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Dual-Routing RF Mesh-NB-IoT Architecture for Smart Grid Monitoring in Infrastructure-Constrained Distribution Networks

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***Abstract* - The dependability of real-time monitoring at the distribution scale is an urgent issue in smart grid implementation due to the heterogeneous communication environment, node malfunctions, and coverage limitations. Wireless Sensor Networks (WSNs) embedded inside smart meters provide a practical solution for extending monitoring visibility to the distribution layer; however, single mode communication architectures have limited resilience under dynamic network conditions. This paper proposes a dual-routing WSN architecture that integrates RF Mesh (Radio Frequency Mesh) and Narrowband Internet of Things (NB-IoT) to enhance reliability and continuity of data transmission for smart grid monitoring applications. In the proposed model, RF Mesh communication is used for short-range, low-latency neighborhood data transmission, while the NB-IoT is used as a wide-area fallback and backhaul link during times when there is a mesh congestion, degradation, or failure. The architecture incorporates a routing decision process that enables seamless transition between communication modes based on observed network conditions. The dual-routing framework was evaluated through simulation under varying communication distance, traffic load, and channel noise scenarios. The results demonstrate that while RF Mesh provides low-latency performance under favorable conditions, NB-IoT maintains higher delivery stability under adverse link conditions, thereby justifying the integrated architecture. The findings confirm that combining RF Mesh and NB-IoT within a unified WSN structure provides a robust and feasible communication framework for distribution-level smart grid monitoring in infrastructure-constrained environments**

Keywords - Wireless Sensor Networks (WSNs), Smart Grid Monitoring, Dual-Routing Architecture, RF Mesh Communication, NB-IoT, Distribution-Level Power Systems, Infrastructure

I. INTRODUCTION

The distribution-level power networks used in infrastructure-constrained systems continue to inherently experience the problems of limited observation, slow fault detection, and poor real-time monitoring. The problems are increased in areas where the communication infrastructure is not uniform, dependable, or consistent. In this case, traditional monitoring systems that require sparse sensing and predetermined communication backhaul would not be adequate to provide continuous situational awareness. Similar limitations of sparse monitoring in distribution grids have been reported in recent smart grid surveillance studies [1].

Smart meters integrated with Wireless Sensor Networks can offer a viable way of extending the monitoring capacity to the point of distribution. Smart meter-based WSNs provide necessities needed for visibility of the voltage conditions, load behaviour and disturbances in the network by allowing distributed data collection on the levels of the customer meters and the distribution transformers [2], [3]. However, the success of such systems is essentially limited to the reliability and flexibility of the communication architecture through which monitoring data is being transported to utility control centers.

Single-mode communication architectures are used by most implemented smart grid monitoring systems, and in most cases, it is either RF Mesh or cellular technology. RF Mesh networks provide low latency and power-saving in dense deployments, but they become very slow when affected by interference, node failures, longer communication distances, as well as non-uniform network topology [4], [5]. These circumstances are typical in distribution environments that are strained in infrastructure. On the other hand, cellular-based technologies such as NB-IoT provide wide-area coverage and improved link stability, but they introduce higher latency and energy overhead in comparison to short-range mesh networks [6], [7].

This work was carried out to develop and test a communication architecture that reliably delivers data when distribution network conditions are unreliable and unpredictable. The main focus is routing level coordination between short range and wide area communication technology within a smart-meter based Wireless Sensor Network.

This paper presents a dual-routing RF Mesh-NB-IoT WSN design which allows for dynamic choosing of the communication path based on the current network conditions. The study is limited to distribution-level monitoring communication performance assessment with specific emphasis on reliability, latency, and operational continuity. Architectural-level integration of heterogeneous communication technologies has been identified as a practical strategy for improving resilience in smart grid infrastructures operating under dynamic network and stress conditions [8].

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II. RELATED WORKS

A. WSN-Based Distribution-Level Smart Monitoring

Wireless sensor networks have been extensively used in distribution-level smart grid monitoring due to their scalability, distributed sensing abilities, and how suited they are for edge-level data acquisition. Communication reliability, however, remains the dominant limiting factor in real-world WSN deployments for power distribution monitoring, particularly under interference, varying topology, and constrained infrastructure conditions [3].

Recent studies report that WSN-enabled smart meters enhance the visibility of voltage profiles, load behaviour, and transformer-level disturbances, enabling faster operational response and improved situational awareness across the distribution network [1], [2]. By deploying sensing nodes at customer and transformer levels, utilities achieve a better spatial resolution of network events in comparison to the traditional sparse monitoring approaches.

Despite these advantages, empirical results consistently indicate that packet loss and delayed delivery become more pronounced as the network size, hop count, and environmental interference increase [3]. These communication constraints directly impact the dependability of real-time monitoring applications in used heterogeneous distribution environments.

B. RF Mesh Communication in Smart Meter Networks

RF mesh communication is widely adopted in Advanced Metering Infrastructure (AMI) due to its self-organizing topology, distributed routing capability, and low-latency performance in dense node deployments [4]. The multi-hop structure enables local aggregation and redundancy through alternative routing paths, which can improve resilience under moderate network stress.

However, reliability challenges arise when the node density becomes irregular, relay nodes fail, or interference increases. Studies report that RF mesh performance deteriorates significantly under sparse deployments and non-uniform topologies, leading to routing instability, increased retransmissions, and loss of packet [5].

The increasing quantity of the effects of per-hop packet error probability results in a more rapid degradation of end-to-end delivery as the hop count increases. This behavior creates difficulties in infrastructure-constrained distribution systems where node placement is determined by customer density rather than communication optimization [3].

These limitations suggest that RF-mesh-only architectures may not be suitable to sustain reliable monitoring under all operational conditions encountered in practical distribution networks in infrastructure-constrained environments.

C. NB-IoT for Smart Grid Monitoring

NB-IoT has emerged as a promising wide-area communication technology for large-scale smart metering deployments. Its extended coverage range, improved signal penetration, and cellular infrastructure support makes it suitable for geographically dispersed distribution environments [6].

Performance analyses indicate that NB-IoT maintains stable packet delivery across varying propagation conditions, including interference and moderate channel degradation [7]. Unlike the multi-hop mesh systems, NB-IoT relies on a single-hop uplink to the cellular base station which reduces cumulative reliability decay across extended paths.

Irrespective of its advantages, NB-IoT typically introduces higher end-to-end latency due to cellular scheduling procedures and uplink resource allocation. As a result, while it offers robustness and delivery stability, it may not be optimal as a primary communication mode for latency-sensitive monitoring operations within localized distribution environments [6].

D. Hybrid and Heterogeneous Communication Architectures

To address the individual limitations of short-range and wide-area communication technologies, heterogeneous communication frameworks have been proposed in recent smart grid research [8]. These architectures aim to introduce redundancy and alternative transmission paths by integrating WSN-based communication with cellular technologies.

However, many existing implementations focus primarily on system-level or cloud-layer integration, where heterogeneous technologies operate in parallel without coordinated routing decisions at the WSN layer. In such cases, hybridization is often static, relying on predefined fallback configurations rather than dynamic adaptation based on real-time communication performance [9].

Consequently, although heterogeneous communication improves theoretical redundancy, the absence of routing-layer intelligence limits the system’s ability to respond effectively to rapidly changing interference, congestion, and topology conditions.

E. Identified Research Gap

The reviewed literature demonstrates that while RF Mesh and NB-IoT technologies have been individually evaluated [4], [6], and heterogeneous architectures have been conceptually explored [8], there remains limited empirical investigation of coordinated dual-routing mechanisms at the WSN routing layer.

Existing studies typically assess communication technologies independently or integrate them in static configurations without adaptive path selection based on network performance indicators [5], [9].

There is therefore a lack of architectural frameworks that dynamically coordinate RF Mesh and NB-IoT communication within a unified smart meter–based WSN to maintain reliable packet delivery under infrastructure-constrained and unpredictable distribution conditions.

This gap directly motivates the development and evaluation of the dual-routing RF Mesh–NB-IoT WSN architecture proposed in this work.

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III. PROPOSED METHODOLOGY

A. System Architecture Overview

The proposed system is a smart meter–based Wireless Sensor Network designed for distribution-level monitoring in infrastructure-constrained environments. Smart meters act as sensor nodes, collecting electrical and operational data and transmitting them toward the utility control center or a Meter Data Management System (MDMS) through a hierarchical communication structure.

The architecture is organized into three functional layers:

1) Customer Meter (CM) layer
2) Distribution Transformer (DT) aggregation layer
3) Network gateway and utility backend

Smart meters at the CM layer form a local RF Mesh network that supports short-range, multi-hop communication toward the DT aggregation layer. DT-level nodes act as aggregation points and intermediate routing controllers. Under normal operating conditions, DT nodes relay aggregated data to the utility backend through the RF Mesh backhaul. Wide-area fallback connectivity between the DT layer and the utility backend is provided through NB-IoT. Fig. 1 illustrates the system.

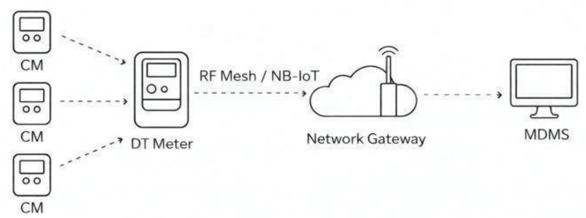

Fig. 1. Dual-Routing RF Mesh–NB-IoT WSN Architecture

Fig. 1 illustrates the proposed smart meter–based Wireless Sensor Network architecture, showing RF Mesh communication at the customer meter (CM) to the DT meter. It also shows RF Mesh communication and NB-IoT backhaul connectivity at the distribution transformer level where the packets are transmitted from the DT to the utility interface.

This layered design ensures that short-range and wide-area communication technologies are structurally integrated within a coordinated routing framework, where the routing adaptation occurs at the DT backhaul level rather than at individual smart meter nodes.

B. RF Mesh Communication Layer

Smart meters build a self-organizing RF Mesh network at the CM layer. The nodes are equipped to interact with adjacent meters within the same radio range, enabling multi-hop forwarding of monitoring information toward the DT layer.

Due to its low latency and energy-efficient characteristics in dense deployments, RF Mesh communication is adopted as the primary routing path between the CM layer and the DT aggregation layer, and as the default backhaul path from the DT node to the MDMS/utility control center. Under normal operating conditions, data packets generated at the CM layer are forwarded over the mesh network to the DT node using shortest-path or minimum-hop routing logic. The DT node then relays the aggregated data to the MDMS/utility control center through the RF Mesh backhaul.

The RF Mesh layer provides local resilience through path redundancy. However, its performance is sensitive to interference, relay-node failure, link asymmetry, and topology variation, which are common in infrastructure-constrained distribution networks. When RF Mesh backhaul performance at the DT level deteriorates beyond predefined thresholds, the DT node activates NB-IoT as an alternative wide-area transmission path to maintain communication continuity.

C. NB-IoT Communication Layer

NB-IoT provides wide-area backhaul connectivity between the Distribution Transformer (DT) nodes and the MDMS/utility control center. It operates as a secondary wide-area transmission path that is activated when RF Mesh backhaul performance at the DT level degrades beyond predefined thresholds.

The main features of NB-IoT include long-range communication capability, strong signal penetration, and stable uplink transmission under challenging propagation conditions. These characteristics make NB-IoT suitable as an alternative communication channel for maintaining continuity of monitoring data delivery when RF Mesh backhaul links are affected by interference, congestion, or topology instability.

Since NB-IoT is associated with comparatively higher latency and increased energy consumption relative to RF Mesh, it is not used as the default routing mode under normal operating conditions. Instead, it functions as a reliability-enhancing fallback mechanism within the dual-routing framework, operating specifically at the DT-to-utility backhaul level.

D. Dual-Routing Mechanism

The architecture incorporates a routing mechanism that dynamically selects between RF Mesh and NB-IoT communication channels at the backhaul level. RF Mesh performance between the Distribution Transformer (DT) node and the MDMS/utility control center is continuously evaluated based on packet delivery ratio and latency measurements.

Under normal operating conditions, data packets generated at the CM layer are forwarded through the RF Mesh network to the DT node and then relayed to the MDMS/utility control center via the RF Mesh backhaul. When RF Mesh backhaul performance at the DT level degrades beyond predetermined thresholds due to interference, congestion, or relay instability, traffic from the DT node to the utility backend is re-routed through NB-IoT.

Routing decisions are therefore performed at the DT aggregation level without centralized control from the utility

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backend. This distributed backhaul-level switching reduces control overhead and enables rapid adaptation to changing network conditions while preserving hierarchical routing integrity.

To formalize the routing behavior at the DT backhaul interface, let:

PDR_m= measured RF Mesh backhaul packet delivery ratio

L_m= measured RF Mesh backhaul average latency

Define threshold parameters:

θ_P= minimum acceptable packet delivery ratio

θ_L= maximum tolerable latency

The routing selection rule is expressed as:

$$R_s = \text{NB-IoT, if } PDR_m < \theta_P \text{ or } L_m > \theta_L \quad (1)$$

$$R_s = \text{RF-Mesh, if otherwise}$$

This deterministic decision model reflects the switching logic implemented in the simulation, where only the DT-to-utility backhaul link is subjected to dynamic mode selection. This switching strategy limits performance degradation under adverse conditions while preserving the hierarchical separation between local RF Mesh routing and DT-level backhaul transmission.

E. Data Flow and Operational Sequence

The workflow of the proposed architecture is as follows:

1) Smart meters capture monitoring information at regular intervals.
2) The RF Mesh transmits data packets from the CM layer to the DT layer.
3) The DT nodes forward the aggregated data to the utility backend through the RF Mesh backhaul under normal operating conditions.
4) Upon detection of RF Mesh backhaul degradation at the DT level, the DT node reroutes the outgoing traffic to the utility backend via the NB-IoT path.
5) When RF Mesh backhaul performance recovers above predefined thresholds, routing is switched back to the primary RF Mesh backhaul path.

This sequence ensures continuity of monitoring data while balancing latency, reliability, and resource utilization across heterogeneous communication modes.

F. Design Constraints and Assumptions

The architecture is based on the following constraints:

1) Distribution networks are heterogeneous in node density and subject to irregular interference conditions.
2) Smart meters operate under budgetary constraints related to processing capability and energy availability.
3) NB-IoT connectivity, although available, must be utilized selectively due to latency, operational cost, and resource considerations.

These constraints reflect the practical realities of infrastructure-limited distribution environments and directly inform the hierarchical dual-routing design, where RF Mesh operates as the primary communication mode and NB-IoT functions as a controlled backhaul fallback at the DT level.

IV. SIMULATION SETUP AND PERFORMANCE METRICS

A. Simulation Environment

A discrete-event simulation framework was developed to evaluate the proposed dual-routing RF Mesh–NB-IoT WSN under distribution-level smart meter deployment conditions. Smart meters are modeled as sensor nodes generating periodic monitoring measurements, while Distribution Transformer (DT) nodes serve as aggregation and routing coordination entities.

The simulation environment emulates heterogeneous communication conditions including variable RF link quality, interference-induced packet loss, and node-level failures. These conditions reflect the operational characteristics of infrastructure-constrained and unpredictable distribution networks.

The Simulation parameters and deployment assumptions were selected to reflect realistic smart meter density and communication constraints typical of stressed distribution environments. The objective of the evaluation is architectural validation under controlled stress scenarios rather than protocol-level micro-optimization.

B. Network Topology and Deployment Model

Smart meter nodes are deployed over a two-dimensional distribution area using a non-uniform spatial distribution to reflect realistic customer density variation. Each RF Mesh node establishes links with neighboring nodes within its communication range, forming a multi-hop topology.

DT nodes aggregate traffic from associated smart meters. Under normal operating conditions, DT nodes forward aggregated data to the utility backend through the RF Mesh backhaul. NB-IoT links provide wide-area connectivity between DT nodes and the utility backend and are activated when RF Mesh backhaul performance at the DT level degrades beyond predefined thresholds.

This topology ensures the coexistence of short-range multi-hop communication and wide-area backhaul redundancy within a unified and hierarchical routing framework.

C. Traffic Model

Smart meters generate monitoring packets at regular intervals, representing periodic reporting of electrical and operational parameters. Traffic is modelled as low-rate, delay-sensitive data consistent with distribution-level monitoring applications.

Generation of packets is synchronized across nodes to emulate realistic reporting cycles. Buffering and service delays

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are incorporated to simulate queuing effects during congestion and failure conditions.

D. Routing and Failover Configuration

RF Mesh routing operates as the default mode. Smart meter nodes forward packets to DT aggregation points through multi-hop RF Mesh paths. Under normal operating conditions, DT nodes relay aggregated data to the utility backend through the RF Mesh backhaul.

Packet delivery ratio and latency of the RF Mesh backhaul link between the DT node and the utility control center are continuously monitored to assess communication performance at the backhaul level.

NB-IoT is activated when RF Mesh backhaul performance exceeds predefined degradation thresholds. When backhaul performance recovers above acceptable limits, routing reverts to the RF Mesh path. The routing decision is executed at the DT level without centralized coordination from the utility backend, ensuring scalability and rapid response to communication degradation.

For an h-hop RF Mesh path with per-hop packet error rate (PER), the end-to-end packet success probability is approximated as:

$$P_{\text{success}} = (1 - \text{PER})^h \quad (2)$$

This relationship illustrates the exponential reduction in reliability as hop count, interference, or link instability increases.

In contrast, the NB-IoT is modelled as a single-hop uplink:

$$P_{\text{success}}^{\text{NB}} = 1 - \text{PER}_{\text{NB}} \quad (3)$$

This analytical distinction explains why multi-hop RF Mesh reliability degrades more rapidly under stress conditions, while NB-IoT maintains comparatively stable delivery performance under similar interference or distance variations.

E. Performance Metrics

The communication architecture is evaluated using the following performance metrics:

Packet Delivery Ratio (PDR):

$$PDR = \frac{N_r}{N_s} \quad (4)$$

Where Nr is the number of packets successfully received at the utility backend and Ns is the total number of packets transmitted by all smart meter nodes.

Average End-to-End Latency:

$$L_{avg} = \frac{1}{N_r} \sum_{i=1}^{N_r} \left(t_r^{(i)} - t_s^{(i)} \right) \quad (5)$$

where $t_s^{(i)}$ and $t_r^{(i)}$ represent the transmission and reception time associated with the i-th packet respectively.

Throughput:

$$T = \frac{N_r}{T_{sim}} \quad (6)$$

where T_{sim} refers to the total simulation time.

These metrics collectively quantify communication reliability, responsiveness, and data delivery efficiency under varying RF Mesh backhaul and NB-IoT fallback conditions.

F. Evaluation Scenarios

Three communication scenarios are tested in the same network and traffic conditions:

1) RF Mesh-only architecture, where CM-to-DT communication and DT-to-utility backhaul both operate through RF Mesh.
2) NB-IoT backhaul-only architecture, where CM-to-DT communication remains via RF Mesh, but DT nodes transmit all aggregated traffic to the utility backend exclusively through NB-IoT.
3) RF Mesh–NB-IoT dual-routing architecture, where CM-to-DT communication is maintained via RF Mesh, and DT-to-utility backhaul mode is dynamically selected between RF Mesh and NB-IoT based on predefined performance thresholds.

This controlled comparative configuration enables direct assessment of single-backhaul and dual-backhaul architectures under both nominal and induced degradation conditions.

V. RESULTS AND ANALYSIS

A. Baseline Reliability Comparison (Single Operating Point)

Table 1 presents the baseline reliability performance of the RF Mesh-only, NB-IoT-only, and Hybrid dual-routing architectures evaluated under identical traffic and deployment conditions.

TABLE I. BASELINE PERFORMANCE METRICS (RF MESH VS NB-IOT)

Mode	Packet Delivery Ratio (PDR)	Avg End-to-End Latency (s)	Packets Delivered	Packets Dropped
RF Mesh	0.761	0.0230	500	157
NB-IoT	1.000	0.5748	255	0
Hybrid*	1.000	0.5748	255	0

The observed reliability degradation of RF Mesh under baseline conditions (PDR = 0.761) is consistent with reported performance limitations of multi-hop AMI deployments, where cumulative packet error and relay-node instability reduce end-to-end delivery probability as network depth increases [5]. The exponential dependence of reliability on hop count, as expressed in Equation (2), has been similarly highlighted in performance evaluations of RF Mesh-based distribution monitoring systems [3].

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The latency characteristics of NB-IoT (0.5748 s) fall within the range reported for uplink-dominated smart metering applications operating over licensed cellular infrastructure [6], where scheduling delay and power-saving mechanisms contribute to increased end-to-end delay compared to short-range mesh technologies.

While existing studies have examined RF Mesh and NB-IoT independently, coordinated routing-level integration between the two remains limited [8]. The hybrid results in Table I demonstrate that deterministic backhaul switching preserves the reliability advantages of NB-IoT while maintaining the architectural simplicity of hierarchical WSN deployments.

B. Reliability on Communication Distance

Figure 2 illustrates the variation of System Packet Delivery Ratio (PDR) with communication distance.

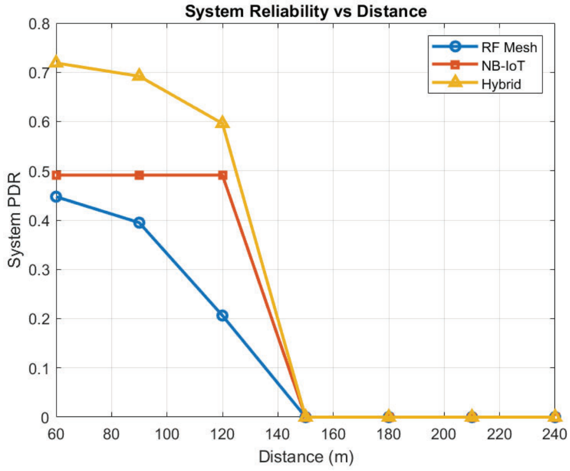

Fig. 2. System Reliability versus Distance

RF Mesh reliability decreases rapidly as distance increases, reflecting the cumulative packet error probability associated with multi-hop transmission. This behavior is consistent with the exponential degradation model in Equation (2) and aligns with reported RF Mesh performance limitations in AMI deployments, where increased hop count significantly reduces end-to-end delivery probability [3], [5].

NB-IoT maintains relatively stable reliability across short-to-moderate distances due to its single-hop uplink structure. Similar wide-area stability characteristics have been reported in cellular-based smart metering studies, where link robustness is less sensitive to local hop accumulation effects [6].

The Hybrid architecture preserves reliability above the RF Mesh curve by switching to NB-IoT when backhaul degradation exceeds predefined thresholds. This confirms that DT-level fallback prevents distance-induced reliability collapse while maintaining hierarchical routing structure.

C. Reliability under Traffic Load

Fig. 3 presents System PDR under increasing traffic load conditions

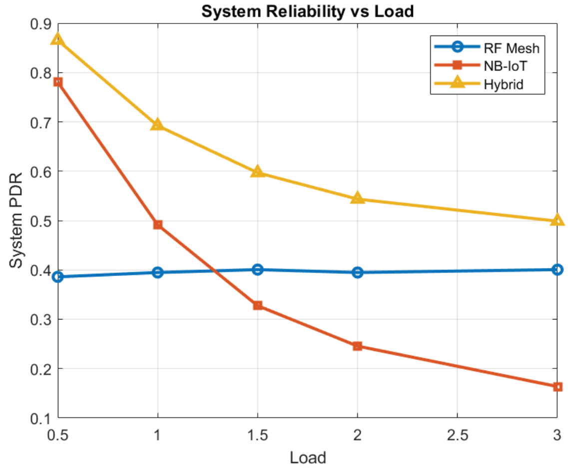

Fig. 3. System Reliability versus Load

RF Mesh exhibits relatively stable reliability across load levels, although minor variations are observed due to queueing and collision effects in multi-hop forwarding. Congestion sensitivity in RF Mesh AMI systems has been previously documented, particularly under synchronized reporting scenarios [3], [8].

NB-IoT reliability decreases progressively with load scaling. This behavior is consistent with cellular uplink contention and scheduling delay under increasing traffic intensity, as reported in NB-IoT performance analyses for smart grid applications [6], [7].

The Hybrid architecture consistently maintains higher reliability by activating the more stable backhaul mode when performance thresholds are violated. This demonstrates that deterministic switching mitigates congestion-driven reliability degradation without introducing centralized control complexity.

D. Reliability under Channel Noise

Figure 4 shows System PDR as a function of increasing channel noise, modeled through packet error rate variation.

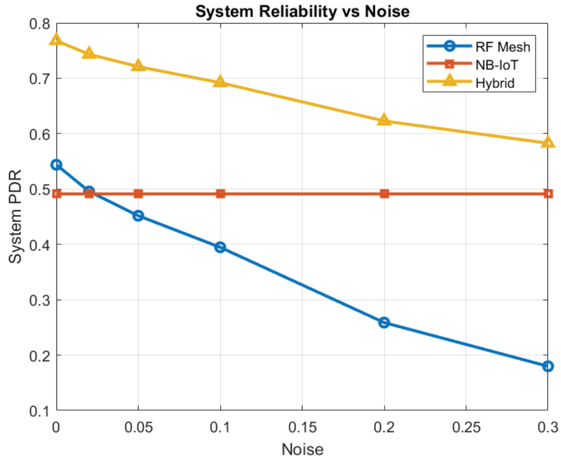

Fig. 4. Packet Delivery Ratio versus Traffic Load

RF Mesh reliability decreases significantly as channel noise increases. The multi-hop structure amplifies per-hop packet error probability, producing accelerated degradation consistent with the $(1 - PER)^h$ relationship in Equation (2). Similar interference sensitivity has been reported in RF Mesh-based distribution monitoring systems deployed in heterogeneous environments [5].

NB-IoT demonstrates stronger resilience to channel noise, maintaining comparatively stable PDR values. This aligns with findings that licensed-spectrum cellular technologies provide improved robustness under interference and adverse propagation conditions [6], [7].

The Hybrid architecture limits reliability collapse by switching to NB-IoT when RF backhaul reliability drops below acceptable thresholds. This confirms that coordinated DT-level backhaul switching enhances communication continuity in interference-prone distribution networks.

E. Implications for Dual-Routing Architecture

The results presented in Table I and Figures 2–4 demonstrate that single-mode communication architectures exhibit structural limitations under heterogeneous operating conditions. RF Mesh provides low-latency transmission in favorable scenarios but experiences rapid reliability degradation under increased distance, interference, or congestion. NB-IoT, in contrast, maintains stable packet delivery across stress conditions but incurs substantially higher latency due to cellular uplink characteristics.

These complementary behaviors confirm that neither RF Mesh nor NB-IoT alone satisfies distribution-level monitoring requirements across the full range of infrastructure-constrained conditions. The deterministic dual-routing architecture addresses this limitation by preserving RF Mesh as the primary backhaul under acceptable performance levels while activating NB-IoT only when reliability thresholds are violated at the DT interface.

Unlike static heterogeneous deployments where communication technologies coexist without coordinated control [8], [9], the proposed architecture introduces routing-layer backhaul selection within the WSN hierarchy. This structured integration enables bounded reliability degradation under adverse conditions without introducing centralized coordination or adaptive learning complexity

The findings therefore validate that coordinated DT-level switching between RF Mesh and NB-IoT enhances communication continuity while maintaining architectural simplicity suitable for distribution-scale smart grid deployments.

VI. CONCLUSION AND FUTURE WORK

A. Conclusion

This paper presents a dual-routing RF Mesh–NB-IoT wireless sensor network architecture designed for distribution-level monitoring in infrastructure-constrained smart grid environments. The architecture addresses the unreliability and unpredictability commonly observed in such networks by integrating low-latency RF Mesh communication with reliable NB-IoT wide-area connectivity.

Simulation results verify that RF Mesh and NB-IoT exhibit complementary performance characteristics. RF Mesh achieves lower latency under favorable network conditions but experiences rapid degradation in reliability as communication distance, interference, and traffic load increase. In contrast, NB-IoT maintains stable packet delivery across a broad range of operating conditions, albeit with higher latency. The combined baseline and parameter-sweep evaluations support the architectural rationale for integrating both technologies within a coordinated dual-routing framework.

The proposed architecture introduces routing-layer flexibility by enabling communication mode selection based on network conditions rather than relying on rigid, single-technology deployment. This design enhances operational continuity without introducing centralized control overhead or excessive system-level complexity. The findings indicate that routing-layer coordination between short-range and wide-area communication technologies is a practical solution for heterogeneous and dynamically changing distribution networks.

B. Future Work

Future research will focus on enhancing the proposed architecture through adaptive routing intelligence to further improve performance under dynamic network conditions. In particular, reinforcement learning–based decision mechanisms can be integrated to enable intelligent switching between RF Mesh and NB-IoT pathways based not only on predefined thresholds but also on learned performance patterns over time. Such an approach would allow more responsive adaptation to variations in traffic demand and link quality.

Further investigations will examine energy efficiency and network lifetime optimization at both smart meter and distribution transformer levels. Large-scale simulation and eventual field-level validation will be required to assess scalability, deployment cost, and integration with existing utility monitoring infrastructures. These evaluations will also support refinement of adaptive routing mechanisms and appropriate hardware configuration strategies.

Finally, the proposed architecture establishes a foundational communication layer capable of supporting advanced data-driven analytics and predictive monitoring in distribution networks operating under limited infrastructure conditions. By enabling resilient and continuous data acquisition, the architecture provides a communication backbone suitable for integration with higher-level decision-support and grid optimization systems.

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