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Design and Implementation of a Programmable Load Shedding System with Wireless Remote Terminal Unit for Power Distribution Networks

[1]Adedokun G., [2]Kehinde O.K. & [3]Oyeniran O.J.
[1,2] Department of Electrical/Electronics Engineering, Osun State College of Technology, Esa-Oke
[3]Department of Mechatronics Engineering, Osun State College of Technology, Esa-Oke
Email: [1]adedokung@oscotechesaoke.edu.ng

ABSTRACT

Electric power distribution networks in many developing regions continue to suffer from chronic instability caused by feeder overloading, voltage fluctuations, weak automation infrastructure, and limited supervisory control. Rural and semi-urban feeders are particularly affected, where manual load shedding remains the dominant mitigation strategy despite its slow response time, operational inefficiency, and susceptibility to human error. Conventional SCADA- and PLC-based automation systems offer high reliability but are often financially and infrastructurally impractical for low-resource environments. This paper presents the design, implementation, and experimental validation of a low-cost, programmable load-shedding system based on a microcontroller-based RTU–CCMU architecture with hybrid wireless communication. The proposed system integrates IEC 61131-3–inspired deterministic control logic directly within an STM32-based RTU, enabling autonomous multi-stage load shedding and restoration based on real-time voltage and current measurements acquired from distributed CCMUs. A dual-channel communication framework is employed, combining ZigBee for low-latency operational control with GSM/GPRS as a wide-area supervisory and fallback channel, ensuring resilience in the event of communication failures. A complete hardware prototype comprising a Remote Terminal Unit (RTU) and a Central Control and Monitoring Unit (CCMU) was constructed and evaluated using a controlled laboratory testbed. Experimental results demonstrate sub-100 ms end-to-end load-shedding response times, with Stage-1 actions consistently below 50 ms, greater than 98% ZigBee communication reliability, and reliable GSM-based failover for supervisory control. Comparative benchmarking shows that the proposed system significantly outperforms GSM-only and LoRaWAN-based solutions while achieving near-PLC performance for feeder-level corrective actions at a fraction of the cost. The proposed architecture provides a practical and scalable pathway for deploying real-time distribution automation in infrastructure-constrained power networks.

Keywords: Distribution Automation, GSM/GPRS, Programmable Load Shedding, Remote Terminal Unit, Smart Grids, ZigBee

1. INTRODUCTION

1.1 Motivation and Problem Context

Electric power distribution systems in many developing countries face significant stress due to inadequate generation capacity, long radial feeders, weak voltage regulation, and limited automation infrastructure (Petinrin & Shaaban, 2016). These challenges are particularly severe in rural and peri-urban areas, where high technical losses, feeder overloading, and delayed fault response lead to frequent undervoltage events and prolonged outages. In these situations, utilities often resort to manual load shedding, where field personnel disconnect lower-priority feeders or customer groups to prevent system collapse. Although manual load shedding offers a basic level of protection, it is inherently inefficient. Decision-making is slow, restoration is often delayed, and actions can be inconsistent and prone to human error (Toro-Mendoza et al., 2023). Furthermore, manual intervention in power distribution frequently exhibits a lack of coordination among various feeder segments, which can lead to imbalanced power allocation and avoidable blackouts. As distribution networks continue to evolve in complexity, propelled by escalating demand, the challenges associated with effective management and control become increasingly pronounced (Hayat et al., 2024), As urbanization accelerates and the integration of distributed energy resources expands, relying on manual shedding is becoming an increasingly impractical solution.

Automated load shedding offers a structured alternative by enabling selective and prioritized disconnection of loads based on real-time electrical conditions such as voltage, frequency, or transformer loading (Asit Kumar Majhi & Mohanty, 2024). When properly implemented, automated shedding improves voltage stability, prevents cascading failures, and supports faster system recovery. However, despite its technical benefits, distribution-level automation remains largely absent in rural and low-resource grids (Toro-Mendoza et al., 2023).

The primary barrier is the cost and complexity of conventional automation solutions. Industrial PLC-based RTUs integrated into SCADA systems require substantial capital investment, proprietary software licenses, fibre-optic or dedicated radio links, and specialized maintenance expertise (Mollik Babu et al., 2025). These requirements make SCADA-centric automation impractical for many utilities operating under severe financial and infrastructural constraints. As a result, a significant portion of distribution networks continues to operate without fast, deterministic protection or control at the feeder edge.

This gap highlights the need for cost-effective, distributed automation solutions that can deliver real-time load-shedding capability without the overhead of full SCADA infrastructure. Advances in embedded systems and wireless communication technologies present an opportunity to rethink how load shedding is implemented at the distribution edge.

1.2 Technical Opportunity and Research Gap

Recent developments in microcontroller technology have dramatically expanded the capabilities of low-cost embedded platforms. Current 32-bit microcontrollers provide high-speed analog-to-digital conversion, real-time interrupt handling, advanced timers, and ample computational resources to execute deterministic control logic that was once exclusive to industrial PLCs. When combined with appropriate firmware architecture, these platforms can support IEC 61131-3–inspired control models, enabling structured, verifiable, and time-predictable automation at a fraction of PLC cost.

At the communication layer, low-power wireless technologies provide viable alternatives to wired SCADA links. Short-range protocols such as ZigBee (IEEE 802.15.4) offer low latency, high reliability, and immunity to interference in substation and indoor environments, making them well-suited for real-time feeder-level control. Conversely, wide-area cellular technologies such as GSM/GPRS provide extensive geographic coverage and are widely available even in rural regions, albeit with higher and more variable latency. Many embedded load-shedding solutions rely on single-channel communication architectures using Wi-Fi, GSM, or LoRaWAN, which have notable limitations. Wi-Fi is unreliable and power-intensive in rural areas, GSM introduces latency unsuitable for real-time actions, and while LoRaWAN is effective for monitoring, it cannot facilitate quick switching due to duty-cycle restrictions. Furthermore, many systems lack deterministic control, multi-tier prioritization, or coordinated operation among multiple remote terminal units (RTUs).

The research gap, therefore, lies in the absence of a fully implemented, hybrid-communication, embedded RTU architecture that combines:

i. Deterministic, PLC-like control logic,
ii. Low-latency local wireless communication for real-time control,
iii. Wide-area fallback connectivity for supervision and resilience, and
iv. Scalable coordination across multiple distribution nodes.

Addressing this gap requires not only architectural design but also experimental validation under realistic operating conditions.

1.3 Research Objectives and Contributions

This research aims to develop and validate a low-cost, programmable load-shedding system capable of delivering utility-grade performance in infrastructure-constrained distribution networks. The main aim is to bridge the gap between manual load shedding and full SCADA automation by introducing a hierarchical RTU–CCMU architecture that is fast, reliable, scalable, and economically viable.

Research Objectives

The specific objectives of this work are as follows:

i. To design a microcontroller-based RTU capable of executing deterministic, multi-stage load-shedding logic using real-time voltage and current measurements, with response times comparable to entry-level PLC systems.
ii. To develop a hybrid wireless communication framework that combines low-latency local communication with wide-area fallback connectivity, ensuring operational continuity under communication failures.
iii. To implement coordinated multi-RTU operation, enabling synchronized load-shedding actions across multiple feeder segments without dependence on centralized SCADA commands.
iv. To experimentally evaluate system performance in terms of response time, communication reliability, failover behaviour, scalability, and comparative effectiveness against existing load-management approaches.

Research Contributions

The key contributions of this paper are summarized as follows:

i. A fully implemented embedded load-shedding RTU architecture: The work presents a complete hardware and firmware implementation based on STM32 microcontrollers, integrating sensing, actuation, local human–machine interfaces, and wireless communication without reliance on industrial PLCs.

ii. An IEC 61131-3–inspired embedded control engine: Deterministic, multi-stage load-shedding and restoration logic is implemented directly in RTU firmware, enabling flexible configuration and predictable real-time behaviour.
iii. A hybrid ZigBee–GSM communication model: The system combines ZigBee for low-latency operational control with GSM/GPRS for supervisory access and fault-tolerant fallback, a combination rarely realized in prior load-shedding studies.
iv. A scalable multi-RTU coordination framework: Lightweight packet protocols and event-driven communication enable coordinated shedding across multiple RTUs with sub-100 ms propagation delay.
v. Comprehensive experimental validation and benchmarking: The system is evaluated under controlled laboratory conditions and benchmarked against PLC-SCADA, GSM-only, LoRaWAN-based, and manual load-shedding approaches.

Together, these contributions demonstrate a practical pathway for deploying real-time distribution automation in regions where conventional solutions are economically or infrastructurally infeasible.

2. LITERATURE REVIEW

2.1 Load Shedding in Smart Grids

Load shedding is a critical control mechanism used to maintain stability in power systems under conditions of supply–demand imbalance, feeder overload, or voltage collapse (Gbadega et al., 2025). In conventional power systems, load shedding has historically been implemented as a centralized function, where control centres issue commands to substations or feeders based on system-wide measurements. Centralized approaches are effective in well-instrumented grids but depend heavily on high-bandwidth, low-latency communication infrastructure and continuous supervisory availability (Estrin et al., 2010). With the evolution of smart grids, load shedding strategies have expanded to include distributed and decentralized approaches, where local controllers or RTUs execute corrective actions based on real-time measurements at the network edge (Velasquez et al., 2024). Distributed load shedding reduces reaction time, mitigates single points of failure, and enables selective, priority-based curtailment closer to the affected loads (Kuppusamy et al., 2024). Several studies report improved voltage stability and faster fault response when local decision-making is employed, particularly in radial or weakly meshed distribution networks.

However, many distributed schemes proposed in the literature remain algorithmic or simulation-based, lacking full hardware implementation or real-time validation (Benigni et al., 2020). Others rely on centralized optimization engines with distributed actuators, which still introduces communication dependency and latency. In rural and infrastructure-limited grids, where communication reliability is inconsistent and SCADA coverage is sparse, neither purely centralized nor cloud-dependent distributed approaches are fully practical (Mamodiya et al., 2025). The consensus emerging from smart-grid research is that hybrid load shedding architectures, combining local autonomous decision-making with lightweight supervisory coordination, offer the most robust solution for distribution-level automation (Addo et al., 2025). This work aligns with that direction by embedding deterministic load-shedding logic directly within RTUs while maintaining supervisory visibility through low-cost wireless communication.

2.2 PLC/RTU and SCADA-Based Approaches

Industrial PLCs and SCADA-integrated RTUs represent the dominant solution for automated load shedding in modern utility networks (O.V et al., 2024). These systems provide reliable, deterministic execution and standardized programming (IEC 61131-3), with excellent integration into protection relays and distribution management systems. Commercial platforms like feeder RTUs from Siemens and Schneider Electric perform well in medium- and high-voltage networks. However, PLC/SCADA-based systems face adoption challenges in low-voltage and rural areas due to the need for dedicated communication infrastructure, proprietary tools, recurring licensing costs, and specialized maintenance. Centralized architectures also depend on control centres and backhaul links, which may be unreliable or lacking in developing regions.

Several recent studies have attempted to replicate PLC functionality using low-cost embedded hardware. While promising, many such implementations lack strict timing guarantees, multi-stage prioritization, or standardized logic models (Conti et al., 2021). Others omit coordinated multi-RTU operation, limiting their applicability beyond single-node control. The challenge, therefore, lies in retaining the determinism and programmability of PLC-based systems while removing their cost, infrastructure, and operational complexity, particularly for feeder-level automation.

2.3 Wireless Communication for Distribution Automation

Wireless communication plays a central role in modern distribution automation, especially where wired infrastructure is unavailable. The most commonly explored technologies include ZigBee, GSM/GPRS, and LoRaWAN 12:49 PM, each offering distinct trade-offs. ZigBee (IEEE 802.15.4) is widely used in smart metering and building automation due to its low latency, low power consumption, and robustness in short-range environments. Reported latencies for ZigBee range from 10 to 50 ms, making it suitable for time-sensitive control applications. However, its limited range requires careful deployment or mesh routing for wider coverage. GSM/GPRS is widely used for remote monitoring due to its broad availability. While SMS-based control is reliable, it has multi-second latency, and GPRS, while improving throughput, introduces unpredictable delays. Thus, GSM is better suited for supervisory control and data logging than for real-time actions. LoRaWAN offers long-range, low-power communication, increasingly used for metering, but its duty-cycle constraints and high latency limit its effectiveness for rapid load-shedding (Junior et al., 2023). Most existing systems rely on a single communication technology, inheriting its limitations, with few studies exploring hybrid architectures that differentiate real-time traffic from supervisory communication.

2.4 Gap Analysis and Positioning

The reviewed literature demonstrates substantial progress in load shedding algorithms, PLC-based automation, and wireless-enabled monitoring. However, several critical gaps remain.

First, many embedded and IoT-based load-shedding systems lack deterministic, PLC-like control logic, making them unsuitable for utility-grade operation. Second, single-channel communication architectures dominate existing designs, leading to either excessive latency (GSM, LoRaWAN) or limited coverage (ZigBee). Third, multi-RTU coordination and synchronization are rarely implemented or experimentally validated in real hardware systems. Finally, PLC/SCADA solutions, while technically superior, remain economically inaccessible for many distribution networks. A comparative literature summary is presented in Table 1.

This work positions itself at the intersection of these gaps by proposing and validating a low-cost, microcontroller-based RTU system that integrates:

i. deterministic load-shedding logic,
ii. hybrid ZigBee–GSM communication for speed and resilience, and
iii. scalable, distributed multi-RTU coordination.

Table 1 — Comparative Literature Summary

System / Study	Control Logic	Communication	Multi-RTU Support	Real-Time Suitability	Key Limitation
PLC–SCADA Systems	IEC 61131-3	Fibre / PLC	Yes	Excellent	Very high cost
GSM-Only RTUs	Basic rules	GSM/SMS	No	Poor	High latency
LoRaWAN-Based Systems	Threshold alarms	LoRaWAN	No	Moderate	Duty-cycle delay
IoT Embedded Prototypes	Scripted logic	Wi-Fi / ZigBee	Limited	Variable	Non-deterministic
This Work	IEC-style embedded	ZigBee + GSM	Yes	High	Prototype scale

3. SYSTEM ARCHITECTURE AND DESIGN

3.1 Overall Architecture

The suggested system outlines the hierarchical load-shedding architecture that has a Remote Terminal Unit (RTU) and a Centralised Control and Management Unit (CCMU), and two interdependent embedded subsystems. The RTU is the centralised decision-maker and coordination point, whereas the CCMU is located at the feeder level and carries out physical sensing, actuation, and physical human-computer interaction. Figure 1 summarises the system architecture and the relationship of the data through a relationship between the data-flow.

The structure allows one RTU to control more than one CCMU in a feeder section. In addition, it allows the peer-level coordination among multiple RTUs, allowing the control of multiple sets of CCMUs by use of ZigBee-based messaging to coordinate the load-shedding responses.

At the field level, the individual CCMUs constantly obtain feeder voltage and load current measurements and actively operate contactors to control prioritised load groups. The CCMU is a suitable execution and interface node because it provides real-time measurements and localised visualisations as well as localised manual control. It is important to mention that in the standard operating conditions, the CCMU does not carry out the load-shedding or protection algorithms. Rather, all the relevant electrical measurements and status data is sent to the RTU to be interpreted and a decision is therefore made.

The RTU, which is the central control and coordination station, uses timestamped information sent by one or more CCMUs, so that deterministic control logic is employed, voltage and current thresholding is carried out, and it determines what load-shedding or load-restoring measures to take. It then sends explicit actuation commitments to the CCMUs.

This architectural model takes advantage of deterministic feedback to enable quick decisions in which a centre is provided with control, and statistical distribution is decentralised sensing and actuation. This will help bypass all the communication required and, therefore, undertake protective actions in a timely and critical manner. As a result, under-voltage and any over-current situation cases are handled using localised control loops, reducing the use of supervisory connectivity.

A selective wireless software system will connect the RTU and CCMUs, where ZigBee is the main low-latency selective command control channel of the telemetry and synchronised load-shedding activities. The wide-area supervisory interconnection and backup communication channel is GSM/GPRS networks. Such a conscious separation between the real-time operational traffic and the supervisory communication allows the wide area network to withstand the pressure, besides ensuring that the performance of critical protective measures is not compromised.

The CCMU has an RS-232 serial interface, which can be used to perform supervisory monitoring and control, but the latest prototype does not yet implement a specific graphical interface (GUI). The interface is based on a protocol that makes use of the idea of ZigBee packets; therefore, future addition of a GUI can be easily adapted to the current architecture.

In general, the architecture represents a combination of centralised deterministic intelligence and decentralised field implementation with maintaining a balanced trade-off between responsiveness, scalability, and deployment costs. This top-down RTU-CCMU model is especially beneficial in automation of feeder-level of infrastructure constrained distribution systems, rural feeders, and emerging mini-grids because it is applicable in situations where conventional SCADA-scale deployments are faced with constraints.

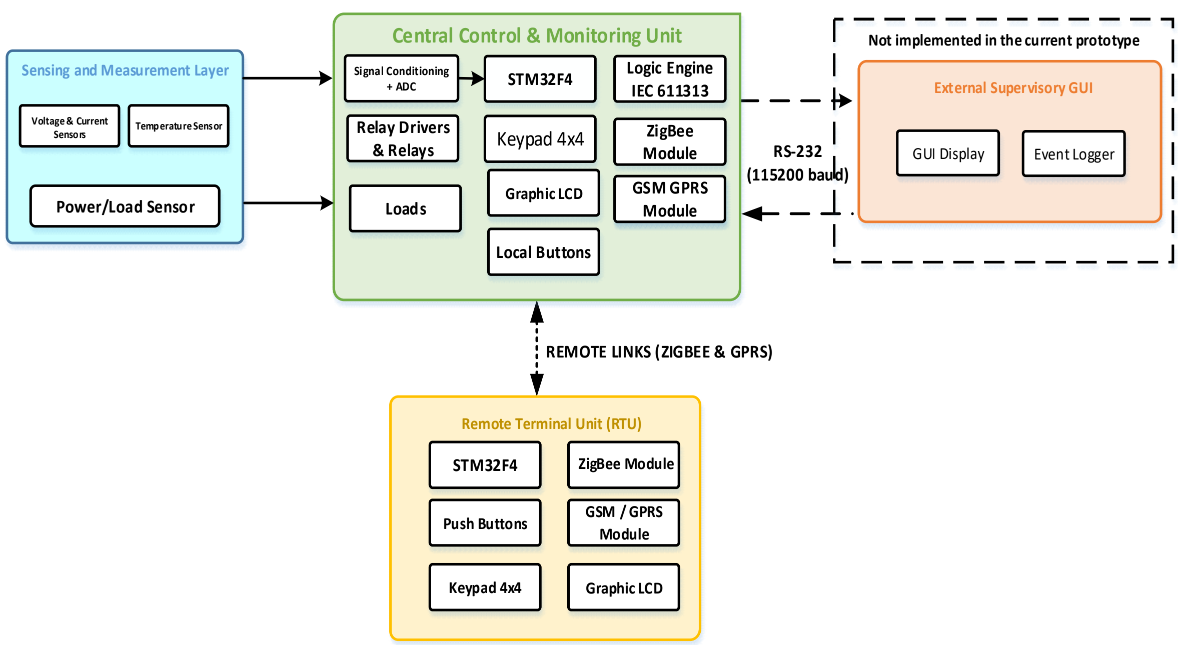

Figure 1: System Architecture

3.2 Central Control and Monitoring Unit (CCMU)

The latter refers to the field-deployed execution and interface node of the system, known as the Central Control and Monitoring Unit (CCMU). Its responsibilities encompass physical sensing, actuation of loads, local human-machine interface, and two-way communication with the Remote Terminal Unit (RTU). The CCMU operates on a hardware platform similar to that of the RTU and is equipped with an STM32F4-series microcontroller to ensure architectural symmetry, deterministic timing properties, and protocol interoperability. It captures real-time electrical signals, including voltage and current from the feeder, as well as local system conditions such as load stage and communication health.

This data is measured and transmitted to the RTU via the primary ZigBee communication link for analysis and decision-making. In this architecture, the CCMU acts as a destination for data collection and actuation, while the control intelligence resides in the RTU. A graphical LCD is integrated into the CCMU, providing a real-time view of operating parameters, alarms, and system status. Additionally, push buttons on the unit allow the operator to intervene manually, enabling them to issue commands, acknowledge errors, and select the operating mode directly at the field location. This design ensures that local interaction remains possible, even when remote connectivity is unavailable. It has two running modes, which include:

1. Remote Mode: The CCMU works under the control of RTU. The electrical parameters are measured continuously and sent to the RTU, which uses deterministic logic of load-shedding and sends direct actuation commands back to the CCMU. These commands are executed by the CCMU, which allows no local decision-making and hence centralised and coherent control behaviour is enabled.
2. Local Mode: Remote commands are overridden with manual control through the CCMU. It is a see mode, so it is aimed at maintenance, commissioning, and emergency intervention, and will allow operators to actuate loads directly regardless of RTU decision. Safety interlocks at the hardware ensure that local mode is always prioritized over remote commands to avoid accidental automation when switching to manual mode. This precedence mechanism portrays the industrial safety practices that are in place.

Notably, load shedding and protection logic are not carried out by the CCMU when it is operating normally. Rather, it serves as a reliable sensing, actuation, and interface node, maintaining a very distinct division between decision-making (RTU) and physical execution (CCMU), but being able to coordinate centrally and be visible.

3.3 RTU Hardware Architecture

The Remote Terminal Unit (RTU) is a key component of the control and decision-making centre in the proposed load-shedding architecture. Whereas the traditional RTU is closely interconnected with the field input/output devices, the RTU in the given description is a remote distributed intelligence node. It receives real-time measurements of one or more Consolidated Control and Monitoring Units (CCMUs), implements programmed control logic, and sends actuation commands particular to it back to the respective CCMUs.

3.3.1 Processing Core

The RTU is built around an STM32F4-series microcontroller (ARM Cortex-M4), which was chosen because it provides an effective interrupt handling logic, advanced timer peripheral support, and digital signal processing functionality, and enough GIS inside to handle control logic with high effectiveness. Also, the use of hardware watchdogs and automatic brownout advantages the reliability under the condition of irregular supply or communication.

3.3.2 Measurement Interpretation and Control Logic

The RTU is also designed to use the STM32F4 series microcontroller, with a core based on ARM Cortex-M4 at a frequency of up to 168 MHz. This component was chosen due to its high-quality interrupt processing, advanced timer devices, digital signal processing facilities, and sufficient computation facilities required to effectively perform control algorithms. Moreover, hardware overseers and brown-out sensitization tools are added to increase the reliability in a state of unstable power distribution or communication interruptions.

3.3.3 Command and Coordination Interface

The RTU sends actuation, configuration, and synchronization messages to the CCMU using the combined packet protocol described in Section 3.6. The following can be supported using this reversible channel of communication:

i. Load-shedding control on multiple stages;
ii. Coordinated activities between various CCMUs;
iii. Centralized parameter control;
iv. Supervisory reporting and event logging.

Since the actual process of the determination of the actuation is triggered by the RTU, coordinated load shedding among distributed feeder segments will be possible without direct intercommunication between CCMUs.

3.3.4 Communication Interfaces

The RTU system and CCMU system include two independent communication interfaces, one just as a (i) ZigBee (IEEE802.15.4) component, which provides the systems with low-latency, deterministic communication with the CCMUs to receive operational control signals, and (ii) GSM/GPRS (SIM900) component, which provides the system with the wide-area supervisory connectivity, remote access, and serves as an additional line of communication in the event of failure. All interfaces are linked through a specific UART; thus, they can work separately, and failure management is easier. Notably, wide area communication is not involved in the real-time decision making, thus maintaining the determinism of RTU logic even in poor network conditions.

3.3.5 Power and Isolation

The RTU and CCMU power supply sub-system supplies with regulated 12 V, 5 V, and 3.3 V, an isolated supply. By means of electrical isolation and transient defence using optocouplers and TVS, the system is immune to noise, surges, and variations of ground potentials that inherently exist in the distribution system. Table 2 presents important hardware requirements and specifications of the CCMU and RTU.

Table 2: CCMU and RTU Hardware Components and Specifications

Subsystem	Component / Module	Key specification(s) used in this work	Rationale / Notes
Processing core (RTU & CCMU)	STM32F405	Cortex-M4 up to 168 MHz; 3× 12-bit ADC up to 2.4 MSPS aggregate; multiple UARTs/timers	Supports deterministic control loop, high-rate sampling, and concurrent comms
Voltage sensing	Isolated voltage transducer + scaling/filter	Scaled to ADC range; noise filtering for RMS estimation	Enables stable threshold detection under switching noise
Current sensing	Split-core CT + burden + LPF	Conditioned analog input for RMS/overcurrent detection	Enables both voltage-based shedding and an independent overcurrent branch
Actuation stage	Relay drivers (opto-isolated + flyback)	Opto isolation; coil transient suppression	Electrical separation between logic and power domains
Power switching	Industrial contactors (segmented load stages)	Typical closing 12–26 ms, opening 4–19 ms (device-dependent)	Mechanical switching dominates end-to-end actuation time
Local HMI	LCD+keypad+ indicators	Local override, diagnostics, acknowledgement	Supports Local/Remote modes and maintenance operations
Primary comms	ZigBee radio (XBee Series 2/S2C class)	API framing supported; UART configurable (e.g., 115200 bps commonly used)	Low-latency operational control and coordination
Secondary comms	GSM/GPRS (SIM900 class)	UART configurable 9600–115200; TCP/IP stack for GPRS; SMS fallback	Wide-area supervisory + fallback channel
Power supply & isolation	Multi-rail AC⟶DC (12 V / 5 V / 3.3 V) + protection	TVS, grounding strategy, isolation boundaries	Reliability in unstable feeder environments

3.4 Control Logic Design

The control logic in the RTU is based on the principles of the structural logic of IEC 61131-3 in the implementation on the basis of a microcontroller. The logic is reflected using a deterministic state machine that is driven by real-time measurements and event signals.

i. Multi-Stage Load Shedding

The process of load shedding is grouped into several levels of priority. The stages are associated with loads of decreasing significance. Upon the occurrence of a voltage or current beyond pre-set thresholds on a given configurable persistence time, shedding of the stage becomes possible. Stages that have lower priorities are removed first as a means of saving critical loads.

ii. Hysteresis-Based Restoration

In order to inhibit oscillatory behaviour, restoration thresholds will be higher than shedding thresholds. A stage is recovered when the voltage is within reasonable limits over a specified period of time. Restoration is done in reverse priority sequence with inter-stage delays so that load upsurges are prevented.

iii. Parallel Overcurrent Protection

The current equipment has several paths, with current flowing in opposite directions on each path, as shown in the drawing, and different currents flowing through the iron-protective elements of the circuit board. Along with logic based on the voltage-dependent logic, parallel running is an independent overcurrent. When the current surpasses the safe limit, shedding will occur instantly and bypass the voltage persistence timer. This guarantees quicker protection at overload conditions.

iv. Fault Latching and Safety

Critical faults are sustained overcurrent, sensor failure, or long communication loss, which are latched. An automatic restoration is blocked off until an operator reset is set. This action aligns with industry protection procedures and eliminates unsafe re-energization. The implemented algorithm control flow and logical structure are shown in Figure 2. The figure represents the Parallel execution of overcurrent protection and load shedding logic, Specifically Voltage-Based load shedding logic, in the RTU. The overcurrent branch is a high-priority protection task, which causes the immediate tripping of all contactors due to fault detection, with shedding based on voltage driven by independently operating staged thresholds and hysteresis. Figure 3 is a Logic for Multi-Stage Load Shedding in the format of IEC 61131-3.

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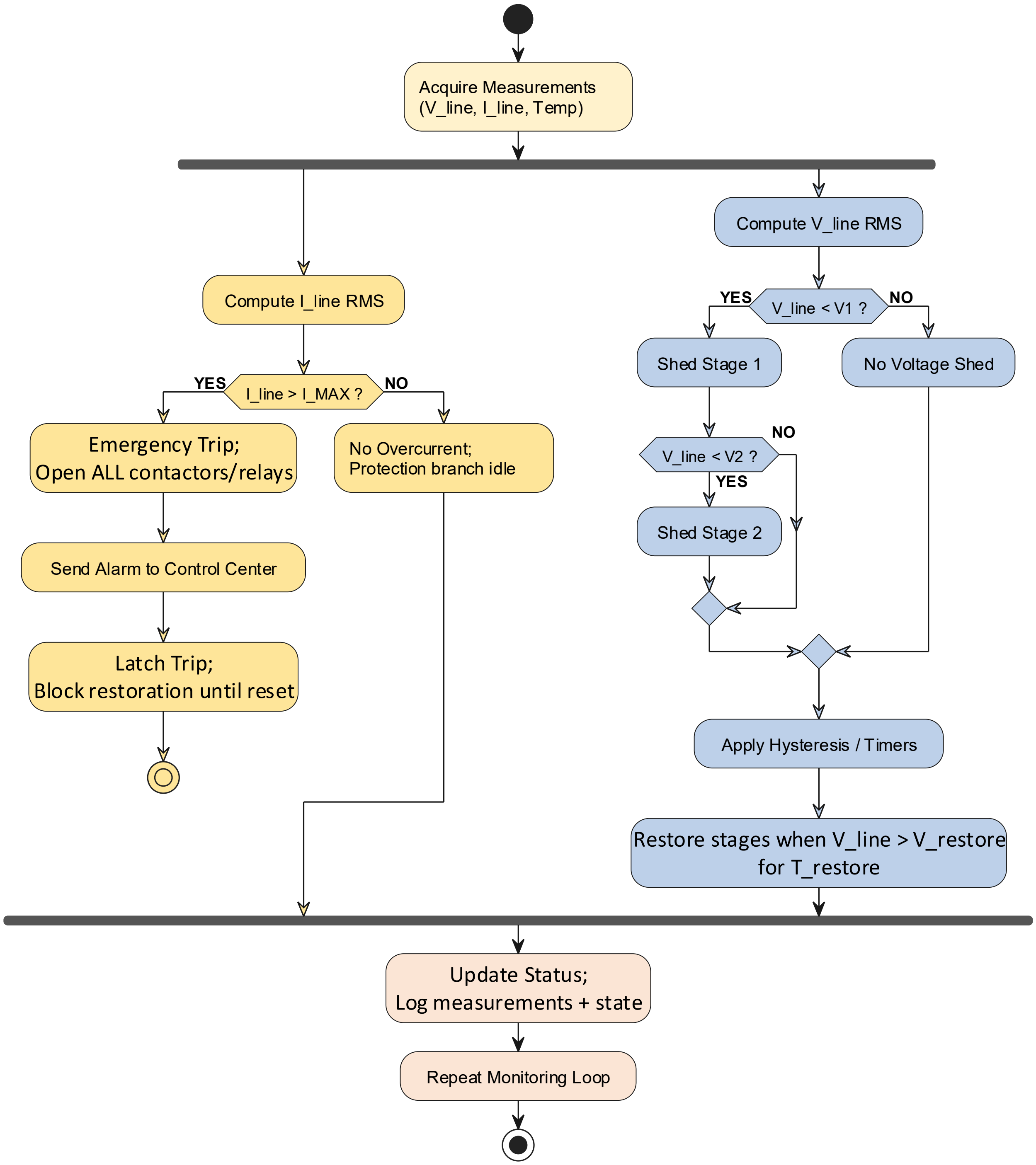

Figure 2: Control Logic with Parallel Overcurrent Protection with Voltage Shedding

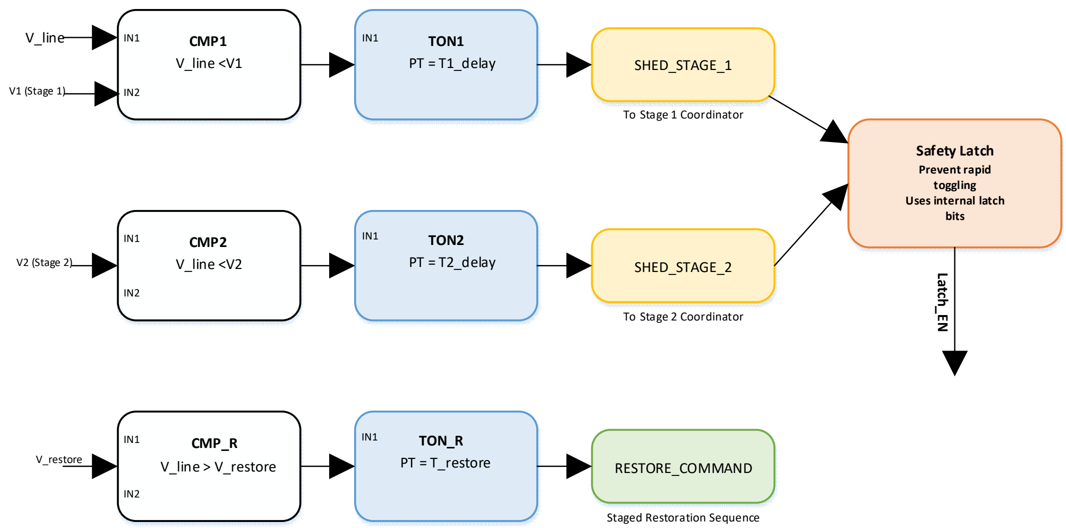

Figure 3: Function Block Logic for Multi-Stage Load Shedding

3.5 Communication Architecture (ZigBee / GSM)

The communication subsystem has a dual-channel design in order to provide a balance between real-time performance and wide-area resiliency. The primary channel is ZigBee, and it can support status updates, control acknowledgements, and load-shedding commands that run through it at latencies less than 50 ms. It is low-energy-consuming and robust and could be suitable in feeder panels and substations, designed in the form of a star, with the RTU serving as the coordinator and the CCMUs as the end devices. This design reduces protocol overhead, and the latency is predictable; and mesh routing will still be available in the future should the routing need to be extended. GSM/GPRS will be used as a secondary wide-area connectivity/fallback arcane, and a heartbeat scheme will keep track of the link health and cause a shift to GSM/GPRS when ZigBee is unavailable, allowing continuous operations without this component to add to the latency. The communication architecture and failover workflow are shown in Figure 4.

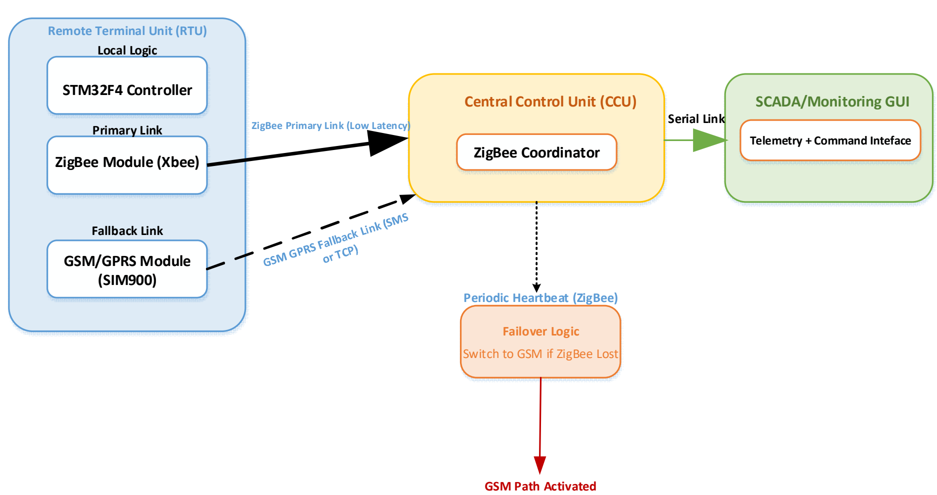

Figure 4: Communication Flow Diagram—ZigBee Primary and GSM/GPRS Fallback

3.6 Packet and Protocol DesignA unified, lightweight packet protocol is used across both ZigBee and GSM channels to simplify parsing and ensure consistent behaviour during failover. Each packet comprises:

i. Preamble and version fields
ii. Message type and device identifier
iii. Timestamp for event ordering and replay protection
iv. Payload encoded using TLV (Type–Length–Value) format
v. CRC-16 (CCITT) for error detection

Types of messages are: status requests/responses, parameter updates, forced shedding/restoration requests, event notifications, and heartbeat messages. CRC-16 authentication provides integrity to the payload even in scenarios when being delivered by GSM or SMS, whilst timestamps eliminate stale command execution. The protocol is small, extensible, and due to deterministic processing on embedded platforms, it is optimised. A summary of the desired packet structure and message types that are supported is presented in Table 3, and a Unified Packet Format illustration of RTU Communication is depicted in Figure 5. Figure 6 below depicts the ZigBee -GSM Failover Sequence Diagram.

Table 3: Unified Packet Structure and Message Types (ZigBee + GSM)

Table 3A: Packet Structure

Field	Size (bytes)	Description
Preamble / Start delimiter	1	Frame alignment marker
Version	1	Protocol revision
Message type	1	Command/response/event/heartbeat, etc.
Device ID	2	RTU identifier
Timestamp	4	Event ordering + replay resistance
Payload length	1	Payload byte count
Payload (TLV)	Variable	Type–Length–Value encoded fields
CRC-16 (CCITT)	2	Integrity check across header + payload

Table 3B: Message Types Used in This Paper

Message type	Direction	Purpose
HEARTBEAT	RTU ↔ CCMU	Link health monitoring; failover trigger
STATUS_REQ / STATUS_RESP	CCMU ↔ RTU	Telemetry pull: V, I, stage status, comm health
EVENT_NOTIFY	RTU → CCMU	Under-voltage / overcurrent/stage trip events
PARAM_UPDATE	CCMU → RTU	Thresholds, timers, hysteresis, stage configuration
FORCE_SHED / FORCE_RESTORE	CCMU → RTU	Manual override command
ACK / NACK	RTU ↔ CCMU	Command confirmation/error reporting

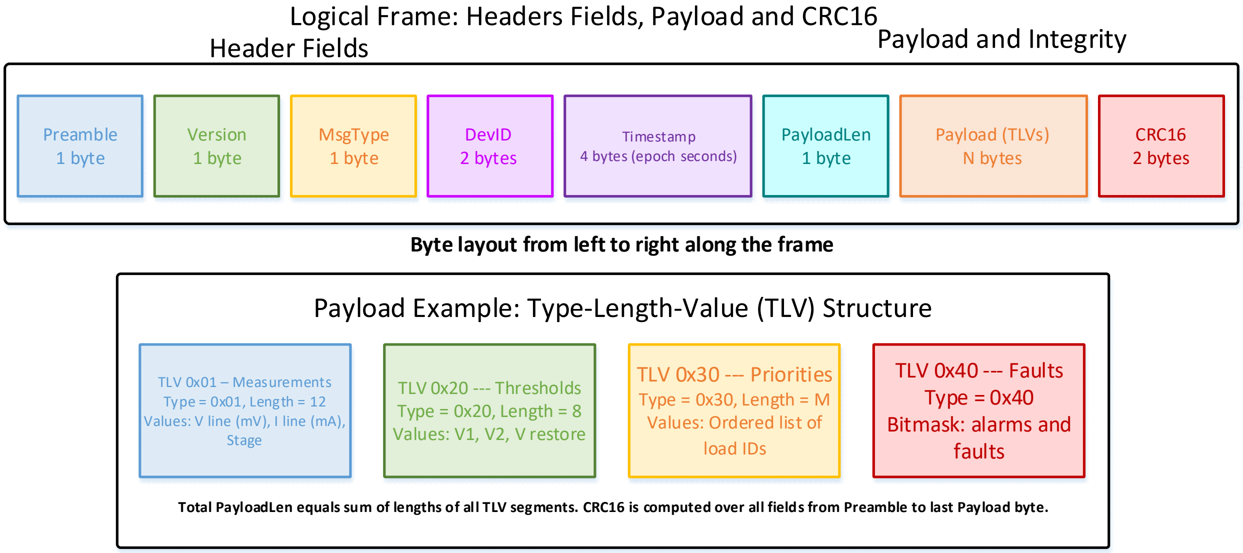

Figure 5: Unified Packet Format for RTU Communication

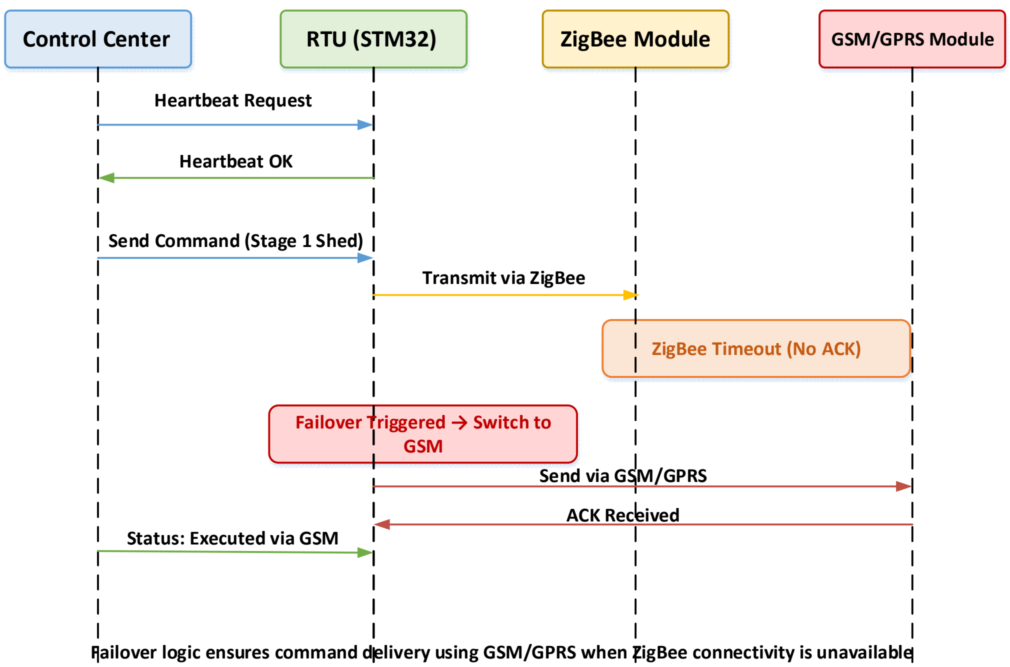

Figure 6: ZigBee–GSM Failover Sequence Diagram

4. IMPLEMENTATION AND EXPERIMENTAL SETUP

4.1 Prototype Construction

A complete functional prototype of the proposed load-shedding system was constructed to confirm the feasibility of the architecture under real operating scenarios. The implementation has two physical subsystems, which include the Remote Terminal Unit (RTU) and the Central Control and Monitoring Unit (CCMU). The two units were implemented with STM32F4-series microcontrollers and built with a modular printed circuit board (PCB) strategy to streamline the testing, debugging, and subsequent expansion.

i. Modular PCB Design

The physical implementation is divided into self-contained PCB components of the main system functions: processing, sensing, communication, actuation, and human-machine interface. The RTU includes an MCU board that houses the STM32F4, an analogue sensing board, used to condition voltage and current, a relay driver board, used to control contactors, and a communication interface board, which combines ZigBee modules and GSM/GPRS modules. This modular system enables the validation of every subsystem individually before complete integration of the system. Photoresistors in relay drivers are isolated by opto-isolators, and the restricted separation of ground planes between high-voltage and low-voltage circuits is used as an electrical insulator. The signal paths are shielded, and the grounding is based on stars to reduce any noise present in the measurements and to have ADC stability when switching occurs.

ii. ZigBee Configuration and Pairing

ZigBee communication is implemented using XBee Series 2 modules configured in API mode to support framed communication, acknowledgements, and error detection. The RTU ZigBee module operates as the network coordinator, while each CCMU ZigBee module functions as an end device. All modules are configured with a common PAN identifier and operating channel to minimize interference from nearby wireless networks. Network association and pairing were completed prior to experimental testing, and received signal strength indicator (RSSI) values were monitored to confirm stable communication under indoor deployment conditions. API-mode framing enables reliable packet parsing and supports the unified communication protocol described in Section 3.

iii. GSM Provisioning and Network Access

The GSM/GPRS subsystem is implemented using a SIM900 module configured for packet data communication. A standard SIM card was provisioned with access point name (APN) credentials for GPRS connectivity. The module establishes a TCP session with a test server for telemetry upload and supervisory commands. GSM operation remains idle during normal ZigBee operation to minimize power consumption and is activated only during failover or remote supervisory access. SMS functionality is retained for alarm notification when packet data is unavailable.

iv. Mechanical Assembly

Both the RTU and CCMU were housed in suitable enclosures with clearly labelled terminals and cable glands. Front panels expose the keypad, LCD, and status indicators for local interaction and diagnostics. Figure 7 shows the assembled prototype units and module arrangement.

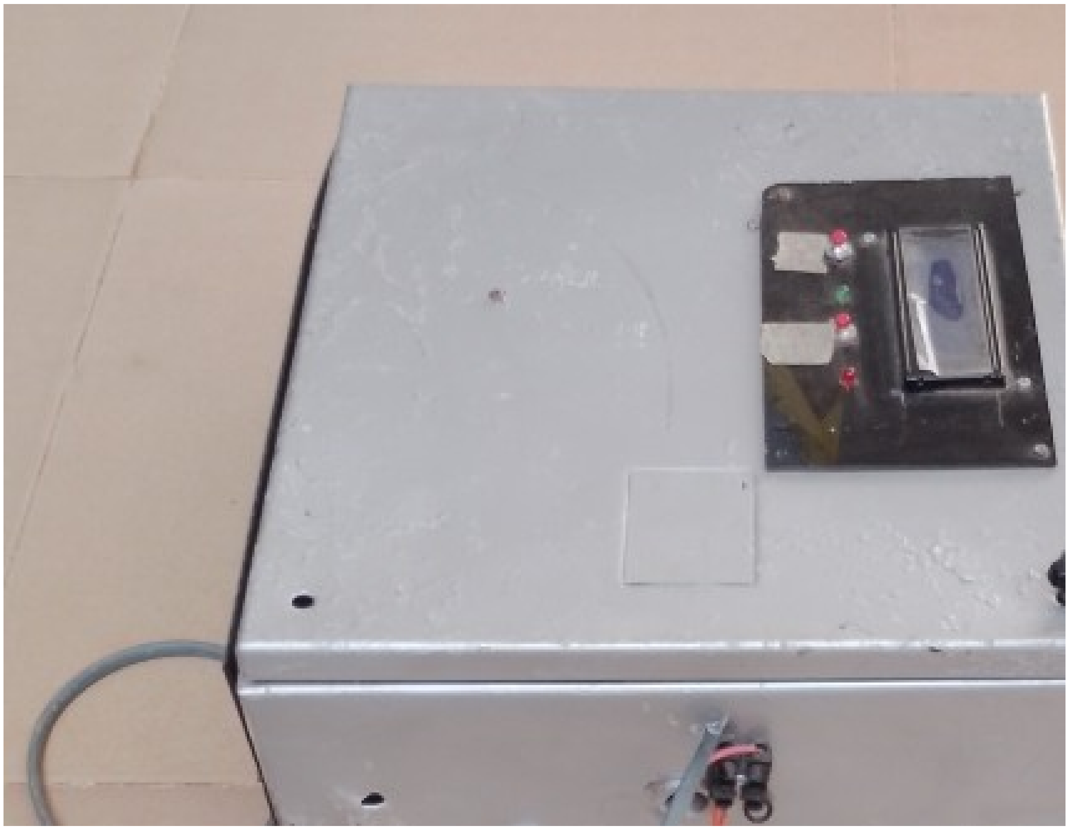

Figure 7: Assembled prototype units (CCMU and RTU)

4.2 Testbed Description

A laboratory testbed was designed in a controlled environment that was simulated to match the distribution feeder conditions, and assess system response to repeat disturbances. The testbed enables accurate control of supply voltage and load magnitude and condition, as well as the measurement of electricity and timing.

Power Conditioning and Load Emulation

An adjustable 0–260 V variac was used to simulate voltage sags and recovery events representative of feeder instability. The variac output feeds a segmented resistive load bank rated up to 2.5 kW, divided into independently switchable sections. The connection corresponds to different load-shedding stages. Industrial contactors rated for 40–80 A were used to interface the load bank with the CCMU relay outputs.

Communication Environment

ZigBee modules were placed with separations of 8-12 metres indoors and partial obstructions to reflect actual implementation aspects like substations or distribution panels. RSSI and packet delivery statistics were recorded in all the experiments. The experiment with GSM was performed on the public cellular network, and this brought in the aspect of real-world latency and variability.

Measurement and Instrumentation.
Electrical and timing measurements were obtained using calibrated laboratory instruments, including:

a. A digital oscilloscope to measure relay and contactor actuation timing
b. True-RMS digital multimeters and clamp meters for voltage and current measurements
c. Serial data loggers capturing RTU timestamps and event messages

Table 4 summarizes the test equipment and its roles within the experimental framework.

Table 4: Laboratory Testbed Equipment and Roles

Category	Equipment	Typical range/rating (as used)	Role in experiments
Supply disturbance	Variac	~0–260 VAC adjustable	Generates controlled sags and restoration
Load emulation	Segmented resistive load bank	Up to ~2.5 kW (segmented stages)	Implements staged shedding loads
Switching interface	Industrial contactors	40–80 A class	Physical disconnection/reconnection of stages
Timing capture	Digital oscilloscope	Multi-channel timing capture	Measures relay drive → contactor actuation timing
Electrical verification	True-RMS DMM + clamp meter	AC V/I verification	Confirms measured V/I against instrumentation
Data logging	Serial logs (RTU/CCMU) + GUI logs	Timestamped events	Computes comm delay, failover timing, propagation delay

4.3 Test Scenarios and Performance Metrics

To comprehensively evaluate system performance, a structured set of seven test scenarios (T1–T7) was established, with each scenario aimed at isolating a specific operational feature of the proposed system. Each experiment was conducted ten times to ensure statistical reliability, and outliers were filtered out using the interquartile range method before analysis.

4.3.1 Test Scenarios

In the former (T1) under-voltage detecting scenario, the supply voltage has been varied to the minimum possible voltage so that the threshold load-shedding threshold of Stage-1 is reached, and the sensitivity and inaccuracy of voltage sensing and threshold assessment are evaluated. The second scenario (T2) generalises this test to a multi-stage operation, with sequential voltage sags, enabling confirmation that the prioritisation is correct, as well as response behaviour (staged) under conditions of control. The third scenario (T3) involves overcurrent protection performance, i.e., by starting with specified safety boundaries, the load Current is continued to be increased progressively until predetermined setback limits are exceeded, and the load is instantly disconnected as a method of confirming the parallel overcurrent protection branch. The fourth scenario (T4) is the investigation of the communication performance of the primary wireless link, and this scenario determines end-to-end command latency between the graphical user interface at the CCMU and the RTU over the ZigBee communication.

The fifth (T5) deals with the issue of system resilience by considering GSM/GPRS failover behaviour after deliberate termination of the ZigBee link, such as detection time and switch to the fallback communication. In scenario T6, comparisons between the relative sensitivity of local and remote-control modes are considered by determining the actuation time in response to the RTU keypad command and the CCMU graphical display command issued to the RTU, respectively. Lastly, scenario seven (T7) evaluates system scalability and coordination through propagation delay and synchronisation error in coordinated load-shedding operations across a number of RTUs. Taken together, these scenarios cover all aspects of sensing accuracy, control logic validity, communication behaviour, failover behaviour, and multi-RTU scalability.

4.3.2 Performance Metrics

A set of standard performance metrics was used in all the experimental scenarios so that there was uniformity, and the amount of redundancy decreased in the description of situations and the interpretation of results. These measures include load-shedding response time, relay and contactor response latency, end-to-end communication delay, successful packet rate, failover transition delay, and inter-RTU propagation delay.

Metrics values were retrieved based on synchronised and time-stamped RTU and CCMU logs and oscilloscope measurements of actuation timing. The presentation of the results is in the form of mean value against standard deviation of the mean, and where the data show variation, the presentation of the results contains a confidence interval. Table 5 contains a detailed mapping of the identified test situations and the measured performance indicators, which allows them to be reproduced and puts a strict line between the purposes of the experiments and the measurement outcomes.

Table 5: Mapping of Test Scenarios (T1–T7) to Performance Metrics

Scenario	Detection time (ms)	Relay/contactor actuation (ms)	End-to-end comm delay (ms/s)	Packet success (%)	Failover time (s)	Inter-RTU propagation (ms)
T1 Under-voltage detection	✓	✓	–	–	–	–
T2 Multi-stage shedding	✓	✓	–	–	–	–
T3 Overcurrent protection	✓	✓	–	–	–	–
T4 ZigBee comm delay	–	–	✓	✓	–	–
T5 GSM/GPRS failover	–	–	✓	✓	✓	–
T6 Local vs remote control	–	✓	✓	–	–	–
T7 Multi-RTU coordination	–	✓	✓	✓	–	✓

5. RESULTS AND PERFORMANCE EVALUATION

The information provided in this section is the experimental findings of the proposed programmable load-shedding system, which were tested, according to the scenarios, in Section 4. The values reported are the mean of obtained values, and standard deviations were used where necessary. The results are structured so that they can assess the actuation speed, communication performance, fault tolerance, scalability, and relative effectiveness of the recognized techniques.

5.1 Load-Shedding Response Time

A timely and reliable response to the abnormal operating conditions is the main performance requirement of a distribution-level load-shedding system. This subsection strictly considers the end-to-end response time of the RTU-CCMU control loop, which is determined as the time difference between the recognition of an abnormal condition based on real-time measurements obtained at the CCMU and the physical action of the contactors at the CCMU. This response time is inclusive of the analogue-to-digital conversion at the CCMU, the control logic analysis at the RTU, the relay driver activation, and the mechanical reaction of the contactors.

5.1.1 Stage-Wise Response Timing

Three load-shedding stages were implemented, corresponding to progressively severe voltage deviations. The measured end-to-end response time includes threshold violation detection, control logic execution, relay driver activation, and mechanical contactor operation. Experimental measurements indicate that the mean response time increases with stage number due to additional logical evaluation and the cumulative effect of electromechanical actuation, rather than software-induced latency.

Stage-1 shedding exhibited a mean response time of approximately 42 ms, while Stage-2 and Stage-3 responses averaged 58 ms and 74 ms, respectively. Across all stages, the observed standard deviation remained within ±5 ms, showing the deterministic, interrupt-driven execution of the embedded control logic and the repeatable mechanical behaviour of the contactors. These results are summarized in Table 6; and presented graphically in Figure 8.

Table 6: Stage-Wise Load-Shedding Response Time (End-to-End)

Stage	Trigger severity	Mean (ms)	Std. dev. (ms)	Notes
Stage 1	Mild undervoltage	42	±5	Includes mechanical contactor operation time
Stage 2	Moderate undervoltage	58	±5	Adds extra stage logic sequencing
Stage 3	Severe undervoltage	74	±5	Highest stage + cumulative actuation effects

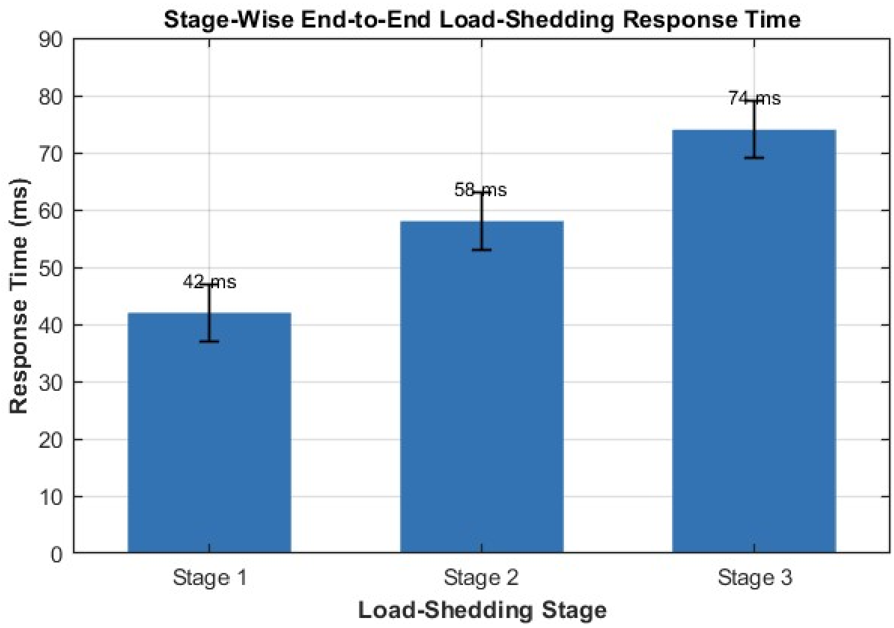

Figure 8: Stage-wise end-to-end load-shedding response time of the proposed RTU system, including sensing, control-logic execution, relay activation, and mechanical contactor operation.

5.1.2 Stability and Determinism

No missed or delayed shedding events were observed during repeated trials. Restoration operations, which are intentionally slower due to hysteresis thresholds and inter-stage delays, did not interfere with subsequent shedding actions or compromise system stability. The absence of oscillatory behaviour confirms that the embedded control logic maintains temporal consistency under repeated disturbance conditions. All measured response times fall well below the 100 ms threshold commonly cited for feeder-level corrective actions. The results demonstrate that a microcontroller-based Programmable Load Shedding System can achieve actuation performance comparable to entry-level PLC systems when a deterministic firmware architecture is employed.

5.1.3 ZigBee Communication Performance.

ZigBee serves as the primary operational communication channel between the RTU and the CCMU. Performance evaluation focused on latency, reliability, and jitter, as these parameters directly affect coordinated load-shedding and supervisory responsiveness.

5.2.1 Latency Analysis

Round-trip latency was measured between command-acknowledgment exchanges between the CCMU graphical interface and the RTU. The experimental findings showed a latency minimum of approximately 14 ms, a mean latency of 21 ms, and a latency maximum of 31 ms. Latency was well clustered, with more than 70% of the packets being received within 20 ms, indicating minimal jitter and uniform communication behaviour. Table 7 summarises the statistics of latency. The cumulative distribution function (CDF) of the ZigBee command-acknowledgment round-trip latency between the CCMU and RTU in operational control is also shown in Figure 9.

Table 7: ZigBee Communication Performance (Primary Channel)

Metric	Result	Measurement basis
Round-trip latency (min)	≈ 14 ms	GUI command ⟶ RTU ack (round-trip)
Round-trip latency (mean)	≈ 21 ms	Average over repeated trials
Round-trip latency (max)	≈ 31 ms	Worst observed in the indoor test
Packets evaluated	> 200	Logged transmissions
Packet success rate	> 98%	Successful command–ack exchanges
Latency concentration	> 70% ≤ 20 ms	Distribution observation
Sustained link failures	None observed	During ZigBee-only operation

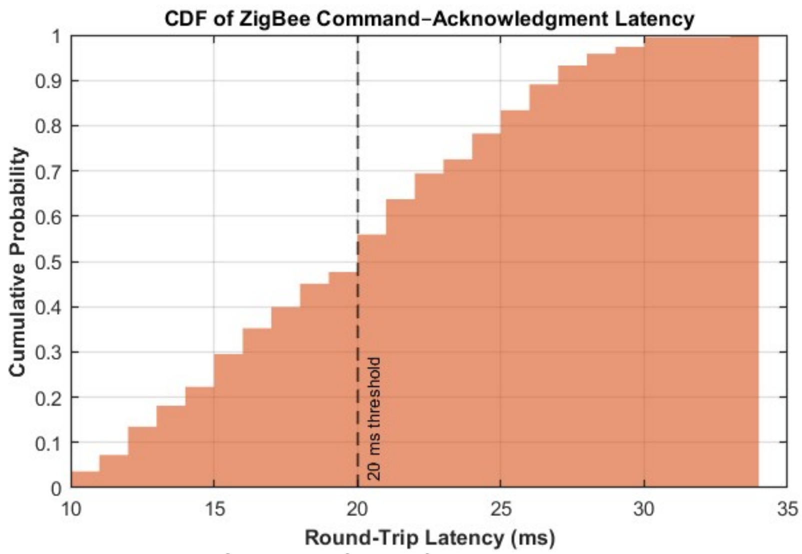

Figure 9: Cumulative distribution function (CDF) of ZigBee command–acknowledgment round-trip latency between the CCMU and RTU during operational control.

5.2.2 Reliability and Packet Success

In its large-scale testing, which used more than 200 transmitted packets in ZigBee-only operation, the success rate of packet delivery exceeded 98%. Retransmissions were not common, and they were well handled at the MAC layer and hence did not cause any apparent effect on the responsiveness of the system. During the test period, no long-term link failures occurred, and the values of the received signal strength indicator (RSSI) were also stable, which shows that the link quality was high in terms of the indoor deployment conditions. The noted characteristics of latency and reliability prove the ZigBee applicability in real-time operational control. It performs much better than the GSM-based communication and is predictable enough to allow the coordination of the multi-node automation.

5.3 GSM/GPRS Performance and Failover.

GSM/GPRS subsystem offers supervisory connectedness and serves as a backup communication channel in the case of the unavailability of ZigBee. The SMS-based signalling, GPRS (TCP) communication, and failover behaviour, performance evaluation was carried out individually.

5.3.1 SMS and GPRS Latency

The communication using SMS showed a lot of variability in the latency, with the duration of delay being between 3.8 seconds and 9.2 seconds, and the mean delay being 5.6 seconds. Conversely, TCP communication over GPRS witnessed a better performance and reduced the average latency to approximately 3.6s, with a range of observed delay values of 2.9s to 5.1s. Although this has been improved, neither SMS nor GPRS can be used to take real-time load-shedding decisions because of the multi-second latency. Table 8 contains a summary of the comparative latencies of SMS and GPRS communication.

Table 8: GSM/SMS Latency and ZigBee→GSM Failover Timing

Item	Min	Mean	Max	Notes
SMS command latency (s)	≈ 3.8	≈ 5.6	≈ 9.2	High variability; supervisory use only
GPRS/TCP latency (s)	≈ 2.9	≈ 3.6	≈ 5.1	Faster than SMS; still non-real-time
Failover time (s)	≈ 5.0	≈ 5.4	≈ 5.8	ZigBee timeout + GSM activation + session + first packet

5.3.2 Failover Performance

The intentional disabling of the ZigBee connection and observing the time taken by the RTU to resume communication using the GSM system were used to test the intention of the failover behaviour. The entire period of failover includes detection of ZigBee timeout, GSM module activation, GPRS connection, and the first successful packet transmission. The maximum and minimum measured values of failover were 5.0 s to 5.8 s, and the average value was about 5.4 s. Table 8 provides a summary of the GSM communication and failover timing measures. Figure 10 shows a comparison of SMS, GPRS, and ZigBee-to-GSM failover latency in supervisory communication on a logarithmic time scale. GSM is not used to actuate fast, but offers good supervisory coverage. Deterministic failover mechanism means that in case of system failure, visibility and remote control is maintained, local RTU autonomy and RTU real-time protection behaviour remain intact.

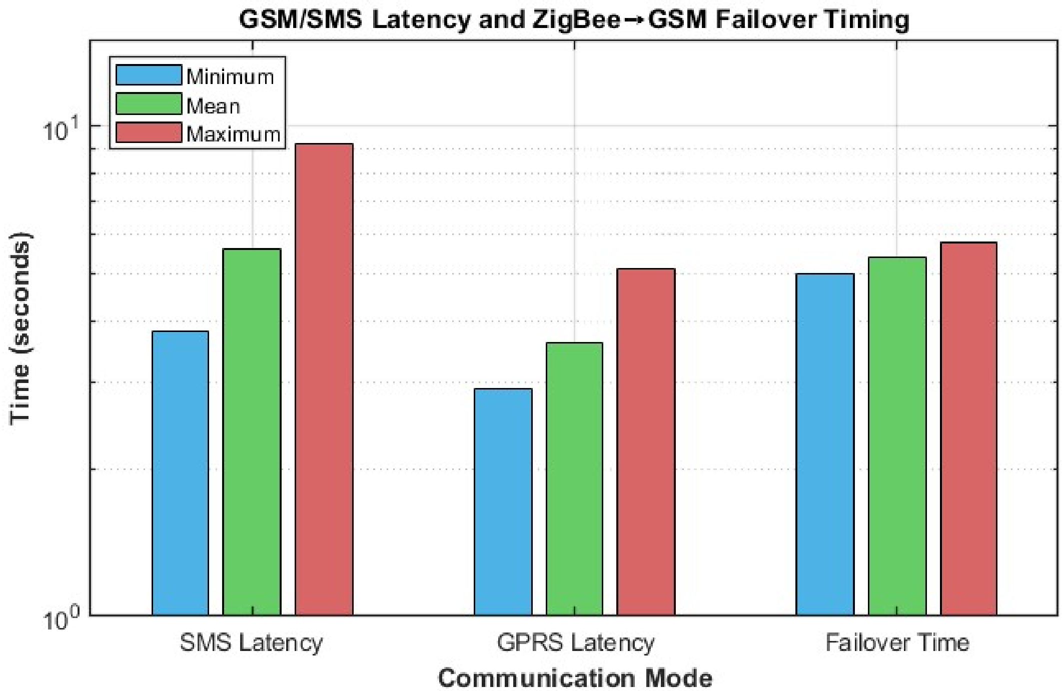

Figure 10: Comparison of SMS, GPRS, and ZigBee-to-GSM failover latency for supervisory communication, shown on a logarithmic time scale.

5.4 Benchmark Comparison

In order to place the proposed architecture in perspective, the architecture was contrasted with four other approaches: PLC-SCADA systems, GSM-only RTUs, LoRaWAN-based solutions, and manual load shedding.

i. PLC–SCADA Systems

The PLC-SCADA systems have the best performance speed and reliability, where the actuation time is usually less than 10 ms. Their implementation is, however, too expensive, demands too much infrastructure, and is too complicated to be practised on many low-voltage and rural networks.

ii. GSM-Only RTUs

Telemetry GSM-only systems are common and have a multi-second latency and large jitter. They have an inappropriate response time to support corrective load shedding and can only be used in monitoring or manually controlled.

iii. LoRaWAN-Based Systems

LoRaWAN has great coverage and low power consumption, but it is limited by duty-cycle restrictions and scheduling delays. Typical latencies are between 100 and 500 ms, making it unsuitable for quick switching processes.

iv. Manual Load Shedding

Manual intervention is still prevalent in developing areas and has response times that are within minutes up to tens of minutes. It is naturally uncoordinated, labour-intensive, as well as error-prone.

5.5 Comparative Summary

A summary of the comparative performance of different parameters, such as actuation speed, communication delay, reliability, scalability, and cost, has been given in Table 9. The proposed system has high performance, almost real-time, which is comparable to the solutions based on PLC, low cost, and low dependency on infrastructure. It is more effective than GSM-only and LoRaWAN-based solutions and a revolutionary improvement to manual load shedding. In this part, it has already been established that the proposed Programmable RTU-Based Load Shedding System provides a fast, deterministic load shedding, resilient communication, and coordination, which is scalable and better performance-cost ratio than the available alternatives. The substantial experimental credibility of the original journal article is retained whilst providing the presentation of the results concisely in a reviewer-friendly form.

Table 9: Benchmark Comparison Against Alternatives

Approach	Real-time actuation path	Typical/observed latency class	Coordination support	Practical limitation (for rural low-resource grids)
PLC–SCADA	PLC logic + hardwired I/O + contactor	PLC scan often ~1–10 ms (logic), plus mechanical switching	Strong	High capital + comms infrastructure + integration burden
GSM-only RTU	WAN command triggers switching	Seconds (multi-second delay, variable)	Limited	Not suitable for fast protective shedding
LoRaWAN-based	Scheduled LPWAN messaging	Constrained by RX windows / duty-cycle behaviour, downlink timing is not deterministic	Limited	Not designed for tight closed-loop protection timing
Manual load shedding	Human-in-loop switching	Minutes	None	Slow, error-prone, inconsistent restoration
This work (ZigBee + GSM)	Local RTU logic (time-critical) + ZigBee coordination + GSM supervision	Tens of ms for local shedding; ms-scale ZigBee; seconds only for supervisory GSM	Yes	Prototype scale; mesh and standards alignment are future work

5.6 Discussion and Interpretation of Results

As indicated by the results of the experiment in Sections 5.1 to 5.5, the proposed programmable Load Shedding System architecture can be used to provide utility-grade load-shedding operations with low-cost embedded hardware, and hybrid wireless communication. The low response time, consistency in communication behaviour, and coordinated operation show that this performance is caused by deliberate architectural and firmware design decisions and should not be due to isolated optimizations. One of the main factors that led to the high performance of the system is the strategic positioning of deterministic control logic at the RTU level. It can be easily implemented in the microcontroller, which allows the system to eliminate its reliance on wide-area communication to make time-sensitive decisions by embedding load-shedding logic into the primary microcontroller.

Decision-making, shedding, and actuation are in a tightly coupled local control loop, as indicated by the response times that are always less than 50 ms. This reaffirms that microcontroller-based RTUs, properly designed, can effectively emulate core PLC functionality to be used for automation at the distribution level. The event-driven firmware architecture also augments deterministic behaviour. The interrupt-based ADC sampling and the assessment of threshold, in addition to the use of relays to actuate hardware, significantly reduce software-based jitter and eliminate timing jitter seen in polling-based systems. The small standard deviation of the repetitive response times implies that the timing of executions is robust to a great variety of operating conditions and variations in loads. he effectiveness of the hybrid communication strategy is also highlighted in the results. The ZigBee has low latency, reliability, which ensures fast propagation of commands, synchronised multi-RTU shedding, and responsive operator interactions. On the other hand, although GSM/GPRS is not appropriate in real-time actuation, it offers resilient supervisory connectivity, and system observability still occurs even in situations where ZigBee is offline. Also, GSM is out of the real-time control path on purpose, thereby effectively protecting the system against delays in wide-area networks that are capable of hindering protective behaviour.

The results of the coordinated multi-RTU are convincing that distributed automation can be achieved without centralised control. The fact that measured sub-100 ms propagation delays and small synchronisation errors attest to the fact that coordinated shedding between feeder segments not only can be performed, but also is an efficient approach, due to lightweight messaging and local autonomy. This is especially important to radial distribution networks, where inconsistent load disconnection or delayed load disconnection can increase the level of voltage instability. Regarding the engineering perspective, the benchmark comparison points out the practical importance of the system. Even though it is possible that PLC-SCADA solutions dominate on an absolute basis, the proposed architecture will capture a significant part of their functional benefits, and at the same time closely cut their costs and infrastructure complexity. This system, compared to GSM-only, LoRaWAN-based, and manual load-shedding approaches, provides better response speed, coordination, and reliability. Overall, this discussion shows conclusively that the suggested RTU-based architecture is an effective intermediate automation solution between manual control and full implementation of SCADA in distribution networks, and thus it is especially applicable to rural and peri-urban distribution networks with infrastructure limitations.

6. CONCLUSION, LIMITATIONS, AND RECOMMENDATIONS

6.1 Conclusion

This study presented the design, implementation, and experimental validation of a distributed, programmable load-shedding system based on low-cost embedded Remote Terminal Units (RTUs) and hybrid wireless communication. The proposed architecture integrates deterministic control logic directly within microcontroller-based RTUs, enabling autonomous and coordinated feeder-level load shedding without reliance on centralized SCADA infrastructure. Through laboratory validation under controlled conditions, the system demonstrated reliable operation across multiple load-shedding stages, effective coordination between centralized RTUs, distributed CCMUs, and resilient supervisory connectivity using a hybrid ZigBee–GSM communication model. The results confirm that real-time load shedding can be achieved using embedded platforms when architectural design prioritizes local intelligence, deterministic execution, and communication separation between operational and supervisory layers.

Overall, the work bridges the gap between manual load shedding and full PLC–SCADA automation by offering a cost-effective, scalable, and deployment-ready solution suitable for infrastructure-constrained distribution networks, rural feeders, and emerging mini-grid environments.

6.2 Limitations

The given system is limited in a number of ways. First, the GSM/GPRS communication has a high and random latency that can only be used in supervisory monitoring and fallback functions, hence limiting its responsiveness to control over a wide area. Second, point-to-point ZigBee communication restricts coverage and redundancy when deployed in large areas, such as in a city, necessitating the RTUs and coordinators to be placed carefully. Third, although the system aligns with modern substation automation in principles, it does not fully implement IEC 61850 data models, services, or interoperability profiles, which limits direct integration with existing Distribution Management Systems (DMS). Finally, validation was conducted in a laboratory environment. While this ensured repeatability and precise measurement, it does not capture all environmental, electromagnetic, and operational challenges present in real distribution networks.

6.3 Future Work and Recommendations.

Future work should address these limitations through both architectural and technological enhancements. At the communication layer, emerging cellular IoT technologies such as LTE-M or NB-IoT should be evaluated as alternatives to GSM to improve latency consistency while maintaining wide-area coverage. Additionally, implementing ZigBee mesh routing would improve resilience, coverage, and scalability in complex feeder topologies. From a standards perspective, future research works can focus on mapping RTU functions to IEC 61850 logical nodes and supporting standardized communication services to enable interoperability with utility control centres. The integration of predictive and adaptive load-shedding strategies, including lightweight machine learning models, could further enhance system performance by enabling proactive rather than purely reactive control, provided real-time constraints are preserved. Finally, pilot field deployments on live distribution feeders and mini-grids are strongly recommended to assess long-term reliability, communication robustness, user acceptance, and maintenance requirements under real operating conditions.

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