T24 Interim Design Review Report

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***Abstract*—ABSTRACT**
***Index Terms*—KEYWORDS**

INTRODUCTION:

Singapore, a frontrunner in sustainable urban development, grapples with a crucial data gap: the lack of a dedicated Wireless Sensor Network (WSN) to monitor harmful gas (CO_2)z emissions and their intricate link to temperature fluctuations across diverse urban environments. This absence of comprehensive data impedes our ability to accurately track progress towards ambitious environmental targets and formulate informed policies for critical issues like CO_2 reduction and urban heat island mitigation.

PROBLEM STATEMENT

The lack of comprehensive environmental monitoring poses a significant challenge within Singapore. Currently, there is a dearth of real-time data on CO_2 levels and temperature, hindering informed decision-making and sustainable practices in the country. This data gap inhibits the establishment of correlations between environmental factors and their impact on campus well-being and sustainability. Consequently, there is a critical need to develop and deploy a scalable and energy-efficient mesh network utilizing efficient communication protocols to address this challenge.

A. Objectives

By providing real-time environmental data, this project aims to enable:

- Identification of correlations between CO_2 levels, temperature, and campus environmental conditions.
- Evaluation of the performance and suitability of LoRa and ESP-Now protocols in comparison to

traditional mesh algorithms, addressing concerns regarding data latency, reliability, network scalability, and reach.

- Provision of actionable insights to policymakers and stakeholders, facilitating evidence-based strategies for enhancing environmental sustainability within NYP Campus and contributing to broader sustainability initiatives in Singapore.

Through the resolution of this pressing problem, the project endeavors to pave the way for data-driven decision-making and sustainable management practices within NYP Campus, aligning with Singapore's commitment to environmental stewardship.

Literature Review

B. Routing Protocol for Low Power Lossy Networks (RPL)

Designing a robust and efficient mesh network for real-time environmental monitoring using Wireless Sensor Networks (WSNs) faces challenges due to resource constraints. RPL emerges as a promising solution [1]–[3], offering dynamic routing, energy efficiency [4], and scalability. D-RPL enhances multihop routing [5]. Security concerns [6]–[8] and protocol complexity [5] require attention. Optimizing RPL's features can facilitate timely data collection in dynamic environments, contributing to successful monitoring applications.

C. Ad hoc On-Demand Distance Vector routing protocol (AODV)

Various solutions, such as integrating Long-Range (LoRa) networks with mesh architecture [9], [10], have emerged to address the data gap in environmental monitoring. This approach enhances LoRa networks by enabling the creation of mesh structures for routing data packets through multiple intermediate nodes [11]. Among routing algorithms for mesh LoRa networks, the Ad-hoc On-demand Distance Vector (AODV) protocol emerges as promising [12]. AODV's on-demand mechanism optimizes bandwidth by establishing routes when needed, minimizing resource wastage, and its adaptive nature ensures robustness and reliability [13]. However, AODV's overhead and potential congestion are challenges [14]. Nonetheless, it shows potential for monitoring CO2 emissions and temperature fluctuations in urban areas [9], [10].

D. Hybrid Wireless Mesh Protocol (HWMP)

In the quest to enhance environmental monitoring within Singapore, the exploration of the Hybrid Wireless Mesh Protocol (HWMP) stands out for its critical relevance [15]. HWMP, celebrated for its flexibility [16], ability to scale [17], and adherence to international standards, promises easy integration with a wide array of sensor technologies. This exploration, while insightful, indicates that the protocol's potential has not been fully leveraged, particularly in comparison to other networking alternatives that might offer greater operational efficiency and minimized system overhead [18]. Recognizing the gaps in this review is essential for the development of a robust, scalable, and energy-efficient network architecture. Such a network is indispensable for Singapore, aiming to meticulously track environmental parameters and support the nation's ambitious sustainability objectives. By broadening the analysis to include a variety of protocols, we can identify optimal solutions that enhance environmental monitoring capabilities, facilitating more informed and effective policy decisions for the environmental stewardship of Singapore and beyond.

E. Dynamic Source Routing (DSR)

The Dynamic Source Routing (DSR) protocol is a reactive algorithm for projects not requiring real-time data, as it minimises unnecessary transmissions at the cost of initial latency, beneficial for environmental data analysis [19]. While the scalability issues in large networks due to route discovery flooding which may potentially increases the workload and energy consumption of the nodes[19] can be challenging, the adaptability to netowrk changes and energy efficiency of DSR protocol are remarkable, with the ability to quickly find new routes and conserve energy through dormant nodes as well as route caching [20], [21]. This caching also enhances network reliability, allowing quick switches to alternative paths if one route fails, ensuring consistent data collection [21].

F. Optimised Link State Routing (OLSR)

In networks using OLSR, nodes select one-hop reachable neighbors to form Multi-Point Relay (MPR) sets, optimizing packet transmission. OLSR's scalability benefits island-wide CO2 monitoring deployments by efficiently managing routing tables and reliably forwarding packets[22] [23] [24]. Proactive routing minimizes throughput, reducing energy consumption for non-forwarding nodes[25]. OLSR adapts to node failure, ensuring message forwarding reliability, ideal for large urban deployments like Singapore. However, continuous routing table updates increase power consumption, requiring efficient energy management[26]. While lacking inherent security, encryption and access control mitigate unauthorized access risks. Overall, OLSR offers scalability, reliability, and low latency.

G. Summary

In Wireless Sensor Networks (WSNs) tailored for environmental monitoring, the selection of the Dynamic Source Routing (DSR) protocol as the primary routing method for both ESP-NOW and LoRa technologies will significantly boost the network's adaptability and operational efficiency [27]. The choice of DSR, out of the five algorithms considered, stands as the optimal choice for our project due to its flexible and on-demand routing capabilities, which are particularly beneficial in addressing the dynamic conditions typical of environmental monitoring scenarios [19]. Leveraging DSR for our network's routing strategy enhances resource efficiency and ensures reliable data transfer across both short-range (ESP-NOW) and long-range (LoRa) communications. This approach not only streamlines the network setup by consolidating the routing protocol across different communication technologies but also achieves superior scalability, dependability, and minimal latency. These attributes are vital for the effective functioning of large-scale environmental monitoring systems, making DSR the most fitting routing protocol for our project's specific needs.

Design

H. Architecture

././Figures/architecture.png

Fig. 1. Proposed System Architecture

Our system architecture aims to streamline data collection and analysis from a Wireless Sensor Network (WSN) Mesh, comprising two main components: the WSN Mesh itself and the data collection sink. Sensor nodes equipped with the Liligo T3S3 Lora 2.4Ghz module form the WSN Mesh, communicating via ESP-Now and LoRa Protocols for efficient node discovery and routing. The root node establishes a MQTT connection with the broker via a Raspberry Pi 4b, responsible for aggregating data from the WSN Mesh and forwarding it to the Elasticsearch, Logstash, and Kibana Stack (ELK Stack) for visualization and analysis.

I. Prototyping

For prototyping, our strategy involves deploying sensor nodes equipped with the Liligo T3S3 Lora 2.4Ghz module. These nodes will utilize ESP-Now and LoRa Protocols for seamless communication. One node will be connected to the SCD41 Sensor, while others will generate synthetic data. The root node will establish a connection to the sink via MQTT, ensuring smooth data collection, analysis, and visualization. As an enhancement, we aim to implement protocol switching to adapt to fluctuating network conditions.

We intend to develop a modified algorithm (**DSR**) for each protocol. Each protocol mesh will include a common master node, configured with Message Queueing Technology (MQTT). This master node will interface with the backbone ELK Stack through Mosquitto MQTT Broker and filebeat with Elasticsearch for data aggregation. Kibana will be used for visualization.

1) ESP-Now Prototype: In crafting a sophisticated network for environmental monitoring, our collective effort harnessed the combined strengths of the ESP-NOW protocol and the Dynamic Source Routing (DSR) algorithm. This integrated approach was strategically chosen to navigate the intricate challenges associated with collecting and analyzing environmental data in real time. Engineered to deliver exceptional efficiency, flexibility, and scalability, the network stands poised to fulfill the stringent demands of a wide array of environmental monitoring projects.

The initial phase involved setting up ESP32 modules to operate with ESP-NOW, a protocol distinguished by its minimal power usage and effective direct communication features. This choice was motivated by the need for a system capable of operating in energy-constrained environments while maintaining reliable data transmission over short distances. The integration of environmental sensors, such as those for measuring temperature, humidity, and air quality, was a critical step in enabling the network to collect a wide range of data, vital for comprehensive environmental analysis.

To enhance the network's adaptability and efficiency in data routing, we will develop a custom implementation of the Dynamic Source Routing (DSR) algorithm across the devices. DSR's flexible, on-demand routing mechanism will allow the network to dynamically adjust to changes and maintain data flow when required, even in the face of node failures or alterations in network topology. This will ensure uninterrupted collection and transmission of environmental data, a key requirement for real-time monitoring applications.

In our planned setup using ESP-NOW, each peer node will regularly collect data from its SCD41 sensor. It will then consult its peer list, which will serve as a routing table, containing only the MAC addresses of the root node and those peer nodes that are either directly linked to the root node or have knowledge of the route to it. The node will then send the data from the SCD41 sensor to an appropriate node available in its peer list.

Should the peer list be empty, indicating there are no known routes, the node will initiate a route discovery process by sending out a broadcast request to surrounding nodes. When a node receives such a request, it will respond if it knows the way to the root node. The node that made the request will update its peer list with this new route information from any responder. This route discovery will continue until all neighbouring nodes have been discovered. We will also implement a hop count list to refine routing efficiency, allowing the peer node to choose the route with the shortest path to the root node to ensure the most efficient data transmission within our routing framework.

Another pivotal component of our system will be the central ESP32 module, designated as the master node. This module will serve a dual purpose: it will act as a receiver for data collected via ESP-NOW from the sensor-equipped nodes and as a transmitter, forwarding this data to a cloud service or server via WiFi using the MQTT protocol. This dual functionality will enable seamless integration of the sensor network with internet-based data processing and analysis tools, extending the capabilities of our monitoring system beyond local data collection.

2) LoRa Prototype: In our planned deployment of a LoRa mesh network, distinct from our ESP-NOW prototype, we aim to construct a network architecture that features a central node equipped with internet capabilities and several leaf nodes to establish the mesh. Every node within this architecture will be assigned a distinct identifier, possibly through methods like UUID, to assure uniqueness throughout the network. The central node will facilitate network coordination and internet-based data transmission, while the leaf nodes will focus on tasks such as sensing and data gathering.

Upon starting up the master nodes and leaf nodes for setup, the master node will start listening for a ”route discovery message” (RDM). This RDM will be structured to contain a message type, the node's level (indicates number of hops from master node) and the node's MAC address as a unique identifier. The leaf nodes broacast its RDM to its neighbouring nodes. When a node receives a RDM, it saves the nodes with the lowest level in the node.

After saving the the Address and level of the peer node RDM a leaf node has received, the node raises its node level by one, indicating that it is one level higher further from the master node from a known route to the master node. The node then broadcast its RDM to its surrounding nodes. Nodes will ignore messages with a level higher than iteself. This process will continue until the timer ends and all niehgbouring peer routes have been stored in each node's ”routing table” (RT), lining up multiple potential routes.

For data transmission, the leaf node will pick the first route saved in its routing table and now send the message packet to that neighbouring peer. The message sent will be successful if it receives a ”data reply message” (DRM) and the message passing continue down each level until the master node. The node will try resending the DM via a different route from its RT, making use of various RDRMs to find another viable path.

In our LoRa32 DSR mesh network, the master node acts as the central hub, collecting data from leaf nodes distributed throughout the network. It then efficiently transmits this data to our server for visualization and analysis. This pivotal role enables real-time monitoring and informed decision-making based on the insights gained from the data collected by our LoRa mesh network.

To optimise our LoRa mesh to better suit our project needs, we propose several strategies aimed at enhancing energy efficiency, reliability, and fault tolerance. By developing tailored routing algorithms and leveraging multi-path routing techniques, we aim to achieve these objectives while maintaining the scalability and adaptability inherent in LoRa networks.

Energy-Effecient routing can be achieved by saving and prioritising the use of shorter hops to the master node only swapping to other routes in the case of neighbouring node failure. By selecting paths with smaller hop counts, we can reduce transmission power and decrease energy consumption during data forwarding.

Multi-path routing ensures reliability and fault tolerance in our LoRa mesh network. to achieve this, multiple routes can be stored in the routing table aside from the shortest route hop discovered during route discovery phase.

3) Elasticsearch and Kibana Integration: In the proposed network architecture, each protocol node will include a central master node equipped with a Liligo MCU connected to a Raspberry Pi 4 via a USB connection. A script running on the Raspberry Pi will facilitate the transmission of serial data to the server using MQTT (Message Queueing Telemetry Transport), ensuring smooth integration with the ELK Stack infrastructure. The combination of Mosquitto MQTT Broker and Filebeat will enable efficient data aggregation and storage management, while Kibana will serve as the user-friendly visualization interface.

Data forwarding will be handled by a separate thread/core of the ESP32 MCU. Data received from the LoRa/ESP-Now protocols will be serialized into JSON format and sent to a designated topic on the MQTT Broker through the Raspberry Pi.

The deployment of the ELK Stack and MQTT will be orchestrated using Docker Compose, chosen for its ease of setup and deployment. Filebeat will function as an MQTT Client, subscribing to a predefined topic to capture data packets transmitted from the master node. It will then convert this data into JSON format and forward it to Elasticsearch for storage and indexing. Kibana will subsequently retrieve the data from the database and present it on the dashboard for visualization. Networking will be done as part of the Docker Compose environment.

In an ideal scenario, the master node will oversee a limited number of interconnected devices (of around 10-15 nodes) arranged in a tree or mesh structure. It will aggregate, organize, and transmit the received data to the MQTT Broker, where Filebeat will process it. As a proof of concept, the mesh Wireless Sensor Network (WSN) will consist of a small number of nodes and one master, with data streams flowing from the master to the Mosquitto Broker for collection.

J. Testing

In our upcoming system evaluation, we will start with unit testing on sensor nodes to confirm their communication and data generation capabilities by testing protocols between nodes. This will be followed by integration testing to assess the Wireless Sensor Network (WSN) Mesh's interoperability and its ELK stack integration, confirming efficient data transmission to the sink node. To further assess the system's adaptability and endurance, we will undertake stress testing under conditions of intense load. The outcomes of these tests are expected to demonstrate successful intra-mesh communication, reliable data conveyance to the sink, and overall system integrity, confirming our system's readiness for deployment.

Building on this foundation, our forthcoming evaluations will concentrate on meticulously analyzing the system's throughput and power consumption across both peak and normal operational phases. For measuring throughput, we will conduct a series of structured tests, using the number of packets received or transmitted over a set duration, to evaluate the data transmission capabilities of the WSN Mesh protocols across different scenarios, from optimal to high-traffic conditions. This entails systematically increasing the data load to gauge the system's capacity and pinpoint any potential bottlenecks.

Simultaneously, our approach to assessing power consumption involves real-time monitoring of the sensor nodes' energy usage across different operational states. Utilizing the S1 Energy Socket, we aim to capture and compare the power demands during idle, normal, and peak activity periods. This detailed power usage profiling over time is designed to shed light on the system's energy efficiency and spotlight areas for potential optimization.

This integrated testing framework, leveraging both simulation tools and real-world environments, is devised to offer a holistic evaluation of the system's performance and operational efficiency. By rigorously verifying that the system meets our defined benchmarks for throughput capacity and energy consumption, we ensure its suitability for widespread deployment across varied contexts, underscoring our commitment to delivering a robust and efficient solution.

IMPLEMENTATION:

K. ESP-Now Mesh

L. LORA Mesh

M. Master Node Infrastructure

The Master Node Infrastructure encompasses a suite of pivotal components meticulously designed to harmoniously facilitate the monitoring and management of IoT devices. Charged with duties spanning data aggregation, processing, and user interface provisioning, the Master Node assumes a central role in orchestrating system functionalities. Core elements of this infrastructure comprise the Liligo Gateway, a Raspberry Pi MQTT Client and Broker, and the ELK Stack. Furthermore, our implementation integrates a router to establish an artificial cloud-based server for the ELK Stack.

1) Protocol Master: Serving as the protocol master within the Master Node setup, the Liligo Module shoulders the vital responsibilities of traffic monitoring, serialization, and MQTT-based transmission to the ELK stack. In collaboration with a Raspberry Pi configured as both MQTT Client and Broker, the Liligo Module establishes a USB connection for seamless data transfer to the Raspberry Pi. Subsequently, the Raspberry Pi orchestrates the dissemination of serialized data to the ELK stack via MQTT.

Configured to monitor Lora and ESP-Now Protocol packets, the Liligo Module acts as the primary data acquisition unit. Upon reception, data undergoes serialization and is then forwarded to the MQTT Broker by the Raspberry Pi 4b, facilitating streamlined integration with the ELK stack for subsequent processing.

./Figures/elk/elk_dashboard.png

Fig. 2. ELK Dashboard

2) ELK Stack: The deployment of the ELK Stack is streamlined through the utilization of Docker and Docker Compose, enabling efficient deployment with minimal configuration overhead. Comprising Elasticsearch, Logstash, and Kibana, the ELK Stack offers a robust framework for data storage, processing, and visualization. Elasticsearch, a distributed, RESTful search and analytics engine, serves as the cornerstone for storing extensive datasets. Logstash functions as a versatile data processing pipeline, ingesting data from diverse sources, transforming it, and then forwarding it to a designated "stash" such as Elasticsearch. Kibana, a powerful data visualization dashboard, empowers users to interact with and explore data stored in Elasticsearch.

Raw data emanating from the Liligo Module is routed to the Raspberry Pi before being relayed to the ELK stack for processing. Following processing, data is stored within Elasticsearch. Kibana is subsequently employed to create visualization dashboards, offering insights into various metrics such as packet transmission, environmental parameters, device connectivity, and protocol distribution.

These visualizations furnish valuable insights facilitating the monitoring of the Wireless Sensor Network (WSN), enabling performance evaluation of protocol switching. This analysis, outlined in Section -M3, encompasses metrics including packet transmission, environmental data, device connectivity, protocol distribution, and power consumption analysis.

3) Switching: A pivotal feature ingrained within all slave nodes is the capability to seamlessly transition between the LORA and ESP-Now protocols in response to evolving network dynamics. This feature assumes paramount significance in the comprehensive evaluation of each protocol's efficacy across diverse network conditions. The switching mechanism, autonomously activated by individual slave nodes, predicates its decision on the observed packet failure rate. Upon discerning a notable uptick in packet failures, the slave node instigates a judicious transition to the alternative protocol. Such a mechanism stands as a linchpin in preserving network robustness and fostering optimal performance amidst fluctuating network exigencies.

An inherent advantage of this mechanism lies in its facilitation of comparative performance assessments between the two protocols amidst varying network topologies and conditions. By juxtaposing their respective performance metrics, stakeholders can glean invaluable insights into the aptness of each protocol for specific application scenarios contingent upon the prevailing network milieu. Moreover, the dynamic switching functionality serves as a potent tool for pinpointing the protocol best suited to a given network configuration, thereby engendering heightened network efficiency and reliability.

ANALYSIS

4) Bandwidth Comparison: Figure 3 delineates the distribution of transmitted packets across the Lora and ESP-Now protocols. The graph portrays Lora Packets denoted in blue and ESP-Now Packets in green. Evidently, the ESP-Now protocol emerges as the predominant choice, exhibiting a higher packet count vis-à-vis the Lora protocol.

./◦/Figures/elk/protocol_count.png

Fig. 3. Protocol Distribution

The discernible instances of protocol switching, notably observed around the timestamps 10:46 and 10:54, underscore the dynamic nature of the implemented ESP-Now Mesh and LORA Mesh. During these transitions, a shift from Lora to ESP-Now and vice versa is perceptible, as delineated by the transitions between the blue and green segments in the graph.

An intriguing observation pertains to the periodic dips in bandwidth, indicative of intervals where the network experiences a diminished packet reception rate. Plausible factors contributing to this phenomenon encompass variances in protocol efficiency or disparities in mesh implementation. Despite both protocols being instantiated with the DSR mesh algorithm, the Lora protocol potentially suffers from a lower packet reception rate owing to its inherent characteristics, including a lower data rate and extended transmission range.

5) Power Analysis:

CONCLUSION

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