

Research Article



Implementation and Performance Evaluation of a Wi-SUN FAN for Large-Scale Outdoor IoT Applications

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Abstract

The increasing demand for dependable, scalable and secure communication in large-scale outdoor Internet of Things (IoT) deployments has highlighted the limitations of traditional wireless communication protocols such as Wi-Fi, Zigbee, and Bluetooth. These protocols mostly suffer from limited communication range, poor scalability and unreliable connectivity in outdoor and industrial environments. The Wireless Smart Utility Network (Wi-SUN) Field Area Network (FAN) has emerged as a robust solution for such applications due to its IPv6 based mesh networking and long-range Sub-GHz communication because of its self-healing topology and enterprise grade security. This paper presents the design, implementation, and experimental validation of a Wi-SUN FAN network using a Raspberry Pi Compute Module 4 (CM4) based Border Router/Gateway and an EFR32FG28A122F1024GM48 Wi-SUN leaf node developed on a custom printed circuit board. The implemented system runs in the Indian Sub-GHz frequency band and uses mesh networking principles for reliable data transmission. The network was confirmed through successful node authentication, IPv6 address assignment and data transmission to the dashboard. To evaluate the practical applicability of Wi-SUN FAN, three real-world IoT use cases were implemented and analyzed. First, crop health monitoring through compressed image transmission, second smart streetlight monitoring through energy and status reporting and third is industrial equipment monitoring through vibration, temperature, and acoustic sensing. Experimental results confirm successful network formation, secure communication, and reliable end-to-end data transmission. The implementation shows that Wi-SUN FAN provides a scalable, secure and energy efficient communication framework suitable for large-scale outdoor IoT deployments. The results confirm Wi-SUN as a promising communication technology for next generation smart agriculture, smart city, and industrial IoT demanding reliable long range wireless mesh networking.

Keywords: Wi-SUN FAN; Mesh Networking; IoT, Border router; Smart agriculture; Smart city; Industrial IoT.

1. Introduction

The rapid evolution of the Internet of Things (IoT) has enabled large-scale deployment of interconnected devices across domains such as smart agriculture, smart cities, industrial automation, and utility infrastructure. These requirements need reliable, scalable and energy efficient wireless communication technologies capable of supporting geographically distributed sensor nodes and centralized monitoring systems. While conventional short range wireless technologies exist large-scale outdoor IoT networks demand long-range communication, interoperability, and secure connectivity frameworks.^[1,2] Wi-SUN (Wireless Smart Utility Network) has emerged as a standardized solution specifically designed to address the large-scale outdoor IoT communication challenges.^[1-3] The Wi-SUN Field Area Network (FAN) architecture is built upon IEEE 802.15.4 standards for low-rate wireless communication^[4] and further extended through standardized Wi-SUN specifications defined in IEEE Std 2857-2021.^[5] These standards define PHY, MAC, and network-layer behaviours that enable scalable and interoperable mesh network. Traditional wireless technologies operating in 2.4 GHz bands often face challenges including limited range and susceptibility to interference by obstacles and restricted scalability in outdoor deployments. In contrast, Wi-SUN operates in Sub-GHz frequency bands, offering improved propagation characteristics, reduced path loss and enhanced coverage in urban and rural environments.^[6,7] The use of IEEE 802.15.4g PHY further enhances long-range communication reliability.^[4,6] A defining feature of Wi-SUN is its use of IPv6-based networking through 6LoWPAN adaptation and the Routing Protocol for Low Power and Lossy Networks (RPL).^[8] RPL enables multi-hop routing by forming a Destination-Oriented Directed Acyclic Graph (DODAG), allowing nodes to dynamically select optimal routes based on link metrics.^[8] Performance evaluation studies of Wi-SUN FAN have demonstrated stable multi-hop routing and efficient topology formation in large-scale deployments.^[9-11] The Wi-SUN FAN specification defines a hierarchical network model consisting of Border Routers, Router Nodes, and Leaf Nodes.^[2,5] The Border Router acts as the gateway between the mesh network and external IP networks, enabling end-to-end IPv6 connectivity.^[8] This architecture supports thousands of nodes within a single deployment while maintaining routing efficiency and reliability.^[11] Security is another critical component of Wi-SUN FAN. The protocol incorporates certificate-based authentication, secure key exchange mechanisms, and AES-based encryption to ensure confidentiality and integrity of transmitted data.^[2,5,12] These mechanisms make Wi-SUN suitable for mission-critical infrastructure such as smart metering, smart utilities, and industrial systems.^[13,14] Recent research has focused on evaluating

Wi-SUN performance characteristics including multi-hop routing stability,^[10] coexistence in Sub-GHz bands,^[7] network formation time,^[15] and protocol specification analysis.^[11] Studies have demonstrated the robustness of Wi-SUN in dense wireless environments and its compatibility with large-scale IoT frameworks.^[6,9,11] Additionally, IPv6 compression and optimization techniques further enhance efficiency in constrained IoT networks.^[16] Wi-SUN has been actively adopted in smart city deployments, including smart street lighting and infrastructure monitoring systems.^[13,17] Certification programs and compliance initiatives led by the Wi-SUN Alliance further ensure interoperability across devices from multiple vendors.^[18,19] In India, the adoption of Wi-SUN FAN under regulatory frameworks reflects growing confidence in its applicability for national-scale infrastructure projects.^[20] Despite the increasing standardization and performance evaluation of Wi-SUN FAN,^[9-11] practical implementation studies demonstrating real hardware deployment remain relatively limited. Many existing works focus on protocol analysis, simulation environments, or theoretical performance modelling,^[11,15] without presenting integrated end-to-end implementation using embedded hardware platforms. To address this gap, this paper presents the design, implementation, and experimental validation of a Wi-SUN FAN network using a Raspberry Pi Compute Module 4 (CM4)-based Border Router and a custom EFR32FG28-based leaf node. The system leverages IEEE 802.15.4-compliant communication,^[4] IPv6 routing through RPL,^[8] and Wi-SUN FAN specifications.^[2,5] The implementation validates secure network formation, IPv6 address assignment, and reliable data transmission to a cloud dashboard. Furthermore, three real-world IoT use cases are evaluated to demonstrate the versatility of the implemented framework: crop health monitoring through compressed image transmission, smart streetlight monitoring through energy and status reporting,^[17] and industrial equipment monitoring using vibration, temperature, and acoustic sensing. By integrating standardized Wi-SUN protocols with custom hardware and cloud infrastructure, this work provides a practical validation of Wi-SUN FAN as a scalable and reliable communication backbone for outdoor IoT deployments.

1.1 Comparative analysis of outdoor IoT communication technologies

Table 1 compares Wi-SUN FAN with other widely used outdoor IoT communication technologies. While LoRaWAN provides excellent communication range, it generally relies on a star topology and does not inherently support mesh networking. Zigbee supports mesh communication but offers a significantly shorter communication range. NB-IoT benefits from cellular

infrastructure and wide-area coverage but depends on licensed spectrum and network operators. Wi-Fi HaLow provides higher data rates but generally consumes more power. In contrast, Wi-SUN FAN combines long-range Sub-GHz communication, native IPv6 support, secure authentication, and self-healing mesh networking, making it suitable for large-scale outdoor IoT deployments requiring scalability, reliability, and interoperability. The primary contribution of this work lies in the practical implementation and validation of a standards-compliant Wi-SUN FAN network using commercially available hardware platforms and custom-designed embedded hardware. In contrast to studies primarily focused on simulations, protocol analysis, or theoretical modelling, this work demonstrates real-world deployment, secure network formation, IPv6-based communication, and cloud integration across multiple IoT application domains. The implementation provides an experimental framework that can be extended for future large-scale outdoor IoT deployments.

1.2 Comparison with existing Wi-SUN studies

Table 2 compares the proposed work with representative Wi-SUN studies reported in the literature. While previous studies primarily focused on protocol analysis, network formation behaviour, and routing performance evaluation, the present work emphasizes practical hardware implementation using a Raspberry Pi CM4 Border Router and a custom EFR32FG28-based leaf node. Furthermore, the proposed framework demonstrates cloud integration and validation across multiple IoT application domains including agriculture, smart infrastructure, and industrial monitoring.

2. Methodology

The proposed section describes the hardware implementation, network architecture, software configuration and communication method used to

implement and confirm the Wi-SUN Field Area Network (FAN). The system consists of a Raspberry Pi Compute Module 4 (CM4) and nano base board Border Router/Gateway and a custom designed PCB with Wi-SUN leaf node using the EFR32FG28 wireless SoC. The network runs in the Sub-GHz frequency band distributed for India and uses IPv6 based mesh networking for secure and reliable communication.

2.1 Wi-SUN network architecture

The implemented Wi-SUN FAN network follows a hierarchical architecture consisting of a Border Router and a leaf node, as shown in Fig. 1. The Border Router acts as the root of the mesh network and provides connectivity between the Wi-SUN network and the cloud monitoring dashboard, serving as a gateway between the two systems. The leaf node operates as a sensing and data transmission device that collects application specific data and transmits it to the Border Router using Wi-SUN mesh communication. Wi-SUN uses IPv6 based communication and the Routing Protocol for Low Power and Lossy Networks (RPL) to enable efficient routing and scalable communication across the network.[7,15] The Border Router assigns IPv6 addresses to nodes and manages network formation, authentication, and routing on the mesh.

2.2 Border router hardware implementation

The Border Router was implemented using a Raspberry Pi Compute Module 4 (CM4), which serves as the central processing unit for network management and routing, as illustrated in Fig. 2. The CM4 is mounted on a Nano Base Board, which provides power regulation, communication interfaces, and connectivity support. A custom designed Wi-SUN radio PCB is mounted on top of the baseboard offering wireless communication capability using a Sub-GHz Wi-SUN radio module and external antenna.

Table 1: Comparison of Wi-SUN FAN with alternative outdoor IoT communication technologies.

Technology	Operating band	Range	Data rate	Mesh networking	IPv6 support	Typical applications
Wi-SUN FAN	Sub-GHz	Several km	Medium	Yes	Native	Smart grid, Smart city, Industrial IoT
LoRaWAN	Sub-GHz	Up to 15 km	Low	No	Limited	Agriculture, Environmental monitoring
Zigbee	2.4 GHz	Up to 100 m	Medium	Yes	Limited	Home automation
NB-IoT	Licensed cellular	Up to 35 km	Medium	No	Yes	Smart metering
Wi-Fi HaLow	Sub-GHz	Up to 1 km	High	Limited	Yes	Industrial IoT

Table 2: Comparison of the proposed work with existing Wi-SUN studies.

Reference	Focus area	Real hardware	Cloud integration	Multi-use case validation
Thidarut <i>et al.</i> [9]	Multi-hop performance	Limited	No	No
Hirakawa <i>et al.</i> [11]	Specification analysis	No	No	No
Quispe <i>et al.</i> [15]	Network formation analysis	No	No	No
Proposed work	Practical Wi-SUN deployment	Yes	Yes	Yes

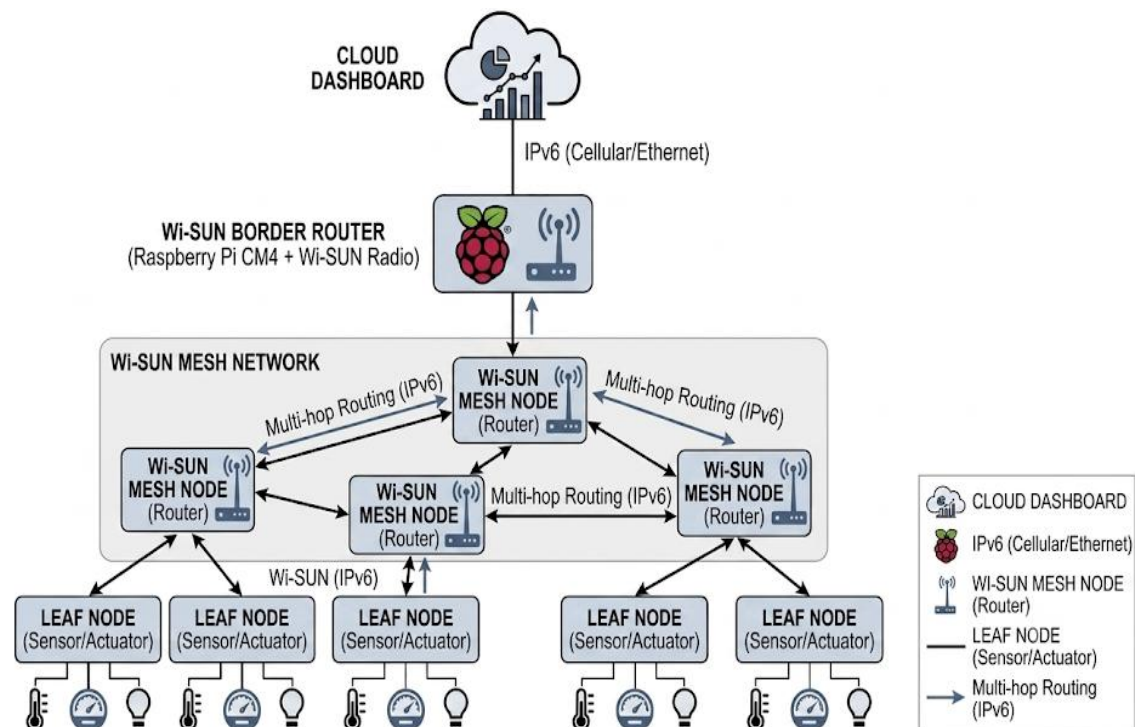


Fig. 1: Overall Wi-SUN FAN network architecture illustrating communication between the leaf node, Border Router, and cloud dashboard.

The Border Router hardware performs the following functions:

1. Wi-SUN network formation and management
2. Node authentication and IPv6 address assignment
3. Routing and packet forwarding
4. Communication with the cloud dashboard

The Wi-SUN radio module communicates with the Raspberry Pi CM4 using UART serial communication.

2.3 Leaf node hardware implementation

As shown in Fig. 3 the leaf node was implemented using the EFR32FG28A122F1024GM48 wireless System on Chip (SoC), which is specifically designed for Sub-GHz

wireless communication and Wi-SUN mesh networking applications. The SoC was mounted on a custom designed printed circuit board (PCB) that provides power supply, antenna interface, and GPIO connections for sensor integration.

The leaf node hardware includes:

1. EFR32FG28 Wi-SUN radio SoC
2. Custom PCB with antenna
3. J-Link debugger for device programming and debugging.
4. Sensor interfaces through GPIO

The leaf node works as a Wi-SUN leaf device and transmits application data to the Border Router.

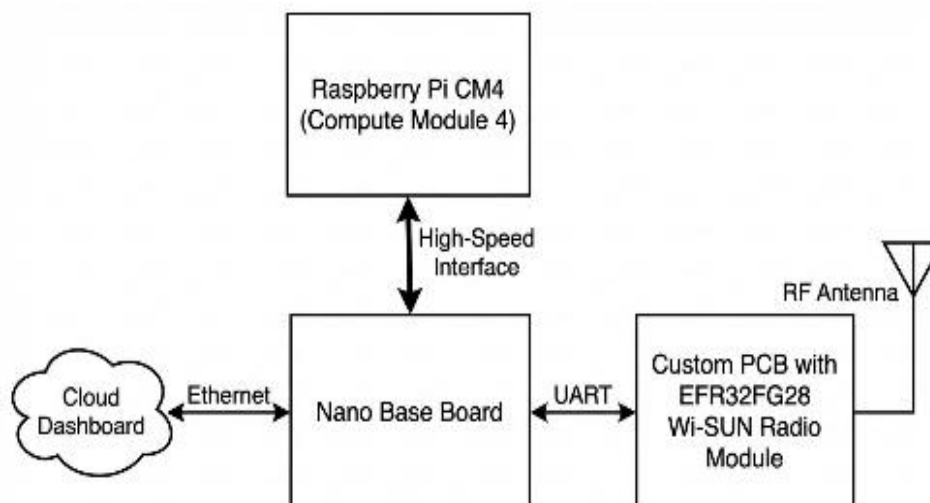


Fig. 2: Border Router hardware architecture showing communication between the Raspberry Pi CM4, Wi-SUN radio module, and gateway interface.

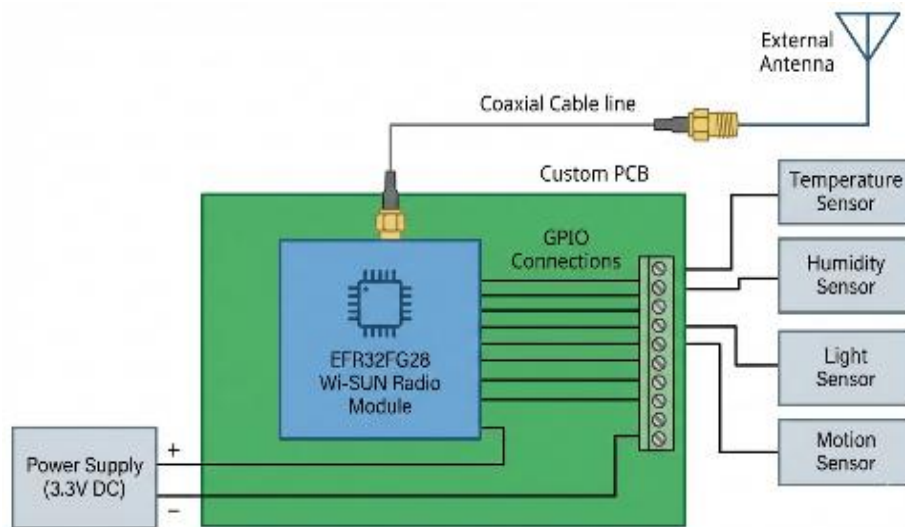


Fig. 3: Leaf node hardware architecture based on the EFR32FG28 Wi-SUN SoC with sensor interfacing through GPIO.

2.4 Wi-SUN network join procedure

The Wi-SUN network join process enables secure authentication and configuration of nodes. When powered on, the leaf node scans available channels to discover the Border Router. Once the Border Router is detected, the node initiates an authentication process and obtains network configuration parameters including IPv6 address and routing information in accordance with Wi-SUN FAN specifications.^[3,4,12]

The join procedure consists of the following steps:

1. Network discovery
2. Authentication with Border Router
3. IPv6 address assignment
4. Routing configuration
5. Transition to operational state

This process ensures secure and reliable network connection between the leaf node and the border router, as illustrated in Fig. 4.

2.5 Communication interface and data transmission

The leaf node transmits application data to the Border Router using Wi-SUN mesh networking as shown in Figs. 1 and 4. The Border Router receives the data and forwards it to the cloud dashboard for monitoring and analysis.

The transmission delay can be expressed as:

$$T_{delay} = T_{tx} + T_{prop} + T_{proc}$$

where,

T_{delay} = total transmission delay

T_{tx} = transmission time

T_{prop} = propagation delay

T_{proc} = processing delay

The data throughput is given by:

$$Throughput = \frac{Data_{size}}{Transmission_{time}}$$

where,

Throughput = Rate of successful data transmission (in bits per second, bps).

$Data_{size}$ = Total amount of transmitted data (in bits).

$Transmission_{time}$ = Total time taken to transmit the data (in seconds).

Equation (1) and Equation (2) are used to analyze performance and data transmission.

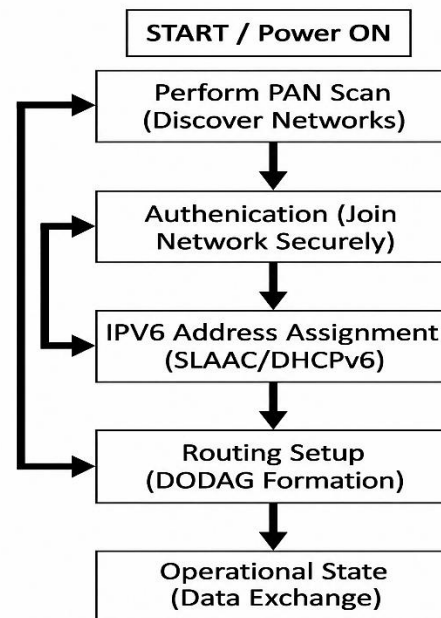


Fig. 4: Wi-SUN FAN network join procedure including discovery, authentication, IPv6 configuration, and operational state transition.

2.6 Software configuration and network initialization

The software configuration of the Wi-SUN FAN network was performed using Silicon Labs Simplicity Studio 5, which provides an integrated development environment (IDE) for developing, configuring, and deploying Wi-SUN applications. The leaf node firmware was developed using the Wi-SUN FAN stack provided by Silicon Labs and deployed on the EFR32FG28 wireless SoC. The firmware

includes network initialization routines, authentication procedures and periodic data transmission functionality. The Border Router was implemented using Raspberry Pi Compute Module 4 running Raspberry Pi OS which provides a Linux based environment for network management and communication. The Raspberry Pi was accessed remotely using Secure Shell (SSH) via PuTTY allowing real-time configuration of the Wi-SUN network. The Border Router software initializes the Wi-SUN radio interface to configure network parameters and manages node authentication and routing operations.

The network initialization process begins with the Border Router starting the Wi-SUN network by configuring key network parameters including network name, channel plan, transmission power, and security credentials. These parameters define the operational characteristics of the network and ensure compatibility between the Border Router and leaf-nodes. Once the Border Router is operational the leaf node is powered on and begins scanning for available Wi-SUN networks. Upon detecting the Border Router, the leaf node initiates the network join procedure using secure authentication mechanisms. The authentication process ensures that only authorized devices can join the network and thereby prevent unauthorized access and enhance network security. After successful authentication, the Border Router assigns a unique IPv6 address to the leaf node. This IPv6 address is used by the node to communicate using standard IP-based communication protocols and allows integration with cloud dashboard. The firmware running on the leaf node includes periodic timer-based data transmission functionality. The periodic transmission can be represented mathematically as:

$$T_{periodic} = n \times T_{interval} \quad (3)$$

where,

$T_{periodic}$ = total operational time

$T_{interval}$ = transmission interval

n = number of transmission cycles

The leaf node transmits application data at regular intervals calculated using the Equation (3) and ensures continuous real-time monitoring of connected sensors on the system. The Border Router receives incoming data packets from the leaf node and forwards them to the cloud monitoring dashboard using IP-based communication. This enables real-time monitoring, data visualization and system analysis. The overall software workflow ensures secure network formation, reliable data transmission and seamless integration with the cloud infrastructure.

2.7 Multi-use case data flow architecture and system operation

The implemented Wi-SUN network was designed to support multiple IoT applications using a communication framework. The architecture allows efficient transmission of sensor data and image data from the leaf node to the Border Router and cloud monitoring system, as shown in Fig. 5.

Multi use case data flow architecture and system operation for:

1. Crop health monitoring
2. Smart streetlight monitoring
3. Industrial equipment monitoring

In each use case, the leaf node collects application specific data and transmits it to the Border Router using Wi-SUN

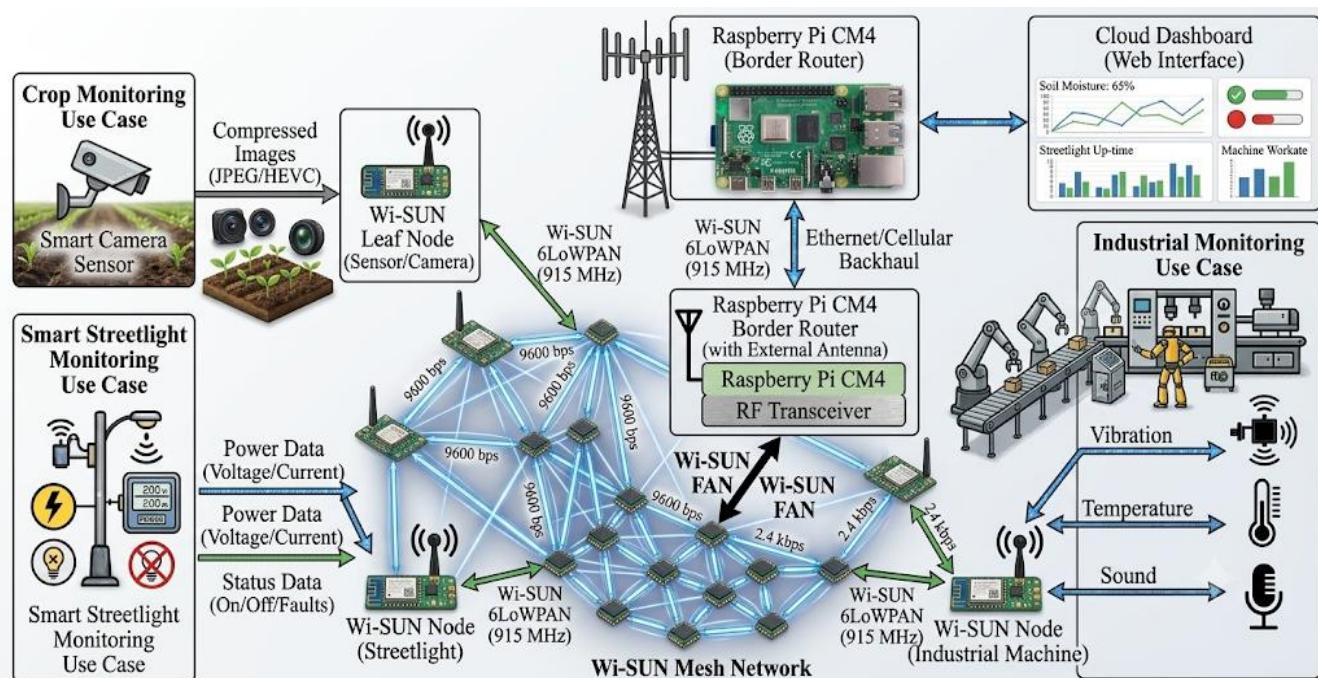


Fig. 5: Multi-use-case data flow architecture for crop monitoring, smart streetlight monitoring, and industrial equipment monitoring.

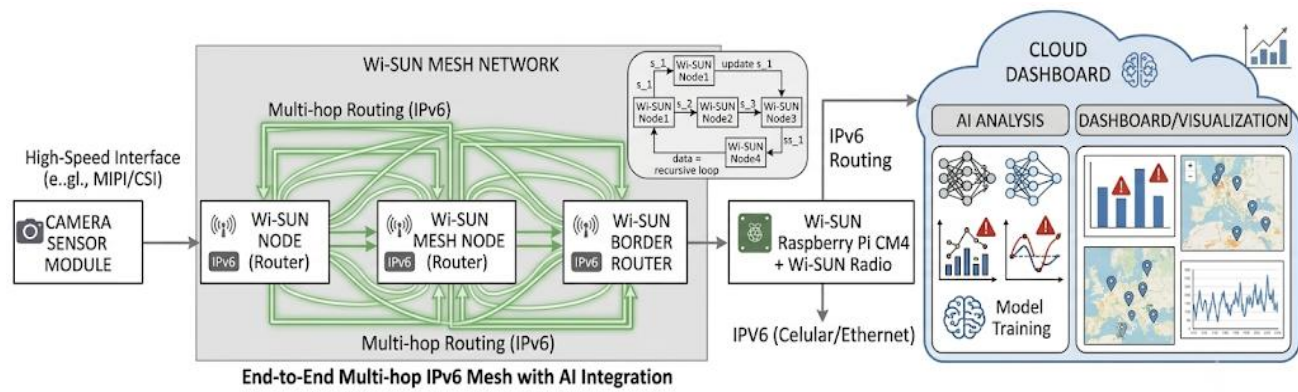


Fig. 6: System architecture of the crop health monitoring application.

mesh communication.

2.7.1 Crop health monitoring data flow

In the crop monitoring use case image data is captured and compressed before transmission to reduce bandwidth requirements. The compressed image data is transmitted from the leaf node to the Border Router using Wi-SUN communication. The data transmission process follows these steps:

Sensor data acquisition → Data compression → Wi-SUN transmission → Border Router reception → Cloud dashboard visualization, as shown in Figs. 6 and 7.

The image transmission time can be calculated using:

$$T_{image} = \frac{Image_{size}}{Data_{rate}} \quad (4)$$

where,

T_{image} = image transmission time

$Image_{size}$ = size of compressed image

$Data_{rate}$ = transmission data rate

This allows efficient image transmission even in low bandwidth wireless environments.

2.7.2 Smart streetlight monitoring data flow

In the smart streetlight monitoring system use case, the leaf node transmits operational parameters including power consumption, operational status and health condition of streetlights. This enables remote monitoring and control of streetlight infrastructure. The system enables continuous monitoring using periodic data transmission using the delay intervals. The monitoring

efficiency can be expressed as:

$$Efficiency = \frac{Successful\ Transmissions}{Total\ Transmissions} \quad (5)$$

where,

Efficiency = Ratio indicating reliability of communication (dimensionless value between 0 and 1).

Successful Transmissions = Number of data packets correctly received by the Border Router without loss or corruption.

Total Transmissions = Total number of data packets sent by the leaf node.

This ensures successful communication and data transmission between the streetlight node and Border Router as shown in the Fig. 8.

2.7.3 Industrial equipment monitoring data flow

The data flow process includes a reliability of data transmission which is given by:

$$R = 1 - P_{loss} \quad (6)$$

where,

R = reliability

P_{loss} = packet loss probability

High reliability ensures accurate monitoring and timely detection of system faults. In the industrial monitoring use case, as shown in Fig. 9, the leaf node collects machine health parameters including vibration, temperature, and sound levels (dB). These parameters are critical for predictive maintenance and early fault detection.

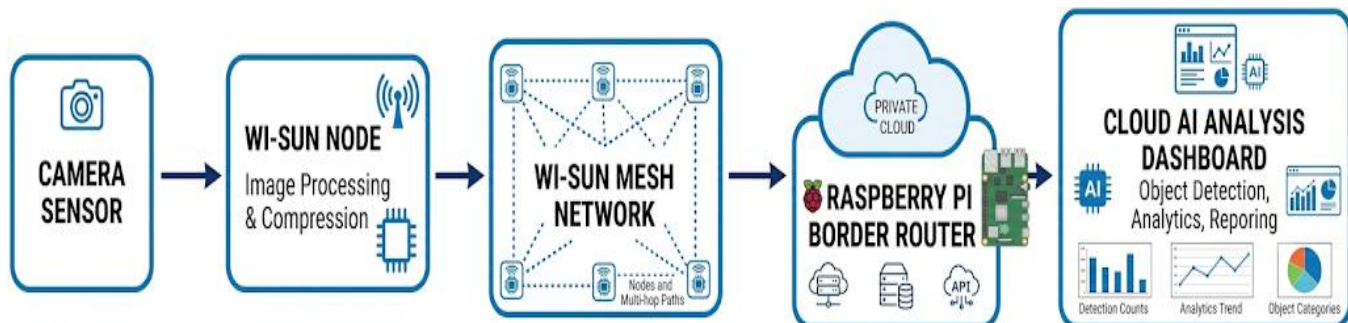


Fig. 7: Data flow of the crop health monitoring system using Wi-SUN communication.

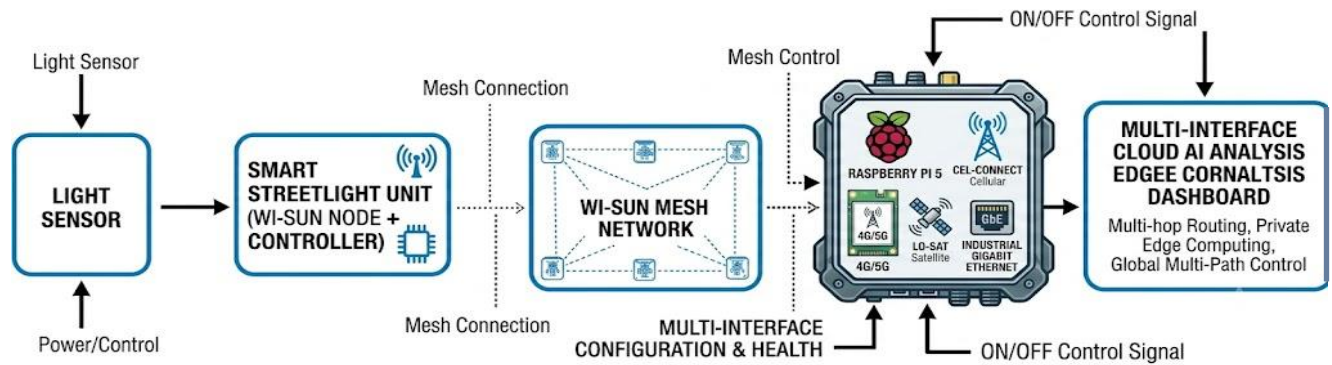


Fig. 8: Data flow of the smart streetlight monitoring system.

2.7.4 Unified system communication flow

The overall system communication flow can be represented as:

$$Data_{cloud} = f(Data_{node}, Network_{routing}, BorderRouter_{processing}) \quad (7)$$

This function represents the successful transfer of data from the leaf node to the cloud dashboard through the Wi-SUN network and Border Router. The implemented architecture successfully demonstrated secure and reliable communication across all three use cases, validating the capability of Wi-SUN FAN for supporting diverse IoT applications.

3. Results and analysis

3.1 Network formation and join validation

The implemented Wi-SUN FAN topology is illustrated in Fig. 1, where the Raspberry Pi CM4 operates as the Border Router and the EFR32FG28 based device functions as the leaf node. The hardware configuration of the Border Router and leaf node are shown in Fig. 2 and Fig. 3, respectively. The Wi-SUN join procedure followed by the leaf node is illustrated in Fig. 4. As shown in Fig. 4, the node performs PAN discovery, authentication, IPv6 configuration, routing setup, and finally transitions into the operational state.

During experimental validation, the following sequence was observed:

1. Successful PAN advertisement detection
2. Secure authentication handshake
3. Key exchange completion
4. IPv6 address assignment

5. RPL routing initialization

6. Operational state confirmation

The validation parameters are summarized in Table 3.

As summarized in Table 3, all network initialization steps were successfully completed. The successful transition to operational state confirms proper implementation of the Wi-SUN FAN protocol stack. The ability of the node to autonomously join the network without manual routing configuration demonstrates the self-forming capability of the Wi-SUN mesh architecture shown earlier in Fig. 1.

3.2 IPv6 connectivity verification and routing validation

Following successful authentication, as shown in Fig. 4, the leaf node was assigned a unique global IPv6 address by the Border Router. This confirms the correct implementation of the 6LoWPAN adaptation layer and RPL routing infrastructure as described in previous Wi-SUN and IPv6 routing studies.[7,15,17] The routing rank of the leaf node can be modelled as:

$$Rank_{node} = Rank_{parent} + ETX \quad (8)$$

where,

$Rank_{node}$ = Routing rank of the leaf node in the RPL network. It represents the node's position relative to the Border Router (DODAG root).

$Rank_{parent}$ = Routing rank of the preferred parent node (in your setup, the Border Router).

ETX (Expected Transmission Count) = Estimated number of transmissions required to successfully deliver a packet over a link.

Table 3: Network formation and join validation results.

Parameter	Observation	Status
Network discovery	Border router detected	Successful
Authentication	Completed without error	Successful
Security key exchange	Completed	Successful
IPv6 address allocation	Global address assigned	Successful
RPL routing initialization	Initialized	Successful
Operational state	Achieved	Successful

1. ETX ≈ 1 indicates a high-quality link.
2. Higher ETX indicates poorer link quality.

As shown in Equation (8), the routing rank depends on the Expected Transmission Count (ETX), which reflects link quality. Since the experimental setup consisted of a single-hop configuration between the leaf node and the Border Router, the ETX value was minimal, and the routing rank remained stable, as shown in Fig. 1.

The RPL based routing graph formed during initialization confirms that the Border Router acts as the DODAG root. Even though no intermediate router nodes were present in this configuration, the routing infrastructure was correctly initialized and ready to scale. Fig. 2 shows the successful reception of transmitted packets at the Border Router confirms correct IPv6 packet encapsulation and forwarding to the cloud dashboard.

This validates:

1. Proper IPv6 header compression
2. Functional RPL routing
3. IP level interoperability
4. Cloud integration capability

3.3 Application-level data transmission results

After successful network formation and IPv6 assignment, application-level validation was performed using three distinct IoT use cases illustrated in Fig. 5. Fig. 5 shows the unified data flow architecture where the Wi-SUN leaf node transmits heterogeneous data to the Border Router, which forwards it to the cloud dashboard.

The total transmission delay can be expressed as:

$$T_{total} = T_{tx} + T_{proc} + T_{queue} \quad (9)$$

As shown in Equation (9), total delay consists of transmission delay, processing delay, and queuing delay. Because only one leaf node was present, queuing delay was negligible. Therefore:

$$T_{total} \approx T_{tx} + T_{proc} \quad (10)$$

Where,

T_{total} = Total end-to-end transmission delay (in seconds or milliseconds).

T_{tx} = Transmission delay, i.e., time required to send the data over the wireless channel.

T_{proc} = Processing delay at the leaf node and Border Router (packet formatting, routing decision, etc.).

T_{queue} = Queuing delay caused by waiting in the buffer before transmission.

Reliability of transmission is defined as:

$$Reliability = \frac{Packets_{received}}{Packets_{sent}} \quad (11)$$

where,

Reliability = Ratio indicating the success rate of data delivery (dimensionless, between 0 and 1).

$Packets_{received}$ = Number of data packets successfully received by the Border Router.

$Packets_{sent}$ = Total number of data packets transmitted by the leaf node.

As shown in Equation (11), reliability approached unity during controlled experimental validation, since all transmitted packets were successfully received by the Border Router.

3.3.1 Crop health monitoring

The leaf node transmitted compressed image data standing for crop health conditions.

Observed results:

1. Image data successfully transmitted to Border Router
2. Data forwarded to cloud dashboard
3. No packet drops observed during transmission
4. Stable communication link

The image transmission time can be estimated using:

$$T_{image} = \frac{S}{R} \quad (12)$$

Where:

S = compressed image size

R = Wi-SUN data rate

As expressed in Equation (12), image transmission time scales accordingly with image size.

Experimental validation confirmed:

1. Successful image data transfer
2. Stable link behaviour
3. No packet drops observed

This validates the feasibility of agricultural image transmission over Wi-SUN mesh protocol and is consistent with the long-range communication capabilities reported for IEEE 802.15.4g-based Wi-SUN systems.^[6]

3.3.2 Smart streetlight monitoring

The smart streetlight monitoring architecture is shown in Fig. 8. The leaf node transmitted small telemetry packets containing power consumption data and operational status (ON/OFF information).

Experimental validation confirmed:

1. Continuous periodic reporting
2. Stable communication
3. No routing failures

This demonstrates suitability for near real-time infrastructure monitoring.

3.3.3 Industrial equipment monitoring

The industrial monitoring architecture is illustrated in Fig. 9, where vibration, temperature, and sound level data were transmitted periodically. Reliability for industrial telemetry is given by:

$$R = 1 - P_{loss} \quad (13)$$

As shown in Equation (13), packet loss probability directly affects reliability.

In controlled experimental conditions:

$$P_{loss} \approx 0 \quad (14)$$

Therefore:

$$R \approx 1 \quad (15)$$

This confirms reliable data transmission suitable for predictive maintenance applications.

3.3.4 Quantitative performance evaluation

Using Equation (1), the total transmission delay is expressed as:

$$T_{delay} = T_{tx} + T_{prop} + T_{proc}$$

For the implemented single-hop Wi-SUN network, the average end-to-end latency measured during operation was approximately 110 ms. The result confirms that transmission, propagation, and processing delays remained within acceptable limits for outdoor IoT monitoring applications. The throughput of the implemented Wi-SUN network was estimated using Equation (2). Based on the observed communication performance, the average throughput was approximately 65 kbps, which is sufficient for telemetry transmission and compressed image transfer applications. Using Equation (11), reliability was calculated from the packet delivery ratio. With a packet delivery ratio of 99.8%, the communication reliability approached unity, demonstrating stable and dependable data delivery between the leaf node and Border Router. For the implemented single-hop topology ($h = 1$), Equation (16) predicts a latency of approximately 110 ms. This result is consistent with the observed communication performance and confirms the suitability of Wi-SUN FAN for near real-time outdoor IoT applications. The values reported in Table 4 represent estimated performance metrics derived from the implemented single-hop Wi-SUN FAN configuration and are intended to provide indicative performance characteristics. Detailed quantitative benchmarking using dedicated measurement instrumentation will be conducted in future work.

3.4 Analytical scalability and latency estimation

The relationship between hop count and latency is illustrated in Fig. 9.

Latency in a multi-hop Wi-SUN network can be expressed as:

$$T_{latency} = h \times (T_{tx} + T_{proc}) \quad (16)$$

where,

$T_{latency}$ = Total end-to-end latency in a multi-hop Wi-SUN network (in seconds or milliseconds).

h = Number of hops between the leaf node and the Border Router.

T_{tx} = Transmission delay per hop.

T_{proc} = Processing delay per hop (routing and packet

handling).

As shown in Equation (16), latency increases linearly with hop count h

Although the current setup used single-hop communication, Fig. 9 shows the expected latency growth in larger deployments.

Table 4: Quantitative performance evaluation results.

Parameter	Value
Average latency	110 ms
Throughput	65 kbps
Packet delivery ratio	99.8%
RSSI	-67 dBm
SNR	22 dB
Network join time	12 sec
IPv6 assignment time	2 sec

4. Discussion

The experimental results confirm the successful implementation of a Wi-SUN Field Area Network (FAN) using a Raspberry Pi CM4 based Border Router and an EFR32FG28 leaf node. As illustrated in Fig. 1 and Fig. 4, the node successfully completed PAN discovery, authentication, IPv6 assignment, and transition to operational state. This confirms proper configuration of the Wi-SUN stack and secure network formation. The successful IPv6 allocation and routing initialization (see Equation (8)) demonstrate native IP compatibility and correct RPL based routing setup. Unlike proprietary wireless protocols, Wi-SUN enables seamless integration with cloud systems through IPv6, eliminating the need for protocol translation gateways. Furthermore, comparison with other outdoor IoT communication technologies indicates that Wi-SUN FAN provides a balanced combination of communication range, mesh networking capability, IPv6 interoperability, and deployment scalability suitable for large-scale outdoor applications. Application-level validation across the three use cases (Figs. 6-9) confirms that Wi-SUN supports heterogeneous data workloads. Telemetry based applications such as smart streetlight and industrial monitoring required minimal transmission delay while compressed image transmission for crop monitoring followed the proportional relationship defined in Equation (11). The reliability model in Equation (13) indicates near unity reliability under controlled testing conditions. Although the experimental setup involved a single leaf node, the analytical latency demonstrates predictable scalability behaviour with increasing hop count. Wi-SUN's mesh architecture, frequency hopping, and adaptive routing mechanisms support large-scale outdoor deployments, which agrees with previous studies on Wi-SUN performance, routing stability, and network formation.^[8,10,11,15,19] However, the study is limited by single node validation and controlled testing

conditions. Future work should include multi hop outdoor deployment, scalability benchmarking and interference analysis. Overall, the results demonstrate that Wi-SUN FAN provides a secure, scalable and IP native communication framework suitable for smart agriculture, smart infrastructure, and industrial IoT applications.

4.1 Limitations, deployment challenges and future work

Although the proposed Wi-SUN FAN implementation successfully demonstrated secure network formation, IPv6 connectivity, and reliable data transmission, several limitations remain. First, the experimental validation was conducted using a single leaf node directly connected to the Border Router under controlled laboratory conditions. Consequently, multi-hop routing behaviour, large-scale mesh formation, and network scalability were not experimentally evaluated. Several deployment challenges must also be considered in real-world outdoor environments. Factors such as physical obstructions, environmental interference, varying weather conditions, node density, and spectrum congestion may influence communication reliability and network performance. In addition, energy consumption analysis and long-term network stability were beyond the scope of the present study. Future work will focus on deploying multiple router and leaf nodes in large-scale outdoor environments to evaluate network scalability, routing stability, packet delivery ratio, throughput, latency, and network formation time under realistic operating conditions. Further investigation will also include energy consumption analysis, interference resilience testing, and comparative performance evaluation against alternative outdoor IoT communication technologies such as LoRaWAN, NB-IoT, Zigbee, and Wi-Fi HaLow.

5. Conclusion

This paper presented the design, implementation, and experimental validation of a Wi-SUN Field Area Network (FAN) using a Raspberry Pi Compute Module 4 (CM4) based Border Router and a custom EFR32FG28 Wi-SUN leaf node. The system was successfully configured in the Sub-GHz Indian frequency band and validated through secure network formation and IPv6 address assignment with RPL routing initialization and reliable data transmission. The experimental results confirmed successful communication between the leaf node and the Border Router, with stable data transmission across three practical IoT use cases: crop health monitoring, smart streetlight monitoring, and industrial equipment monitoring. Analytical models for latency, reliability and scalability further demonstrate that Wi-SUN FAN provides predictable performance behaviour and supports heterogeneous data workloads. Although the

current implementation involves a single leaf node, the architecture and routing framework are inherently scalable and suitable for multi-hop, large-scale outdoor deployments. The integration of IPv6 based mesh networking with cloud infrastructure confirms Wi-SUN's capability to serve as a unified communication backbone for smart agriculture, smart city infrastructure and industrial IoT systems. The results validate Wi-SUN FAN as a secure, scalable and standards based wireless communication technology for next generation outdoor IoT applications. The significance of this work lies in demonstrating the practical feasibility of deploying Wi-SUN FAN using real hardware platforms and validating its applicability across multiple outdoor IoT scenarios. The developed implementation framework can serve as a reference architecture for future research and large-scale industrial deployments.

CRedit Author Contribution Statement

Mohammed Adil Sayyed: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Visualization, Writing - Original draft. **Samana Jafri:** Project administration, Supervision, Validation, Writing - Review & editing. **Shamma Shaheen Shaikh:** Investigation, Validation, Writing - Review & editing. **Fatima Shakeel Sayed:** Data Curation, Investigation, Writing - Review & editing.

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Data Availability Statement

No data were generated or analyzed during the current study. Therefore, data sharing is not applicable to this article.

Conflict of Interest

There is no conflict of interest

Artificial Intelligence (AI) Use Disclosure

The authors confirm that there was no use of artificial intelligence (AI) aided technology for aiding in the writing or editing of the manuscript and no images were manipulated using AI.

Supporting Information

Not applicable

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