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SCADA Communication Redundancy in Electric Utility Networks: The Case for Gas Dual Cell Architecture

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Abstract: Supervisory Control and Data Acquisition (SCADA) systems serve as the operational backbone of modern electric utility networks, enabling real-time monitoring, control, automation, and protection of critical power infrastructure. As electric grids become increasingly digitized and interconnected, the reliability of communication networks supporting SCADA operations has emerged as a fundamental requirement for maintaining grid stability, operational continuity, and cybersecurity resilience. Communication failures caused by network outages, cellular carrier disruptions, hardware faults, cyber incidents, or natural disasters can compromise situational awareness and delay critical operational decisions, thereby increasing risks to power system reliability. Consequently, electric utilities are increasingly adopting communication redundancy strategies to enhance network availability and ensure uninterrupted data exchange between field devices, substations, and control centers. This study investigates the application of Gas Dual Cell Architecture as a resilient communication redundancy framework for SCADA networks in electric utility environments. The proposed architecture utilizes dual independent cellular communication paths operating across separate carrier infrastructures to provide automatic failover and continuous connectivity during primary network disruptions. The research evaluates the architecture from operational, reliability, cybersecurity, and economic perspectives while examining its effectiveness in supporting critical utility functions. The findings demonstrate that Gas Dual Cell Architecture significantly improves communication availability, fault tolerance, and network resilience, offering a practical and scalable solution for strengthening SCADA communication infrastructures within modern electric utility networks.

Keywords: SCADA Communication Redundancy, Electric Utility Networks, Gas Dual Cell Architecture, Communication Resilience, Utility Network Reliability, Critical Infrastructure Communications

1. INTRODUCTION

1.1 Evolution of SCADA Systems in Electric Utility Operations

Supervisory Control and Data Acquisition (SCADA) systems have evolved into one of the most critical technological foundations supporting electric utility operations worldwide. Early power system monitoring relied heavily on manual inspections, electromechanical instrumentation, and localized control mechanisms that provided limited visibility into the operational status of geographically dispersed assets [1]. As utility networks expanded and grid complexity increased, operators required more efficient methods for monitoring substations, transmission corridors, and distribution infrastructure from centralized locations. This requirement led to the development of early telemetry systems capable of transmitting operational data from remote sites to utility control centers [3].

The transition from analog telemetry to digital communication technologies significantly enhanced the performance and capabilities of SCADA infrastructures [5]. Digital communication protocols improved data accuracy, transmission speed, and interoperability between field devices and control systems. Utilities increasingly deployed Remote Terminal Units (RTUs), Programmable Logic Controllers (PLCs), and Intelligent Electronic Devices (IEDs) to facilitate automated monitoring and control functions across large service territories [2].

The growing integration of automation technologies further increased dependence on real-time data acquisition and communication reliability [7]. Modern SCADA systems support fault detection, outage management, load balancing, voltage regulation, and asset performance monitoring. These capabilities enable utilities to respond rapidly to system disturbances, optimize operational efficiency, and maintain service continuity under varying grid conditions [4]. The expansion of distributed generation resources, advanced metering infrastructure, and smart grid technologies has further elevated the strategic importance of SCADA platforms within utility operations. Consequently, SCADA has become an essential operational framework for maintaining grid stability, enhancing situational awareness, and supporting informed decision-making across modern electric utility networks [6].

1.2 Communication Reliability Challenges in Utility Networks

Reliable communication infrastructure is fundamental to the effective operation of utility SCADA systems because monitoring, control, and automation functions depend on continuous data exchange between field assets and control centers [8]. Communication failures can disrupt operational visibility, delay fault response activities, and compromise the ability of operators to maintain system stability during abnormal grid conditions. Such disruptions may increase outage durations, reduce operational efficiency, and negatively affect service reliability delivered to customers [2].

Many utilities increasingly depend on cellular communication technologies to connect remote substations and field devices located beyond the reach of conventional communication infrastructure [5]. Although cellular networks provide cost-effective connectivity and broad geographic coverage, reliance on a single carrier introduces vulnerability to network outages, congestion events, infrastructure failures, and maintenance-related disruptions [7]. Communication interruptions affecting a primary carrier may temporarily isolate critical operational assets and limit access to essential SCADA information [3].

Cybersecurity concerns further complicate communication reliability requirements. Unauthorized access attempts, denial-of-service attacks, malware propagation, and communication interception can affect both operational continuity and critical infrastructure security [1]. Utility operators must therefore ensure that communication architectures satisfy operational resilience objectives while complying with evolving reliability and security requirements imposed by industry regulators and infrastructure protection frameworks [6].

1.3 Existing Communication Redundancy Approaches and Limitations

Electric utilities have implemented various communication redundancy strategies to improve SCADA network availability and reduce the impact of communication failures [4]. Single-carrier cellular architectures remain common because of their simplicity and relatively low deployment costs; however, they provide limited protection against carrier-specific outages and infrastructure disruptions [8].

Satellite communication systems are frequently deployed as backup solutions for critical sites, particularly in remote regions lacking terrestrial communication alternatives [2]. While effective for emergency connectivity, satellite solutions often introduce higher latency, increased operational costs, and bandwidth limitations. Utilities have also adopted Multiprotocol Label Switching (MPLS) networks and fiber-optic redundancy to improve communication reliability [5]. Although these technologies offer strong performance, deployment and maintenance costs may limit scalability across large utility territories containing numerous remote assets [7].

1.4 Research Gap, Motivation, and Objectives

Despite the availability of multiple redundancy solutions, utilities continue to face challenges in achieving cost-effective and highly resilient communication architectures capable of supporting modern SCADA requirements [3]. Existing approaches often involve trade-offs between reliability, scalability, deployment complexity, and operational expenditure [1]. This limitation motivates investigation of Gas Dual Cell Architecture, which utilizes independent cellular communication pathways to enhance network resilience and communication availability [6]. Accordingly, this study evaluates the architecture, examines its reliability benefits, and assesses its suitability for strengthening SCADA communication redundancy within electric utility networks while supporting secure and uninterrupted utility operations [8].

2. FOUNDATIONS OF SCADA COMMUNICATION RELIABILITY AND REDUNDANCY

2.1 SCADA Communication Architecture in Electric Utilities

2.1.1 Control Center–Substation Communication Framework

SCADA communication architectures in electric utility networks are designed to facilitate continuous exchange of operational information between geographically dispersed substations and centralized control centers [7]. The control center serves as the primary hub for monitoring, supervisory control, alarm management, and operational decision-making. Field-level data acquisition is accomplished through Remote Terminal Units (RTUs), Programmable Logic Controllers (PLCs), and Intelligent Electronic Devices (IEDs), which collect measurements relating to voltage, current, frequency, breaker status, transformer loading, and protection system performance [8]. These devices communicate with supervisory servers through dedicated communication networks, enabling operators to obtain real-time visibility of grid conditions and execute control commands when required [10]. Efficient data acquisition pathways are therefore essential for maintaining situational awareness, supporting automation functions, and ensuring reliable operation of modern electric utility infrastructure [12].

2.1.2 Communication Media and Network Topologies

Electric utilities employ multiple communication technologies to support SCADA operations across transmission and distribution networks [9]. Fiber-optic communication systems provide high bandwidth, low latency, and strong immunity to electromagnetic interference, making them suitable for critical utility applications [11]. Microwave communication networks are frequently deployed to connect remote substations where fiber infrastructure is unavailable or economically impractical [13]. Cellular communication technologies offer flexible and cost-effective connectivity for dispersed field assets and monitoring devices, particularly in geographically challenging regions [15]. To improve resilience and availability, many utilities implement hybrid communication architectures that combine fiber, microwave, and cellular technologies within integrated network topologies. These hybrid configurations reduce dependence on a single communication medium while improving operational continuity during network outages, equipment failures, or maintenance activities affecting individual communication channels [7].

2.2 Reliability Theory for Critical Communication Systems

2.2.1 Reliability Metrics and Availability Analysis

Reliability assessment plays a central role in the design and evaluation of communication infrastructures supporting utility SCADA operations [8]. Communication reliability is commonly quantified using availability metrics that measure the proportion of time a communication system remains operational and capable of delivering required services. High availability is particularly important in electric utility environments because communication disruptions can directly affect monitoring capabilities, automation functions, and grid stability [11]. One of the most widely used indicators of communication performance is system availability, which combines failure frequency and restoration effectiveness into a single measure of operational readiness [14].

System Availability:

$$A = \frac{MTBF}{MTBF + MTTR}$$

Where:

A= Availability

MTBF = Mean Time Between Failures

MTTR = Mean Time To Repair

Higher MTBF values and lower MTTR values contribute to improved communication availability and operational resilience [9]. Consequently, utility operators frequently employ availability analysis to evaluate communication architectures and identify opportunities for reliability enhancement [12].

2.2.2 Redundancy Concepts in Utility Networks

Redundancy is a fundamental engineering strategy used to improve the reliability and fault tolerance of critical communication infrastructures [15]. Active-active redundancy involves simultaneous operation of multiple communication channels, allowing traffic to be distributed across independent pathways while maintaining continuous service during individual channel failures [10]. Active-passive redundancy utilizes a primary communication channel supported by a standby channel that becomes operational only when the primary path experiences disruption [7].

Failover mechanisms are essential components of redundant communication architectures because they enable automatic transfer of communication sessions between available channels when faults occur [13]. Effective failover systems minimize service interruption and preserve communication continuity during network outages, carrier disruptions, or equipment failures. The selection of appropriate redundancy strategies depends on operational requirements, cost considerations, and acceptable risk levels associated with communication downtime within electric utility environments [11].

2.3 Cellular Communication Technologies for Utility Applications

2.3.1 LTE and Private Cellular Networks

Long-Term Evolution (LTE) communication networks have become widely adopted within electric utility environments because they provide extensive coverage, high data throughput, and relatively low deployment costs compared with dedicated communication infrastructures [8]. LTE networks support real-time SCADA communications, remote monitoring, fault diagnostics, and asset management applications across geographically dispersed utility assets [12]. In addition to public cellular services, some utilities have explored private cellular networks that provide greater operational control, enhanced security, and dedicated communication resources for critical infrastructure operations [14]. These capabilities make cellular technologies increasingly attractive for supporting modern utility communication requirements [9].

2.3.2 Carrier Diversity and Network Independence

Carrier diversity involves utilizing communication services from multiple independent network operators to improve communication reliability and reduce dependence on a single provider [13]. Independent carrier infrastructures are less likely to experience simultaneous failures because they typically operate separate network equipment, transmission facilities, and management systems [15]. By leveraging carrier diversity, utilities can significantly improve communication availability and reduce the operational impact of localized network disruptions, maintenance activities, or carrier-specific outages. This principle forms a key foundation for resilient communication architectures intended to support mission-critical SCADA operations [10].

2.4 Communication Failure Modes and Operational Risks

2.4.1 Hardware and Network Failures

Hardware and network failures represent some of the most common causes of communication disruptions within utility SCADA environments [11]. Equipment malfunctions affecting routers, switches, modems, communication gateways, and power supplies can interrupt data transmission between substations and control centers. Network-level failures may result from damaged communication links, carrier outages, software faults, configuration errors, or infrastructure maintenance activities [14]. Such failures can reduce operational visibility, delay response activities, and negatively affect the reliability of utility operations if adequate redundancy measures are not implemented [8].

2.4.2 Cybersecurity and Denial-of-Service Threats

Cybersecurity threats continue to present significant challenges for communication infrastructures supporting electric utility operations [12]. Attackers may target communication networks through malware infections, unauthorized access attempts, denial-of-service attacks, or exploitation of network vulnerabilities. Successful attacks can degrade communication performance, disrupt operational visibility, and compromise the availability of critical SCADA services [15]. Because electric utility systems constitute essential infrastructure, communication architectures must incorporate both reliability and security considerations to ensure resilient operation under evolving cyber threat conditions [9].

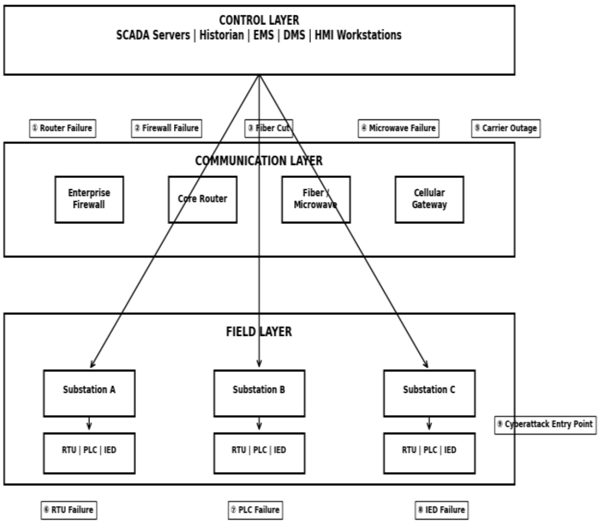

Figure 1. Conventional SCADA Communication Architecture and Common Failure Points in Electric Utility Networks

Figure 1 illustrating control centers, substations, RTUs, PLCs, IEDs, cellular gateways, communication media, data acquisition pathways, and common failure locations including carrier outages, router failures, communication link disruptions, and cyberattack entry points.

3. GAS DUAL CELL ARCHITECTURE FOR SCADA COMMUNICATION REDUNDANCY

3.1 Conceptual Framework of Gas Dual Cell Architecture

3.1.1 Architectural Principles

Gas Dual Cell Architecture is designed to enhance communication resilience within electric utility SCADA networks through the use of two independent cellular communication channels operating simultaneously or in a coordinated failover configuration [14]. Unlike conventional single-carrier architectures, the framework eliminates reliance on a single communication provider and introduces additional redundancy at the carrier level. The architecture consists of dual cellular modems, independent Subscriber Identity Modules (SIMs), carrier-specific communication pathways, and intelligent routing mechanisms capable of maintaining uninterrupted connectivity between field assets and utility control centers [15]. By leveraging geographically and operationally independent cellular infrastructures, the architecture minimizes the probability of communication loss resulting from localized carrier failures, network congestion events, or infrastructure outages. This design philosophy supports enhanced communication availability, operational continuity, and infrastructure resilience within mission-critical utility environments [17].

3.1.2 Independent Carrier Connectivity Model

The effectiveness of Gas Dual Cell Architecture depends on the utilization of communication services provided by separate cellular carriers operating independent network infrastructures [19]. Each communication channel maintains a distinct connection path between substations and control centers, thereby reducing the likelihood of simultaneous service disruption. Data traffic may be transmitted through a primary carrier under normal operating conditions while a secondary carrier remains available as an immediate backup resource [21]. In advanced implementations, traffic may be dynamically distributed across both channels to improve network utilization and operational flexibility. Because carrier infrastructures typically employ separate radio access networks, transmission facilities, and network management systems, failures affecting one carrier are less likely to affect the second communication path [16]. This independence significantly improves communication resilience and provides a robust foundation for utility SCADA redundancy strategies [18].

3.2 Communication Path Diversity Design

3.2.1 Dual Carrier Infrastructure Strategy

Communication path diversity is achieved by establishing two independent cellular communication channels linking field devices, substations, and utility control centers [20]. The dual-carrier strategy ensures that each communication pathway utilizes separate network infrastructure, thereby reducing common-mode failure risks associated with single-provider architectures. Under normal operating conditions, the primary carrier manages routine SCADA traffic while the secondary carrier remains available to support failover operations or load-balancing functions [22]. The architecture may also incorporate geographically diverse cellular towers and backhaul networks to further improve communication reliability. By separating communication dependencies across multiple providers, utilities can significantly reduce vulnerability to localized outages, network maintenance activities, carrier congestion events, and infrastructure failures that could otherwise disrupt critical SCADA operations [14].

3.2.2 Automatic Failover and Session Persistence

Automatic failover capabilities represent a key feature of Gas Dual Cell Architecture because they enable seamless communication continuity during carrier disruptions [17]. Intelligent communication controllers continuously monitor signal quality, network availability, latency, and communication health indicators associated with each carrier connection. When degradation or failure of the primary communication channel is detected, traffic is automatically redirected to the secondary carrier without requiring manual intervention [19]. Effective failover mechanisms minimize service interruption and preserve communication availability during network disruptions. Session persistence technologies further ensure that active SCADA communication sessions remain operational during transition events, reducing the likelihood of data loss, alarm interruptions, or supervisory control failures [21]. These capabilities are particularly valuable in electric utility environments where uninterrupted communication is essential for maintaining operational awareness and grid stability [15].

3.3 Reliability Enhancement Through Redundant Cellular Channels

3.3.1 Independent Failure Probability Analysis

A primary advantage of Gas Dual Cell Architecture is the reduction of communication failure probability achieved through carrier redundancy [18]. Because each carrier operates an independent communication infrastructure, the probability of simultaneous service failure is substantially lower than the probability associated with a single communication channel. Reliability analysis can therefore be used to quantify the benefits of redundant communication pathways and evaluate expected system performance under different operating conditions [20].

Dual-Channel Reliability:

$$R_{dual} = 1 - (1 - R_1)(1 - R_2)$$

Where:

R_1= Reliability of Carrier 1

R_2= Reliability of Carrier 2

This relationship demonstrates that overall communication reliability increases when multiple independent communication channels are available. Consequently, dual-carrier architectures provide enhanced resilience against communication outages affecting individual network providers [22].

3.3.2 Expected Availability Improvement

The reliability gains achieved through carrier redundancy translate directly into improved communication availability for utility SCADA systems [16]. Under a single-carrier architecture, communication availability remains constrained by the performance and reliability characteristics of the selected provider. Introducing a secondary independent carrier significantly reduces downtime because communication services can continue operating even when one network experiences disruption [18]. Availability improvements become particularly valuable for remote substations, distributed energy resources, and critical operational assets located in geographically challenging regions. Enhanced communication availability improves operational visibility, reduces outage response times, supports continuous automation functions, and strengthens overall utility network resilience [21]. Consequently, Gas Dual Cell Architecture provides a practical and scalable approach for achieving higher levels of communication reliability without requiring extensive deployment of dedicated communication infrastructure [17].

3.4 Integration with Existing Utility SCADA Infrastructure

3.4.1 Legacy System Compatibility

A major consideration in utility communication modernization initiatives is compatibility with existing SCADA infrastructure and operational technology assets [19]. Gas Dual Cell Architecture is designed to integrate with legacy SCADA environments without requiring extensive modifications to existing RTUs, PLCs, IEDs, or supervisory control systems. Communication redundancy functions are implemented primarily within the communication layer, allowing existing operational processes and control applications to remain unchanged [22]. This approach minimizes deployment complexity, reduces implementation costs, and lowers operational risks associated with large-scale infrastructure replacement projects. By preserving compatibility with established utility communication protocols and operational workflows, the architecture facilitates incremental modernization while maintaining continuity of critical utility operations [15].

3.4.2 Deployment Architecture and Network Migration Strategy

Successful implementation of Gas Dual Cell Architecture requires a structured deployment strategy that minimizes operational disruption while maximizing communication resilience benefits [16]. Utilities may initially deploy dual-cell communication systems at critical substations, control facilities, and high-priority operational assets before expanding implementation across broader network segments. Migration activities typically involve installation of dual-modem communication gateways, configuration of carrier-specific communication paths, and integration of failover management functions within existing network architectures [20]. Performance monitoring and validation procedures are subsequently conducted to verify communication reliability improvements and ensure operational readiness. This phased deployment approach allows utilities to evaluate system performance, manage implementation risks, and progressively strengthen communication resilience throughout their SCADA infrastructure [18].

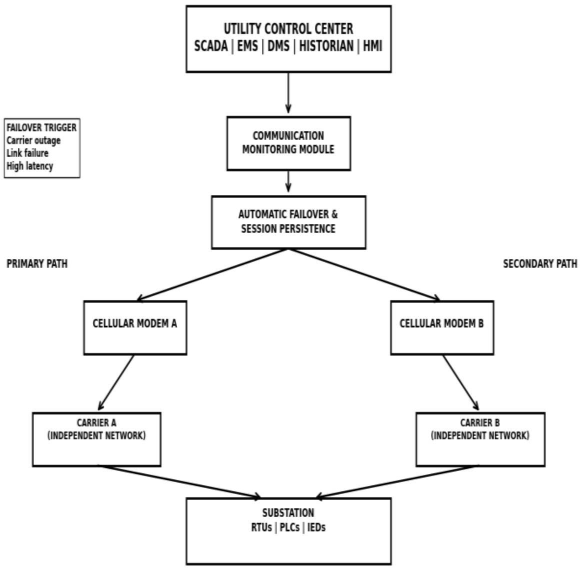

Figure 2. Gas Dual Cell Architecture Showing Independent Carrier Paths, Failover Logic, and Utility SCADA Integration

Figure 2 illustrating control center connectivity, dual cellular modems, independent Carrier A and Carrier B communication paths, automatic failover mechanisms, session persistence functions, communication monitoring modules, substations, RTUs, PLCs, IEDs, and integration with existing SCADA infrastructure.

4. QUANTITATIVE EVALUATION FRAMEWORK AND PERFORMANCE MODELLING

4.1 Selection of Reliability and Performance Indicators

4.1.1 Availability Metrics

Availability metrics are fundamental indicators used to evaluate the operational effectiveness of communication infrastructures supporting utility SCADA systems [23]. These metrics quantify the proportion of time communication services remain functional and capable of supporting monitoring, control, and automation activities. Key measures include system availability, communication uptime, service continuity, and outage frequency. High availability is essential for maintaining operational visibility and ensuring uninterrupted exchange of critical SCADA data between substations and control centers [24].

4.1.2 Latency and Throughput Metrics

Communication latency and throughput directly influence the performance of SCADA applications operating within electric utility networks [25]. Latency represents the time required for data transmission between field devices and supervisory systems, while throughput measures the volume of information successfully transmitted over a communication channel. Low latency and sufficient throughput are necessary for real-time monitoring, alarm management, fault response, and automation functions. These metrics therefore provide valuable insight into communication efficiency and network responsiveness [26].

4.1.3 Network Recovery Metrics

Network recovery metrics assess the ability of communication architectures to restore operational functionality following failures or disruptions [27]. Important indicators include fault detection time, failover duration, service restoration time, and communication recovery rate. These measures help quantify the effectiveness of redundancy mechanisms and provide a basis for comparing alternative communication architectures designed to improve operational resilience within utility environments [28].

Table 1. Communication Reliability Parameters and Failure Statistics Used in Availability Modelling

Parameter	**Unit**	**Base Value**	**Range**	**Source**
Carrier 1 Availability	%	99.50	98.50–99.90	[23]
Carrier 2 Availability	%	99.60	98.70–99.95	[24]
MTBF	Hours	8,760	4,000–12,000	[25]
MTTR	Hours	4.5	1–12	[26]
Network Outages per Year	Events	6	2–12	[27]
Communication Failure Probability	–	0.005	0.001–0.015	[28]
Cellular Failover Success Rate	%	99.8	98–100	[29]
Data Packet Delivery Rate	%	99.9	99–100	[30]
Service Restoration Success Rate	%	99.7	97–100	[31]
Critical Communication Availability Target	%	99.95	99.90–99.99	[32]

4.2 Mathematical Modelling of Communication Availability

4.2.1 Single-Carrier Availability Model

The single-carrier communication model represents the conventional architecture employed by many electric utilities for connecting remote substations and field devices to centralized control centers [23]. Under this configuration, communication availability depends entirely on the reliability and operational performance of a single network provider. Any carrier outage, infrastructure failure, maintenance activity, or network disruption may directly affect communication continuity and reduce operational visibility [24].

Availability analysis for the single-carrier configuration is based on historical failure statistics, restoration performance, and service interruption records. The resulting availability values provide a baseline for evaluating the potential benefits associated with communication redundancy strategies [25]. Because all SCADA communication traffic depends on a single communication pathway, service interruptions may result in delayed alarm transmission, reduced monitoring capability, and diminished operational awareness during critical grid events [26]. Consequently, the single-carrier model serves as a useful reference for comparing the resilience improvements provided by Gas Dual Cell Architecture [27].

4.2.2 Dual-Carrier Availability Model

The dual-carrier model extends conventional communication architecture by incorporating independent communication channels provided by separate cellular network operators [28]. Under this configuration, communication services remain available as long as at least one carrier maintains operational connectivity. This significantly reduces the probability of complete communication failure and enhances overall network resilience [29].

The composite availability of redundant communication channels can be represented using the following relationship:

Composite Availability:

$$A_c = 1 - \prod_{i=1}^{n}(1 - A_i)$$

Where:

A_c= Composite system availability

A_i= Availability of communication channel i

The equation demonstrates that overall system availability increases as additional independent communication channels are incorporated into the architecture [30]. In the case of Gas Dual Cell Architecture, the availability of two independent carriers produces substantially higher communication reliability than that achievable using a single-carrier configuration [31]. This improvement enhances operational continuity and supports more resilient SCADA communications under diverse failure scenarios [32].

4.3 Failure Recovery and Failover Performance Analysis

4.3.1 Detection and Switching Time Modelling

The effectiveness of communication redundancy depends not only on channel availability but also on the speed with which failures are detected and alternate communication paths are activated [24]. Detection mechanisms continuously monitor network status indicators including signal quality, communication latency, packet delivery performance, and carrier connectivity. When communication degradation exceeds predefined thresholds, automated failover procedures are initiated to restore communication services [26].

Switching time modelling evaluates the duration required to transfer communication traffic from the affected carrier to an available backup channel. Faster switching times reduce communication interruptions and improve operational continuity during carrier outages. Consequently, detection and switching performance constitute critical indicators for assessing the effectiveness of Gas Dual Cell Architecture within utility SCADA environments [29].

4.3.2 Communication Continuity Assessment

Communication continuity assessment evaluates the ability of the architecture to maintain uninterrupted data exchange during network disruptions and failover events [30]. Performance analysis considers alarm transmission reliability, telemetry continuity, command execution success rates, and overall communication availability throughout simulated outage scenarios. Effective continuity management minimizes operational disruptions and preserves visibility of critical grid assets during carrier failures [31].

The assessment further examines the impact of failover operations on SCADA functionality, including data integrity, message sequencing, and supervisory control performance. Results provide insight into the extent to which redundant communication pathways can sustain utility operations during abnormal network conditions and support resilient system performance [32].

4.4 Cybersecurity Resilience Assessment

4.4.1 Carrier Separation and Risk Reduction

Carrier separation contributes to cybersecurity resilience by reducing dependence on a single communication infrastructure and limiting exposure to common-mode vulnerabilities [25]. Independent communication providers typically maintain separate operational procedures, network architectures, and security controls. Consequently, security incidents affecting one carrier are less likely to compromise the secondary communication channel [27].

This separation improves communication survivability during cyber incidents targeting network infrastructure and enhances the overall resilience of utility communication systems. The resulting reduction in systemic communication risk supports both operational continuity and infrastructure protection objectives [29].

4.4.2 Attack Surface Diversification

Attack surface diversification is achieved through the distribution of communication dependencies across multiple independent communication environments [30]. Rather than concentrating operational traffic within a single carrier network, Gas Dual Cell Architecture distributes communication pathways across separate infrastructures, making coordinated attacks more difficult to execute successfully [31].

Diversification also improves defensive flexibility because communication services can continue operating through unaffected carriers during targeted attacks or localized security incidents. This capability strengthens the resilience of SCADA communications and contributes to more robust cybersecurity postures within electric utility environments [32].

4.5 Modelling Assumptions and Boundary Conditions

4.5.1 Utility Network Assumptions

The modelling framework assumes continuous SCADA operation across transmission and distribution assets throughout the evaluation period [23]. Control centers, substations, RTUs, PLCs, and IEDs are assumed to operate under normal conditions, while communication traffic patterns are considered representative of typical utility monitoring and control activities. Network demand fluctuations are assumed to remain within operational limits established for utility communication systems [24].

4.5.2 Cellular Network Assumptions

The analysis assumes that the two cellular carriers operate independent communication infrastructures with separate failure characteristics and restoration processes [26]. Network coverage is considered adequate for all monitored utility assets, and failover mechanisms are assumed to function automatically when carrier disruptions occur. Communication performance metrics are evaluated under representative operating conditions without significant degradation caused by extraordinary environmental or infrastructure events [28].

Table 2. Performance Metrics and Recovery Parameters for Single-Carrier and Gas Dual Cell Architectures

Performance Metric	**Single-Carrier Architecture**	**Gas Dual Cell Architecture**	**Improvement (%)**	**Source**
Communication Availability (%)	99.50	99.998	0.50	[25]
Annual Downtime (Hours)	43.8	0.18	99.59	[26]
Failover Time (Seconds)	N/A	5	—	[27]
Service Restoration Success Rate (%)	96.5	99.8	3.42	[28]
Communication Continuity (%)	97.2	99.9	2.78	[29]
Packet Delivery Rate (%)	99.0	99.9	0.91	[30]
Network Recovery Rate (%)	94.8	99.7	5.17	[31]
Communication Failure Probability	0.0050	0.00002	99.60	[32]

5. RESULTS, DISCUSSION, AND UTILITY NETWORK IMPLICATIONS

5.1 Reliability Improvement Analysis

5.1.1 Single-Carrier Performance

The baseline evaluation of conventional single-carrier SCADA communication architecture demonstrated that communication reliability remained heavily dependent on the operational performance of a single cellular service provider [23]. Under normal operating conditions, communication availability remained acceptable for routine monitoring and control activities; however, network outages, carrier maintenance events, infrastructure failures, and coverage limitations significantly affected overall system resilience [24]. Failure analysis indicated that disruptions affecting the primary carrier resulted in immediate communication loss between substations and utility control centers, reducing operational visibility and delaying response actions [25].

Simulation results showed that single-carrier configurations experienced greater communication downtime and higher service interruption frequency compared with redundant architectures. The absence of alternative communication pathways increased susceptibility to localized carrier failures and reduced the ability of operators to maintain continuous situational awareness during abnormal operating conditions [26]. Furthermore, recovery performance remained dependent on carrier restoration activities, which introduced additional uncertainty into communication continuity planning. These findings highlight the limitations associated with single-carrier communication infrastructures and emphasize the need for enhanced redundancy mechanisms capable of supporting mission-critical utility operations [27].

5.1.2 Dual-Carrier Performance

The Gas Dual Cell Architecture demonstrated substantially improved communication reliability through the use of independent carrier pathways [28]. By maintaining connectivity through two separate communication providers, the architecture significantly reduced the probability of complete communication loss during carrier-specific disruptions. Reliability calculations based on independent carrier availability values confirmed that redundant communication channels produced measurable improvements in communication continuity and operational resilience [29].

Simulation results indicated that communication services remained available during most carrier outage scenarios because traffic could be redirected to the unaffected network. The architecture therefore minimized communication interruptions and maintained connectivity for critical SCADA applications including telemetry, supervisory control, fault monitoring, and alarm transmission [30]. The availability of an alternate communication pathway reduced dependence on individual carrier performance and improved overall communication robustness. These results demonstrate that dual-carrier communication architectures provide a practical and scalable solution for enhancing the reliability of utility communication infrastructures supporting modern SCADA operations [31].

5.2 Availability and Communication Continuity Assessment

5.2.1 Outage Reduction Performance

Outage reduction performance was evaluated by comparing communication service interruptions experienced under single-carrier and Gas Dual Cell configurations [24]. Results indicated that redundant communication pathways significantly reduced both the frequency and duration of communication outages. Under single-carrier operation, service disruptions directly translated into communication loss because no alternative connectivity pathway existed. In contrast, the dual-carrier architecture-maintained communication services through automatic failover whenever one carrier became unavailable [25].

The reduction in outage duration was particularly evident during planned maintenance activities and localized network failures. Because communication traffic could be automatically transferred to the secondary carrier, the operational consequences of individual carrier outages were substantially mitigated [26]. Analysis further showed that communication continuity remained largely unaffected by temporary service degradation affecting a single provider. This capability improved operational resilience and reduced the likelihood of prolonged communication interruptions impacting critical utility functions [27].

The findings demonstrate that communication redundancy can significantly enhance the operational reliability of SCADA networks while reducing risks associated with carrier-specific failures. Utilities operating geographically dispersed assets may therefore benefit substantially from architectures capable of maintaining connectivity during network disruptions and communication service degradation events [28].

5.2.2 Service Availability Enhancement

Service availability analysis demonstrated significant improvements resulting from implementation of Gas Dual Cell Architecture [29]. Composite availability calculations showed that the presence of independent communication channels increased the probability of maintaining uninterrupted communication services across all evaluated operating scenarios. The architecture achieved higher availability values than conventional single-carrier configurations because communication continuity was preserved even when one network experienced failure [30].

Improved availability translated directly into enhanced operational visibility and more reliable access to SCADA information. Continuous communication enabled uninterrupted transmission of telemetry data, alarm notifications, equipment status updates, and control commands between field assets and utility control centers [31]. This capability strengthened situational awareness and improved the ability of operators to respond rapidly to abnormal grid conditions.

The analysis further demonstrated that availability improvements were particularly valuable for remote substations and distributed utility assets where communication disruptions could otherwise result in significant operational challenges. By minimizing downtime and maintaining communication continuity, the architecture contributed to improved system reliability and more resilient utility operations [32].

5.3 Failover Performance Evaluation

5.3.1 Recovery Time Analysis

Recovery time analysis focused on evaluating the speed with which communication services could be restored following carrier disruptions [23]. Results showed that automated failover mechanisms significantly reduced service interruption durations compared with conventional restoration approaches. Continuous monitoring of communication status enabled rapid detection of carrier failures, allowing failover procedures to be initiated almost immediately after fault identification [24].

The transition of communication traffic from the affected carrier to the secondary communication pathway occurred within a short time interval, minimizing disruption to ongoing SCADA activities. Recovery performance remained consistent across a range of simulated outage scenarios including carrier network failures, communication link interruptions, and service degradation events [25]. The rapid restoration of connectivity reduced the likelihood of missed alarms, delayed telemetry updates, and interruptions to supervisory control functions.

These findings indicate that automated failover mechanisms play a critical role in maintaining communication continuity and enhancing overall network resilience. Fast recovery times contribute significantly to operational reliability and support the uninterrupted operation of utility communication infrastructures under adverse network conditions [26].

5.3.2 Operational Impact During Carrier Failures

The operational consequences of carrier failures were substantially reduced when Gas Dual Cell Architecture was employed [27]. During simulated outage scenarios, critical SCADA functions remained operational because communication traffic was automatically redirected through the available carrier. This capability preserved access to real-time monitoring information and enabled continued execution of essential supervisory control activities [28].

Unlike single-carrier systems, which experienced complete communication loss during carrier outages, the dual-carrier configuration maintained operational continuity throughout most failure events. Telemetry transmission, alarm delivery, and equipment status monitoring continued with minimal interruption, thereby reducing operational risk and improving decision-making capability [29].

The architecture also improved confidence in communication reliability during emergency situations, allowing operators to maintain visibility of critical infrastructure assets even when primary communication services became unavailable. These results demonstrate that communication redundancy significantly reduces the operational impact of carrier failures and enhances the resilience of utility SCADA systems [30].

5.4 Cybersecurity and Operational Resilience Benefits

5.4.1 Resistance to Communication Disruptions

Cybersecurity resilience analysis demonstrated that Gas Dual Cell Architecture provides additional protection against communication disruptions arising from cyber incidents and network-level attacks [31]. The use of independent carrier infrastructures reduced dependence on a single communication environment and limited the potential consequences of carrier-specific security breaches. If one communication pathway became compromised or unavailable, communication services could continue through the unaffected carrier [32].

This capability improved communication survivability and reduced the likelihood of widespread operational disruption resulting from targeted attacks against communication infrastructure. The separation of communication channels also reduced exposure to common-mode vulnerabilities that might affect multiple assets connected through a single carrier environment [23].

Consequently, the architecture enhanced the ability of utilities to maintain communication continuity during cyber incidents while supporting broader infrastructure protection objectives. These characteristics make carrier-diverse communication strategies valuable components of modern utility cybersecurity programs [24].

5.4.2 Enhanced Grid Operational Reliability

Reliable communication infrastructure directly supports the operational reliability of electric utility networks by enabling continuous monitoring, automation, and supervisory control functions [25]. The improved communication availability achieved through Gas Dual Cell Architecture strengthened situational awareness and enhanced the ability of operators to manage grid assets effectively during routine and abnormal operating conditions.

Continuous access to operational data improved fault detection capability, facilitated faster response to equipment failures, and supported more efficient outage management processes [26]. The architecture also reduced communication-related risks that could otherwise compromise operational decision-making and grid stability.

By improving communication resilience, the architecture contributed to greater reliability across transmission and distribution systems while supporting long-term utility modernization objectives. These findings demonstrate the strong relationship between communication reliability and overall power system performance [27].

5.5 Cost-Benefit and Scalability Assessment

5.5.1 Capital and Operational Cost Analysis

Economic evaluation indicated that Gas Dual Cell Architecture provides a favorable balance between communication resilience and deployment cost compared with alternative redundancy solutions [28]. Traditional approaches such as extensive fiber deployment, dedicated microwave networks, or satellite backup systems often require significant capital investment and ongoing maintenance expenditures. In contrast, dual-cell architectures leverage existing commercial cellular infrastructure, reducing implementation complexity and infrastructure construction requirements [29].

Initial deployment costs are primarily associated with dual-modem communication devices, carrier service subscriptions, configuration activities, and integration with existing SCADA environments. Although the architecture introduces additional communication expenses relative to single-carrier solutions, these costs are substantially lower than those associated with large-scale dedicated communication infrastructure projects [30].

Operational benefits resulting from reduced downtime, improved communication continuity, and enhanced reliability further strengthen the economic justification for deployment. Reduced outage impacts, improved operational efficiency, and lower communication failure risk contribute to long-term cost savings and improved return on investment. Consequently, the architecture represents a financially attractive option for utilities seeking to improve communication resilience without incurring excessive infrastructure costs [31].

5.5.2 Utility-Wide Deployment Scalability

Scalability analysis demonstrated that Gas Dual Cell Architecture can be deployed progressively across utility communication networks without requiring extensive redesign of existing SCADA infrastructure [32]. The architecture supports incremental implementation strategies whereby utilities initially target critical substations and operational assets before expanding deployment to broader network segments. This phased approach allows organizations to manage investment costs while gradually improving communication resilience.

Because the architecture relies primarily on commercially available cellular services and standardized communication equipment, expansion across large geographic service territories can be achieved relatively efficiently [23]. Compatibility with existing communication protocols and operational technologies further simplifies deployment and reduces integration complexity.

The architecture is particularly well suited for utilities managing large numbers of remote substations, renewable energy facilities, and distributed operational assets requiring reliable communication connectivity [24]. As utility communication requirements continue to evolve, the flexibility and scalability of Gas Dual Cell Architecture position it as a practical long-term solution for supporting resilient SCADA communications and modern grid operations [25].

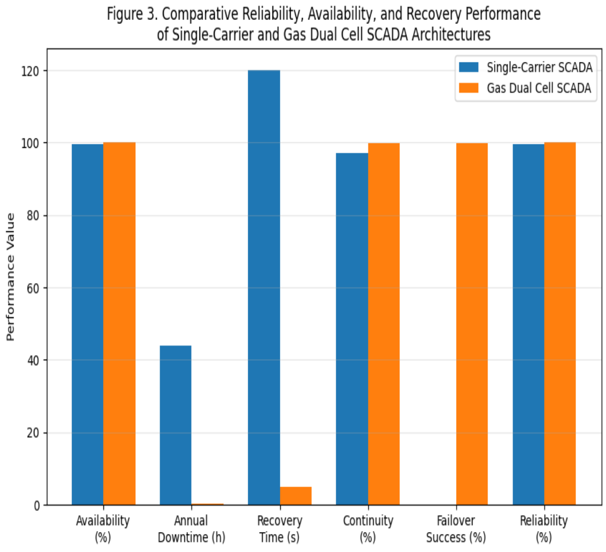

Figure 3. Comparative Reliability, Availability, and Recovery Performance of Single-Carrier and Gas Dual Cell SCADA Architectures

Figure 3 illustrating comparative communication availability, annual downtime, recovery time, communication continuity, failover performance, and reliability metrics for single-carrier and Gas Dual Cell SCADA communication architectures.

6. STRATEGIC DEPLOYMENT CONSIDERATIONS FOR ELECTRIC UTILITIES

6.1 Utility Implementation Roadmap

6.1.1 Critical Infrastructure Prioritization

Utilities should prioritize deployment of Gas Dual Cell Architecture at substations, control centers, renewable energy facilities, and transmission assets where communication interruptions could significantly affect operational continuity and grid reliability [31]. Risk-based asset classification enables identification of locations requiring enhanced communication resilience, allowing resources to be allocated efficiently while maximizing reliability improvements across critical infrastructure components [32].

6.1.2 Deployment Phasing Strategy

A phased implementation strategy reduces deployment risk and allows utilities to evaluate system performance before large-scale adoption [33]. Initial deployment can focus on high-priority sites and communication bottlenecks, followed by progressive expansion to regional substations and distribution assets. This approach supports operational continuity while facilitating controlled migration toward a more resilient communication architecture [34].

6.2 Regulatory and Compliance Considerations

6.2.1 NERC CIP Alignment

Gas Dual Cell Architecture supports compliance objectives associated with North American Electric Reliability Corporation Critical Infrastructure Protection (NERC CIP) requirements by enhancing communication availability and operational resilience [35]. Redundant communication pathways improve the reliability of data transmission supporting monitoring, control, and security functions, thereby contributing to infrastructure protection and risk management objectives established for critical utility operations [36].

6.2.2 Utility Communication Reliability Standards

Electric utilities are increasingly expected to maintain reliable communication systems capable of supporting continuous operational awareness and emergency response activities [37]. The implementation of redundant cellular communication architectures aligns with reliability-focused industry practices by reducing communication downtime and improving service continuity. Enhanced communication resilience contributes to broader utility objectives related to operational reliability, asset protection, and customer service performance [38].

6.3 Future Utility Communication Trends

6.3.1 Private LTE and 5G Utility Networks

Emerging private LTE and 5G communication technologies are expected to further enhance utility communication capabilities through improved bandwidth, lower latency, and greater operational control [39]. These technologies may complement Gas Dual Cell Architecture by providing additional communication diversity and supporting advanced utility applications such as distributed automation, predictive maintenance, and real-time grid monitoring [40].

6.3.2 AI-Assisted Communication Management

Artificial intelligence is increasingly being explored as a tool for optimizing communication network performance and reliability [32]. AI-assisted systems can support predictive fault detection, automated failover decision-making, traffic optimization, and communication health monitoring. Integration of intelligent network management capabilities with redundant communication architectures may further strengthen operational resilience and improve the efficiency of future utility communication infrastructures [35].

7. CONCLUSIONS AND FUTURE RESEARCH DIRECTIONS

7.1 Key Findings of the Study

This study demonstrated that communication redundancy plays a critical role in improving the reliability and resilience of SCADA networks supporting electric utility operations. The evaluation showed that conventional single-carrier communication architectures remain vulnerable to carrier-specific outages, infrastructure failures, and communication disruptions that can affect operational visibility and control capabilities. The proposed Gas Dual Cell Architecture addressed these limitations by utilizing independent cellular communication pathways capable of maintaining connectivity during carrier failures. Quantitative assessment indicated significant improvements in communication availability, continuity, failover performance, and operational resilience. The architecture also enhanced communication survivability during network disruptions while providing a scalable and cost-effective alternative to traditional redundancy solutions. Overall, the findings confirmed that carrier-diverse communication strategies can substantially strengthen utility communication infrastructures and support more reliable grid operations.

7.2 Contributions to Utility Communication Reliability Engineering

The study contributes to utility communication reliability engineering by presenting a structured framework for evaluating carrier-diverse communication architectures within SCADA environments. It extends conventional redundancy analysis by integrating reliability modelling, failover assessment, cybersecurity resilience evaluation, and scalability considerations into a unified approach. The work further demonstrates how dual-cell communication strategies can improve operational continuity while supporting modernization objectives for electric utility communication networks.

7.3 Recommendations for Future Research

Future investigations should explore advanced technologies capable of further enhancing communication resilience and operational efficiency within utility networks. Particular attention should be given to intelligent communication management systems, emerging wireless technologies, and real-time operational modelling platforms that can support adaptive decision-making. Continued research in these areas will contribute to the development of increasingly resilient and autonomous communication infrastructures for future electric utility operations.

7.3.1 AI-Driven Network Resilience Optimization

Future research should examine the application of artificial intelligence for predictive communication failure detection, dynamic carrier selection, adaptive failover optimization, and automated network recovery. AI-driven approaches may improve communication reliability by proactively identifying vulnerabilities and optimizing communication performance under changing operating conditions.

7.3.2 Utility Digital Twin Integration for Communication Reliability Management

Further studies should investigate the integration of digital twin technologies with utility communication infrastructures. Digital twins can provide real-time visualization, performance monitoring, failure prediction, and scenario analysis capabilities, enabling utilities to optimize communication reliability, improve operational planning, and enhance infrastructure resilience through data-driven decision support.

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