conducted research on applicable industry standards and ensured alignment during system design and development.
- Contributed to the ethical, economic, and environmental impact analysis of the project.

Tatyana P.:

- Assisted with debugging and troubleshooting the gateway-to-MQTT broker communication to ensure reliable data transmission.
- Managed documentation efforts, including system requirements and technical deliverables.
- Performed project risk analysis and oversaw compliance with relevant engineering standards.
- Organized and monitored project timelines, ensuring milestones were achieved on schedule.