PowerMesh

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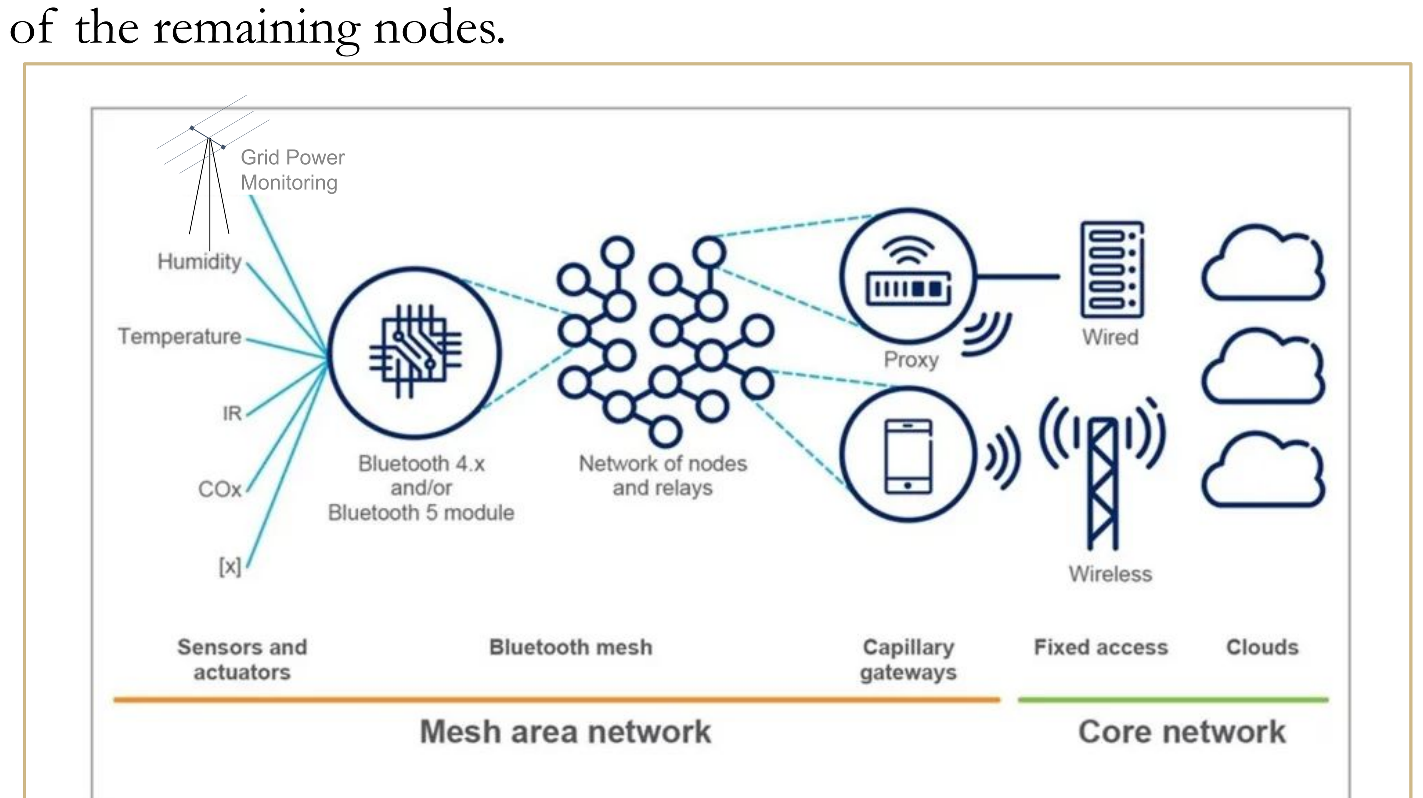
Abstract

This project aims to design and implement a Bluetooth Low Energy (BLE) mesh network capable of demonstrating multiple key features required for modern IoT cyber-physical sensor-based systems. Our implementation showcases essential capabilities including self-healing path rerouting when nodes fail, bidirectional data exchange with a cloud service, and node-to-node communication. This will be demonstrated by modern DC power monitoring and control.

Introduction

Cyber-physical mesh networks are composed of multiple nodes that connect using ad-hoc networking. The communication is characterized by self-healing routing with automatic path discovery, support for multi-hop relay for extended coverage and flexible node roles. A new node can join, and an existing node can leave the networking without impacting the overall communication abilities of the remaining nodes.



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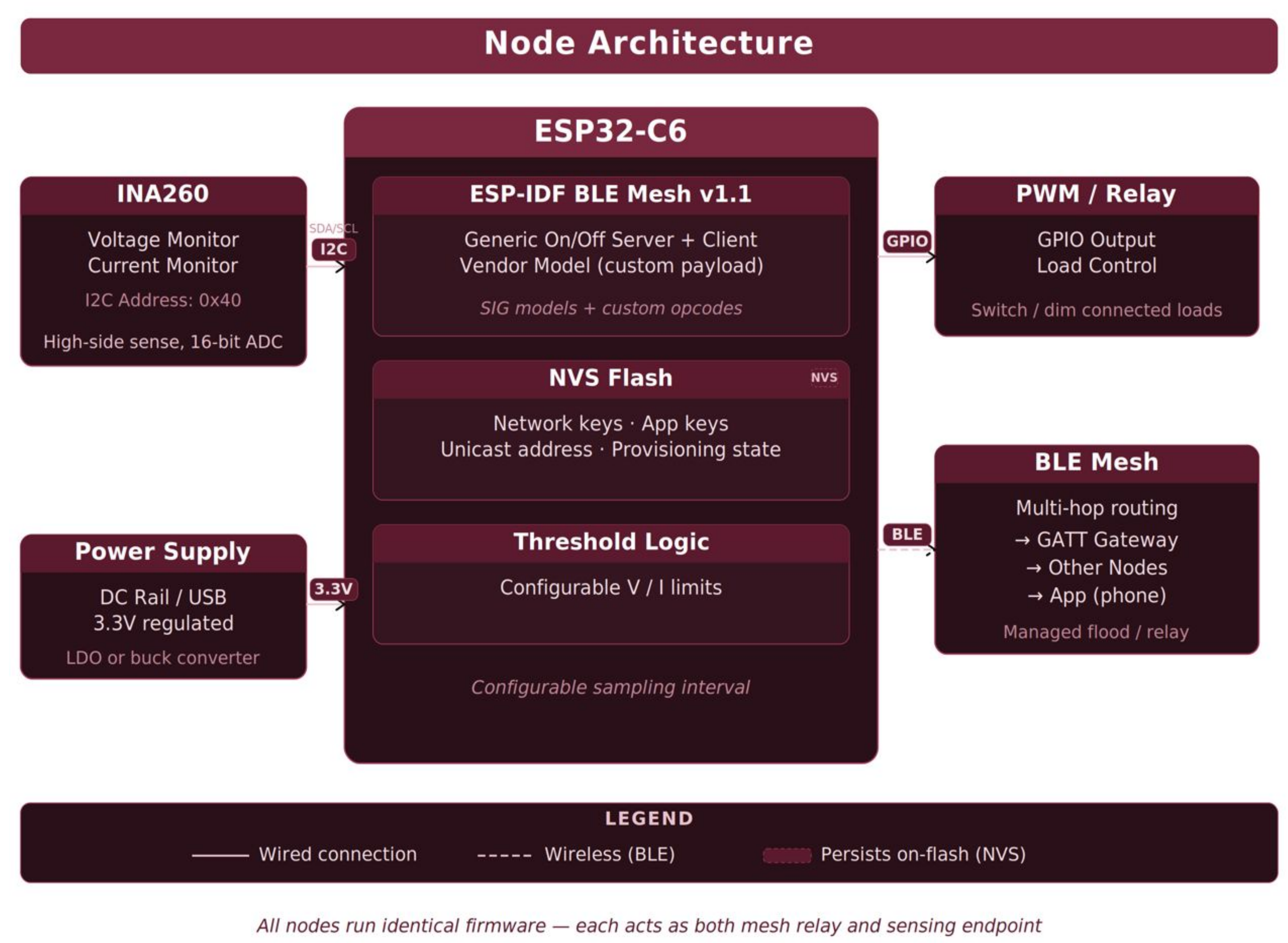
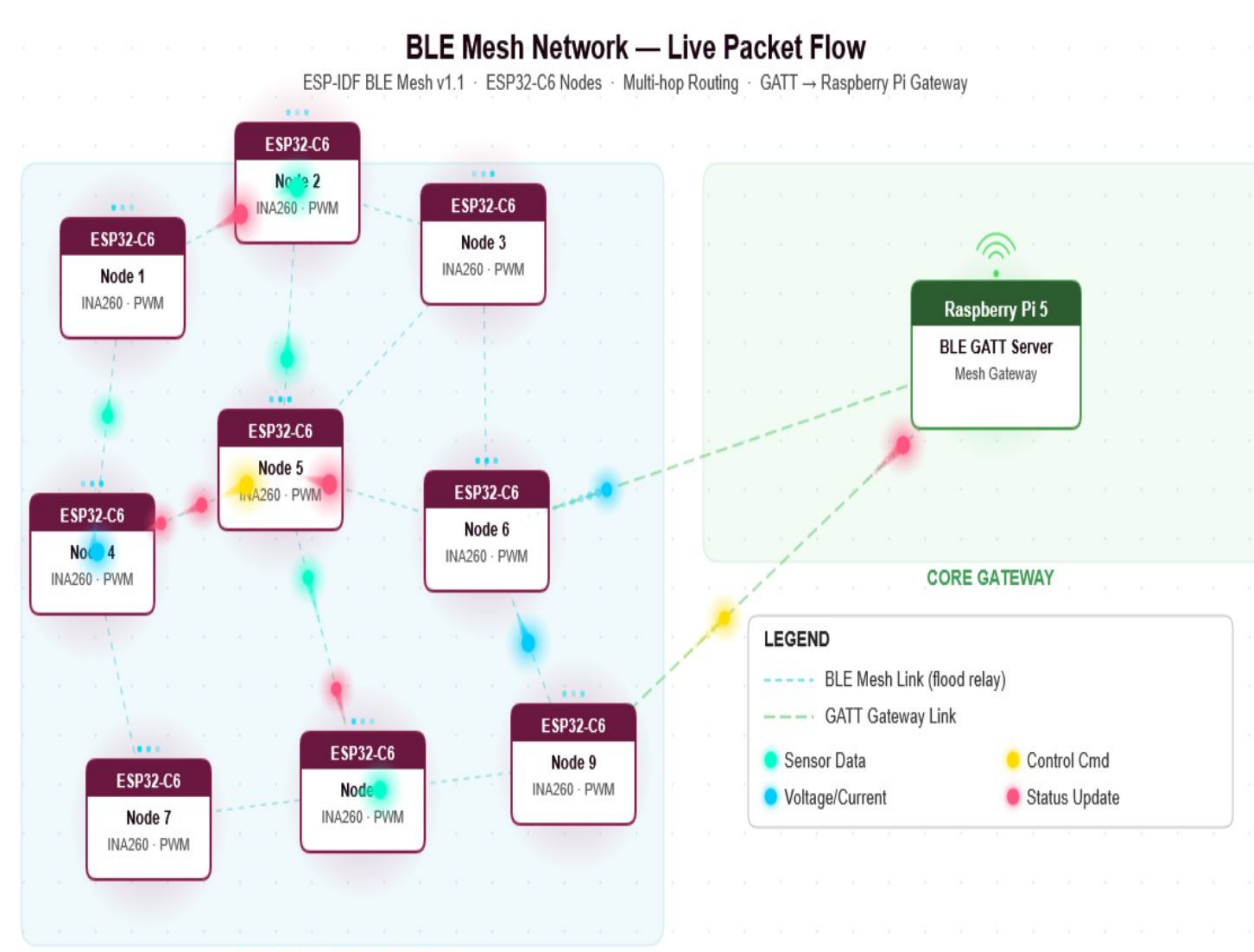
Such networks can be used for various types of cyber-physical systems. Modern power distribution systems require real-time node-level visibility and remote control. We have used it for Power Grid monitoring wherein installed monitoring nodes can join and leave the network without adjustment of configuration and need for further networking. The data from each node can hop through the network until it reaches the gateway. The gateway can also configure any node remotely. We have demonstrated the functionality using a DC grid.

This framework can be used in other applications such as asset tracking, inventory control and supply chain management.

System Architecture



System Topology



Implementation

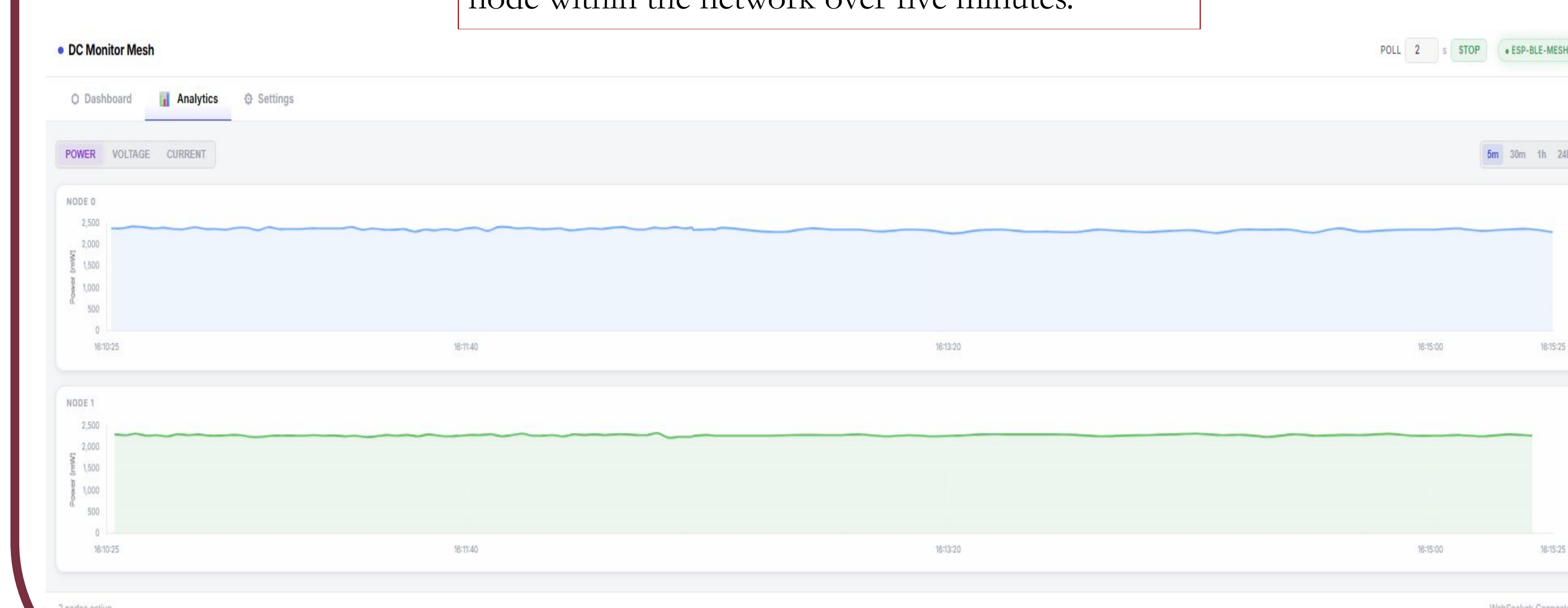
Each node pairs a DC voltage/current sensor (INA260) with a microcontroller (ESP32-C6) through the I^{2}C protocol. Nodes communicate via the ESP-IDF BLE Mesh stack, enabling multi-hop message propagation without relying on centralized routing infrastructure. Sensor data flows through the mesh to a Bluetooth Generic ATTribute Profile (GATT) Gateway node, which connects the mesh to the gateway (Raspberry Pi) over BLE. Configurable voltage and power thresholds allow the gateway to issue closed-loop control commands back through the mesh in real time.

The system successfully demonstrates bidirectional mesh communication, automatic node provisioning, and real-time threshold-based control. Using Non-Volatile Storage (NVS) backed state persistence on each node allows the mesh to fully restore after power loss without requiring the provisioner to be present — a critical feature for unattended deployment in off-grid and renewable energy settings.

Limitations remain in gateway failover — if the GATT Gateway node goes offline, mesh control is interrupted until it reconnects. Future work will implement automatic GATT Gateway promotion from a standby mesh node. Additional planned improvements include a communications watchdog ("dead man's switch") on each sensing node, headless system-based Pi gateway operation, and a web User Interface (UI) for live dashboard monitoring.

Results

Graph of the data collected at a Power Monitoring node within the network over five minutes.



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