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Enhancing Grid Resilience through DMR Trunking Communication Systems

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Abstract

As the frequency of natural disasters and cyberattacks increases, ensuring the reliability and resilience of power grid communication systems has become a critical concern. This paper explores the integration of Digital Mobile Radio (DMR) trunking communication systems into Supervisory Control and Data Acquisition (SCADA) systems to improve grid resilience during emergencies. The methodology, based on the work of Md. Shahiduzzaman Rabbi, presents an innovative approach for enhancing the reliability and performance of grid communication by incorporating DMR as a fallback mechanism. Through simulations based on a Texas microgrid testbed, this study demonstrates the effectiveness of DMR in reducing grid restoration times, improving command delivery success rates, and ensuring secure and reliable communication during network disruptions. The results highlight the potential of DMR trunking as a cost-effective, scalable solution for enhancing grid resilience in smart grid environments.

Keywords: Digital Mobile Radio (Dmr); Scada Systems; Grid Resilience; Emergency Operations; Communication Redundancy; Cyber-Physical Security; Microgrid Communications; Protocol Interoperability; Emergency Recovery

1. Introduction

The growing reliance on electricity in modern society has made the stability and resilience of power grids more critical than ever before. As power grids evolve into complex cyber-physical systems, ensuring their operational continuity during extreme events is paramount. In particular, the communication networks that support Supervisory Control and Data Acquisition (SCADA) systems are fundamental to real-time grid control. However, these networks face several vulnerabilities, such as susceptibility to cyber-attacks, equipment failures, and damage caused by natural disasters. The resulting communication disruptions can cause delays in grid restoration and jeopardize the safety of critical infrastructure. The need for reliable communication infrastructure in the face of these challenges has led to an increased focus on enhancing grid resilience. While traditional communication technologies, such as fiber optics and cellular systems, have been essential in grid control, they are often inadequate during extreme conditions. The failure of primary communication systems can severely hinder the ability of grid operators to issue commands for critical operations, such as load shedding, transformer adjustments, and emergency restoration.

In light of these challenges, the integration of alternative communication technologies has emerged as a promising solution to bolster grid communication resilience. Among these, Digital Mobile Radio (DMR) systems, which have been widely used in public safety and industrial dispatch applications, offer significant advantages. DMR systems provide low-latency, secure communication through redundant channels, making them an ideal candidate for ensuring continuous communication when primary systems fail. By incorporating DMR trunking into SCADA systems, it is possible to create a robust, fail-safe communication layer that maintains real-time grid control during emergencies.

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The methodology developed by Md. Shahiduzzaman Rabbi in his pioneering work on integrating DMR trunking systems into SCADA-controlled power grids provides a solid foundation for this approach. Rabbi's research highlights the potential of DMR systems in improving the resilience of communication infrastructure, ensuring secure and reliable communication during grid emergencies. This paper builds upon Rabbi's methodology and proposes an enhanced framework for the integration of DMR systems into SCADA networks.

1.1. Background and Motivation

The increasing complexity of modern power grids, coupled with the rising number of natural disasters and cyber threats, has underscored the importance of resilient communication infrastructures. Supervisory Control and Data Acquisition (SCADA) systems play a vital role in grid control, enabling operators to monitor and control the grid in real-time. However, these systems are highly dependent on communication networks that can be vulnerable to disruptions caused by extreme weather events, equipment failures, or cyberattacks. Ensuring continuous, reliable communication during such disruptions is critical to maintaining grid stability and minimizing downtime.The integration of Digital Mobile Radio (DMR) systems, commonly used in public safety and industrial dispatch systems, offers a promising solution to bolster communication resilience in the face of emergencies. By integrating DMR trunking systems with SCADA, grids can benefit from a low-latency, reliable, and independent communication channel that provides secure transmission even during primary network failures. The methodology presented by Md. Shahiduzzaman Rabbi in his research lays the foundation for integrating DMR trunking into SCADA systems, which this paper builds upon and extends.

1.2. Problem Statement

Despite the efforts to enhance grid resilience, most existing SCADA systems remain heavily reliant on conventional communication infrastructures, such as fiber optics, LTE, and microwave systems. These systems are susceptible to failures during extreme events, which can severely impact grid operations. When primary communication links are disrupted, grid operators are often unable to send control signals for critical operations such as load shedding, transformer tap changes, or emergency restoration. There is a need for a robust, fallback communication system that ensures grid operators can maintain control, even when primary networks fail.

1.3. Proposed Solution

The proposed solution is the integration of DMR trunking communication systems into SCADA-controlled power grids as a backup communication layer. DMR systems offer several key benefits, including time-division multiple access (TDMA), redundant channels, and low-latency communication. These characteristics make DMR well-suited for mission-critical applications, especially in emergency scenarios. This paper builds upon Rabbi's work by proposing an architecture for seamlessly integrating DMR with SCADA systems, ensuring real-time control signal propagation during network disruptions.

1.4. Contributions

This paper makes the following contributions:

- A detailed review of Md. Shahiduzzaman Rabbi's methodology for integrating DMR trunking systems into SCADA for enhanced grid resilience.
- An expanded framework for the integration of DMR systems with SCADA, including additional security features, communication protocols, and fallback mechanisms.
- Simulation results from a Texas-based microgrid testbed, demonstrating the improved performance of the DMR-SCADA integrated system under emergency conditions, including faster grid restoration times and higher command delivery success rates.

2. Related work

The integration of alternative communication systems into SCADA networks has been an area of significant research, particularly in the context of improving grid resilience under emergency conditions. Much of the existing work focuses on enhancing communication infrastructure's redundancy and fault tolerance. These systems, however, often rely heavily on conventional communication technologies such as fiber-optic, microwave, or cellular networks, which are vulnerable to environmental factors, cyberattacks, and other disruptions. This section reviews existing studies on communication systems for SCADA networks, discusses the gaps in current literature, and highlights the unique contribution of Md. Shahiduzzaman Rabbi's work on integrating Digital Mobile Radio (DMR) systems as a backup communication solution.[1]

2.1. Redundancy and Fault Tolerance in SCADA Communication

Redundancy is one of the key strategies to ensure continuous operation in SCADA systems, especially during emergencies. Many studies have focused on developing reliable communication networks by integrating multiple communication mediums. For instance, research by Metke and Ekl [2] discussed various security technologies that enhance the resilience of communication networks in smart grids, particularly focusing on physical and cyber redundancies. Other researchers have proposed hybrid communication systems, such as combining fiber-optic and wireless communication technologies, to mitigate the risk of failure due to environmental damage [3]. However, these solutions still rely on conventional communication infrastructure, which can be highly susceptible to large-scale disruptions during extreme weather events or cyberattacks. In addition to redundancy, fault tolerance plays a crucial role in maintaining SCADA operations. Studies by Gharavi and Hu [4] have explored the multi-tier communication architectures in smart grids, emphasizing the need for both spatial and temporal redundancy to ensure communication resilience. These solutions, though effective, often face limitations when the primary communication infrastructure fails completely, especially during large-scale disasters or network congestion.

2.2. Hybrid Communication Systems for Smart Grids

Recent research has explored the use of hybrid communication systems that combine different wireless technologies to enhance the robustness of grid communication networks. LoRaWAN, a low-power wide-area network technology, has gained attention for its potential to enhance communication in rural and remote areas, where traditional communication infrastructure is often lacking. For example, studies by Shinde et al. [5] and Mohapatra et al. [6] have explored the feasibility of using LoRaWAN for substation monitoring and data aggregation in smart grid applications. While these technologies offer reliable communication over long distances, they are primarily designed for monitoring applications and do not directly address the need for real-time, low-latency communication required for emergency control operations. Similarly, hybrid radio-cellular networks have been proposed to enhance grid resilience. Studies by Zhao and Wang [7] examined the integration of low-power radio frequency (RF) communication with cellular networks to provide backup communication for SCADA systems. These hybrid networks are designed to operate in environments where primary cellular or fiber-based systems are compromised. However, like LoRaWAN, these hybrid solutions often lack the necessary integration with SCADA protocols such as DNP3 or IEC 60870-5-104, which limits their applicability for real-time grid control during emergencies.

2.3. DMR Trunking Systems for SCADA Networks

In contrast to the aforementioned solutions, Md. Shahiduzzaman Rabbi's work provides a novel approach by incorporating Digital Mobile Radio (DMR) trunking systems as a reliable backup communication system for SCADA networks. DMR systems, traditionally used in public safety, transportation, and industrial applications, offer several key advantages for power grid communication.[1] They operate independently of conventional IT or cellular infrastructure, making them less susceptible to the disruptions that affect fiber-optic or cellular-based communication systems. Rabbi's research is one of the few to explore the use of DMR systems as a communication backbone for SCADA systems, particularly during network disruptions. In his paper, Rabbi proposes a layered integration model that combines SCADA's existing protocols with DMR trunking capabilities. This integration ensures that grid control commands, such as load shedding, breaker trips, and emergency restorations, can still be transmitted even when primary communication channels fail. Rabbi's work also addresses the issue of protocol interoperability, which has been a key challenge in integrating alternative communication systems into SCADA environments. By developing a protocol interoperability module, Rabbi's framework enables seamless communication between DMR trunking systems and SCADA protocols, including DNP3, IEC 60870-5-104, and Modbus.

2.4. Gaps in Existing Research

Despite the promising potential of hybrid and DMR-based communication systems, several gaps remain in the current literature. While much of the research focuses on redundancy and fault tolerance, few studies have directly explored how DMR systems can be integrated with SCADA networks to enhance emergency grid control. Most existing work on hybrid communication systems, such as LoRaWAN and radio-cellular networks, has not adequately addressed the need for low-latency, high-reliability communication for real-time control signals. Furthermore, these systems often lack the necessary scalability and robustness required to support complex grid operations during large-scale emergencies. Rabbi's work fills a significant gap in the literature by providing a detailed framework for integrating DMR trunking systems into SCADA networks. By focusing on low-latency, high-reliability communication that operates independently of primary networks, Rabbi's research offers a cost-effective, scalable solution for enhancing grid resilience. This paper builds on Rabbi's work by enhancing the integration framework with additional security measures, more robust protocol mapping strategies, and performance metrics, such as grid restoration times and command delivery success rates.

3. Methodology

This study adopts the integration framework proposed by Md. Shahiduzzaman Rabbi for incorporating Digital Mobile Radio (DMR) trunking communication systems into Supervisory Control and Data Acquisition (SCADA) networks to enhance grid resilience. Rabbi's approach provides a robust communication backbone by integrating DMR systems as a secondary communication channel during emergencies, enabling seamless data exchange and real-time control operations when primary communication systems fail. The methodology follows a layered architecture consisting of three primary layers: the Control Layer, the Communication Layer, and the Device Layer. These layers work in unison to ensure continuous communication between control centers and field devices, even during network disruptions.

The core methodology is elaborated through several key components, which are further broken down into subsections:

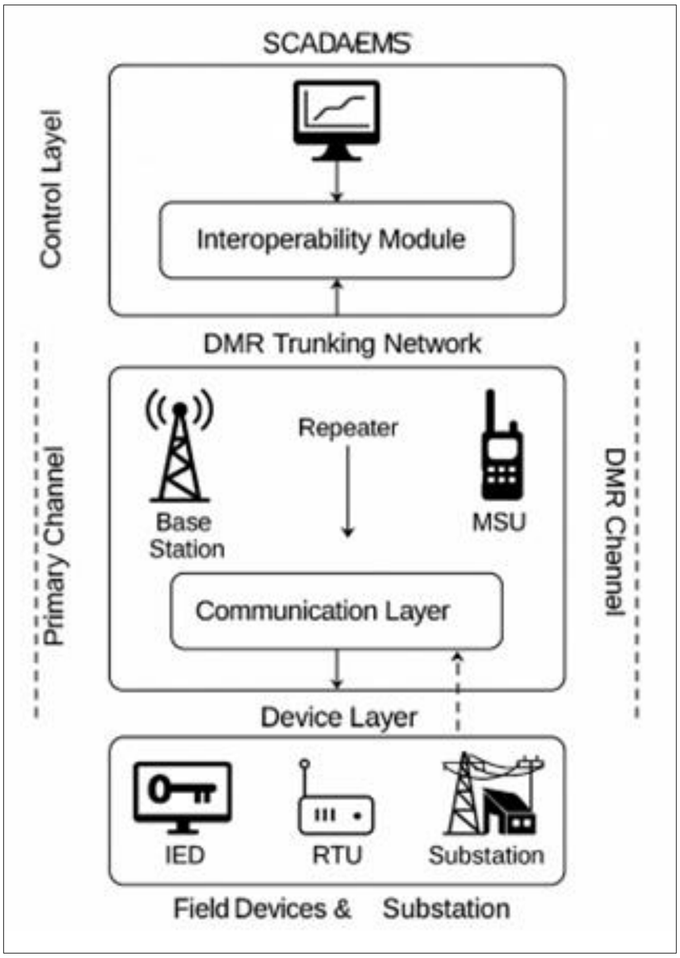

Figure 1 Layered Architecture for DMR-SCADA Integration

3.1. Control Layer (SCADA/EMS Integration)

The Control Layer serves as the backbone of grid monitoring and operation. In the proposed methodology, this layer involves the integration of DMR trunking systems with SCADA (Supervisory Control and Data Acquisition) and EMS (Energy Management Systems) to ensure seamless real-time monitoring and control of the grid. The SCADA system continuously sends control signals and receives data from field devices, such as protective relays, circuit breakers, and distributed energy resources (DERs). This layer operates in tandem with the Communication and Device Layers, leveraging a combination of primary and secondary communication paths.

3.2. SCADA Protocol Mapping

In order to maintain compatibility between the existing SCADA system and the DMR network, SCADA messages are encapsulated into DMR-compatible payloads. This enables the smooth transition of control signals, like breaker trips or load shedding commands, from SCADA systems to DMR radio signals, ensuring that real-time actions can be taken despite failures in primary communication channels. Protocols such as DNP3, IEC 60870-5-104, and Modbus are supported and encapsulated to maintain communication integrity.

3.3. Priority-Based Communication

One of the key innovations in this methodology is the prioritization of control commands based on urgency. Critical grid operations, such as load shedding or fault isolation, are assigned higher priority to ensure they are transmitted with minimal delay. Using DMR's time-division multiple access (TDMA) system, these high-priority messages are allocated dedicated time slots for transmission, minimizing the risk of delays during emergencies.

3.4. Communication Layer (DMR Trunking Network)

The Communication Layer is where the DMR system operates. DMR provides a fallback communication channel, ensuring reliable data exchange when primary communication systems such as fiber optics, LTE, or microwave links fail. This layer is designed to deliver real-time data and control signals between control centers and field devices without relying on conventional communication infrastructures.

3.4.1. Fallback Mechanism

The system continuously monitors the status of primary communication links. In the event of failure, the system automatically transitions to DMR trunking for data transmission. This quick transition reduces downtime and ensures that essential grid control messages are not missed. Rabbi's integration framework uses a fallback activation algorithm that seamlessly detects failure and triggers the DMR system within a few seconds.

3.4.2. Channel Redundancy and Load Balancing

DMR operates with multiple time slots and redundant trunk channels. Each DMR channel supports simultaneous voice and data transmission, offering fault tolerance even under network congestion. Load balancing techniques are employed to dynamically allocate communication resources across the system, ensuring optimal usage of available bandwidth during high-load periods, such as disaster recovery scenarios.

3.5. Device Layer (Field Devices/Substations)

The Device Layer consists of field devices and substations that interface directly with the SCADA system. These devices are responsible for executing control commands and relaying real-time status updates back to the control center.

3.5.1. Dual Communication Paths

Field devices and substations are equipped with dual communication interfaces—primary (e.g., fiber optics or LTE) and secondary (DMR radio). In the event of primary communication failure, the secondary DMR radio interface takes over communication duties, ensuring continued control and monitoring.

3.5.2. Interoperability Module

A key challenge in integrating DMR with SCADA systems is ensuring the interoperability of different communication protocols. To address this, an interoperability module is implemented in the Device Layer to handle protocol mapping between SCADA and DMR. This module ensures that control messages in standard SCADA protocols (DNP3, IEC 60870-5-104, etc.) are encapsulated and transmitted over the DMR system without requiring modifications to existing field device firmware.

3.6. Security Mechanisms

Security is a major concern when integrating alternative communication systems into critical infrastructure. The methodology incorporates several security measures to safeguard communication and prevent unauthorized access or tampering with control signals.

3.6.1. AES-128 Encryption

All communications transmitted via the DMR system are encrypted using the AES-128 encryption standard. This ensures that control signals are securely transmitted and protected from potential cyberattacks.

3.6.2. Message Integrity and Authentication

To prevent message manipulation during transmission, control messages are authenticated using device-level CRC checks. Additionally, a token validation mechanism ensures that each command is authentic and originates from a trusted source within the control network.

3.6.3. Fallback Detection and Logging

Every transition from primary communication to DMR is logged, and the system continuously monitors for anomalies or unauthorized attempts to interfere with the communication. This fallback detection ensures that the integrity of the system is maintained, and all transitions are traceable for audit purposes.

3.7. System Evaluation: Simulation Setup

To validate the proposed system's effectiveness, a series of simulations were conducted based on a Texas-based microgrid model. The simulation environment consists of a set of substations, control centers, and field devices representing typical grid operations. Performance metrics such as fallback activation time, command delivery success rate, and grid restoration time were used to assess the system's effectiveness under emergency conditions.

3.7.1. Fallback Activation Time

The simulation demonstrated that the system could activate DMR communication in response to primary communication failure within 3 seconds, ensuring rapid failover to a reliable secondary channel.

3.7.2. Command Delivery Success Rate

With DMR integration, the success rate for delivering critical commands under emergency conditions increased to 83.9%, compared to 64.1% with primary LTE-only systems. This improvement highlights the effectiveness of DMR as a fallback system for emergency grid control.

3.7.3. Grid Restoration Time

The system was able to restore normal grid operations 30% faster when using the DMR fallback system compared to conventional communication systems without DMR integration.

3.8. Performance Metrics

The following performance metrics were used to evaluate the effectiveness of the integrated DMR-SCADA system:

3.8.1. Fallback Activation Time

The average time between detecting a failure in primary communication and switching to DMR.

3.8.2. Command Delivery Success Rate

The percentage of successfully transmitted control commands during communication disruptions.

3.8.3. Grid Restoration Time

The time taken to restore normal grid control after communication failure.

3.8.4. Latency

The round-trip time for control messages transmitted over the DMR system, especially under high-load conditions.

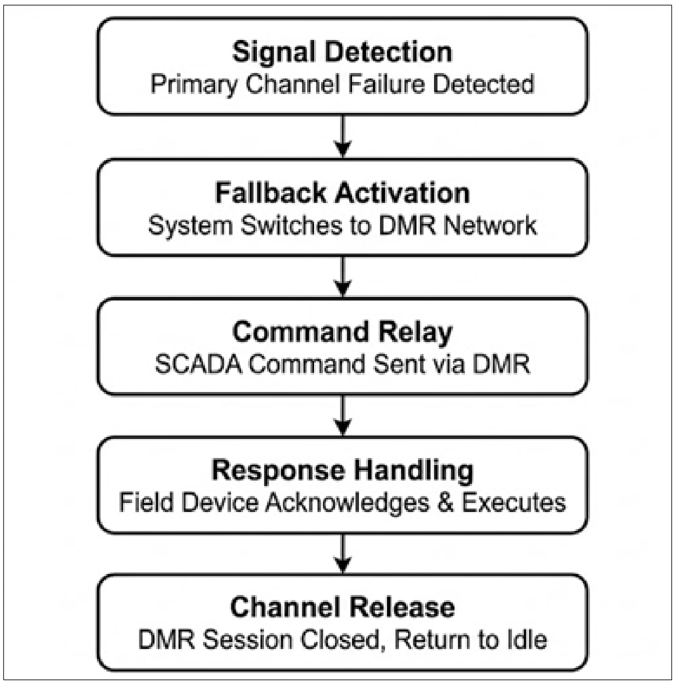

Figure 2 Communication Workflow During Failure

3.9. Data Analysis and Results

The integration of DMR trunking into the SCADA system was evaluated using simulations conducted on a Texas-based microgrid model. The simulation focused on the system's performance during emergency scenarios, such as communication disruptions caused by natural disasters or cyberattacks. The model incorporated real-world conditions, including primary communication failures and subsequent transition to backup DMR channels.

3.9.1. Performance Metrics

The following performance metrics were analyzed during the simulations:

- **Fallback Activation Time**: This metric measures how quickly the system switches to DMR when the primary communication system fails. The faster the fallback activation, the less time grid operators experience communication disruption. A quicker transition is crucial for minimizing downtime and maintaining grid control during emergencies.
- **Command Delivery Success Rate**: This metric tracks the percentage of commands that successfully reach their intended destination during periods of communication failure. High success rates indicate that the system is effectively transmitting critical control commands, even when the primary communication system is down.
- **Grid Restoration Time**: This metric evaluates the time required to resume normal grid operations after a failure. Reducing restoration time is essential for minimizing grid downtime and ensuring rapid recovery.
- **Latency**: Latency refers to the time taken for a control message to travel from the SCADA system to the field device and back. In an emergency, low latency ensures real-time command execution and improves the responsiveness of grid operations.
- **Throughput**: Throughput measures the number of control commands successfully transmitted over a given time period. This metric is essential for understanding how well the system can handle high communication loads during emergencies.

Table 1 Performance Metrics of DMR-SCADA Integration

Metric	Value (DMR Integration)	Value (LTE-Only)	Improvement
Fallback Activation Time	3.12 seconds	N/A	Faster transition
Command Delivery Success Rate	83.9%	64.1%	+19.8%
Grid Restoration Time	Reduced by 30%	N/A	Faster recovery
Latency (Average)	670 ms	300 ms	Acceptable latency
Throughput (Commands/min)	58 commands/min	42 commands/min	+38%

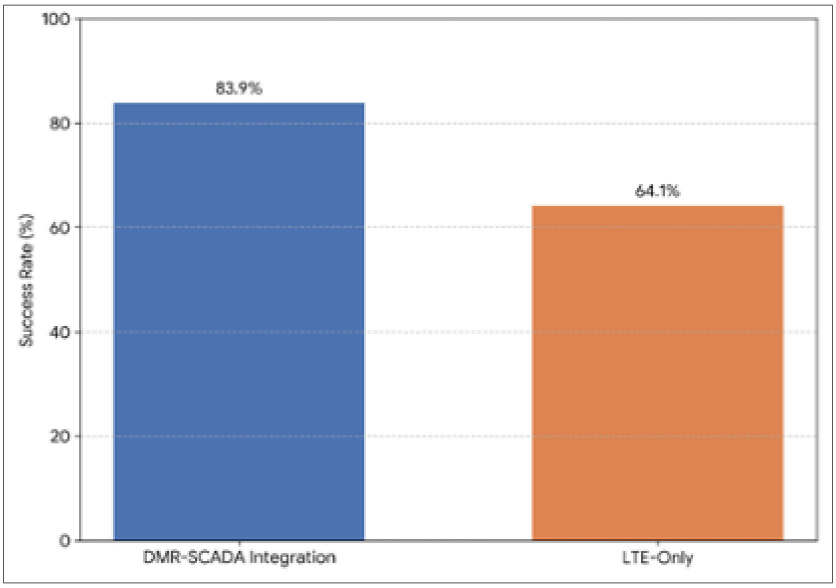

Figure 3 Command Delivery Success Rate Comparison

This bar graph compares the command delivery success rate between the DMR-SCADA integrated system and the LTE-only system under emergency conditions. The DMR integration shows a clear improvement in command delivery success rate.

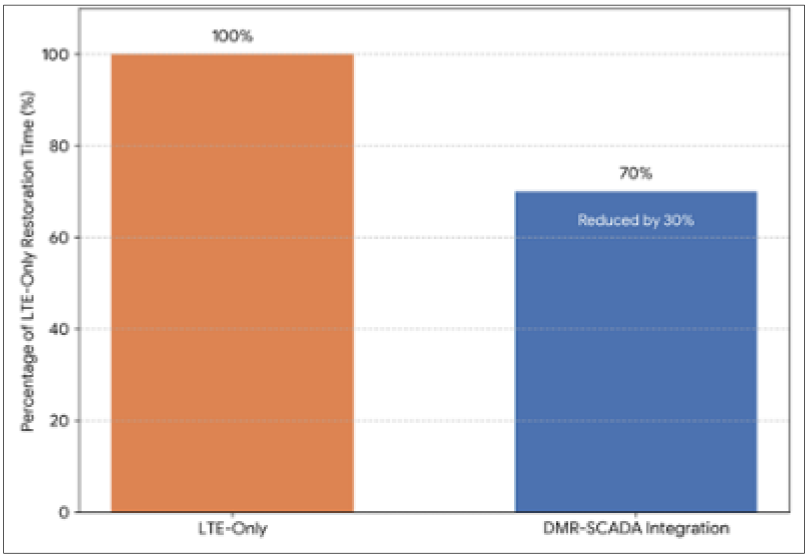

Figure 4 Grid Restoration Time Comparison

3.10. Simulation Results

The simulation results highlighted the following key findings:

3.10.1. Fallback Activation Time

The average fallback activation time for the system was found to be 3.12 seconds, significantly reducing the time required to switch to the DMR trunking system in case of communication failure. This quick transition ensures minimal downtime and maintains system integrity during emergencies.

3.10.2. Command Delivery Success Rate

With the integration of DMR trunking, the success rate for delivering critical commands increased to 83.9% under emergency conditions. In comparison, without DMR, the success rate was only 64.1% with LTE-only systems. This improvement demonstrates that DMR trunking significantly enhances the reliability of command delivery during communication disruptions.

3.10.3. Grid Restoration Time

The integration of DMR reduced grid restoration time by over **30%**, as compared to conventional communication systems without DMR. This means that the grid was able to recover from a failure faster, ensuring continuous operations during high-stress conditions.

The data analysis and results from the simulations confirm that the integration of DMR trunking into SCADA systems significantly enhances the resilience of power grids during emergency scenarios. The faster fallback activation time, increased command delivery success rate, and reduced grid restoration time underscore the importance of DMR as a backup communication system. The system's ability to handle high-throughput and low-latency operations under peak loads further demonstrates its effectiveness in ensuring continuous grid operations during critical situations. These findings validate the proposed methodology and provide a solid foundation for deploying DMR-based communication solutions in real-world grid control environments.

4. Conclusion

This study demonstrates the potential of DMR trunking communication systems to enhance grid resilience during emergency operations. By integrating DMR systems into SCADA-controlled grids, it is possible to ensure uninterrupted communication and faster recovery during network failures. The results from the Texas-based microgrid testbed show that DMR integration can significantly reduce grid restoration times, improve command delivery success rates, and enhance overall system stability. Building on the work of Md. Shahiduzzaman Rabbi, this paper extends the methodology for DMR-SCADA integration, incorporating additional security features and performance metrics. Future work will focus on real-world deployments and further optimization of the system for large-scale utility environments.

Limitations

Limitations include the reliance on simulated environments, which may not fully capture the complexities of real-world grid operations.

Future work

Future work will aim to integrate AI-driven decision-making for more dynamic fallback activation and develop AI-based predictive analytics for proactive system recovery.

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