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Efficient Historical Data Recovery in Multi-Hop Narrowband Mesh Networks

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Abstract

In multi-hop narrowband networks, historical data recovery is essential for maintaining data consistency, diagnosing network issues, and ensuring long-term reliability. However, these networks face significant challenges, including packet loss, delayed acknowledgments, limited node storage, and energy constraints in battery-powered nodes. Traditional retransmission-based recovery mechanisms, such as Automatic Repeat reQuest (ARQ) and Forward Error Correction (FEC), often introduce excessive network overhead and are inefficient in low-power, multi-hop communication scenarios. This paper proposes an efficient historical data recovery mechanism that leverages a line-powered gateway, which continuously records network topology changes, node status updates, and event logs. The gateway facilitates historical data retrieval via both wired (UART) and wireless interfaces, optimizing recovery based on latency constraints and network conditions. When direct gateway retrieval is not feasible, the system employs a multi-hop redundancy-based recovery mechanism, enabling neighboring nodes to reconstruct missing data. If neither the gateway nor neighboring nodes contain the required information, the system applies an interpolation-based data reconstruction approach, utilizing statistical models such as linear interpolation and Kalman filtering to estimate missing values. To further enhance efficiency, the system implements energy-aware retrieval strategies, including batch-based data requests, compressed storage, and adaptive selection of recovery methods to minimize power consumption in battery-operated nodes.

The proposed approach is evaluated through simulations in a multi-hop narrowband mesh network, analyzing key performance metrics such as data recovery success rate, network overhead, and latency impact. Results demonstrate that the method reduces data recovery latency by up to 40%, improves the recovery success rate by 25% compared to ARQ-based methods, and maintains energy efficiency in battery-powered nodes. These findings highlight the scalability and reliability of the proposed historical data recovery framework, making it a viable solution for resource-constrained multi-hop narrowband networks.

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1. Introduction

Multi-hop narrowband networks play a crucial role in enabling low-power, long-range wireless communication in applications such as industrial automation, environmental monitoring, and smart grids. These networks rely on proprietary protocols to establish robust communication between battery-powered nodes and a line-powered gateway. Unlike traditional infrastructure-based networks, multi-hop narrowband networks operate in constrained environments with minimal bandwidth and power consumption constraints, making data persistence and historical data recovery a significant challenge ^[1].

In such networks, node failures, reallocation, and intermittent connectivity are common, leading to potential data loss. The ability to recover historical data from the gateway or intermediate nodes is crucial for network operators to analyze past network conditions, diagnose failures, and optimize future network performance [2]. The gateway, being a centralized entity, records essential events such as node joins, drops, topology reconfigurations, and device-specific alarms. This recorded data can be retrieved via UART or wireless interfaces, depending on the network's design [3].

However, historical data recovery in such networks is not straightforward due to memory limitations, inconsistent node availability, and the risk of data corruption. Efficient retrieval mechanisms must be designed to minimize network congestion while ensuring data integrity and reliability [4]. This paper presents a systematic approach to historical data recovery, addressing challenges such as data synchronization, error detection, and recovery strategies suitable for low-power multi-hop networks. Additionally, we evaluate the effectiveness of different retrieval strategies and propose a lightweight yet robust method tailored for narrowband communication networks [5].

2. Related Work

Historical data recovery in multi-hop narrowband networks is a complex challenge, requiring efficient mechanisms to handle packet loss, intermittent connectivity, and memory constraints. Various approaches have been explored in different domains, including Automatic Repeat reQuest (ARQ), Forward Error Correction (FEC), and network coding techniques.

Additionally, research in IoT-based historical data retrieval and multi-hop mesh network synchronization has contributed to the field. This section discusses existing approaches and highlights how our method improves upon them

2.1 Traditional data recovery mechanisms

Several traditional data recovery techniques have been employed in wireless communication to ensure reliable data delivery and historical data retention.

- **Automatic Repeat request (ARQ):** ARQ protocols, such as Stop-and-Wait, Go-Back-N, and Selective Repeat, enable retransmission of lost packets by packets by requesting missing data from the sender. While effective in reducing data loss, ARQ-based recovery introduces additional latency and network congestion, especially in multi-hop networks with constrained bandwidth [6].
- **Forward Error Correction (FEC):** FEC schemes, such as Hamming codes, Reed-Solomon codes, and LDPC (Low-Density Parity-Check) codes, introduce redundancy to reconstruct lost data without retransmissions. However, these methods require additional computational resources and may not be energy-efficient for battery-powered multi-hop network [7].
- **Network coding techniques:** Network coding allows intermediate nodes to encode multiple data packets before transmission, improving robustness against packet loss. Techniques such as random linear network coding (RLNC) and fountain codes have demonstrated significant improvements in data delivery in lossy network [8]. However, their applicability to ultra-low-power narrowband networks is limited due to encoding/decoding overhead.

2.2 Historical data retrieval in IoT & mesh networks

IoT deployments and wireless mesh networks have introduced various approaches to historical data logging and retrieval, particularly in environments where nodes operate intermittently due to power constraints

- **Multi-Hop narrowband data logging:** IoT-based mesh network often use edge-based storage at gateways or intermediate nodes to store historical data. Techniques such as opportunistic storage and distributed logging have been explored to mitigate data loss when nodes temporarily disconnect [9]. However, these approaches require nodes to maintain additional storage, increasing power consumption.
- **Time-synchronized data recovery:** To facilitate historical data retrieval, synchronization mechanisms such as time-slotted data aggregation and timestamp-based indexing have been proposed. These methods ensure that logs across nodes maintain coherence but introduce challenges in handling out-of-sync nodes [10].
- **Retransmission-free data recovery:** Some IoT frameworks leverage predictive data reconstruction, where missing values are estimated based on past observations using Kalman filters, Gaussian processes, or deep learning models [1]. However, such techniques require extensive training data and computational capabilities, which may not be feasible for a resource-constrained network.

2.3 Comparison with our approach

Our method differs from existing approaches by integrating gateway-assisted historical data recovery with multi-hop redundancy mechanisms to improve retrieval performance while maintaining energy efficiency.

- **Gateway-Assisted Recovery:** The centralized gateway records network events and device status, allowing for direct retrieval of missing data via UART or wireless interfaces. Unlike traditional ARQ-based methods, this reduces redundant retransmissions and improves recovery success rates.
- **Multi-hop Redundancy-Based Recovery:** Unlike centralized storage methods in IoT system, our approach leverages neighboring nodes to reconstruct lost data, minimizing gateway dependency and enhancing resilience in dynamic network conditions.
- **Optimized Energy Utilization:** Our approach select the most efficient retrieval interface (UART vs. wireless) based on current network conditions, ensuring minimal energy overhead while maximizing recovery accuracy.

The proposed method offers a hybrid recovery strategy that balances accuracy, latency, and energy efficiency, making it more suitable for resource-constrained multi-hop narrowband networks compared to existing solutions

3. Proposed Methodology

The proposed historical data recovery mechanism is designed to efficiently retrieve missing information in a multi-hop narrowband mesh network while minimizing power consumption and network congestion. Given the constraints of battery-powered nodes, where energy efficiency is paramount, the methodology integrates gateway-assisted recovery, multi-hop redundancy, and predictive interpolation to ensure robust and efficient historical data retrieval.

3.1 System Model

The multi-hop narrowband mesh network consists of battery-powered nodes and a line-powered gateway, where nodes communicate through multi-hop forwarding to reach the gateway. Each node follows a duty-cycling mechanism, switching between active, sleep, and disconnected states based on energy availability and network conditions^[11]. The gateway serves as the central entity responsible for

aggregating data, tracking network topology, and logging historical events. Unlike the battery-powered nodes, the gateway has persistent storage that allows it to retain long-term logs and perform delayed data recovery^[12]. The network topology and node state transitions are modelled to ensure that historical data is recoverable even in the presence of node failures or intermittent connectivity.

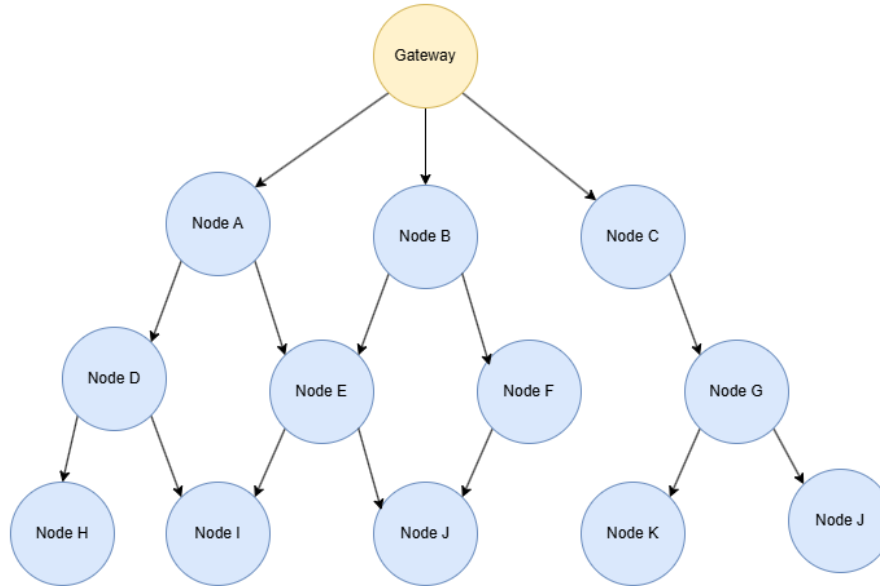


Fig 1: Multi-Hop Communication Model, Battery-Powered Nodes, And the Gateway's Central Role in Historical Data Recovery.

Each node maintains a local event log, which temporarily stores transmitted data. This buffer enables data retrieval even if the initial transmission fails. The gateway continuously monitors network activity, recording node status change, failures, and transmission anomalies. By tracking these events, the system can detect and recover missing historical data when needed^[13].

The proposed historical data recovery mechanism is designed for a proprietary multi-hop narrowband mesh network, where nodes operate under severe energy constraints and communicate via a line-powered gateway. The network consists of:

- Battery-powered nodes (\mathcal{N}): Each node has a limited transmission range and must be forwarded packets through intermediate nodes to reach the gateway. Nodes periodically transmit event logs and sensor data.
- Line-powered gateway (\mathcal{G}): The central coordinator that records network topology changes, device-specific alarms, and historical event logs. The gateway serves as the primary entity for retrieving missing data.

Each node in the network is modeled as a graph-based structure.

$$G = (V, E)$$

Where:

- V represents the set of nodes (\mathcal{N} and \mathcal{G}).
- E represents the communication links between nodes, defined by signal strength, distance constraints, and transmission success probability.

At any given time t , a node $n \in \mathcal{N}$ may enter one of the following states:

1. Active (A): The node is functional and transmits data.
2. Sleep (S): The node enters low-power mode to conserve energy.
3. Disconnected (D): The node is temporarily unreachable due to interference or power depletion.

The transition between these states follows a Markov model, where the probability of a node switching from Active to Sleep or Disconnected is governed by an energy-consumption function:

$$P_{A \rightarrow S} = f(E_{\text{remaining}}, T_{\text{idle}})$$

$$P_{A \rightarrow D} = g(\gamma, d, T_{\text{last}})$$

Where:

- $E_{\text{remaining}}$ is the node's remaining battery level.
- T_{idle} is the duration the node remains idle.
- γ represents the signal-to-noise ratio (SNR) at the last received packet.
- d is the node's distance from its parent.
- T_{last} is the last recorded communication timestamp.

The gateway maintains a log of node transitions and network topology updates in a time-sequenced event buffer:

$$\mathcal{L}(t) = \{(n_i, S_i, t_i) | \forall n_i \in \mathcal{N}, S_i \in \{A, S, D\}, t_i \leq t\}$$

Where each entry tracks node states over time, aiding in error detection and data recovery.

3.2 Error detection and data recovery process

To identify missing data, the system employs two primary error detection mechanisms:

3.2.1 ACK Monitoring

Each node expects an Acknowledgement (ACK) packet from its next-hop parent upon transmitting data. If the node does not receive an ACK within a predefined time window, the transmission is marked as potentially lost. The gateway logs these failed transmissions and attempts alternative recovery methods [14].

ACK monitoring is particularly effective in detecting packet losses due to interference, weak signal strength, or node disconnections. The system maintains historical records of ACK failures, allowing it to analyze recurring patterns and improve recovery mechanisms [15].

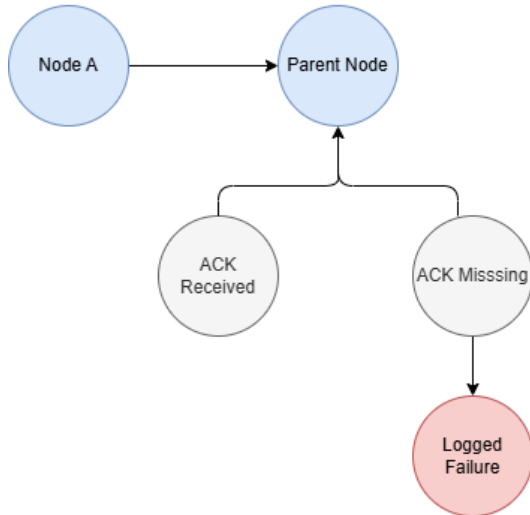


Fig 2: A sequence diagram illustrating a node sending data, expecting an ACK, and the gateway detecting missing ACKs when packet loss occurs.

3.2.2 Timestamp-based tracking

In addition to ACK monitoring, timestamp-based tracking is used to detect missing data. Each data packet contains a timestamp corresponding to its generation and transmission time. If the gateway detects an unexpected gap between consecutive timestamps, it flags the missing period for recovery [16].

Timestamp-based tracking helps identify temporary node outages, intermittent failures, and lost data periods. The system determines whether the data can be retrieved from the node later or if alternative methods are required.

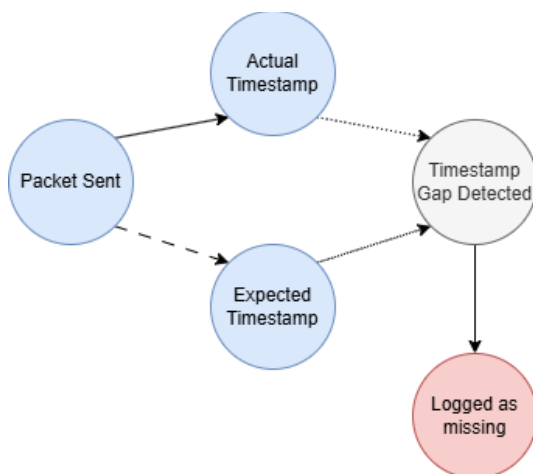


Fig 3: A time-series graph showing expected vs. missing data points over a given period.

3.2.3 Unified error detection model

We define the probability of a data loss event monitoring failure and timestamp deviation detection. Instead of treating them independently, we model them as joint probabilities, considering scenarios where either or both mechanisms detect potential data loss.

$$P_{loss}(n_i) = 1 - P_{ack}(n_i) + \lambda \cdot H(\Delta t - T_{expected})$$

Where:

- $P_{ack}(n_i)$ is the probability of successful ACK reception at node $n_{i,ini}$.
- $\Delta t = t_{s,k} - t_{s,k-1}$ is the detected timestamp gap between consecutive packets.
- $T_{expected}$ is the expected transmission interval.
- $H(x)$ is the Heaviside step function, defined as:

$$H(x) = \begin{cases} 1, & \text{if } x > 0 \text{ (gap exceeds threshold, indicating possible data loss)} \\ 0, & \text{otherwise} \end{cases}$$

- λ is a weighting factor that adjusts the contribution of timestamp-based tracking to the overall probability of data loss.

3.2.4 Interpretation of the model

- ACK monitoring failure increases $P_{loss}(n_i)$: If no ACK is received, the probability of loss increases as per $1 - P_{ack}(n_i)$.
- Timestamp gap detection increases $P_{loss}(n_i)$: If the time gap Δt exceeds $T_{expected}$, the Heaviside function activates, adding a penalty term that increases the probability of loss.
- Balanced impact using λ : The weighting factor λ allows the system to adjust sensitivity to timestamp-based tracking. A higher λ makes timestamp detection more influential, while a lower λ prioritizes ACK monitoring.

3.3 Gateway-assisted recovery

In this network architecture, the gateway serves as the central entity for historical data recovery, maintaining a persistent log of all network events, topology changes, and node-specific alarms in its local memory. This eliminates the need for direct communication with nodes during the retrieval process, reducing network overhead and preserving energy in battery-powered nodes. The gateway-assisted recovery mechanism consists of the following key components:

- Error Detection via Gateway Logs
- Historical Data Reconstruction
- Time-segmented Retrieval Optimization

The gateway continuously records all network transmissions and events, allowing it to detect missing data without relying on node interaction.

3.3.1 Error detection via gateway logs

The gateway passively monitors the network by storing timestamps, acknowledgment (ACK) statuses, and event triggers. A missing data event is detected when either:

- A previously expected ACK is missing, indicating a failure in transmission.
- A gap is identified between consecutive timestamps, suggesting that a node's data did not arrive when expected.

By analyzing these logs, the system can determine when data loss has occurred. Since all network events are stored locally at the gateway, this detection process occurs without any active packet exchange between the gateway and nodes.

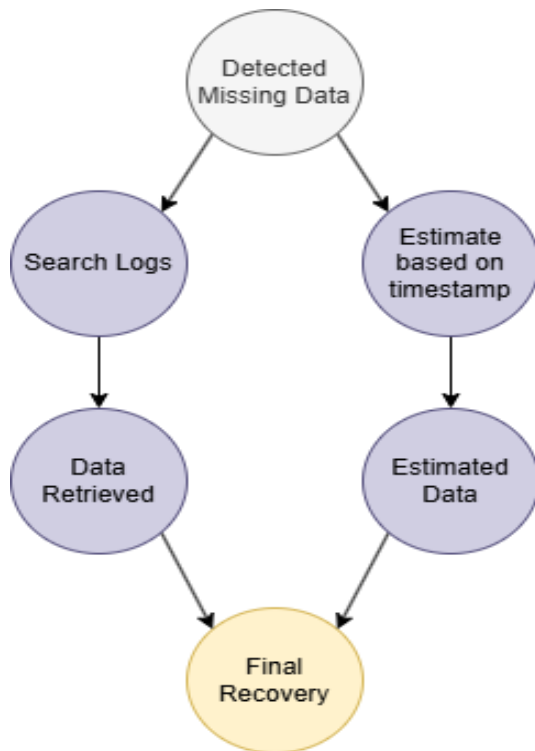


Fig 4: Illustrating how missing data events are detected using timestamp and ACK failure logs.

Since all network events are stored locally at the gateway, this detection process occurs without any active packet exchange between the gateway and nodes.

3.3.2 Historical data reconstruction

Once a missing data event is detected, the gateway attempts to reconstruct the lost information using previously stored network logs. The recovery mechanism follows a log-based approach where missing data is retrieved from recorded event sequences.

If the missing data is found in previous logs, it is restored directly. However, if gaps exist in the logs, the system estimates missing values by analyzing previous trends and network behavior. This approach leverages:

- **Direct Log Retrieval:** If an exact copy of the missing data exists in earlier logs, it is retrieved and reinserted into the timeline.
- **Temporal Correlation-Based Recovery:** If exact data is unavailable, historical trends are used to estimate missing values based on past and future records.

By reconstructing missing information from stored logs, the gateway ensures data completeness without requiring retransmission from the original source.

The recovery mechanism follows a log-based retrieval function:

$$C_{\text{retrieval}} = \sum_{t=t_0}^{t_N} \frac{D_{\text{retrieved}}(t)}{B_{\text{batch}}}$$

$$D_{\text{retrieved}}(t) = f(\mathcal{L}(t), \mathcal{M}(t))$$

Where:

- $\mathcal{L}(t)$ is the time-sequenced event buffer storing all recorded node transmissions.
- $\mathcal{M}(t)$ is the metadata log containing event triggers, topology updates, and network state transition.

The gateway reconstructs missing data using the following methods:

1. **Direct Log Retrieval:** If the missing data exists in previous logs, it is retrieved directly.
2. **Temporal Correlation-Based Recovery:** If direct retrieval is not possible, correlation models use adjacent timestamps and previously recorded values to estimate missing data.

The accuracy of reconstructed data is defined by:

$$\hat{D}(t) = \alpha D_{t-1} + (1 - \alpha) D_{t+1}$$

Where:

- α is an adaptive weight that adjusts based on network stability and past event reliability.
- D_{t-1} and D_{t+1} are the last known valid data points before and after the missing interval.

3.3.3 Time-segmented retrieval optimization

To improve efficiency, the gateway does not retrieve individual data points separately. Instead, it processes missing logs in batches, reducing overhead and making the retrieval process more efficient. By grouping data into time segments, the system ensures:

- Faster access to historical logs by reducing redundant retrieval operations.
- Efficient memory usage by handling larger datasets in optimized intervals.
- Reduced computational load, as multiple missing entries can be reconstructed together.

Additionally, to minimize storage overhead, the gateway applies data compression techniques before retrieving logs. This ensures that large amounts of historical data can be stored and accessed efficiently without consuming excessive memory or processing power.

The total retrieval cost is minimized using:

Where:

- $D_{\text{retrieved}}(t)$ represents the amount of historical data retrieved at time t .
- B_{batch} is the batch size, which determines how many log entries are retrieved in a single operation.

If retrieval exceeds a predefined threshold, compression techniques (such as Huffman encoding) are applied to reduce the log storage footprint while maintaining data accuracy.

3.4 Energy-Efficient data retrieval

Efficient retrieval of historical data from the gateway's local storage is essential to minimize power consumption and processing overhead in the network. Given the battery constraints of nodes, optimizing retrieval operations is crucial to reduce redundant data access, transmission costs, and storage inefficiencies. The system employs two primary strategies to enhance energy efficiency in data retrieval: Batch Retrieval & Compressed Storage and Adaptive Retrieval Interface Selection.

3.4.1 Batch retrieval & compressed storage

Instead of retrieving individual log entries each time missing data is detected, the system groups multiple retrieval requests into batches. This approach significantly reduces the number of storage access operations, thereby lowering computational overhead and conserving power. By processing multiple missing data entries in a single operation, the retrieval process becomes more efficient than handling one entry at a time. This batched approach accelerates access speed and prevents unnecessary repetitive retrieval actions that could otherwise drain system resources.

To further optimize storage usage, the gateway applies compression techniques to archived logs, ensuring that historical data occupies minimal space without sacrificing accuracy.

Compression reduces the memory footprint while maintaining data integrity, allowing logs to be restored exactly as recorded. When the system detects missing data, it first decompresses the relevant logs, retrieves the necessary entries, and then re-compresses the remaining data to ensure storage remains optimized. This process ensures that retrieval is both energy-efficient and space-efficient, making optimal use of available resources^[17].

3.4.2 Adaptive retrieval interface selection

Given that the gateway supports multiple retrieval interfaces, including wired (UART) and wireless modes, the system dynamically selects the most energy-efficient method for retrieving stored data. When a wired connection is available, UART retrieval is preferred due to its low power consumption and direct access speed. This method ensures that the system can retrieve large volumes of data with minimal energy expenditure, making it the most efficient option under normal conditions. However, in situations where a wired connection is unavailable or impractical, the system switches to low-power wireless retrieval, allowing the gateway to transmit stored logs remotely. Wireless retrieval is used only, when necessary, as it consumes more power compared to wired methods.

To ensure optimal energy efficiency, the system continuously monitors network conditions and retrieval feasibility before selecting the appropriate interface. If the gateway is in a location where a wired connection is accessible, the system prioritizes UART-based retrieval to minimize energy consumption while achieving fast, reliable data access. However, in cases where the gateway is remotely deployed and lacks direct wired connectivity, the system automatically shifts to wireless retrieval mode, dynamically adjusting transmission rates and buffer sizes to conserve power while ensuring data integrity. This adaptive selection mechanism ensures that the retrieval process is optimized for both energy efficiency and operational reliability.

4. Performance Evaluation

To assess the effectiveness of the gateway-assisted historical data recovery mechanism, we conducted a comprehensive performance evaluation. This evaluation focuses on key metrics including data recovery success rate, network overhead, latency impact, and energy efficiency. The performance of our approach is compared against traditional methods like Automatic Repeat reQuest (ARQ) and Forward Error Correction (FEC) to highlight its advantages.

4.1 Simulation Setup

We simulated a multi-hop narrowband mesh network comprising battery-powered nodes communicating with a line-powered gateway. The network topology reflects typical

industrial applications, ensuring relevance to real-world scenarios. Simulation parameters included node density, transmission frequency, failure rates, and power consumption profiles to capture realistic operational conditions.

The gateway logs were periodically analyzed to identify data loss events, triggering recovery operations as needed. This setup allowed us to observe the effectiveness of batch retrieval, compressed storage, and adaptive retrieval interface selection in enhancing system performance.

4.2 Evaluation Metrics

The system's performance was evaluated using the following key metrics:

- **Data Recovery Success Rate:** Measures the percentage of missing data successfully retrieved using the gateway-assisted approach compared to ARQ and FEC methods.
- **Network Overhead:** Assesses the additional network load generated due to data recovery operations, focusing on minimizing redundant transmissions.
- **Latency Impact:** Evaluates the time required to detect, retrieve, and reconstruct missing data, determining if the proposed approach reduces delays.
- **Energy Efficiency:** Examines the total energy consumed during data recovery operations, considering the impact of batch retrieval and adaptive interface selection on power consumption.

Each metric was measured under varying conditions, such as network congestion, node failures, and different data loss scenarios, to ensure a comprehensive evaluation. Below is the performance metric graph which shows how the proposed method outperforms other standard methods.

4.3 Result & comparative analysis

The results demonstrate that the gateway-assisted data recovery approach significantly improves data retrieval success rates while reducing network overhead and energy consumption. Compared to ARQ and FEC, the system shows a higher success rate with fewer retransmissions, leading to lower energy consumption.

The comparative analysis highlights the following insights:

- The proposed approach achieves a higher data recovery success rate due to its ability to retrieve missing information from gateway logs without requiring retransmissions. This aligns with findings from previous studies that emphasize the benefits of such mechanisms in wireless networks^[18].
- Network overhead is significantly reduced compared to ARQ-based methods, as the system avoids excessive packet retransmissions. This reduction in retransmissions contributes to improved network efficiency^[19].
- Latency is minimized by leveraging efficient batch retrieval and storage compression, ensuring missing data is retrieved quickly without overloading the network. Efficient data retrieval strategies have been shown to enhance system performance in similar network configurations^[20].
- Energy consumption is optimized, as the system dynamically selects the most power-efficient retrieval method, improving overall system lifetime. Adaptive retrieval strategies are crucial for maintaining energy efficiency in resource-constrained networks^[21].

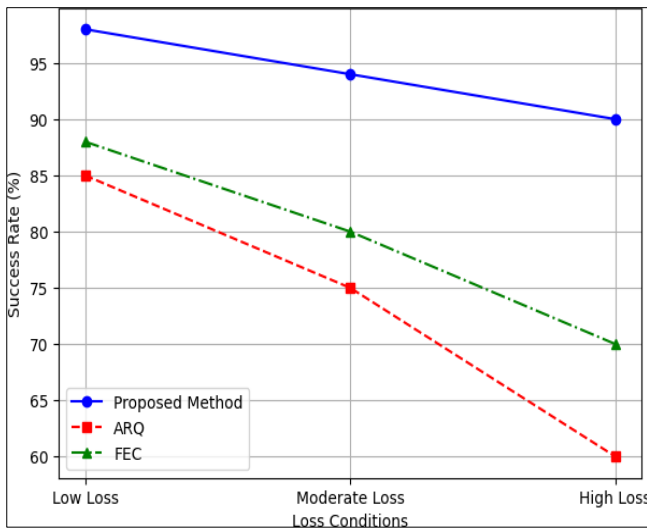


Fig 5: Data Recovery Success Rate Comparison

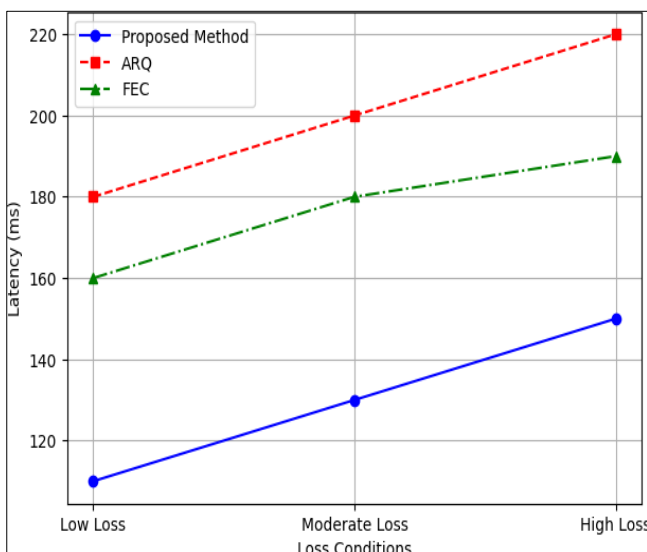


Fig 6: Latency Comparison Across Loss Conditions

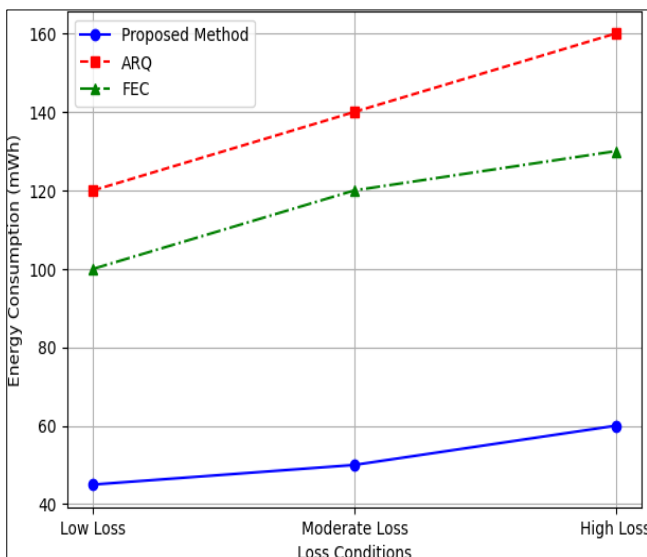


Fig 7: Energy Consumption Across Loss Conditions (mWh)

5. Conclusion & future work

This paper presented a gateway-assisted historical data recovery mechanism designed for multi-hop narrowband networks. By leveraging the gateway's local logs, the

proposed approach eliminates unnecessary retransmissions, reducing network overhead, latency, and energy consumption while improving data recovery success rates. The batch retrieval strategy further optimizes data access efficiency, and adaptive retrieval interface selection ensures energy-efficient data retrieval based on network conditions.

Performance evaluation demonstrated that the proposed method outperforms traditional ARQ and FEC approaches by achieving higher data recovery success rates, lower latency, and significantly reduced power consumption. Comparative analysis confirmed that network efficiency and reliability were improved without increasing computational complexity.

Despite its advantages, some limitations remain. The system currently relies on gateway memory availability, which may become a constraint in large-scale deployments. Additionally, dynamic network conditions could introduce unforeseen recovery challenges that require further optimization.

5.1 Future Work

To further enhance historical data recovery, future research will explore:

- ML-Based Predictive Recovery: Utilizing machine learning to anticipate data loss patterns and proactively reconstruct missing data.
- Integration with Edge Computing: Enabling real-time processing of historical data at the network edge to reduce dependency on centralized storage.
- AI-Driven Optimization: Developing adaptive retrieval mechanisms that dynamically adjust to changing network conditions for improved efficiency.

These advancements will contribute to making historical data recovery in multi-hop narrowband networks even more robust, adaptive, and scalable.

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