An Embedded Context-Aware Gateway for Heterogeneous IoT Mesh Networks

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Introduction: Modern IoT deployments combine devices that speak a growing number of incompatible wireless standards. Bluetooth Low Energy (BLE) Mesh, Thread, and LoRa each target distinct trade-offs between range, power, and topology: short-range flood-routed mesh for lighting and sensing, IP-based mesh with hop-by-hop reliability, and long-range sub-GHz star links that reach kilometers beyond any local network. Most commercial gateways forward packets between networks without evaluating application-level semantics, so prioritization and event handling are typically delegated to cloud backends. As a consequence, even trivial cross-domain reactions, such as raising an alert from a Thread node on a BLE actuator, require a full cloud round-trip. Integrated devices that combine all three standards are rare in the mainstream market, typically realized only as Linux-class edge gateways with optional radio co-processors.

Approach: This work presents a semantic-aware multiprotocol IoT mesh gateway (Fig. 1) with a single Nordic nRF54L15 microcontroller running Zephyr/NCS. BLE Mesh and Thread share the on-chip 2.4 GHz radio under an application-level time-division scheduler, while a Semtech SX1303 LoRa concentrator on the self-designed PCB extends the system into the sub-GHz domain and provides gateway-to-gateway forwarding of semantic events. A uniform transport-adapter interface decouples the three radios from a protocol-agnostic gateway core consisting of an event-ingest pipeline, a per-node store, a threshold-based semantic handler, a rule engine with compact binary IPv6 addressing, and an asynchronous command router (Fig. 2). A web-based dashboard connects through BLE NUS for provisioning, live monitoring, and rule configuration.

Result: The firmware concurrently sustains BLE Mesh, Thread, and LoRa traffic with static memory bounds on a 256 KB RAM target. 12-hour reliability tests measure 0.04% packet loss across all BLE Mesh nodes and 0.00% loss on Thread. Under aggressive traffic (200 ms BLE, 500 ms Thread), the scheduler successfully shifts airtime toward the active alert protocol but exposes a strong cross-protocol trade-off (Fig. 3): BLE-alert prioritization reduces BLE Mesh loss from 24.4% to 7.3%, while Thread loss rises from 7.0% to 67.0%. Thread-alert prioritization shows the opposite effect, lowering Thread loss from 5.9% to 3.0%, while BLE Mesh loss increases from 23.2% to 32.5%. The Thread-side gain is marginal. Thread already recovers most losses through link-layer acknowledgments on every hop combined with Constrained Application Protocol (CoAP) confirmable retransmissions, whereas BLE Mesh relies on unacknowledged flooding and has no comparable recovery mechanism. The asymmetric outcome reveals a hard limit: priority scheduling shields the alerting transport, but the cost on the other transport can be severe, and the mechanism alone cannot resolve both directions. Cross-gateway actuation over LoRa is demonstrated end-to-end. A node input on one gateway switches an actuator on a node attached to a second gateway. The custom PCB integrating the SX1303, two SX1250 front-ends, an SKY66420 power amplifier, and a GPS timing reference was produced and brought up. The SX1303 was configured, and its automatic gain control (AGC) and arbiter firmware loaded and verified. However, an undocumented AGC start-up state machine blocks the TX path, so the LoRa link falls back to a single-channel SX1276 transceiver, sufficient for the demonstrated use case.

Fig. 1. Gateway: 1: nRF54L15 with antenna, 2: SX1303 LoRa subsystem, 3: power management, 4: GPS module, 5: SX1276.
Own presentment

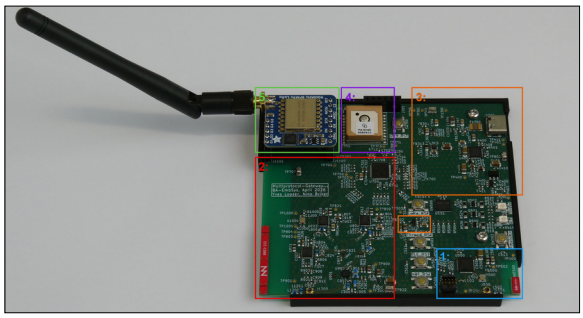


Fig. 2. Each protocol is abstracted behind an adapter interface. All events run through a single event-ingest pipeline.
Own presentment

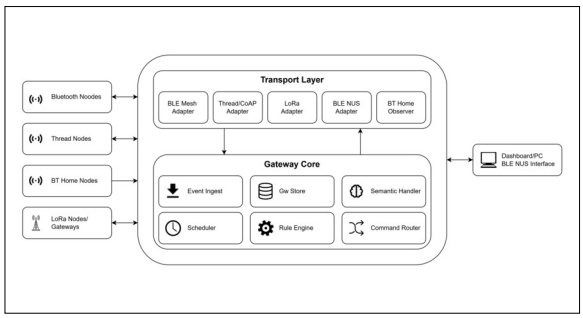
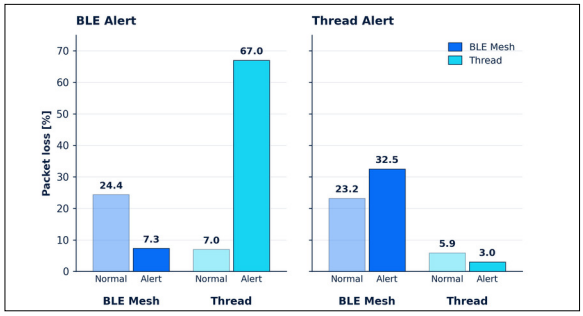


Fig. 3. Per-transport packet loss under BLE Alert (left) and Thread Alert (right). Normal baseline drawn in light shade.
Own presentment



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