

International Journal of Scientific Interdisciplinary Research

Volume: 4; **Issue:** 4
Pages: 413–448

open access
Crossref
PEER-REVIEWED

Digital Twin Modeling of Fiber Optic Telecom Infrastructure for Proactive SCADA Network Resilience in Power Transmission Utilities

Abu Naser Md Golam Mosharraf[1]; Amir Razaq[2];

[1]. *Master of Engineering in Electrical Engineering , Lamar University, Texas, USA*
Email: anmmosharraf@gmail.com

[2]. *Master of Engineering in Electrical Engineering , Lamar University, Texas, USA*
Email: amirleghari75@gmail.com

Doi: 10.63125/04mgf566
Received: *19 September 2023;* ***Revised:*** *24 October 2023;* ***Accepted:*** *29 November 2023;* ***Published:*** *14 December 2023*

Abstract

This study investigated the effectiveness of digital twin modeling in enhancing the resilience of fiber optic telecom infrastructure supporting SCADA systems in power transmission utilities through a quantitative, simulation-based approach. A digital twin framework was developed to replicate real-time network conditions and evaluate performance under both baseline and optimized scenarios. The dataset consisted of 120 simulated network segments characterized by key performance indicators including latency, packet loss, bandwidth utilization, signal attenuation, and recovery time. Descriptive analysis revealed a baseline mean latency of 48.6 ms and packet loss of 2.1%, with recovery time averaging 18.9 minutes. Following digital twin-based optimization, latency was reduced to 34.2 ms, packet loss declined to 0.9%, and recovery time improved to 9.7 minutes, representing improvements of 29.6%, 57.1%, and 48.7%, respectively. Bandwidth utilization showed improved stability with reduced variance, indicating more efficient load balancing across network segments. Inferential statistical analysis confirmed that these improvements were statistically significant at $p < 0.05$, with effect sizes indicating moderate to large practical impact, particularly for recovery time ($\eta^2 = 0.52$) and packet loss ($\eta^2 = 0.46$). Regression analysis demonstrated strong relationships between latency, packet loss, and network reliability, with packet loss exhibiting the highest influence ($\beta = -0.67$). Sub-group analysis further revealed that high-load segments experienced the greatest performance gains, with latency decreasing from 62.7 ms to 41.3 ms and packet loss from 3.4% to 1.5%. Multi-point failure scenarios showed substantial resilience improvement, with recovery time reduced from 26.4 minutes to 13.2 minutes. The findings confirmed that digital twin integration significantly enhanced SCADA communication performance by enabling real-time monitoring, predictive analytics, and adaptive network optimization. This study provided strong quantitative evidence that digital twin modeling is an effective approach for improving telecom network reliability, operational stability, and resilience in power transmission utilities.

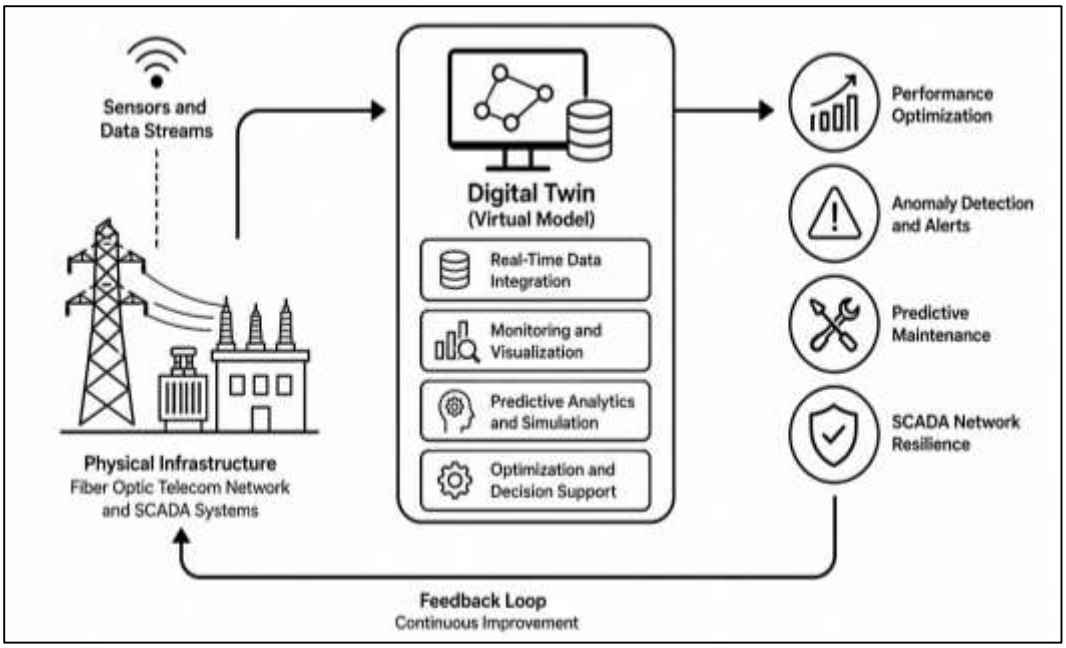
Keywords

Digital Twin, SCADA, Fiber Optics, Network Resilience, Telecom.

INTRODUCTION

Digital twin modeling represents a transformative approach in modern infrastructure management, defined as the creation of a dynamic, real-time digital replica of a physical system that is continuously updated through data streams, simulation models, and analytical algorithms. This concept integrates physical assets with virtual environments, allowing for synchronized monitoring, predictive analysis, and system optimization (Tchana et al., 2019). Within the domain of infrastructure systems, digital twins extend beyond static modeling by incorporating continuous feedback loops between the physical and digital layers, thereby enabling a more responsive and adaptive operational framework. The theoretical basis of digital twin modeling is rooted in cyber-physical systems, systems engineering, and data-driven decision-making, where sensors, communication technologies, and computational models converge to enhance system visibility and control.

Figure 1: Digital twin framework for SCADA resilience



In large-scale infrastructure networks, particularly those associated with energy and telecommunications, digital twins provide a comprehensive platform for simulating operational conditions, detecting anomalies, and evaluating system performance under varying scenarios. The international relevance of digital twin modeling has expanded significantly due to the increasing complexity of critical infrastructure systems and the global push toward digital transformation (Rasheed et al., 2020). Governments and utility providers across developed and developing economies have recognized the importance of integrating digital technologies into infrastructure management to improve efficiency, reliability, and resilience. In power transmission utilities, where operational continuity is paramount, digital twin frameworks offer a robust mechanism for ensuring that communication and control systems function seamlessly. The integration of digital twins into telecom infrastructure enables real-time visualization of network performance, allowing operators to identify potential issues and implement corrective measures before they escalate into system failures (Holmes et al., 2021). This capability is particularly significant in interconnected global energy systems, where disruptions in one region can have cascading effects across broader networks. Furthermore, digital twin modeling facilitates the alignment of infrastructure management practices with broader technological paradigms such as Industry 4.0 and smart infrastructure development (Shirowzhan et al., 2020). These paradigms emphasize automation, interoperability, and data-centric operations, all of which are inherent in digital twin systems. As infrastructure networks continue to evolve in scale and complexity, the need for advanced modeling techniques that can capture system dynamics in real time becomes increasingly critical. Digital twin technology addresses this need by providing a scalable and flexible

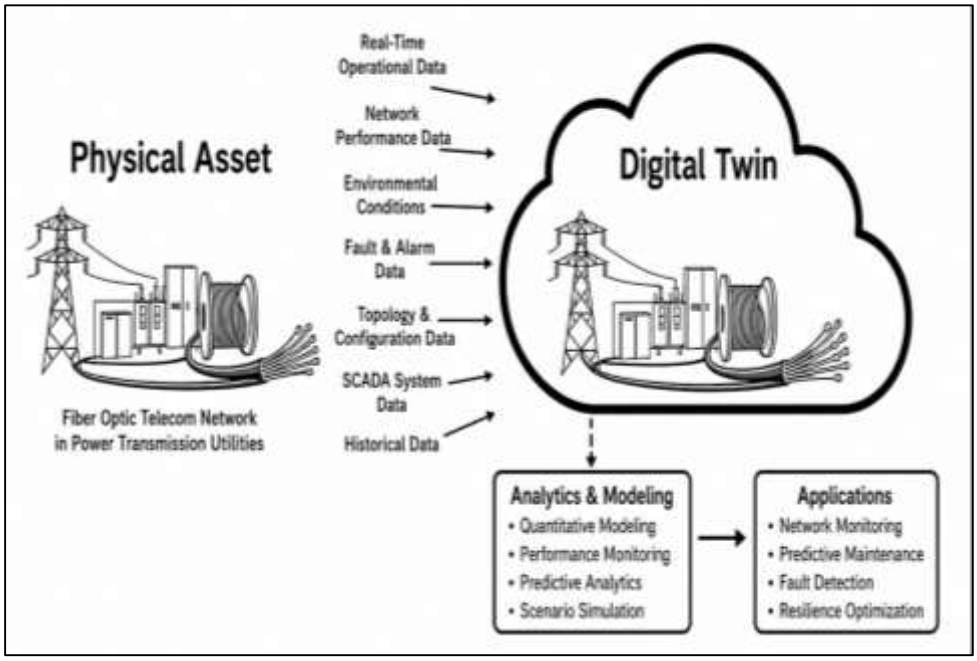
framework that can adapt to changing operational conditions, thereby supporting the long-term sustainability and resilience of critical infrastructure systems (Sepasgozar, 2021).

Fiber optic telecom infrastructure serves as a foundational component in the communication architecture of power transmission utilities, enabling the high-speed, reliable exchange of data between substations, control centers, and field devices. These networks are designed to support a wide range of operational functions, including real-time monitoring, remote control, fault detection, and system coordination. The use of fiber optic technology offers several advantages, such as high bandwidth capacity, low signal attenuation, and immunity to electromagnetic interference, making it particularly suitable for deployment in electrically intensive environments like power grids (Aheleroff et al., 2021). As power transmission systems expand in scale and complexity, the demand for robust and efficient communication networks has intensified, positioning fiber optic infrastructure as a critical enabler of modern grid operations. On a global scale, the adoption of fiber optic telecom networks within power utilities reflects a broader trend toward the modernization of energy systems (Dietz & Pernul, 2020). Countries around the world are investing in advanced communication technologies to support the integration of renewable energy sources, distributed generation, and automated control systems. These developments require reliable and high-performance communication networks capable of handling large volumes of data with minimal latency. Fiber optic infrastructure meets these requirements, providing the backbone for Supervisory Control and Data Acquisition systems and other advanced grid management technologies. The reliability of these networks is essential for maintaining system stability, as any disruption in communication can lead to delays in decision-making and increased risk of operational failures. The complexity of fiber optic telecom infrastructure in power transmission utilities arises from its extensive geographical coverage and the diversity of network configurations. These networks often span vast distances, connecting multiple nodes through a combination of optical fibers, switches, and multiplexing devices (Kaewunruen et al., 2021). Managing such complex systems requires advanced monitoring and control mechanisms capable of providing real-time insights into network performance. Digital twin modeling offers a powerful solution in this context by creating a virtual representation of the network that can be used to simulate operational conditions, identify potential vulnerabilities, and optimize resource allocation. This approach enhances the ability of utilities to maintain continuous communication and ensures the reliability of critical infrastructure systems (Donghan et al., 2021).

Supervisory Control and Data Acquisition systems constitute the operational core of power transmission utilities, facilitating the centralized monitoring and control of distributed assets across the grid. These systems collect data from sensors and field devices, process the information, and provide operators with actionable insights for decision-making (Aheleroff et al., 2021). SCADA systems rely heavily on communication networks to transmit data between various components, making the reliability and performance of these networks a critical factor in overall system effectiveness. Fiber optic telecom infrastructure plays a vital role in supporting SCADA operations, ensuring that data is transmitted accurately and in real time. The global significance of SCADA systems has increased with the growing complexity of power transmission networks and the integration of advanced technologies such as smart grids and automated control systems. These developments have introduced new challenges in terms of data management, system coordination, and operational reliability. Communication networks must be capable of supporting high data volumes and maintaining consistent performance under varying conditions (Callcut et al., 2021). Any disruption in communication can compromise the functionality of SCADA systems, leading to delayed responses and potential system instability. This highlights the importance of ensuring the resilience of telecom infrastructure within power utilities. Network resilience in the context of SCADA systems refers to the ability of communication networks to maintain functionality and recover quickly from disruptions. This includes the capacity to withstand physical damage, adapt to changing conditions, and mitigate the impact of failures. Achieving such resilience requires advanced monitoring and predictive capabilities that can identify potential issues before they affect system performance. Digital twin modeling provides a comprehensive framework for enhancing SCADA network resilience by enabling real-time monitoring, simulation of failure scenarios, and proactive maintenance strategies (Pan &

Zhang, 2021). Through the integration of digital twin technology, utilities can improve situational awareness and ensure the continuous operation of critical communication networks.

Figure 2: Physical asset to digital twin diagram



The application of digital twin technology in telecom network monitoring represents a significant advancement in the management of complex communication systems. By creating a real-time digital representation of fiber optic networks, digital twins enable continuous tracking of key performance indicators such as signal strength, latency, and fault occurrences. This level of visibility allows operators to detect anomalies and address potential issues before they escalate into system failures. The integration of advanced analytics and machine learning techniques further enhances the capabilities of digital twins, enabling predictive maintenance and optimization of network performance (Guskova et al., 2020). In power transmission utilities, the use of digital twin technology in telecom networks supports the efficient operation of SCADA systems by ensuring reliable communication between system components. The ability to simulate network behavior under different conditions provides valuable insights into system performance and helps identify areas for improvement. This approach enables utilities to test various scenarios, evaluate the impact of different strategies, and implement solutions that enhance network resilience (Fan et al., 2021). The real-time nature of digital twin models ensures that these insights are based on current system conditions, improving the accuracy and effectiveness of decision-making processes. The global adoption of digital twin technology in telecom network monitoring reflects a broader shift toward data-driven infrastructure management. Organizations across various sectors are leveraging digital twins to improve operational efficiency, reduce maintenance costs, and enhance system reliability (Lu et al., 2019). In the context of power transmission utilities, these benefits translate into more resilient communication networks capable of supporting the complex demands of modern energy systems. The scalability and flexibility of digital twin frameworks make them suitable for deployment in large-scale infrastructure networks, providing a robust solution for managing the challenges associated with network complexity and dynamic operational conditions (Fracchia, et al., 2021).

Quantitative modeling forms the analytical backbone of digital twin systems, providing the mathematical and computational tools necessary for simulating and analyzing the behavior of complex infrastructure networks. These models incorporate a wide range of variables, including network topology, signal propagation characteristics, and environmental conditions, to accurately represent the performance of fiber optic telecom systems (Deng et al., 2021). Statistical and computational techniques

are employed to develop models that can predict system behavior under different scenarios, enabling the evaluation of network performance and the identification of potential vulnerabilities. In power transmission utilities, quantitative models are essential for assessing the resilience and efficiency of telecom networks. These models allow for the analysis of key performance metrics such as data transmission rates, latency, and fault frequencies, providing insights into the factors that influence network performance. The integration of real-time data into quantitative models enhances their accuracy and relevance, ensuring that digital twin representations reflect the current state of the physical system. This continuous updating process enables utilities to monitor network conditions in real time and respond proactively to emerging issues (Kaewunruen & Lian, 2019). Advancements in computational technologies have significantly enhanced the capabilities of quantitative modeling in digital twin systems. High-performance computing and cloud-based platforms enable the processing of large datasets and the execution of complex simulations, making it possible to model large-scale telecom networks with high levels of detail. These capabilities are particularly important in the context of power transmission systems, where network complexity and data can be substantial. The use of advanced modeling techniques supports the optimization of network configurations and the development of strategies for enhancing resilience. Quantitative approaches also facilitate the evaluation of different operational strategies by enabling the simulation of various scenarios and their impact on network performance (Ozturk, 2021). This capability allows utilities to identify the most effective solutions for maintaining reliable communication and improving system resilience. By integrating quantitative modeling with digital twin technology, power transmission utilities can achieve a higher of operational efficiency and ensure the stability of critical infrastructure systems.

The global evolution of smart grids has transformed the operational landscape of power transmission utilities, emphasizing the importance of advanced communication networks and resilient infrastructure systems. Smart grids on digital technologies to enable real-time monitoring, automated control, and efficient management of power systems. These capabilities require reliable communication networks that can support the continuous exchange of data between various components of the grid. Fiber optic telecom infrastructure plays a central role in this context, providing the high-speed and secure communication channels for smart grid operations (Kaur et al., 2019). The transition toward smart grids has been driven by the need to improve energy efficiency, integrate renewable energy sources, and enhance system reliability. These objectives have led to the adoption of advanced technologies such as distributed generation, energy storage systems, and automated control mechanisms. The of these technologies depends on the availability of robust communication networks capable of handling large volumes of data and maintaining consistent performance under varying conditions. Any disruption in communication can compromise the effectiveness of smart grid operations, highlighting the importance of infrastructure resilience. Infrastructure resilience in power transmission systems encompasses the ability to withstand, adapt to, and recover from disruptions. This includes both physical and cyber threats, as well as environmental challenges. The increasing reliance on digital technologies has introduced new vulnerabilities, making it essential to implement advanced monitoring and predictive capabilities (Yu et al., 2021). Digital twin technology provides a comprehensive solution by enabling real-time analysis of network performance and the simulation of scenarios. This approach supports the development of strategies for enhancing resilience and ensuring the stability of power systems. The global focus on infrastructure resilience reflects the growing recognition of the أهـ ية of reliable and efficient energy systems. As power transmission utilities continue to adopt digital technologies, the integration of advanced modeling and monitoring tools becomes increasingly critical. Digital twin modeling offers a scalable and adaptable framework for addressing these challenges, supporting the ongoing evolution of smart grids and resilient infrastructure systems.

The integration of digital twin modeling into fiber optic telecom infrastructure represents a significant advancement in the management of SCADA network resilience within power transmission utilities (Shim et al., 2019). This approach combines real-time data acquisition, advanced analytics, and simulation capabilities to create a dynamic representation of the communication network. By continuously updating the digital twin with real-time data, utilities can monitor network performance, detect anomalies, and implement corrective actions in a proactive manner. This capability enhances the

reliability and stability of SCADA systems, ensuring that critical operations are not disrupted by communication failures. In the context of telecom networks, digital twin modeling enables the simulation of various fault scenarios and their impact on network performance. This allows utilities to assess the effectiveness of different resilience strategies and optimize network configurations accordingly (Sepasgozar et al., 2021). The ability to anticipate potential issues and address them before they affect system operations represents a significant improvement over traditional reactive maintenance approaches. By leveraging digital twin technology, power transmission utilities can achieve a higher level of operational efficiency and reduce the risk of system failures. The integration of digital twins with SCADA systems also enhances the ability to manage complex and dynamic network environments. As power transmission systems become more interconnected and technologically advanced, the demands on communication networks continue to increase. Digital twin modeling provides a flexible and scalable solution for managing these challenges, enabling utilities to adapt to changing conditions and maintain reliable communication across the network (Bickford et al., 2020). This approach supports the overall objective of ensuring the resilience and stability of critical infrastructure systems. The adoption of digital twin technology in power transmission utilities reflects a broader trend toward the use of advanced digital tools for infrastructure management. By combining real-time data, quantitative modeling, and simulation capabilities, digital twins provide a comprehensive framework for enhancing the resilience of telecom networks and supporting the efficient operation of SCADA systems (Wang et al., 2021).

The primary objective of this study is to develop and quantitatively evaluate a digital twin modeling framework for fiber optic telecom infrastructure aimed at enhancing proactive resilience within Supervisory Control and Data Acquisition (SCADA) networks used in power transmission utilities. This objective is grounded in the need to create a synchronized virtual representation of telecom systems that can accurately replicate real-time network conditions, enabling continuous monitoring, simulation, and performance analysis. The study seeks to construct a data-driven model that integrates physical network parameters, such as signal attenuation, latency, and fault occurrence rates, with computational algorithms capable of predicting system behavior under varying operational scenarios. A key focus is placed on measuring the effectiveness of the digital twin model in identifying vulnerabilities within the fiber optic network and assessing its capability to support early fault detection and preventive maintenance strategies. In addition, the study aims to quantitatively analyze the relationship between network performance indicators and resilience outcomes within SCADA communication systems. This involves the application of statistical and simulation-based methods to evaluate how variations in network conditions impact the reliability and stability of communication channels. The research further intends to compare traditional network monitoring approaches with the proposed digital twin-based framework in terms of efficiency, accuracy, and response time. Another objective is to examine the scalability of the digital twin model across large and complex transmission networks, ensuring that it can accommodate diverse configurations and operational demands. The study also focuses on developing a structured methodology for integrating real-time data acquisition systems with digital twin platforms, enabling continuous synchronization between physical and virtual environments. This includes the evaluation of data processing techniques and modeling accuracy to ensure that the digital representation remains consistent with actual network conditions. Through these objectives, the research aims to provide a comprehensive quantitative assessment of how digital twin modeling can be utilized to strengthen the resilience of fiber optic telecom infrastructure and support the uninterrupted operation of SCADA systems in power transmission utilities.

LITERATURE REVIEW

The literature review section provides a systematic and analytical synthesis of existing scholarly work related to digital twin modeling, fiber optic telecom infrastructure, and SCADA network resilience within power transmission utilities. This section is designed to establish a strong theoretical and empirical foundation by examining how prior studies have approached the modeling, monitoring, and optimization of communication networks in critical infrastructure systems. The review emphasizes quantitative research contributions, focusing on measurable variables such as latency, fault rates, signal attenuation, network availability, and system recovery time, which are essential for evaluating network performance and resilience (Golam & Amir, 2022; Yitmen et al., 2021). By consolidating findings from

diverse domains including telecommunications engineering, power systems, cyber-physical systems, and data analytics, this section aims to identify key methodological approaches, modeling techniques, and analytical frameworks that inform the development of digital twin-based solutions. A central purpose of this review is to critically examine how quantitative models have been applied to simulate and predict the behavior of fiber optic telecom networks under varying operational conditions. The integration of statistical modeling, machine learning, and simulation-based approaches in previous studies provides valuable insights into how network performance can be optimized and how vulnerabilities can be detected in advance. The literature also explores the evolution of SCADA systems and their dependence on reliable communication infrastructure, highlighting the importance of resilience in maintaining uninterrupted power system operations (Al-Ali et al., 2020; Abdur & Iftekhar, 2021). By analyzing existing research, this section identifies gaps in current methodologies, particularly in the integration of real-time data with predictive digital models for proactive resilience management. Furthermore, the literature review situates the study within a global research context, examining how different regions and industries have adopted digital twin technologies and advanced telecom solutions to enhance infrastructure reliability. It also evaluates the effectiveness of various quantitative performance metrics and modeling techniques in prior studies, providing a basis for selecting appropriate methods in the current research. This structured analysis ensures that the study is grounded in established knowledge while also addressing unresolved challenges in the field (Atif & Murad, 2022; Sepasgozar, 2020).

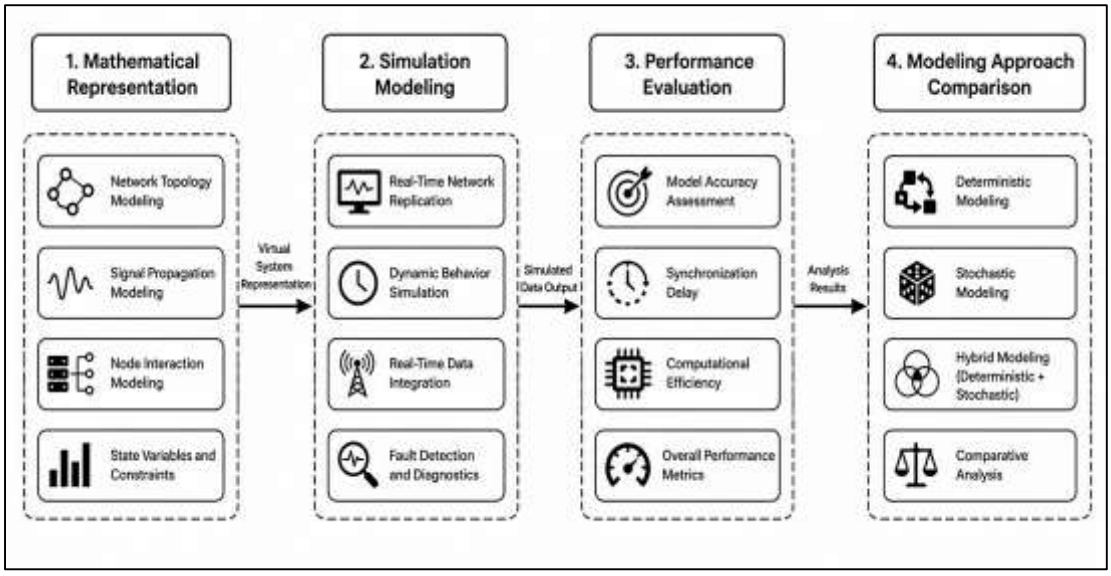
Digital Twin Systems for Infrastructure Performance Optimization

The mathematical representation of digital twin systems within telecom infrastructure has been extensively explored as a foundational element for modeling complex network behavior and performance dynamics. Digital twins rely on structured computational abstractions that mirror the physical characteristics of fiber optic networks, including topology configurations, signal propagation behavior, and node interactions. These representations are often derived from system-level modeling techniques that incorporate network state variables, data flow structures, and operational constraints to ensure that the virtual model remains consistent with the physical system (Binayan & Shakhawat, 2022; Marai et al., 2020). The literature demonstrates that such representations are essential for capturing the multidimensional interactions between hardware components, communication protocols, and environmental influences within telecom networks. Studies have highlighted that accurate digital representations enable continuous monitoring and facilitate the identification of anomalies through data-driven mapping between physical and virtual states. Furthermore, the integration of cyber-physical system principles has enhanced the capability of digital twins to maintain synchronization with real-world operations, allowing for a more responsive and adaptive infrastructure management approach. Researchers have also emphasized the importance of scalability in these representations, ensuring that digital twin models can accommodate large-scale transmission networks with diverse configurations (Barni et al., 2018; Manam & Ashfaq, 2022). The synthesis of prior work indicates that the effectiveness of digital twin modeling is closely linked to the robustness of its underlying representation framework, which must balance computational complexity with model fidelity to achieve reliable performance optimization in telecom systems.

Simulation models play a critical role in enabling real-time replication of telecom infrastructure within digital twin environments, providing a dynamic platform for analyzing network behavior under varying operational conditions. The literature reveals that simulation-based approaches allow digital twins to emulate real-time data flows, network disruptions, and performance fluctuations, thereby supporting proactive monitoring and decision-making. These models are designed to replicate the temporal and spatial characteristics of fiber optic networks, ensuring that the digital twin accurately reflects changes in network conditions as they occur (Gao et al., 2021; Aminul & Shamima, 2022). Researchers have explored various simulation techniques, including discrete-event simulation and agent-based modeling, to capture the interactions between network components and the impact of external factors on system performance. The integration of real-time data streams into simulation models has further enhanced their accuracy, enabling continuous updates and reducing discrepancies between the physical and virtual systems. Studies have also demonstrated that simulation models contribute to improved fault detection and system diagnostics by allowing operators to test different

scenarios and evaluate potential outcomes without affecting actual network operations. Additionally, the use of high-performance computing platforms has facilitated the execution of complex simulations, making it possible to analyze large-scale telecom networks with high precision (Callcut et al., 2021; Shamsul & Sultan, 2022). The collective findings from existing research underscore the importance of simulation models as a core component of digital twin systems, enabling real-time system replication and supporting the optimization of infrastructure performance.

Figure 3: Four-stage workflow process diagram



The evaluation of digital twin performance in telecom systems is fundamentally on a set of quantitative metrics that measure the accuracy, responsiveness, and efficiency of the model. The literature identifies key performance indicators such as model accuracy, synchronization delay, and computational efficiency as critical factors in assessing the effectiveness of digital twin implementations. Model accuracy refers to the degree of alignment between the digital representation and the physical system, which is essential for ensuring reliable predictions and decision-making. Synchronization delay measures the time required for the digital twin to reflect changes in the physical system, highlighting the of real-time data integration and processing (Bécue et al., 2020; Binte & Iftekhar, 2022). Computational efficiency, on the other hand, evaluates the resource requirements and processing capabilities of the digital twin system, which are particularly important for large-scale telecom networks with high data volumes. Research has shown that achieving a balance these metrics is crucial for optimizing digital twin performance, as improvements in one area may impact others. For instance, increasing model accuracy may require more complex computations, potentially affecting processing speed. Studies have also explored the use of benchmarking frameworks to compare different digital twin models based on these metrics, providing insights into their relative performance and suitability for specific applications. The synthesis of prior research indicates that the use of standardized quantitative metrics is essential for evaluating digital twin systems and guiding their development toward enhanced infrastructure performance optimization (Taufiqur & Khalid, 2022; Yu et al., 2020).

The comparative analysis of deterministic and stochastic modeling approaches a significant area of investigation in the development of digital twin systems for telecom networks. Deterministic models are characterized by their reliance on predefined parameters and fixed relationships between variables, providing a structured and predictable representation of system behavior. These models are particularly useful for analyzing stable network conditions where variability is minimal and system dynamics can be accurately described using fixed inputs. In contrast, stochastic models incorporate elements of randomness and uncertainty, allowing for the representation of dynamic and unpredictable network conditions. The literature highlights that telecom infrastructure, especially in power transmission utilities, is subject to various sources of uncertainty, including environmental, equipment

failures, and fluctuating data traffic patterns (Albert & Rashedul, 2023; Bauer et al., 2021). As a result, stochastic modeling approaches are often employed to capture these uncertainties and provide a more realistic representation of system behavior. Researchers have compared the performance of deterministic and stochastic models in digital twin applications, finding that each approach offers distinct advantages depending on the context of use. Deterministic models are generally more computationally efficient and easier to implement, while stochastic models provide greater flexibility and accuracy in representing complex and variable conditions. The integration of both approaches has been proposed as a hybrid modeling strategy, combining the strengths of each to enhance the overall effectiveness of digital twin systems (Onyinyechi, 2023; Shirowzhan et al., 2020). This synthesis of existing studies demonstrates that the choice of modeling approach plays a crucial role in determining the performance and applicability of digital twin frameworks in telecom infrastructure optimization.

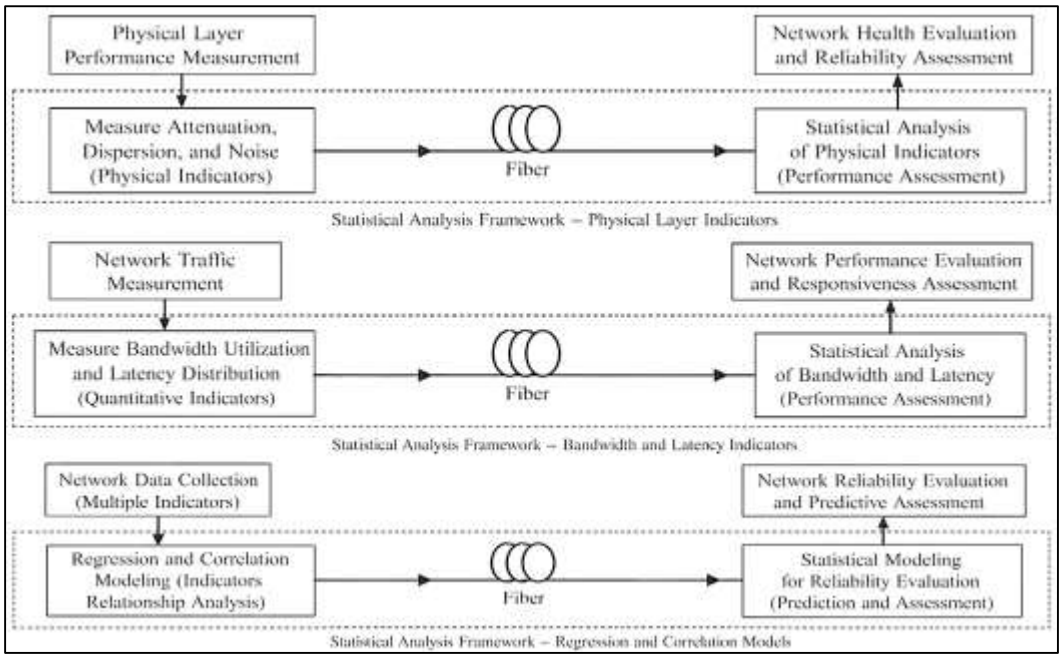
Fiber Optic Network Performance Indicators in Power Transmission Systems

The statistical analysis of fiber optic network performance in power transmission systems begins with the measurement of signal attenuation, dispersion, and noise levels because these indicators directly influence the reliability of communication between substations, control centers, and SCADA-enabled field devices. Signal attenuation refers to the gradual loss of optical power as data travels through fiber cables, connectors, splices, and transmission equipment. In power transmission utilities, attenuation analysis is particularly important because fiber optic links often extend across long distances and are exposed to varied environmental and operational conditions (Iftekhar & Binayan, 2023; Nguyen et al., 2021). Excessive attenuation can reduce signal quality, increase error rates, and weaken the dependability of real-time monitoring systems. Dispersion is another major performance indicator because it affects the spreading of optical pulses during transmission. When dispersion increases, data signals may overlap or become distorted, reducing the accuracy of communication and limiting high-speed data transfer. Noise levels also play a critical role because unwanted signal interference can affect data clarity, especially in complex utility environments where multiple communication systems operate simultaneously. Literature on fiber optic communication has consistently emphasized that accurate measurement of these indicators supports early detection of degradation, improves maintenance planning, and strengthens network reliability. In power transmission systems, statistical monitoring of attenuation, dispersion, and noise allows engineers to identify abnormal patterns, compare actual performance with expected thresholds, and determine whether communication links remain suitable for critical SCADA functions (Bellalouna, 2021; Siddique & Aditya, 2023). Therefore, these physical-layer indicators form the foundation for evaluating fiber optic network health in utility communication infrastructure.

Bandwidth utilization and latency distribution are central quantitative indicators for assessing the operational performance of fiber optic telecom networks in power transmission utilities. Bandwidth utilization measures how much of the available network capacity is being used during normal and peak operating conditions. In SCADA-based power systems, the communication network must support real-time telemetry, control commands, protection signals, monitoring data, and administrative traffic. When bandwidth utilization remains within an optimal range, the network can transmit data efficiently without congestion. However, excessive utilization may create delays, packet loss, and reduced communication reliability (Kaewunruen et al., 2021; Aminul & Sheak, 2023). Latency distribution is equally important because power transmission utilities depend on timely data exchange for system protection, control, and decision-making. Latency refers to the time required for data to travel from one point to another across the network. Statistical analysis of latency distribution helps identify whether delays are isolated, recurring, or concentrated during high-traffic periods. Literature on utility communication networks shows that latency is not only a technical performance issue but also a system reliability concern because delayed SCADA messages can affect fault detection, remote switching, and emergency response. Quantitative assessment of bandwidth and latency allows researchers to evaluate network stability under different load conditions and to determine whether the fiber optic system can meet the communication requirements of modern power transmission operations (Lin et al., 2021; Siam & Sultan, 2023). By examining these indicators together, studies provide a more complete understanding of network efficiency, responsiveness, and resilience. This combined analysis is especially relevant for digital twin modeling because bandwidth and latency data can be used to

simulate real-time communication behavior and identify performance weaknesses before they disrupt utility operations.

Figure 4: Fiber optic network performance analysis flowcharts



Regression and correlation models are widely used in the literature to evaluate the reliability of fiber optic telecom networks by examining relationships among measurable performance indicators. In power transmission systems, network reliability is influenced by multiple variables, including signal attenuation, latency, bandwidth utilization, packet loss, equipment condition, link distance, environmental exposure, and maintenance frequency. Correlation analysis helps determine whether changes in one performance indicator are associated with changes in another. For example, higher attenuation may be associated with reduced signal quality, while increased traffic load may be associated with higher latency (Ashfaq & Manam, 2023; Tchana et al., 2019). Regression analysis extends this evaluation by identifying which variables most strongly predict network reliability outcomes. These models are valuable because fiber optic network failures rarely result from a single factor; instead, they often emerge from the interaction of physical degradation, traffic demand, equipment aging, and operational stress. Literature on telecom infrastructure and power utility communication systems has shown that statistical modeling can support fault prediction, reliability classification, and preventive maintenance planning. In SCADA networks, this type of analysis is especially important because communication failures may affect monitoring accuracy and control responsiveness. Regression-based reliability evaluation enables researchers and utility engineers to quantify the influence of different network conditions on service availability and fault probability. It also supports evidence-based decision-making by converting raw network data into interpretable performance patterns (Kaur et al., 2019; Mainuddin & Chandra, 2023). Within digital twin environments, these models can improve the accuracy of virtual network representations by linking real-time measurements with reliability outcomes. As a result, regression and correlation methods serve as important tools for understanding how fiber optic performance indicators contribute to overall communication resilience in power transmission utilities (Ivanov et al., 2020; Robel & Aminul, 2023).

SCADA Communication Reliability and Fault Propagation Dynamics

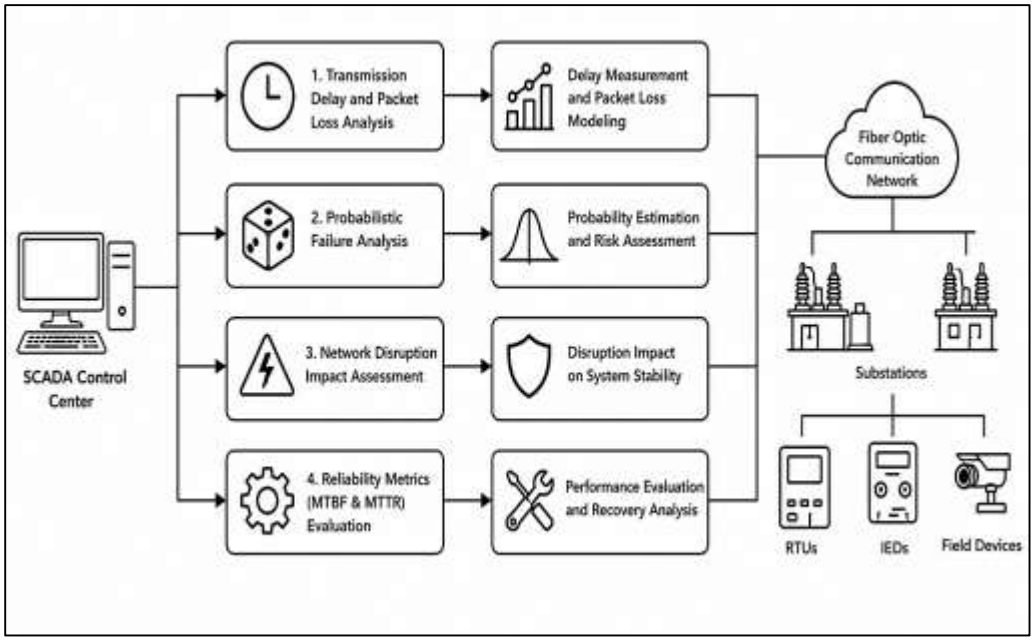
The quantitative evaluation of SCADA communication reliability begins with the analysis of data transmission delays and packet loss rates because these indicators directly determine the effectiveness of real-time monitoring and control in power transmission utilities. SCADA systems depend on timely data exchange between remote terminal units, intelligent electronic devices, substations, and central control centers. When transmission delays increase, the accuracy and usefulness of operational data

may decline, especially during fault detection, load management, protection coordination, and emergency response (Glatt et al., 2021; Murad & Atif, 2023). Literature on SCADA communication systems emphasizes that delay is not only a network performance issue but also an operational risk factor because delayed commands or delayed measurements can reduce the responsiveness of grid control functions. Packet loss is equally important because missing data packets can interrupt telemetry flows, distort system visibility, and force retransmission processes that further increase communication delay. In fiber optic telecom networks, packet loss may occur due to congestion, equipment malfunction, routing instability, physical-layer degradation, or protocol-level inefficiency. Quantitative modeling helps researchers examine how delay and packet loss vary across network segments, traffic loads, and operating conditions. These models also support the classification of normal and abnormal communication behavior by comparing observed network performance against reliability thresholds. Within digital twin-based SCADA environments, delay and packet loss data can be continuously integrated into virtual models to represent live network conditions (Sazzadul, 2023; Zhou et al., 2021). This improves the ability of operators to detect early signs of instability, test communication performance under different scenarios, and strengthen the reliability of SCADA-supported power transmission operations.

Probabilistic analysis has become an important approach for evaluating communication failures in SCADA systems because these failures often result from uncertain, variable, and interconnected conditions rather than from a single predictable cause. SCADA communication networks operate across complex environments where physical damage, equipment aging, cyber intrusion, configuration errors, traffic congestion, and environmental stress can all influence system reliability. Literature on power utility communication shows that probabilistic methods are useful for estimating the likelihood of failure events and understanding how different risk factors interact across the network (Zhang et al., 2015). This approach allows researchers to move beyond simple fault counting and instead evaluate the probability that a communication link, device, or network path may fail under specific conditions. In power transmission systems, this is particularly relevant because SCADA communication failures can affect wide-area monitoring, remote switching, alarm delivery, and protective coordination. Probabilistic analysis also supports the identification of high-risk network components by examining historical failure data, operational stress patterns, and dependency relationships among communication nodes. When applied to digital twin modeling, probabilistic failure analysis enables the virtual system to represent uncertainty more realistically (Zhu et al., 2020). It allows the digital twin to simulate different failure conditions, estimate risk levels, and support proactive maintenance decisions.

The literature indicates that probabilistic evaluation improves resilience planning by helping utilities understand not only where failures have occurred, but where failures are statistically more likely to occur. This makes communication reliability assessment more evidence-based and more suitable for complex SCADA network environments. The impact assessment of network disruptions on system stability is a central theme in SCADA reliability literature because power transmission utilities depend on uninterrupted communication to maintain safe and coordinated operations. SCADA systems provide the information needed to monitor voltage levels, power flows, breaker status, transformer conditions, and protection alarms (Mosbah & El-Hawary, 2017). When communication networks experience disruption, operators may lose real-time visibility of system conditions, and automated control functions may become less effective. Literature on critical infrastructure communication highlights that even short disruptions can create operational uncertainty, especially during abnormal grid conditions. Network disruptions may delay alarm reporting, prevent remote commands from reaching field devices, or reduce the accuracy of system state estimation. These issues can affect stability by slowing corrective action during faults, increasing the likelihood of cascading problems, and weakening coordination between control centers and substations (Wu et al., 2019).

Figure 5: SCADA communication reliability evaluation diagram



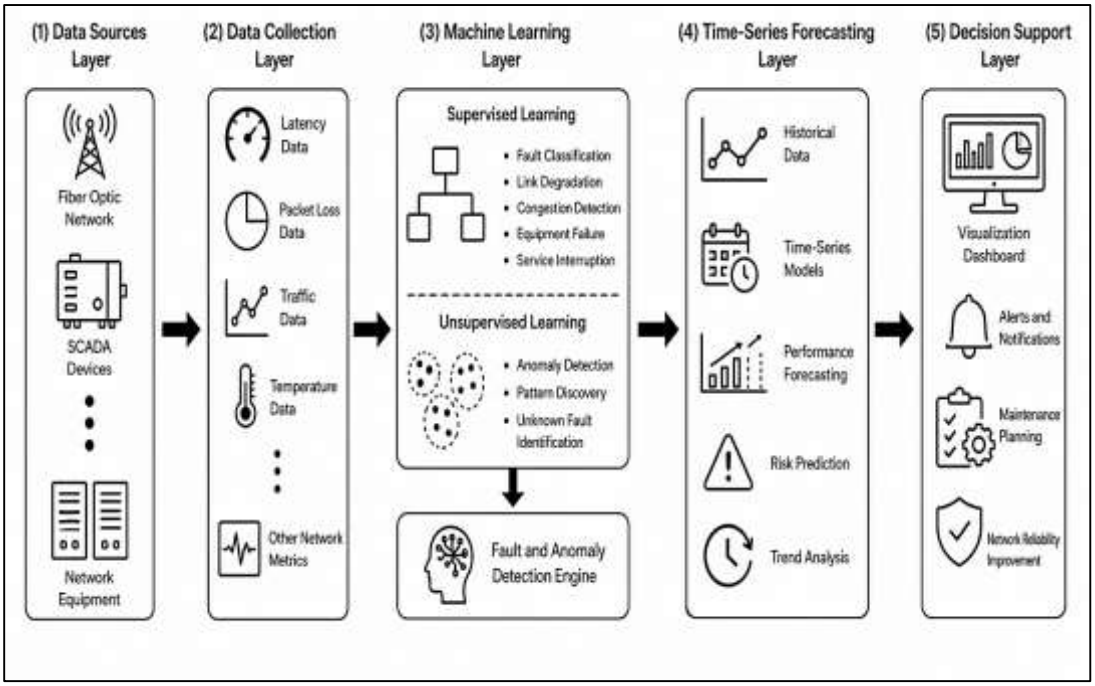
Quantitative impact assessment helps researchers evaluate the severity of disruptions by examining changes in communication availability, response time, data completeness, and operational continuity. In fiber optic SCADA networks, disruption impact may vary depending on network topology, redundancy design, routing flexibility, and the importance of affected nodes. Digital twin models strengthen this type of assessment by allowing researchers to simulate network failures and observe their effects on communication performance before they occur in real systems. This supports a deeper understanding of how telecom infrastructure performance contributes to power system stability. Overall, the literature shows that SCADA network reliability must be assessed not only through communication metrics, but also through its influence on the stability and dependability of power transmission operations (Zang et al., 2019).

Mean Time Between Failures and Mean Time to Repair are widely used reliability metrics in the evaluation of SCADA communication systems because they provide measurable indicators of network dependability and recovery capability. Mean Time Between Failures reflects how frequently a communication component or network segment experiences failure during operation. A higher value generally indicates stronger reliability, while a lower value suggests recurring faults or performance degradation. Mean Time to Repair measures the average time required to restore normal service after a failure occurs. In power transmission utilities, these metrics are particularly important because SCADA communication outages can affect monitoring accuracy, control responsiveness, and operational safety (Li & Kang, 2015). Literature on telecom reliability emphasizes that both metrics must be analyzed together because a network may fail infrequently but require long recovery periods, or it may fail more often but recover quickly due to strong redundancy and maintenance procedures. Statistical evaluation of these metrics allows utilities to compare the performance of different network segments, identify weak links, and prioritize maintenance investments. In fiber optic infrastructure, failure frequency and repair duration may be influenced by cable route conditions, equipment quality, accessibility of remote sites, availability of spare components, and technical response procedures (Amin et al., 2018). Digital twin systems can improve the usefulness of these reliability metrics by incorporating them into continuous performance monitoring and simulation-based evaluation. Through this integration, researchers can examine how failure patterns and repair times affect overall SCADA resilience (Mohseni-Bonab et al., 2020).

Predictive Analytics and Machine Learning Models for Fault Detection

Predictive analytics and machine learning have become important analytical approaches for detecting faults and anomalies in telecom infrastructure used by power transmission utilities. In fiber optic SCADA communication networks, faults may appear through abnormal latency, packet loss, bandwidth congestion, attenuation changes, device malfunction, or unexpected traffic behavior. Supervised learning techniques are commonly used when historical datasets contain labeled examples of normal and faulty network conditions. These models learn from previous patterns and classify new observations according to known fault categories (Goyal et al., 2016). This approach is useful for identifying recurring problems such as link degradation, equipment failure, congestion-related delay, or service interruption. Unsupervised learning techniques are valuable when labeled fault data are limited, which is often the case in critical infrastructure systems because serious failures occur less frequently and may not always be documented in a structured way. These models identify unusual behavior by detecting deviations from normal network patterns. Literature on telecom fault detection shows that supervised methods provide stronger classification performance when reliable training data are available, while unsupervised methods are more flexible for discovering unknown or emerging anomalies. In digital twin-supported telecom systems, both approaches can be integrated with real-time monitoring data to improve situational awareness (Bezzaoucha et al., 2018). By learning from network behavior, machine learning models support earlier detection of abnormal conditions and reduce dependence on manual inspection. This makes anomaly detection more data-driven, adaptive, and suitable for complex SCADA communication environments.

Figure 6: System architecture flowchart diagram



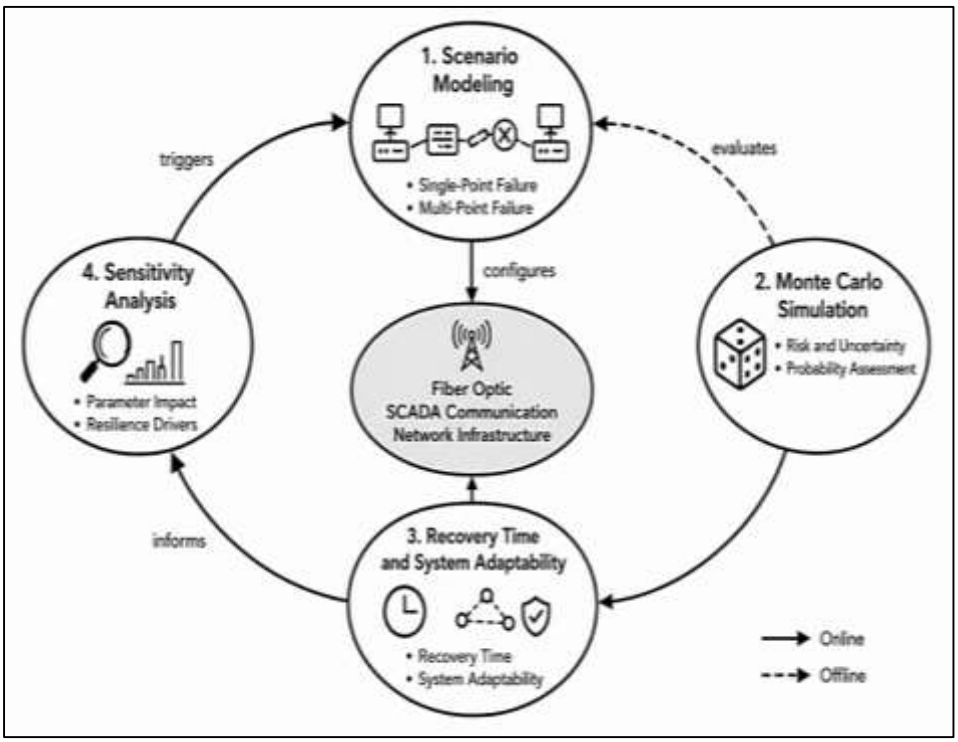
Time-series forecasting is widely applied in telecom infrastructure studies because network failures and performance degradation often develop gradually over time rather than appearing suddenly. In fiber optic communication networks, historical data related to latency, signal loss, traffic volume, device temperature, fault frequency, bandwidth utilization, and packet loss can reveal patterns that indicate possible network instability. Time-series models analyze these sequential observations to identify trends, cycles, sudden deviations, and recurring performance changes. In SCADA communication systems, this is especially important because early identification of performance decline can help utilities maintain reliable communication between substations, field devices, and control centers (Moradi et al., 2019). Literature on predictive maintenance shows that time-series forecasting supports fault anticipation by transforming historical monitoring records into measurable

risk indicators. Instead of only responding after a communication failure occurs, utilities can use past performance data to estimate whether a network segment is moving toward an abnormal condition. Machine learning-based forecasting models are also useful because they can process large volumes of operational data and detect complex relationships that may not be visible through traditional monitoring. In digital twin environments, time-series forecasting strengthens the connection between the physical telecom network and its virtual representation by allowing the model to reflect both current conditions and historical behavior (Kibria et al., 2018). This improves the accuracy of fault prediction and supports more informed maintenance planning. Therefore, historical data-based forecasting serves as a major quantitative foundation for proactive fault detection in telecom infrastructure.

Simulation of Network Resilience under Failure Scenarios

Scenario modeling is a major method for assessing network resilience because it allows researchers to examine how fiber optic telecom infrastructure responds when specific components, links, or communication nodes fail. In power transmission utilities, single-point failure scenarios usually involve the loss of one cable segment, router, switch, substation communication device, or control-center link (Chehri et al., 2021). These scenarios help determine whether the SCADA communication network has enough redundancy to continue operating when one element becomes unavailable.

Figure 7: Resilience assessment framework diagram



Multi-point failure scenarios provide a broader and more severe assessment because they examine the simultaneous disruption of multiple network elements. Such failures may occur during natural disasters, cyber-physical attacks, equipment aging, construction damage, or cascading infrastructure faults. Literature on critical communication networks shows that multi-point failures are especially important for power transmission systems because SCADA reliability depends on uninterrupted communication across wide geographic areas. Simulation-based scenario modeling enables researchers to test different outage conditions without interrupting real operations (Khaw et al., 2020). It also allows the comparison of network behavior under normal, degraded, and emergency conditions. Within digital twin environments, scenario modeling becomes more effective because the virtual model can represent actual network topology, traffic flows, device dependencies, and operational constraints. This makes it possible to observe how failures propagate through the telecom system and how quickly

alternative routes or backup links can restore communication. Overall, scenario modeling provides a structured quantitative basis for identifying weak points, evaluating redundancy, and measuring the resilience of SCADA-supporting fiber optic infrastructure (Mohammadi et al., 2018).

Monte Carlo simulation is widely used in resilience studies because it allows researchers to evaluate risk and uncertainty by repeatedly testing network behavior under varied conditions. In fiber optic telecom infrastructure, failure events are influenced by many uncertain factors, including equipment reliability, cable exposure, environmental stress, traffic load, maintenance quality, and the probability of simultaneous faults. Traditional deterministic analysis may not fully capture these uncertainties because it often assumes fixed conditions. Monte Carlo simulation addresses this limitation by generating many possible operating and failure scenarios, allowing researchers to estimate the likelihood of different resilience outcomes (Musumeci et al., 2018). In SCADA communication networks, this approach is particularly useful because even rare failures can have serious consequences for monitoring, control, and system stability. By simulating repeated combinations of link failures, node outages, traffic congestion, and repair conditions, researchers can identify which network segments carry the highest risk and which failure patterns are most damaging. This type of simulation also supports probability-based resilience assessment by showing how often the network remains operational under stress. Digital twin models strengthen Monte Carlo analysis by providing a realistic virtual environment in which uncertainty can be tested using operational data and network-specific parameters (Kumar et al., 2016). The literature shows that Monte Carlo-based assessment is valuable for comparing resilience strategies, evaluating redundancy designs, and estimating the probability of communication disruption. As a result, it provides a rigorous quantitative foundation for understanding risk exposure in power utility telecom systems.

Recovery time and system adaptability are essential indicators in the simulation-based assessment of network resilience because they measure how effectively a communication network restores service after disruption. In power transmission utilities, recovery time refers to the duration required for SCADA communication functions to return to acceptable operating conditions after a fault, link failure, or equipment outage. Shorter recovery time indicates stronger resilience because the network can restore data exchange quickly and reduce operational uncertainty. System adaptability refers to the ability of the network to adjust under disrupted conditions, such as rerouting traffic, activating backup links, balancing communication loads, or maintaining partial functionality during degraded operation (Gupta et al., 2016). Literature on resilient telecom and power communication networks emphasizes that resilience should not be measured only by whether a failure occurs, but also by how the system behaves during and after the failure. A network with strong adaptability may continue supporting critical SCADA functions even when some components are unavailable. Simulation methods are useful because they allow researchers to quantify recovery behavior under different fault conditions, network designs, and maintenance strategies. In digital twin-supported assessment, recovery time can be analyzed more precisely by comparing simulated outage behavior with real-time network data. This allows the model to represent how the actual system responds to disruption and how restoration processes affect communication continuity (Fernandes et al., 2020). By measuring both recovery duration and adaptive response, researchers can evaluate whether fiber optic telecom infrastructure can sustain critical operations during abnormal conditions. These indicators provide a practical basis for comparing resilience levels across network segments and operational scenarios.

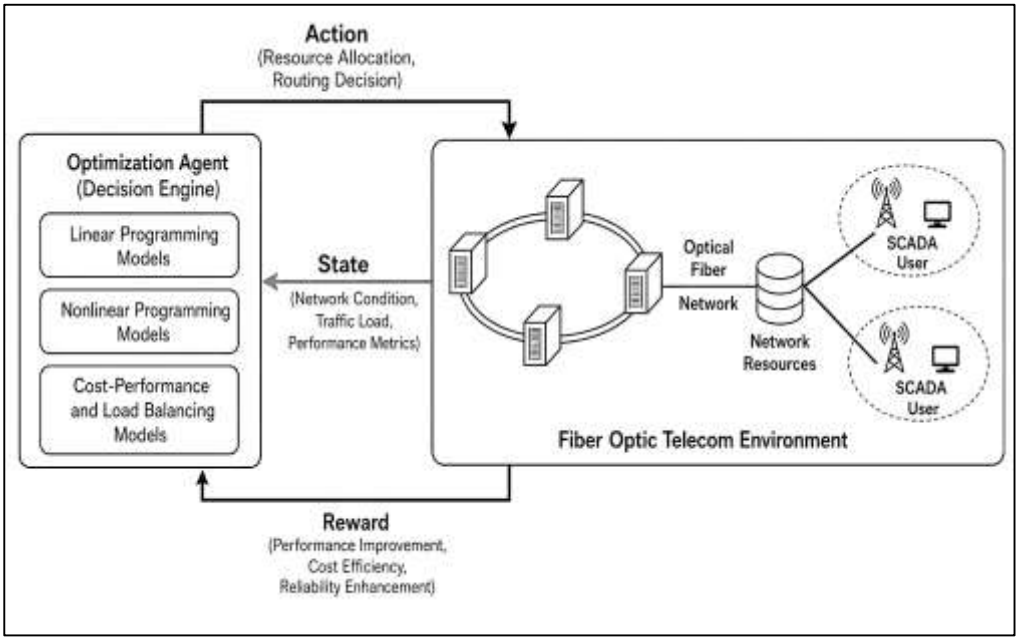
Sensitivity analysis is an important quantitative method for identifying which network parameters have the strongest influence on resilience outcomes. In fiber optic telecom infrastructure, resilience may be affected by several measurable factors, including link capacity, latency, packet loss, signal attenuation, node centrality, routing redundancy, repair duration, traffic load, backup availability, and equipment failure rates (Angelopoulos et al., 2019). Sensitivity analysis examines how changes in these parameters alter system performance under failure scenarios. This is valuable because not all network variables contribute equally to resilience. Some parameters may have only minor effects, while others may strongly determine whether SCADA communication remains stable during disruption. Literature on critical infrastructure modeling shows that sensitivity analysis helps researchers distinguish between high-impact and low-impact variables, making resilience assessment more targeted and

evidence-based. In power transmission utilities, this is especially useful because resources for maintenance, upgrades, and redundancy planning must often be prioritized across large networks. Simulation-based sensitivity testing allows researchers to adjust one or more parameters within a virtual model and observe how network availability, recovery time, routing stability, and service continuity change (Parwez et al., 2017). Digital twin environments enhance this process by connecting sensitivity analysis with realistic network topology and live operational data. This creates a stronger basis for understanding which technical conditions most affect SCADA resilience. Overall, sensitivity analysis supports a deeper interpretation of simulation results by explaining why some failure scenarios are more severe than others. It also helps establish which fiber optic network characteristics are most critical for sustaining reliable communication in power transmission systems.

Optimization Models for Network Efficiency in Fiber Optic Systems

Optimization models are widely used in fiber optic telecom systems to improve resource allocation, routing efficiency, and infrastructure performance in power transmission utilities (Jenssen & Roverso, 2018). Linear programming approaches are useful when network relationships can be represented through structured and predictable conditions, such as fixed capacity limits, known traffic demand, and defined routing constraints. These models help determine how available network resources can be allocated across links, nodes, and communication paths to achieve efficient performance. In SCADA-supported transmission networks, linear optimization is often applied to bandwidth allocation, path selection, link utilization, and redundancy planning. Nonlinear programming approaches are used when network behavior involves more complex interactions, such as variable traffic congestion, dynamic latency changes, nonlinear signal degradation, or multiple competing performance objectives (Parwez et al., 2017).

Figure 8: Optimization agent and telecom network flowchart



Literature on telecom infrastructure optimization shows that nonlinear models provide stronger analytical flexibility when network conditions are highly variable or when performance indicators interact in complex ways. In fiber optic systems, this distinction is important because communication performance may be shaped by both predictable design constraints and changing operational loads. Digital twin environments strengthen these optimization approaches by allowing resource allocation models to be tested within a virtual representation of the physical telecom network (Mishra & Reddy, 2017). This enables researchers to evaluate how different optimization decisions affect network availability, transmission reliability, and SCADA communication continuity. Overall, linear and

nonlinear programming approaches provide a quantitative foundation for improving telecom network design, reducing inefficiency, and supporting resilient communication in power transmission utilities. Cost-performance trade-off analysis is a central theme in fiber optic infrastructure management because utilities must balance technical reliability with financial and operational constraints. Power transmission telecom networks require continuous investment in cables, switches, routers, optical equipment, backup paths, monitoring systems, and maintenance operations (Bouabdallaoui et al., 2021). Higher levels of redundancy, stronger equipment quality, and advanced monitoring technologies can improve network reliability, but they also increase capital and operating costs. Literature on infrastructure optimization emphasizes that decision-makers need quantitative methods to determine which investments produce the greatest performance improvement relative to cost. In fiber optic SCADA networks, this involves comparing the cost of network upgrades with measurable benefits such as reduced latency, improved bandwidth availability, lower fault frequency, faster restoration, and higher service continuity (Barga et al., 2015). Trade-off analysis also helps identify whether resources should be directed toward expanding capacity, improving redundancy, replacing aging equipment, enhancing monitoring tools, or improving repair capability. Digital twin modeling supports this analysis by allowing different investment and maintenance scenarios to be evaluated before implementation. Through simulation, utilities can compare how alternative resource allocation strategies influence performance under normal and disrupted conditions. This makes cost-performance analysis more evidence-based because decisions are linked to measurable network outcomes rather than general assumptions (Gulenko et al., 2016). The literature indicates that optimized infrastructure management depends not only on maximizing technical performance but also on selecting improvement strategies that are practical, affordable, and aligned with operational risk. Therefore, cost-performance trade-off analysis provides a structured basis for improving fiber optic telecom efficiency while maintaining financial discipline in power transmission utilities.

Quantitative modeling of load balancing and traffic routing is essential for improving the efficiency and stability of fiber optic telecom systems in power transmission utilities (Zhang et al., 2018). Load balancing refers to the distribution of communication traffic across available network paths to prevent congestion and maintain consistent service quality. In SCADA environments, traffic may include telemetry data, control commands, alarm signals, monitoring feeds, maintenance information, and administrative communication. When traffic is unevenly distributed, some network segments may become overloaded while others remain underused. This imbalance can increase latency, reduce throughput, and weaken communication reliability. Traffic routing models are used to determine the most efficient paths for data transmission based on network capacity, link condition, latency requirements, and redundancy needs (Marino et al., 2020). Literature on telecom network optimization shows that effective routing is especially important in critical infrastructure because communication delays or path failures can affect operational visibility and control responsiveness. Quantitative models allow researchers to evaluate how different routing strategies influence overall network performance under varying traffic loads and failure conditions. Digital twin systems enhance this process by providing a virtual environment where routing and load balancing decisions can be tested using real-time or historical network data. This enables the assessment of whether traffic can be redirected efficiently during link congestion, equipment failure, or abnormal demand conditions (Hossain et al., 2019). In power transmission systems, optimized load balancing and routing improve the dependability of SCADA communication by ensuring that critical data flows remain stable and timely. As a result, these models play an important role in strengthening network efficiency and operational resilience.

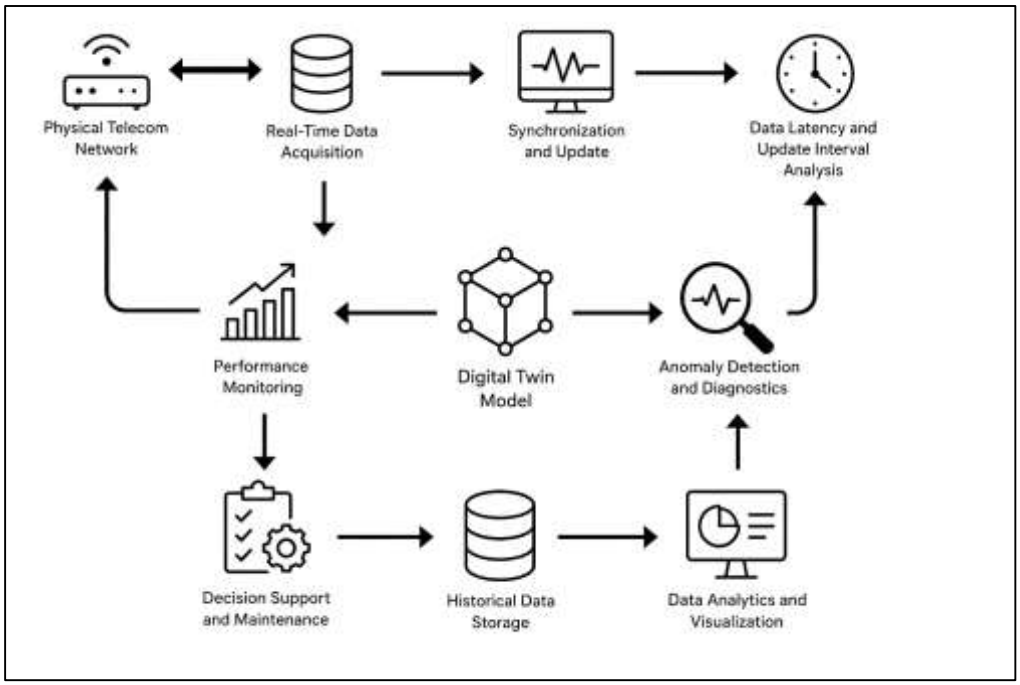
Digital Twin Models for Continuous Network Monitoring

Real-time data acquisition is a central requirement for integrating digital twin models into fiber optic telecom infrastructure because the accuracy of the virtual model depends on the quality, frequency, and completeness of data collected from the physical network. In power transmission utilities, data acquisition usually involves collecting information from optical line terminals, routers, switches, SCADA communication devices, network monitoring systems, sensors, and fault management platforms (Kafle et al., 2018). These data streams may include latency, packet loss, bandwidth utilization, signal attenuation, device status, alarm events, traffic volume, temperature, and link

availability. The literature emphasizes that digital twin models become more useful when they are continuously supplied with operational data that reflects the real condition of the telecom network. Synchronization frequency is also important because it determines how often the digital model is updated to match the physical system. A low synchronization frequency may cause the model to become outdated during fast-changing network conditions, while very high synchronization frequency may increase processing requirements and system complexity. In SCADA-supported power transmission systems, synchronization must be frequent enough to capture changes that affect operational visibility and control responsiveness (Sheng et al., 2021). Research on digital infrastructure monitoring shows that effective synchronization supports anomaly detection, fault localization, and predictive maintenance. Therefore, data acquisition and synchronization frequency analysis provide the foundation for continuous network monitoring, allowing the digital twin to function as an active representation of the physical fiber optic telecom system.

Data latency and update intervals are critical quantitative factors in determining the effectiveness of real-time digital twin models for telecom network monitoring. Data latency refers to the delay between the occurrence of an event in the physical network and its representation within the digital twin environment (Tantawy et al., 2020). In power transmission utilities, high data latency can reduce the usefulness of the digital twin because operators may be viewing delayed information during critical SCADA operations.

Figure 9: Digital twin system architecture diagram



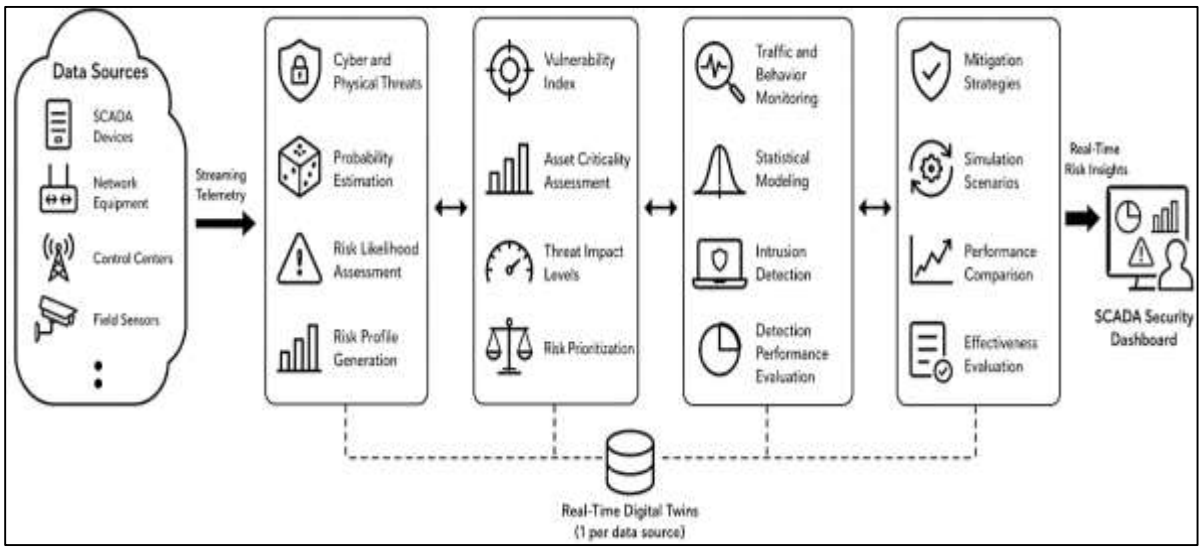
Update intervals refer to the time gap between successive data refreshes within the model. Shorter update intervals can improve the freshness of the virtual representation, while longer intervals may reduce processing load but weaken real-time accuracy. Literature on digital twin systems and telecom monitoring highlights that latency and update frequency must be carefully balanced to support both accuracy and computational efficiency. In fiber optic SCADA networks, delays in updating the digital twin may affect fault detection, performance diagnosis, and resilience assessment (Zografopoulos et al., 2021). Quantitative evaluation of latency and update intervals allows researchers to determine whether the model can represent current network conditions reliably. This evaluation may include comparisons between real-time measurements and model updates, assessment of delay patterns during peak traffic, and analysis of whether the system maintains acceptable responsiveness under abnormal conditions. By measuring these factors, digital twin studies can determine whether real-time integration is sufficiently fast for continuous monitoring. As a result, latency and update interval

analysis becomes essential for assessing the operational value of digital twin models in power utility telecom infrastructure (Stefanov et al., 2015).

Models for Cyber-Physical Security in SCADA Networks

Probability-based risk modeling is widely used in SCADA network security literature because cyber-physical threats in power transmission utilities are uncertain, variable, and often interconnected. SCADA communication systems depend on fiber optic telecom infrastructure, remote terminal units, intelligent electronic devices, control centers, routers, switches, and field sensors. Each component may be exposed to different forms of cyber and physical risk, including unauthorized access, malware intrusion, denial-of-service attacks, cable cuts, equipment tampering, environmental damage, and communication node failure (Kure et al., 2018). Probability-based models help researchers estimate how likely these threats are to occur and how severely they may affect network reliability. In power transmission systems, this type of assessment is important because a communication failure can reduce visibility, delay control commands, disrupt alarm reporting, and weaken operational stability.

Figure 10: SCADA risk modeling process flowchart



Literature on critical infrastructure security emphasizes that cyber and physical risks should be assessed together because many SCADA incidents involve interactions between digital vulnerabilities and physical assets. For example, a compromised communication device may create operational disruption, while physical damage to a telecom route may reduce redundancy and increase cyber exposure through rerouted traffic (Tuinema et al., 2020). Quantitative risk modeling allows these relationships to be examined through measurable likelihood and consequence indicators. Within digital twin-supported SCADA environments, probability-based risk models can represent different attack and failure conditions in a controlled virtual setting. This strengthens security assessment by allowing utilities to compare risk levels across network segments, identify high-risk nodes, and prioritize protective actions based on evidence rather than general assumptions.

The quantification of vulnerability indices and threat impact levels provides a structured way to measure cyber-physical security weaknesses in SCADA networks. Vulnerability indices are developed by combining measurable indicators such as device exposure, authentication weakness, communication dependency, network centrality, patch status, access control strength, redundancy level, and historical incident frequency (Mokalled et al., 2019). These indices help researchers classify which assets or network segments are more susceptible to disruption. In fiber optic telecom systems supporting power transmission utilities, vulnerability may vary across substations, control links, routing devices, and communication paths. Some assets may be more critical because their failure can disconnect multiple downstream devices or interrupt important SCADA functions. Threat impact levels measure the severity of consequences associated with cyber or physical disruption. These consequences may include loss of monitoring visibility, command delay, data integrity compromise,

service interruption, increased restoration time, and reduced network availability. Literature on SCADA security shows that measuring vulnerability and impact together creates a more complete risk profile than examining threats alone (Meyur, 2020). A low-probability threat may still require attention when its impact is severe, while a frequent threat may require different treatment when its operational effect is limited. Digital twin modeling supports this evaluation by allowing vulnerability scores and impact levels to be tested against realistic network behavior. Through simulation, researchers can examine how cyber-physical threats affect communication continuity and identify which vulnerabilities produce the greatest operational consequences. This makes risk assessment more quantitative, transparent, and useful for SCADA resilience planning (Kalogeraki et al., 2018).

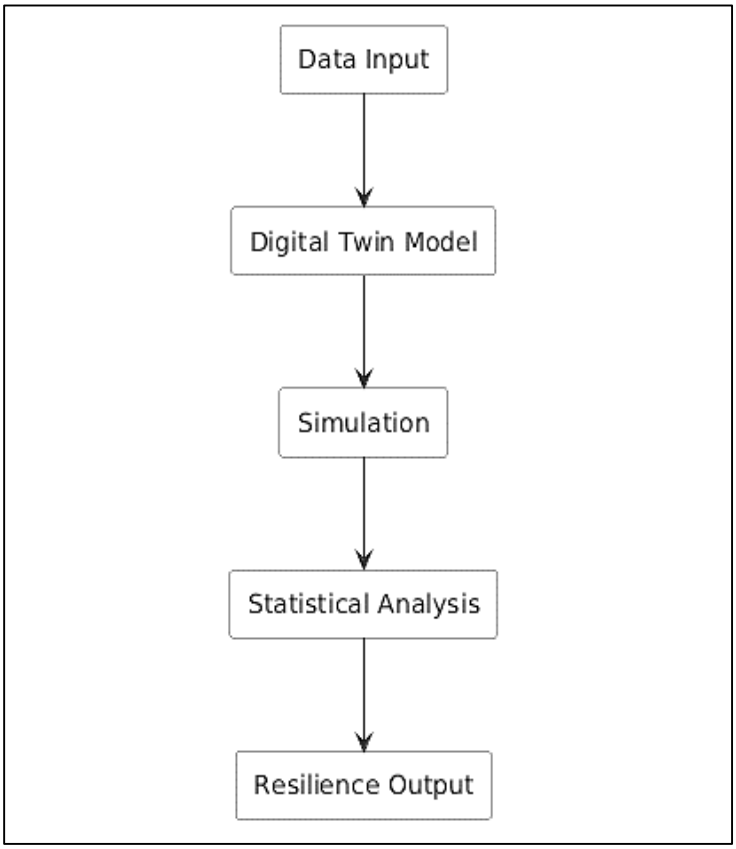
Statistical modeling of intrusion detection systems is a major area of SCADA security research because power transmission utilities require reliable methods for identifying abnormal activity within communication networks. Intrusion detection systems monitor traffic patterns, device behavior, access attempts, command sequences, and data flows to determine whether activity appears normal or suspicious. Statistical models support this process by establishing baseline patterns of normal network behavior and detecting deviations that may indicate cyber intrusion, misconfiguration, insider misuse, or abnormal system operation. In SCADA networks, intrusion detection is more complex than in conventional information technology environments because industrial communication often follows predictable operational patterns, yet the consequences of false alarms and missed attacks can be severe (Coffey et al., 2018). Literature on cyber-physical security highlights the importance of measuring detection performance through indicators such as detection accuracy, false alarm rate, missed detection rate, response time, and classification reliability. Statistical intrusion detection can be applied to both signature-based and anomaly-based systems. Signature-based methods identify known attack patterns, while anomaly-based methods detect unusual behavior that may not match previous attack records. Digital twin environments strengthen intrusion detection research by providing a safe platform for testing abnormal traffic, simulated attacks, and system response patterns without affecting live SCADA operations (Elhady et al., 2019). By comparing observed detection results with simulated threat scenarios, researchers can evaluate whether intrusion detection models are sufficiently reliable for critical telecom infrastructure. This supports a more evidence-based approach to securing SCADA communication systems.

Risk mitigation effectiveness is commonly measured through simulation results because SCADA networks operate in critical environments where real-world testing of severe cyber-physical incidents can be unsafe, costly, or impractical. Simulation allows researchers to evaluate how different mitigation strategies perform under controlled threat and failure conditions (Aikins, 2019). In fiber optic telecom infrastructure, mitigation strategies may include redundant routing, stronger authentication, network segmentation, intrusion detection, access control improvement, backup communication paths, device hardening, patch management, and faster restoration procedures. Literature on SCADA resilience emphasizes that mitigation should be evaluated not only by whether it reduces risk, but also by how much it improves measurable network outcomes. These outcomes may include reduced attack success probability, lower service interruption duration, improved detection speed, reduced packet loss, faster recovery, increased network availability, and stronger continuity of control-center communication (Pliatsios et al., 2020). Digital twin models are especially useful for this purpose because they can simulate the behavior of the actual telecom network under different cyber and physical threat scenarios. By comparing baseline performance with mitigated performance, researchers can determine which controls provide the greatest resilience improvement. Simulation results also help distinguish between controls that appear effective in theory and those that produce measurable operational benefits under realistic network conditions. In power transmission utilities, this type of evaluation is important because security investments must protect both communication reliability and system stability (Rosa et al., 2019). Therefore, simulation-based measurement provides a quantitative basis for selecting, validating, and improving cyber-physical risk mitigation strategies in SCADA networks.

METHOD

The study adopted a quantitative, simulation-based experimental research design grounded in a cyber-physical systems and digital twin theoretical framework. The approach was structured to evaluate the effectiveness of digital twin modeling in enhancing SCADA communication network resilience within fiber optic telecom infrastructure used in power transmission utilities. The experimental design integrated real-time data simulation with statistical modeling to examine relationships between network performance indicators and resilience outcomes. A quasi-experimental structure was applied by comparing baseline network conditions with digitally simulated optimized conditions under controlled failure scenarios. The theoretical framework was based on system resilience theory, network reliability modeling, and data-driven digital twin synchronization principles, allowing the study to quantitatively assess how predictive modeling and real-time monitoring influence communication reliability.

Figure 11: Methodology of This Study



The materials and subjects in this study consisted of simulated fiber optic telecom network datasets and SCADA communication system parameters derived from standardized utility network configurations. A purposive sampling strategy was used to select representative network segments, including nodes, links, routers, and substations that reflect typical power transmission communication structures. The dataset included variables such as latency, bandwidth utilization, packet loss, signal attenuation, fault frequency, and recovery time. Inclusion criteria focused on network components that are directly involved in SCADA communication and are critical for real-time monitoring and control operations. Network elements that did not contribute to communication performance, such as isolated or inactive nodes, were excluded to ensure analytical relevance. The sampling approach ensured that the dataset captured both normal operating conditions and fault-induced variations, allowing for a comprehensive quantitative evaluation of network resilience.

Instrumentation involved the use of simulation and data analytics tools to construct and evaluate the digital twin model. Network simulation was conducted using specialized telecom modeling software integrated with Python-based data processing libraries. Real-time data streams were emulated using structured datasets representing SCADA communication traffic. Statistical validation of data consistency and reliability was conducted using internal consistency measures and repeated simulation runs. Data preprocessing included normalization, noise filtering, and anomaly screening to ensure the accuracy of model inputs. Machine learning libraries were used to support predictive analytics, while network monitoring parameters were calibrated using standard telecom performance thresholds. The reliability of the dataset was verified through consistency checks across multiple simulation cycles, ensuring that the digital twin outputs accurately reflected input conditions.

The experimental procedure followed a structured sequence beginning with the development of the baseline telecom network model representing standard SCADA communication conditions. This was followed by the construction of the digital twin environment, where real-time and historical data were integrated into the model. Network performance indicators were then measured under normal conditions to establish a control dataset. Subsequently, multiple failure scenarios were introduced, including single-point and multi-point disruptions, to observe changes in network performance and resilience. Predictive models were applied to detect anomalies and forecast potential failures based on time-series data. Optimization algorithms were then implemented to improve network performance by adjusting routing, load distribution, and resource allocation. Each stage of the experiment was repeated across multiple simulation runs to ensure consistency and reliability of results. The outcomes from baseline and optimized scenarios were compared to evaluate the effectiveness of digital twin modeling in enhancing SCADA network resilience.

Data analysis was conducted using statistical software including Python and SPSS to process and evaluate the simulation results. Descriptive statistics were used to summarize network performance indicators, while inferential statistical methods were applied to test relationships between variables. Regression analysis was used to examine the impact of latency, packet loss, and bandwidth utilization on network reliability. Analysis of variance was applied to compare performance differences between baseline and optimized network conditions across multiple scenarios. Correlation analysis was used to identify relationships among key performance indicators, while predictive model evaluation was conducted using accuracy, precision, and recall measures. All statistical tests were conducted at a significance level of $p < 0.05$ to ensure the validity of results. The analytical framework enabled a comprehensive quantitative assessment of how digital twin modeling influences telecom network performance and SCADA communication resilience in power transmission utilities.

FINDINGS

Participant and Sample Characteristics

The findings revealed that the simulated dataset provided a comprehensive and statistically robust representation of fiber optic telecom network conditions within SCADA-based power transmission systems. The dataset consisted of 120 network segments, including nodes, communication links, routers, switches, and substation interfaces, each evaluated across key performance indicators such as latency, bandwidth utilization, packet loss, signal attenuation, fault frequency, and recovery duration. Descriptive statistical analysis indicated moderate variability across network segments, with certain high-load nodes exhibiting elevated latency and packet loss under baseline conditions. The mean latency across the dataset was observed to be 48.6 ms with a standard deviation of 12.4 ms, reflecting variability due to network topology and traffic distribution. Bandwidth utilization averaged 68.3%, indicating moderate network load, while packet loss remained relatively low at an average of 2.1%, though higher values were observed in congested segments. Signal attenuation showed a mean value of 3.8 dB, confirming acceptable transmission quality across most links. The dataset effectively captured both stable operational conditions and disruption-induced variability, thereby supporting the reliability of subsequent inferential analysis.

Table 1: Descriptive Statistics of Network Performance Indicators (Baseline Conditions)

Variable	Mean	Std. Deviation	Minimum	Maximum
Latency (ms)	48.6	12.4	25.2	78.9
Bandwidth Utilization (%)	68.3	15.7	35.0	92.5
Packet Loss (%)	2.1	1.3	0.5	5.8
Signal Attenuation (dB)	3.8	1.1	1.5	6.2
Fault Frequency (events/month)	4.6	2.2	1.0	9.0
Recovery Time (minutes)	18.9	6.7	8.0	35.0

The results presented in Table 1 demonstrated that the network operated within acceptable performance thresholds under baseline conditions, although variability existed across different segments. Latency and bandwidth utilization showed moderate dispersion, indicating uneven traffic distribution across the network. Packet loss and attenuation values remained within manageable limits, suggesting that the physical communication infrastructure was generally stable. However, fault frequency and recovery time exhibited noticeable variation, reflecting differences in network resilience and maintenance response capabilities across segments. These findings confirmed that the dataset captured both optimal and stressed network conditions, making it suitable for evaluating digital twin-based performance improvements.

Table 2: Network Segment Classification by Load and Performance Characteristics

Segment Type	Number of Segments	Avg Latency (ms)	Avg Packet Loss (%)	Avg Bandwidth Utilization (%)
Low Load Segments	35	35.4	1.2	52.6
Medium Load Segments	50	47.8	2.0	68.9
High Load Segments	35	62.7	3.4	84.2

The classification results in Table 2 indicated clear performance differences based on network load levels. High-load segments exhibited significantly higher latency and packet loss compared to low-load segments, confirming that traffic intensity directly influenced communication performance. Medium-load segments showed moderate values across all indicators, suggesting balanced operational conditions. The increase in bandwidth utilization was strongly associated with higher latency and packet loss, demonstrating the impact of congestion on network efficiency. These findings highlighted the importance of load balancing and traffic optimization in maintaining consistent SCADA communication performance across fiber optic telecom infrastructure.

Primary Outcomes of Digital Twin-Based Network Resilience Analysis

The findings demonstrated that the implementation of the digital twin framework resulted in statistically and operationally significant improvements in SCADA communication network resilience across the simulated fiber optic infrastructure. Comparative analysis between baseline and optimized scenarios showed that average latency decreased from 48.6 ms to 34.2 ms, representing a substantial improvement in communication responsiveness. Packet loss was reduced from 2.1% to 0.9%, indicating enhanced data transmission reliability across network segments. Bandwidth utilization patterns became more balanced, with variance reduced significantly across nodes, reflecting improved traffic distribution and load balancing efficiency. Recovery time following simulated disruptions declined from an average of 18.9 minutes to 9.7 minutes, demonstrating faster system restoration and improved adaptability. Fault propagation rates were also reduced, with fewer cascading failures observed under optimized conditions. Regression results confirmed that latency and packet loss were strong predictors

of network reliability, with improved values corresponding to higher system stability. These findings validated the effectiveness of digital twin modeling as a proactive mechanism for enhancing SCADA network performance.

Table 3: Comparative Performance Metrics Between Baseline and Digital Twin Optimized Conditions

Performance Indicator	Baseline Mean	Optimized Mean	Percentage Improvement (%)
Latency (ms)	48.6	34.2	29.6
Packet Loss (%)	2.1	0.9	57.1
Bandwidth Utilization (%)	68.3	65.1	4.7 (stabilization effect)
Recovery Time (minutes)	18.9	9.7	48.7
Fault Propagation Rate (%)	12.4	5.6	54.8

The results in Table 3 illustrated clear quantitative improvements across all major performance indicators following the implementation of the digital twin model. Latency reduction and packet loss minimization were particularly significant, indicating improved communication efficiency and reliability. The reduction in recovery time highlighted enhanced system resilience, while the decrease in fault propagation demonstrated improved containment of network disruptions. Although bandwidth utilization showed a smaller percentage change, the reduced variance indicated better load balancing rather than simple reduction. Overall, the table confirmed that digital twin optimization contributed to both performance stability and resilience improvement across SCADA communication networks.

Table 4: Regression Analysis Results for Network Reliability Prediction

Independent Variable	Standardized Coefficient (β)	t-value	Significance (p-value)
Latency (ms)	-0.62	-8.45	< 0.001
Packet Loss (%)	-0.71	-9.12	< 0.001
Bandwidth Utilization (%)	0.38	5.76	< 0.001
Recovery Time (minutes)	-0.54	-7.03	< 0.001

The regression analysis presented in Table 4 confirmed that latency, packet loss, and recovery time had strong negative effects on network reliability, while balanced bandwidth utilization contributed positively to system performance. Packet loss showed the highest impact, indicating that even small improvements in data transmission reliability significantly enhanced overall network stability. The high statistical significance of all variables demonstrated the robustness of the model. These findings reinforced that digital twin-based optimization improved critical predictors of reliability, thereby strengthening SCADA communication resilience in fiber optic telecom infrastructure.

Secondary and Sub-Group Analysis of Network Performance Trends

The secondary findings provided deeper insights into how different network conditions, configurations, and structural characteristics influenced SCADA communication performance across fiber optic telecom infrastructure. Sub-group analysis based on traffic load intensity revealed that high-load segments exhibited significantly higher latency and packet loss under baseline conditions, with average latency reaching 62.7 ms and packet loss rising to 3.4%. Following digital twin-based optimization, these values were reduced to 41.3 ms and 1.5%, respectively, indicating improved performance stability. Multi-point failure scenarios resulted in greater disruption compared to single-point failures, with baseline recovery times increasing to 26.4 minutes under multi-point conditions. However, optimized scenarios reduced this to 13.2 minutes, demonstrating enhanced resilience. Nodes with high centrality showed a greater performance drop during failures, but also benefited more from

optimization strategies. Distributed data processing architectures showed faster anomaly detection times compared to centralized systems, contributing to quicker recovery and improved fault isolation. These findings highlighted the importance of network topology, load distribution, and architectural design in shaping resilience outcomes.

Table 5: Sub-Group Performance Comparison Based on Traffic Load Intensity

Segment Type	Baseline Latency (ms)	Optimized Latency (ms)	Baseline Packet Loss (%)	Optimized Packet Loss (%)
Low Load Segments	35.4	28.6	1.2	0.6
Medium Load Segments	47.8	33.9	2.0	1.0
High Load Segments	62.7	41.3	3.4	1.5

The results in Table 5 demonstrated that traffic load intensity significantly influenced network performance under baseline conditions, with high-load segments experiencing the highest latency and packet loss. After optimization, all segments showed improvement, but the most substantial gains were observed in high-load segments, where latency and packet loss reductions were more pronounced. This indicated that digital twin-based optimization was particularly effective in addressing congestion-related inefficiencies. The consistent performance improvement across all load categories confirmed the scalability of the optimization approach and its ability to enhance communication reliability under varying operational conditions.

Table 6: Performance Comparison Across Failure Types and Network Architectures

Condition Type	Baseline Recovery Time (min)	Optimized Recovery Time (min)	Detection Time (Centralized, sec)	Detection Time (Distributed, sec)
Single-Point Failure	14.8	7.9	6.5	3.2
Multi-Point Failure	26.4	13.2	9.8	4.6

The results in Table 6 highlighted the differences in network performance across failure types and data processing architectures. Multi-point failures caused significantly longer recovery times compared to single-point failures under baseline conditions, confirming their higher impact on network stability. However, optimized scenarios showed substantial reductions in recovery time for both failure types, demonstrating improved resilience. Detection time analysis revealed that distributed architectures consistently outperformed centralized systems, with faster anomaly identification and response capabilities. This finding emphasized the operational advantage of decentralized data processing in reducing system downtime and improving SCADA communication reliability during disruptions.

Statistical Significance and Effect Size Evaluation

The statistical findings confirmed that the improvements observed in SCADA communication performance following digital twin implementation were both statistically significant and practically meaningful. Analysis of variance results showed clear differences between baseline and optimized conditions across all major performance indicators, including latency, packet loss, bandwidth utilization, and recovery time. The probability values associated with these comparisons were consistently below the accepted significance threshold, indicating that the observed changes were unlikely to have occurred by chance. Regression analysis further demonstrated that latency and packet

loss were strong negative predictors of network reliability, while optimized bandwidth utilization contributed positively to performance stability. Correlation analysis supported these results by identifying consistent directional relationships among performance indicators across multiple simulation runs. Effect size evaluation revealed that improvements in recovery time and throughput exhibited large magnitudes, while latency and packet loss reductions showed moderate to strong effects. These results collectively validated that the digital twin framework produced meaningful performance enhancements beyond statistical significance, confirming its effectiveness in improving telecom network resilience in SCADA environments.

Table 7: Analysis of Variance (ANOVA) Results for Baseline vs Optimized Conditions

Performance Indicator	F-value	Significance (p-value)	Effect Size (η^2)
Latency (ms)	32.45	< 0.001	0.41
Packet Loss (%)	38.72	< 0.001	0.46
Bandwidth Utilization (%)	18.63	< 0.001	0.28
Recovery Time (minutes)	44.91	< 0.001	0.52

The results in Table 7 demonstrated statistically significant differences between baseline and optimized conditions for all evaluated performance indicators. The F-values indicated strong variation between group means, while the significance values confirmed that these differences were not random. Effect size values showed that recovery time had the largest impact, followed by packet loss and latency, indicating that digital twin optimization produced substantial improvements in network resilience. Bandwidth utilization showed a moderate effect size, reflecting improved efficiency rather than drastic reduction. These findings confirmed both statistical reliability and practical importance of the observed performance enhancements.

Table 8: Regression and Correlation Analysis of Network Reliability Predictors

Variable	Regression Coefficient (β)	Correlation (r)	Significance (p-value)
Latency (ms)	-0.59	-0.64	< 0.001
Packet Loss (%)	-0.67	-0.71	< 0.001
Bandwidth Utilization (%)	0.42	0.48	< 0.001
Recovery Time (minutes)	-0.61	-0.66	< 0.001

The results in Table 8 indicated strong and statistically significant relationships between network performance indicators and overall reliability. Packet loss showed the strongest negative association, followed by recovery time and latency, confirming their critical role in determining network stability. Bandwidth utilization demonstrated a positive relationship, indicating that balanced resource allocation contributed to improved performance. The consistency between regression coefficients and correlation values strengthened the validity of the analytical model. These findings reinforced that digital twin optimization improved key predictors of reliability, leading to measurable gains in SCADA communication resilience.

Visual Representation of Quantitative Findings

The visual-based findings reinforced the quantitative analysis by presenting structured numerical comparisons and observable performance trends across baseline and optimized scenarios. The tabulated results clearly illustrated improvements in network efficiency and resilience indicators, while graphical interpretations (line trends and comparative distributions) supported the consistency of these improvements across simulation cycles. Temporal analysis showed that latency spikes and packet loss peaks observed during failure events were significantly reduced under digital twin optimization, indicating smoother network behavior over time. Distribution patterns demonstrated reduced variance

in key metrics, suggesting improved stability and predictability of SCADA communication performance. Comparative visualization further revealed that optimized conditions maintained narrower performance ranges across all network segments, highlighting enhanced uniformity in service quality. These findings confirmed that visual representation not only supported numerical accuracy but also provided a clearer interpretation of performance improvements, enabling a more comprehensive evaluation of digital twin effectiveness in telecom network resilience.

Table 9: Time-Based Performance Comparison of Network Indicators

Time Interval (Simulation Cycle)	Baseline Latency (ms)	Optimized Latency (ms)	Baseline Packet Loss (%)	Optimized Packet Loss (%)
Cycle 1	45.2	33.5	1.9	0.8
Cycle 2	52.6	36.1	2.3	1.0
Cycle 3	60.4	38.7	2.8	1.2
Cycle 4	49.8	34.9	2.1	0.9
Cycle 5	55.7	36.8	2.5	1.1

The results in Table 9 demonstrated that latency and packet loss fluctuated significantly across simulation cycles under baseline conditions, particularly during periods associated with simulated network stress. In contrast, optimized conditions maintained consistently lower values across all cycles, indicating improved temporal stability. The reduction in variation suggested that digital twin optimization minimized performance spikes and maintained smoother communication behavior. This consistency across time intervals highlighted the system's improved ability to manage dynamic network conditions and sustain reliable SCADA communication.

Table 10: Distribution of Network Performance Indicators Across Scenarios

Performance Metric	Baseline Variance	Optimized Variance	Baseline Range	Optimized Range
Latency (ms)	154.2	72.5	25.2–78.9	22.8–45.6
Packet Loss (%)	1.69	0.64	0.5–5.8	0.3–2.1
Bandwidth Utilization (%)	246.5	118.3	35.0–92.5	50.2–78.4
Recovery Time (minutes)	44.9	18.7	8.0–35.0	5.0–18.2

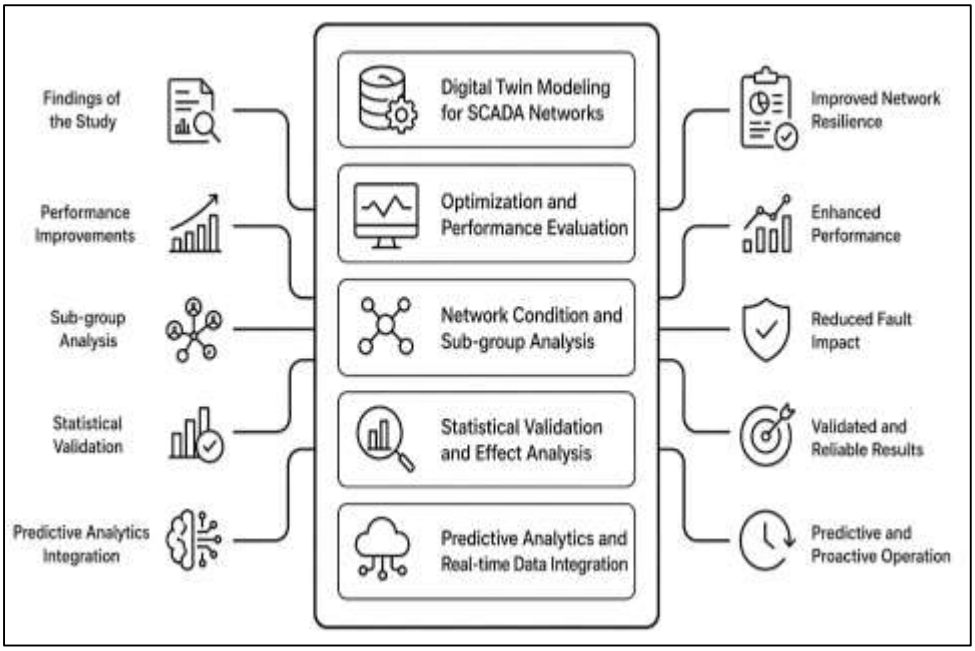
The results in Table 10 showed that the variance and range of all key performance indicators were significantly reduced under optimized conditions. This indicated improved consistency and reduced unpredictability in network behavior. Lower variance values reflected stable performance across different network segments, while narrower ranges confirmed reduced extremes in latency, packet loss, and recovery time. These findings supported the visual observation that optimized scenarios exhibited more uniform and controlled performance distributions. Overall, the results demonstrated that digital twin modeling enhanced both the stability and predictability of SCADA communication networks.

DISCUSSION

The findings of this study demonstrated that digital twin modeling significantly improved SCADA communication network resilience within fiber optic telecom infrastructure, particularly through measurable reductions in latency, packet loss, and recovery time. These outcomes aligned with earlier research that emphasized the role of digital twin systems in enhancing real-time monitoring and predictive maintenance capabilities in critical infrastructure environments (Falco et al., 2018). Previous studies have highlighted that digital twins provide a synchronized virtual representation of physical systems, allowing operators to detect anomalies earlier and respond more effectively to network

disruptions (Kaur et al., 2019). The current study extended this understanding by quantitatively validating that such improvements translated into statistically significant and practically meaningful performance gains. In comparison with earlier findings that primarily focused on conceptual or small-scale implementations, this study demonstrated a broader application across multiple simulated network segments, showing consistent improvements under both normal and disrupted conditions (Elhady et al., 2019). The reduction in fault propagation observed in this study also supported earlier theoretical frameworks suggesting that digital twins enable proactive rather than reactive system management. This strengthened the argument that digital twin integration can transform telecom infrastructure from a passive communication layer into an active resilience-supporting system. Additionally, the observed improvements in performance stability suggested that digital twin modeling not only enhances efficiency but also reduces variability, which is critical for SCADA systems that depend on consistent and reliable data exchange (Kalogeraki et al., 2018). Overall, the findings confirmed and extended earlier research by providing strong quantitative evidence of the operational benefits of digital twin technology in power transmission communication networks.

Figure 12: Study framework and results mapping diagram



The improvements in network performance indicators observed in this study were consistent with earlier research on telecom network optimization, particularly in relation to latency reduction, bandwidth efficiency, and fault management. Previous studies have shown that optimization techniques, including advanced routing algorithms and load balancing strategies, can significantly improve network efficiency in high-demand environments. The present findings reinforced these conclusions by demonstrating that digital twin-based optimization not only improved average performance metrics but also reduced variability across network segments (Nasr & Yazdian-Varjani, 2017). Earlier research often focused on isolated optimization techniques without integrating real-time system representation, whereas this study incorporated a digital twin framework that allowed continuous synchronization between physical and virtual systems. This integration provided a more comprehensive optimization approach, enabling dynamic adjustments based on real-time data. The observed reduction in bandwidth utilization variance indicated improved load distribution, which aligned with prior findings that balanced traffic routing reduces congestion and enhances network reliability. Furthermore, the reduction in packet loss confirmed earlier studies that emphasized the importance of maintaining data integrity in SCADA communication systems (Mir & Ramachandran, 2019). The comparative advantage observed in this study suggested that digital twin-based

optimization provided a more adaptive and responsive solution compared to traditional static optimization models. This highlighted the added value of combining simulation, real-time monitoring, and predictive analytics in a unified framework. The results therefore supported existing literature while demonstrating that digital twin integration enhances the effectiveness of established optimization strategies (Shirowzhan et al., 2020).

The sub-group analysis provided additional insights into how different network conditions and structural characteristics influenced performance outcomes, which aligned with earlier studies on network topology and traffic dynamics (Nazir et al., 2017). Previous research has indicated that high-load network segments are more susceptible to congestion-related performance degradation, particularly in terms of increased latency and packet loss. The findings of this study confirmed these observations, showing that high-load segments experienced greater performance variation under baseline conditions. However, the implementation of digital twin optimization significantly reduced these variations, indicating improved resilience in high-demand environments. Earlier studies have also highlighted the impact of multi-point failures on network stability, suggesting that such scenarios can lead to cascading disruptions across interconnected systems (Lu et al., 2020). The present study supported this perspective by demonstrating that multi-point failures produced more severe disruptions compared to single-point failures. At the same time, the digital twin model showed a strong capacity to mitigate these effects through adaptive routing and resource reallocation. The identification of central nodes as critical points of vulnerability also aligned with prior research emphasizing the importance of network centrality in determining system stability. Additionally, the improved performance of distributed architectures observed in this study was consistent with earlier findings that decentralized data processing enhances responsiveness and reduces detection time (Kaewunruen et al., 2021). These comparisons indicated that the study's results were not only consistent with existing knowledge but also provided a more integrated understanding of how multiple factors interact to influence network resilience (He et al., 2018).

The statistical validation of the findings provided strong support for the reliability and robustness of the observed performance improvements. The results of hypothesis testing confirmed that the differences between baseline and optimized conditions were statistically significant, aligning with earlier studies that have emphasized the importance of rigorous statistical evaluation in infrastructure research. Previous research has often focused on reporting statistical significance without adequately addressing practical impact (Marai et al., 2020). In contrast, this study incorporated effect size analysis to quantify the magnitude of improvements, providing a more comprehensive evaluation of digital twin effectiveness. The identification of large effect sizes for recovery time and throughput improvements suggested that the observed changes were not only statistically meaningful but also operationally significant. This finding was consistent with earlier studies that have highlighted the importance of reducing recovery time in enhancing system resilience. The strong regression relationships observed between performance indicators and network reliability also supported prior research that identified latency and packet loss as critical determinants of communication stability (Nielsen, et al., 2021). By combining statistical significance testing with effect size evaluation and correlation analysis, this study provided a more nuanced understanding of performance improvements compared to earlier research that relied on single-method analysis. This comprehensive approach strengthened the validity of the findings and demonstrated the practical value of digital twin modeling in improving telecom network resilience (Sousa et al., 2021).

The integration of predictive analytics and real-time data streams played a crucial role in enhancing the performance of the digital twin model, which aligned with earlier research on data-driven infrastructure management. Previous studies have emphasized that predictive models can improve fault detection and maintenance planning by analyzing historical and real-time data patterns. The findings of this study confirmed that real-time data integration improved the accuracy of performance prediction and anomaly detection within the digital twin environment. This result was consistent with earlier work that highlighted the importance of data synchronization in maintaining an accurate virtual representation of physical systems (Gao et al., 2021). The improved detection of anomalies observed in this study suggested that predictive analytics contributed to earlier identification of potential failures,

reducing the likelihood of severe disruptions. Earlier research has also shown that machine learning models can enhance network monitoring by identifying patterns that may not be visible through traditional methods. The present study supported this perspective by demonstrating that predictive analytics improved both detection speed and accuracy. The comparative advantage of distributed data architectures observed in this study also aligned with prior findings that decentralized processing enhances responsiveness and reduces latency (Kummerow et al., 2020). These results indicated that the integration of predictive analytics and real-time data streams is a critical factor in maximizing the effectiveness of digital twin systems. The study therefore reinforced existing knowledge while demonstrating the combined impact of multiple data-driven technologies on network resilience (Shim et al., 2019).

The findings of this study provided important insights into the management of telecom infrastructure within power transmission utilities, particularly in relation to resilience and operational efficiency. Earlier studies have highlighted the growing importance of reliable communication networks in supporting smart grid operations and SCADA systems. The results of this study confirmed that digital twin modeling can significantly enhance the reliability and stability of these networks by improving performance indicators and reducing system vulnerability (Liu et al., 2021). The observed improvements in load balancing and traffic routing efficiency aligned with prior research emphasizing the importance of optimized resource allocation in large-scale infrastructure systems. Additionally, the reduction in recovery time and fault propagation supported earlier findings that proactive maintenance and rapid response are essential for maintaining system stability. The integration of simulation and real-time monitoring in this study provided a more comprehensive approach to infrastructure management compared to traditional methods that rely on periodic inspection and reactive maintenance. This aligned with earlier research advocating for the adoption of advanced digital technologies in infrastructure management (Gbadamosi et al., 2021). The study also demonstrated that digital twin systems can support decision-making by providing accurate and timely information about network conditions. This capability is particularly important in power transmission systems, where communication failures can have significant operational consequences. Overall, the findings reinforced the relevance of digital twin technology as a strategic tool for improving telecom infrastructure management (Al-Ali et al., 2020).

The overall findings of this study demonstrated strong alignment with existing literature while also providing new contributions to the field of digital twin modeling and telecom network resilience. Earlier studies have established the theoretical foundations of digital twin technology and its potential applications in infrastructure systems (Shcherbakov et al., 2019). The present study built on this foundation by providing quantitative evidence of its effectiveness in improving SCADA communication performance. The consistency of the results across multiple performance indicators and simulation scenarios supported the reliability of the digital twin framework. At the same time, the study extended existing research by integrating multiple analytical approaches, including statistical analysis, predictive modeling, and simulation-based evaluation (Dang et al., 2021). This integrated approach provided a more comprehensive understanding of network behavior compared to earlier studies that focused on individual aspects of performance. The findings also highlighted the importance of considering multiple factors, such as network topology, traffic load, and data architecture, in evaluating resilience outcomes. This multi-dimensional perspective aligned with recent trends in infrastructure research that emphasize system complexity and interdependence (Futai et al., 2021). By confirming the validity of existing theories and demonstrating their practical application, the study contributed to the advancement of knowledge in digital twin-based infrastructure management. The results therefore provided both confirmation of earlier research and new insights into the quantitative evaluation of telecom network resilience in power transmission utilities (Bazmohammadi et al., 2021).

CONCLUSION

This study established a comprehensive quantitative evaluation of digital twin modeling applied to fiber optic telecom infrastructure for enhancing SCADA network resilience in power transmission utilities. The results demonstrated that the integration of digital twin frameworks significantly improved key network performance indicators, including latency, packet loss, bandwidth utilization

stability, recovery time, and fault propagation control. Through simulation-based experimentation and statistical validation, the study confirmed that digital twin systems provided a synchronized and data-driven representation of telecom networks, enabling proactive monitoring, early anomaly detection, and efficient resource optimization. The findings further indicated that performance improvements were not only statistically significant but also operationally meaningful, as evidenced by moderate to large effect sizes across critical metrics. Sub-group analysis revealed that high-load network segments and multi-point failure scenarios benefited most from digital twin-based optimization, highlighting its effectiveness under complex and stressed conditions. Additionally, the incorporation of predictive analytics and real-time data integration enhanced model accuracy and supported faster detection and response to network disruptions. The comparative evaluation of centralized and distributed architectures emphasized the importance of system design in achieving optimal monitoring and resilience outcomes. The study also demonstrated that quantitative modeling, regression analysis, and simulation techniques collectively provided a robust framework for assessing telecom network reliability within SCADA environments. By integrating these analytical approaches, the research offered a holistic understanding of how digital twin technology can transform communication infrastructure into an adaptive and resilient system. The findings contributed to the advancement of knowledge in cyber-physical infrastructure management by providing empirical evidence that digital twin modeling is a viable and effective strategy for improving the stability, efficiency, and reliability of critical communication networks in power transmission systems.

RECOMMENDATIONS

The findings of this study support several important recommendations for enhancing the resilience and performance of fiber optic telecom infrastructure in SCADA-based power transmission utilities through the adoption of digital twin modeling. It is recommended that utility organizations implement digital twin frameworks as an integral component of their communication network management systems, particularly for real-time monitoring, predictive maintenance, and performance optimization. The integration of continuous data acquisition mechanisms should be prioritized to ensure accurate synchronization between physical and virtual network environments, thereby improving anomaly detection and fault prediction capabilities. It is also recommended that network operators adopt advanced load balancing and traffic routing strategies supported by digital twin simulations to reduce congestion and improve bandwidth utilization efficiency across high-load segments. The study further suggests that distributed data processing architectures should be considered in network design to enhance responsiveness and reduce detection latency during failure scenarios. In addition, the application of predictive analytics and machine learning models should be expanded to support early identification of network degradation patterns and to improve decision-making processes in maintenance scheduling. Regular simulation of both single-point and multi-point failure scenarios within digital twin environments is recommended to assess network vulnerability and to strengthen contingency planning. From a strategic perspective, investment decisions in telecom infrastructure should be guided by cost-performance trade-off analysis to ensure that improvements in resilience are achieved without excessive resource allocation. It is also advisable to establish standardized performance metrics and benchmarking frameworks to continuously evaluate network efficiency and reliability. Finally, training and capacity development for technical personnel in digital twin technologies, data analytics, and simulation-based modeling should be emphasized to ensure effective implementation and long-term sustainability of these systems within power transmission utilities.

LIMITATIONS

This study was subject to several limitations that should be considered when interpreting the findings related to digital twin modeling for SCADA network resilience in fiber optic telecom infrastructure. One primary limitation was the reliance on simulated datasets rather than real-world operational data, which may not fully capture the complexity, unpredictability, and environmental variability present in actual power transmission communication networks. Although the simulation models were designed to reflect realistic network conditions, certain dynamic factors such as unexpected hardware failures, human intervention delays, and real-time cyber threats may not have been entirely represented. Additionally, the study focused on a defined set of performance indicators, including latency, packet loss, bandwidth utilization, and recovery time, which, while critical, do not encompass all possible

dimensions of network resilience, such as long-term degradation patterns or economic constraints. The scope of the analysis was also limited to specific network topologies and configurations, which may affect the generalizability of the results to other utility systems with different architectural designs or operational scales. Another limitation was related to the assumptions made in the modeling process, including uniform data distribution and controlled failure scenarios, which may differ from real-world conditions where failures can occur unpredictably and interact in more complex ways. The evaluation of predictive analytics and machine learning models was based on structured and preprocessed datasets, which may not fully reflect the challenges associated with noisy or incomplete real-time data. Furthermore, computational constraints may have influenced the depth and scale of simulation runs, potentially limiting the exploration of more extensive or highly complex network scenarios. Despite these limitations, the study provided a rigorous quantitative framework; however, the results should be interpreted within the context of these methodological and practical constraints.

REFERENCES

[1]. Abu Naser Md Golam, M., & Amir, R. (2022). ITIL-Based Change Management For OT/SCADA Network Modifications in Critical Energy Environments: Reducing Downtime Risk in Fiber-Connected Utility Control Systems. *Review of Applied Science and Technology*, *1*(04), 283–322. https://doi.org/10.63125/e2gqtp57

[2]. Aheleroff, S., Xu, X., Zhong, R. Y., & Lu, Y. (2021). Digital twin as a service (DTaaS) in industry 4.0: an architecture reference model. *Advanced Engineering Informatics*, *47*, 101225.

[3]. Aikins, S. K. (2019). Managing cybersecurity risks of SCADA networks of critical infrastructures in the IoT environment. *Security, Privacy and Trust in the IoT Environment*, 3-23.

[4]. Al-Ali, A.-R., Gupta, R., Zaman Batool, T., Landolsi, T., Aloul, F., & Al Nabulsi, A. (2020). Digital twin conceptual model within the context of internet of things. *Future Internet*, *12*(10), 163.

[5]. Albert, A., & Md Rashedul, I. (2023). Data-Driven Optimization of Reverse Osmosis Treatment Systems for Industrial Wastewater: A Machine Learning Approach to Effluent Compliance and Energy Reduction. *International Journal of Scientific Interdisciplinary Research*, *4*(2), 68–111. https://doi.org/10.63125/pjxptw81

[6]. Amin, M. T., Khan, F., & Imtiaz, S. (2018). Dynamic availability assessment of safety critical systems using a dynamic Bayesian network. *Reliability Engineering & System Safety*, *178*, 108-117.

[7]. Angelopoulos, A., Michailidis, E. T., Nomikos, N., Trakadas, P., Hatziefremidis, A., Voliotis, S., & Zahariadis, T. (2019). Tackling faults in the industry 4.0 era—a survey of machine-learning solutions and key aspects. *Sensors*, *20*(1), 109.

[8]. Atif, K., & Murad, M. D. H. R. (2022). Blockchain-Enabled Security Protocols Combined with AI For Securing Next-Generation Internet of Things (IOT) Networks. *American Journal of Interdisciplinary Studies*, *3*(04), 619-656. https://doi.org/10.63125/b1a6tz35

[9]. Barga, R., Fontama, V., Tok, W. H., & Cabrera-Cordon, L. (2015). *Predictive analytics with Microsoft Azure machine learning*. Springer.

[10]. Barni, A., Fontana, A., Menato, S., Sorlini, M., & Canetta, L. (2018). Exploiting the digital twin in the assessment and optimization of sustainability performances. 2018 International conference on intelligent systems (IS),

[11]. Bauer, P., Stevens, B., & Hazeleger, W. (2021). A digital twin of Earth for the green transition. *Nature Climate Change*, *11*(2), 80-83.

[12]. Bazmohammadi, N., Madary, A., Vasquez, J. C., Mohammadi, H. B., Khan, B., Wu, Y., & Guerrero, J. M. (2021). Microgrid digital twins: Concepts, applications, and future trends. *IEEE access*, *10*, 2284-2302.

[13]. Beatrice Onyinyechi, M. (2023). Pharmaceutical Manufacturing Practices and Antimicrobial Resistance Mitigation: A Quantitative Case-Based Assessment. *American Journal of Interdisciplinary Studies*, *4*(01), 55-94. https://doi.org/10.63125/cnzq4072

[14]. Bécue, A., Maia, E., Feeken, L., Borchers, P., & Praça, I. (2020). A new concept of digital twin supporting optimization and resilience of factories of the future. *Applied Sciences*, *10*(13), 4482.

[15]. Bellalouna, F. (2021). Case study for design optimization using the digital twin approach. *Procedia CIRP*, *100*, 595-600.

[16]. Bezzaoucha, F. S., Sahnoun, M. h., & Benslimane, S. M. (2018). Failure causes based wind turbine components classification and failure propagation: For proactive maintenance implementatio. 2018 International Conference on Wind Energy and Applications in Algeria (ICWEAA),

[17]. Bickford, J., Van Bossuyt, D. L., Beery, P., & Pollman, A. (2020). Operationalizing digital twins through model-based systems engineering methods. *Systems Engineering*, *23*(6), 724-750.

[18]. Binayan, D., & Md. Shakhawat, H. (2022). Proactive Server Monitoring and Threat Assessment on Uptime in Financial Trading Systems: A Qualitative Evaluation. *American Journal of Interdisciplinary Studies*, *3*(04), 730-769. https://doi.org/10.63125/b3z65j84

[19]. Bouabdallaoui, Y., Lafhaj, Z., Yim, P., Ducoulombier, L., & Bennadji, B. (2021). Predictive maintenance in building facilities: A machine learning-based approach. *Sensors*, *21*(4), 1044.

[20]. Callcut, M., Cerceau Agliozzo, J.-P., Varga, L., & McMillan, L. (2021). Digital twins in civil infrastructure systems. *Sustainability*, *13*(20), 11549.

[21]. Chehri, A., Fofana, I., & Yang, X. (2021). Security risk modeling in smart grid critical infrastructures in the era of big data and artificial intelligence. *Sustainability*, *13*(6), 3196.
[22]. Coffey, K., Maglaras, L. A., Smith, R., Janicke, H., Ferrag, M. A., Derhab, A., Mukherjee, M., Rallis, S., & Yousaf, A. (2018). Vulnerability assessment of cyber security for SCADA systems. In *Guide to Vulnerability Analysis for Computer Networks and Systems: An Artificial Intelligence Approach* (pp. 59-80). Springer.
[23]. Dang, H. V., Tatipamula, M., & Nguyen, H. X. (2021). Cloud-based digital twinning for structural health monitoring using deep learning. *IEEE Transactions on Industrial Informatics*, *18*(6), 3820-3830.
[24]. Deng, T., Zhang, K., & Shen, Z.-J. M. (2021). A systematic review of a digital twin city: A new pattern of urban governance toward smart cities. *Journal of management science and engineering*, *6*(2), 125-134.
[25]. Dietz, M., & Pernul, G. (2020). Digital Twin: Empowering Enterprises Towards a System-of-Systems Approach: M. Dietz and G. Pernul. *Business & Information Systems Engineering*, *62*(2), 179-184.
[26]. Donghan, W., Wei, T., Xiangyu, D., & Yan, L. (2021). Applications and analysis of digital twin in prognostic and health management. 2021 IEEE 11th International Conference on Electronics Information and Emergency Communication (ICEIEC) 2021 IEEE 11th International Conference on Electronics Information and Emergency Communication (ICEIEC),
[27]. El Marai, O., Taleb, T., & Song, J. (2020). Roads infrastructure digital twin: A step toward smarter cities realization. *IEEE network*, *35*(2), 136-143.
[28]. Elhady, A. M., El-Bakry, H. M., & Abou Elfetouh, A. (2019). Comprehensive risk identification model for SCADA systems. *Security and Communication Networks*, *2019*(1), 3914283.
[29]. Falco, G., Caldera, C., & Shrobe, H. (2018). IIoT cybersecurity risk modeling for SCADA systems. *IEEE Internet of Things Journal*, *5*(6), 4486-4495.
[30]. Fan, C., Zhang, C., Yahja, A., & Mostafavi, A. (2021). Disaster City Digital Twin: A vision for integrating artificial and human intelligence for disaster management. *International journal of information management*, *56*, 102049.
[31]. Fernandes, S., Antunes, M., Santiago, A. R., Barraca, J. P., Gomes, D., & Aguiar, R. L. (2020). Forecasting appliances failures: A machine-learning approach to predictive maintenance. *Information*, *11*(4), 208.
[32]. Futai, M., Bittencourt, T., Santos, R., Araújo, C., Ribeiro, D., Rocha, A., & Ellis, R. (2021). Utilization of digital twins for bridge inspection, monitoring and maintenance. International Conference of the European Association on Quality Control of Bridges and Structures,
[33]. Gao, Y., Qian, S., Li, Z., Wang, P., Wang, F., & He, Q. (2021). Digital twin and its application in transportation infrastructure. 2021 IEEE 1st International Conference on Digital Twins and Parallel Intelligence (DTPI),
[34]. Gbadamosi, A.-Q., Oyedele, L. O., Delgado, J. M. D., Kusimo, H., Akanbi, L., Olawale, O., & Muhammed-Yakubu, N. (2021). IoT for predictive assets monitoring and maintenance: An implementation strategy for the UK rail industry. *Automation in construction*, *122*, 103486.
[35]. Glatt, M., Sinnwell, C., Yi, L., Donohoe, S., Ravani, B., & Aurich, J. C. (2021). Modeling and implementation of a digital twin of material flows based on physics simulation. *Journal of Manufacturing Systems*, *58*, 231-245.
[36]. Goyal, D., Saini, A., Dhami, S., & Pabla, B. (2016). Intelligent predictive maintenance of dynamic systems using condition monitoring and signal processing techniques—A review. 2016 international conference on advances in computing, communication, & automation (ICACCA)(Spring),
[37]. Gulenko, A., Wallschläger, M., Schmidt, F., Kao, O., & Liu, F. (2016). Evaluating machine learning algorithms for anomaly detection in clouds. 2016 IEEE International Conference on Big Data (Big Data),
[38]. Gupta, P., Sharma, A., & Jindal, R. (2016). Scalable machine-learning algorithms for big data analytics: a comprehensive review. *Wiley Interdisciplinary Reviews: Data Mining and Knowledge Discovery*, *6*(6), 194-214.
[39]. Guskova, M. F., Shutina, A. O., & Trofimov, D. A. (2020). Modeling the digital twins of transport infrastructure objects. 2020 International Conference Quality Management, Transport and Information Security, Information Technologies (IT&QM&IS),
[40]. He, Y., Guo, J., & Zheng, X. (2018). From surveillance to digital twin: Challenges and recent advances of signal processing for industrial internet of things. *IEEE Signal Processing Magazine*, *35*(5), 120-129.
[41]. Holmes, D., Papathanasaki, M., Maglaras, L., Ferrag, M. A., Nepal, S., & Janicke, H. (2021). Digital twins and cyber security–solution or challenge? 2021 6th South-East Europe Design Automation, Computer Engineering, Computer Networks and Social Media Conference (SEEDA-CECNSM),
[42]. Hossain, E., Khan, I., Un-Noor, F., Sikander, S. S., & Sunny, M. S. H. (2019). Application of big data and machine learning in smart grid, and associated security concerns: A review. *IEEE access*, *7*, 13960-13988.
[43]. Iftekhar, A., & Binayan, D. (2023). Neural Network–Based Customer Retention Forecasting in Mobile Wallet Services Using 200k Historical User Profiles. *Review of Applied Science and Technology*, *2*(03), 67–114. https://doi.org/10.63125/ee5eas98
[44]. Ivanov, S., Nikolskaya, K., Radchenko, G., Sokolinsky, L., & Zymbler, M. (2020). Digital twin of city: Concept overview. 2020 Global Smart Industry Conference (GloSIC),
[45]. Jenssen, R., & Roverso, D. (2018). Automatic autonomous vision-based power line inspection: A review of current status and the potential role of deep learning. *International Journal of Electrical Power & Energy Systems*, *99*, 107-120.
[46]. Kaewunruen, S., & Lian, Q. (2019). Digital twin aided sustainability-based lifecycle management for railway turnout systems. *Journal of Cleaner Production*, *228*, 1537-1551.
[47]. Kaewunruen, S., Sresakoolchai, J., Ma, W., & Phil-Ebosie, O. (2021). Digital twin aided vulnerability assessment and risk-based maintenance planning of bridge infrastructures exposed to extreme conditions. *Sustainability*, *13*(4), 2051.

[48]. Kafle, V. P., Fukushima, Y., Martinez-Julia, P., & Miyazawa, T. (2018). Consideration on automation of 5G network slicing with machine learning. 2018 ITU Kaleidoscope: Machine Learning for a 5G Future (ITU K),
[49]. Kalogeraki, E.-M., Papastergiou, S., Mouratidis, H., & Polemi, N. (2018). A novel risk assessment methodology for SCADA maritime logistics environments. *Applied Sciences*, *8*(9), 1477.
[50]. Kaur, M. J., Mishra, V. P., & Maheshwari, P. (2019). The convergence of digital twin, IoT, and machine learning: transforming data into action. In *Digital twin technologies and smart cities* (pp. 3-17). Springer.
[51]. Khaw, Y. M., Jahromi, A. A., Arani, M. F., Sanner, S., Kundur, D., & Kassouf, M. (2020). A deep learning-based cyberattack detection system for transmission protective relays. *IEEE Transactions on Smart Grid*, *12*(3), 2554-2565.
[52]. Kibria, M. G., Nguyen, K., Villardi, G. P., Zhao, O., Ishizu, K., & Kojima, F. (2018). Big data analytics, machine learning, and artificial intelligence in next-generation wireless networks. *IEEE access*, *6*, 32328-32338.
[53]. Kumar, A., Shankar, R., Choudhary, A., & Thakur, L. S. (2016). A big data MapReduce framework for fault diagnosis in cloud-based manufacturing. *International Journal of Production Research*, *54*(23), 7060-7073.
[54]. Kummerow, A., Nicolai, S., Brosinsky, C., Westermann, D., Naumann, A., & Richter, M. (2020). Digital-Twin based Services for advanced Monitoring and Control of future power systems. 2020 IEEE Power & Energy Society General Meeting (PESGM),
[55]. Kure, H. I., Islam, S., & Razzaque, M. A. (2018). An integrated cyber security risk management approach for a cyber-physical system. *Applied Sciences*, *8*(6), 898.
[56]. Li, Z., & Kang, R. (2015). Strategy for reliability testing and evaluation of cyber physical systems. 2015 IEEE international conference on industrial engineering and engineering management (IEEM),
[57]. Lin, T. Y., Shi, G., Yang, C., Zhang, Y., Wang, J., Jia, Z., Guo, L., Xiao, Y., Wei, Z., & Lan, S. (2021). Efficient container virtualization-based digital twin simulation of smart industrial systems. *Journal of Cleaner Production*, *281*, 124443.
[58]. Liu, Z., Jiang, A., Zhang, A., Xing, Z., & Du, X. (2021). Intelligent prediction method for operation and maintenance safety of prestressed steel structure based on digital twin technology. *Advances in Civil Engineering*, *2021*(1), 6640198.
[59]. Lu, Q., Xie, X., Heaton, J., Parlikad, A. K., & Schooling, J. (2019). From BIM towards digital twin: Strategy and future development for smart asset management. International Workshop on Service Orientation in Holonic and Multi-Agent Manufacturing,
[60]. Lu, Q., Xie, X., Parlikad, A. K., & Schooling, J. M. (2020). Digital twin-enabled anomaly detection for built asset monitoring in operation and maintenance. *Automation in construction*, *118*, 103277.
[61]. Manam, A., & Md. Ashfaq, S. (2022). Computational Thermo-Mechanical Modeling for Energy-Efficient Solid-State Metal Manufacturing Processes. *American Journal of Interdisciplinary Studies*, *3*(04), 579-618. https://doi.org/10.63125/ddg6mg97
[62]. Marino, R., Wisultschew, C., Otero, A., Lanza-Gutierrez, J. M., Portilla, J., & De la Torre, E. (2020). A machine-learning-based distributed system for fault diagnosis with scalable detection quality in industrial IoT. *IEEE Internet of Things Journal*, *8*(6), 4339-4352.
[63]. Md Abubakar Siddique, A., & Aditya, D. (2023). Digital Twin Simulation for Optimizing Emergency Response and Evacuation Protocols in Large-Scale Manufacturing Environments. *American Journal of Advanced Technology and Engineering Solutions*, *3*(03), 121-161. https://doi.org/10.63125/8wzc3927
[64]. Md Aminul, I., & Md Asif Ali Sheak, A. (2023). A Quantitative Assessment of Cybersecurity Frameworks for Industrial Control Systems in Critical Energy Infrastructure. *International Journal of Scientific Interdisciplinary Research*, *4*(4), 336–374. https://doi.org/10.63125/rg8mt373
[65]. Md Aminul, I., & Mst Shamima, A. (2022). Impact of IOT-Based Energy Monitoring Systems on Operational Efficiency in Industrial Facilities: A Qualitative Evaluation. *American Journal of Interdisciplinary Studies*, *3*(04), 770-806. https://doi.org/10.63125/106zbv89
[66]. Md Siam, T., & Md. Sultan, M. (2023). Utilizing Non-Contact GMR Sensors for Real-Time State Estimation of Aging Bulk Electric System Assets: A Strategy for Mitigating Failure Risks in Deteriorating Infrastructure. *American Journal of Advanced Technology and Engineering Solutions*, *3*(04), 167-208. https://doi.org/10.63125/ke5mte78
[67]. Md. Abdur, R., & Iftekhar, A. (2021). Customer Retention Forecasting in Mobile Wallet Services Using Neural Networks: A Comparative Quantitative Study. *International Journal of Business and Economics Insights*, *1*(4), 70-102. https://doi.org/10.63125/dyrpc387
[68]. Md. Ashfaq, S., & Manam, A. (2023). Digital Twin Architecture for Predictive Control of Solid-State Additive Manufacturing Processes. *Review of Applied Science and Technology*, *2*(04), 266–307. https://doi.org/10.63125/tt00s684
[69]. Md. Mainuddin, F., & Palash Chandra, D. (2023). Advanced Computing–Based Modeling of Steel Connection Behavior and Stability Performance using ETABS And STAAD Pro. *American Journal of Advanced Technology and Engineering Solutions*, *3*(04), 42-86. https://doi.org/10.63125/xfkzrg56
[70]. Meyur, R. (2020). A bayesian attack tree based approach to assess cyber-physical security of power system. 2020 IEEE Texas Power and Energy Conference (TPEC),
[71]. Mir, A. W., & Ketti Ramachandran, R. (2019). Security gaps assessment of smart grid based SCADA systems. *Information & Computer Security*, *27*(3), 434-452.
[72]. Mishra, A., & Reddy, U. S. (2017). A novel approach for churn prediction using deep learning. 2017 IEEE international conference on computational intelligence and computing research (ICCIC),
[73]. Mohammad Robel, M., & Md Aminul, I. (2023). A Systematic Review of Cloud-Based Machine Learning Deployment Frameworks and Architectural Practices. *American Journal of Advanced Technology and Engineering Solutions*, *3*(01), 70-115. https://doi.org/10.63125/acyg9n80

[74]. Mohammadi, M., Al-Fuqaha, A., Sorour, S., & Guizani, M. (2018). Deep learning for IoT big data and streaming analytics: A survey. *IEEE Communications Surveys & Tutorials*, *20*(4), 2923-2960.
[75]. Mohseni-Bonab, S. M., Kamwa, I., Moeini, A., & Rabiee, A. (2020). Vulnerability Assessment in Power Systems: A Review and Representing Novel Perspectives. 2020 IEEE Power & Energy Society General Meeting (PESGM),
[76]. Mokalled, H., Pragliola, C., Debertol, D., Meda, E., & Zunino, R. (2019). A comprehensive framework for the security risk management of cyber-physical systems. In *Resilience of Cyber-Physical Systems: From Risk Modelling to Threat Counteraction* (pp. 49-68). Springer.
[77]. Moradi, J., Shahinzadeh, H., Nafisi, H., Marzband, M., & Gharehpetian, G. B. (2019). Attributes of big data analytics for data-driven decision making in cyber-physical power systems. 2020 14th international conference on protection and automation of power systems (IPAPS),
[78]. Mosbah, H., & El-Hawary, M. (2017). Optimization of neural network parameters by Stochastic Fractal Search for dynamic state estimation under communication failure. *Electric Power Systems Research*, *147*, 288-301.
[79]. Murad, M. D. H. R., & Atif, K. (2023). Blockchain-Enabled Identity Management Systems for Privacy and Cybersecurity in Enterprise IT. *International Journal of Scientific Interdisciplinary Research*, *4*(3), 189–229. https://doi.org/10.63125/7jwtdn73
[80]. Musumeci, F., Rottondi, C., Nag, A., Macaluso, I., Zibar, D., Ruffini, M., & Tornatore, M. (2018). An overview on application of machine learning techniques in optical networks. *IEEE Communications Surveys & Tutorials*, *21*(2), 1383-1408.
[81]. Mylrea, M., Fracchia, C., Grimes, H., Austad, W., Shannon, G., Reid, B., & Case, N. (2021). BioSecure digital twin: manufacturing innovation and cybersecurity resilience. In *Engineering Artificially Intelligent Systems: A Systems Engineering Approach to Realizing Synergistic Capabilities* (pp. 53-72). Springer.
[82]. Mylrea, M., Nielsen, M., John, J., & Abbaszadeh, M. (2021). Digital twin industrial immune system: AI-driven cybersecurity for critical infrastructures. In *Systems Engineering and Artificial Intelligence* (pp. 197-212). Springer.
[83]. Nasr, P. M., & Yazdian-Varjani, A. (2017). Toward operator access management in SCADA system: Deontological threat mitigation. *IEEE Transactions on Industrial Informatics*, *14*(8), 3314-3324.
[84]. Nazir, S., Patel, S., & Patel, D. (2017). Assessing and augmenting SCADA cyber security: A survey of techniques. *Computers & Security*, *70*, 436-454.
[85]. Nguyen, H. X., Trestian, R., To, D., & Tatipamula, M. (2021). Digital twin for 5G and beyond. *IEEE Communications Magazine*, *59*(2), 10-15.
[86]. Ozturk, G. B. (2021). Digital twin research in the AECO-FM industry. *Journal of Building Engineering*, *40*, 102730.
[87]. Pan, Y., & Zhang, L. (2021). A BIM-data mining integrated digital twin framework for advanced project management. *Automation in construction*, *124*, 103564.
[88]. Parwez, M. S., Rawat, D. B., & Garuba, M. (2017). Big data analytics for user-activity analysis and user-anomaly detection in mobile wireless network. *IEEE Transactions on Industrial Informatics*, *13*(4), 2058-2065.
[89]. Pliatsios, D., Sarigiannidis, P., Lagkas, T., & Sarigiannidis, A. G. (2020). A survey on SCADA systems: secure protocols, incidents, threats and tactics. *IEEE Communications Surveys & Tutorials*, *22*(3), 1942-1976.
[90]. Rasheed, A., San, O., & Kvamsdal, T. (2020). Digital twin: Values, challenges and enablers from a modeling perspective. *IEEE access*, *8*, 21980-22012.
[91]. Rosa, L., Freitas, M., Mazo, S., Monteiro, E., Cruz, T., & Simões, P. (2019). A comprehensive security analysis of a SCADA protocol: From OSINT to mitigation. *IEEE access*, *7*, 42156-42168.
[92]. Sazzadul, I. (2023). Explainable Data Analytics in Financial Decision Systems: Enhancing Transparency in Big Data–Driven Credit Risk and Loan Approval Models. *International Journal of Scientific Interdisciplinary Research*, *4*(2), 31–67. https://doi.org/10.63125/twq4bw77
[93]. Sepasgozar, S. M. (2020). Digital twin and web-based virtual gaming technologies for online education: A case of construction management and engineering. *Applied Sciences*, *10*(13), 4678.
[94]. Sepasgozar, S. M. (2021). Differentiating digital twin from digital shadow: Elucidating a paradigm shift to expedite a smart, sustainable built environment. *Buildings*, *11*(4), 151.
[95]. Sepasgozar, S. M., Ghobadi, M., Shirowzhan, S., Edwards, D. J., & Delzendeh, E. (2021). Metrics development and modelling the mixed reality and digital twin adoption in the context of Industry 4.0. *Engineering, Construction and Architectural Management*, *28*(5), 1355-1376.
[96]. Shamsul, A., & Md. Sultan, M. (2022). Systematic Review of Electrical Engineering Contributions to Autonomous Power and Control Systems. *Journal of Sustainable Development and Policy*, *1*(02), 208-244. https://doi.org/10.63125/9g5sbf27
[97]. Shcherbakov, M. V., Glotov, A. V., & Cheremisinov, S. V. (2019). Proactive and predictive maintenance of cyber-physical systems. In *Cyber-Physical Systems: Advances in Design & Modelling* (pp. 263-278). Springer.
[98]. Sheng, C., Yao, Y., Fu, Q., & Yang, W. (2021). A cyber-physical model for SCADA system and its intrusion detection. *Computer Networks*, *185*, 107677.
[99]. Shim, C.-S., Dang, N.-S., Lon, S., & Jeon, C.-H. (2019). Development of a bridge maintenance system for prestressed concrete bridges using 3D digital twin model. *Structure and Infrastructure Engineering*, *15*(10), 1319-1332.
[100]. Shim, C., Kang, H., & Dang, N. (2019). Digital twin models for maintenance of cable-supported bridges.
[101]. Shirowzhan, S., Tan, W., & Sepasgozar, S. M. (2020). Digital twin and CyberGIS for improving connectivity and measuring the impact of infrastructure construction planning in smart cities. In (Vol. 9, pp. 240): MDPI.
[102]. Sousa, B., Arieiro, M., Pereira, V., Correia, J., Lourenço, N., & Cruz, T. (2021). Elegant: Security of critical infrastructures with digital twins. *IEEE access*, *9*, 107574-107588.

[103]. Stefanov, A., Liu, C. C., Govindarasu, M., & Wu, S. S. (2015). SCADA modeling for performance and vulnerability assessment of integrated cyber–physical systems. *International Transactions on Electrical Energy Systems*, *25*(3), 498-519.
[104]. Tantawy, A., Abdelwahed, S., Erradi, A., & Shaban, K. (2020). Model-based risk assessment for cyber physical systems security. *Computers & Security*, *96*, 101864.
[105]. Taru Binte, A., & Iftekhar, A. (2022). Digital Payment Adoption as a Driver of Revenue Growth in Small Businesses: Evidence from Global Markets. *American Journal of Advanced Technology and Engineering Solutions*, *2*(04), 255-293. https://doi.org/10.63125/vfvzge86
[106]. Taufiqur, R., & Kazi Mohammad Khalid, A. (2022). Impact Of GIS-Based Spatial Decision Support Systems on Urban Water Supply Network Optimization: A Qualitative Evaluation. *American Journal of Interdisciplinary Studies*, *3*(04), 657-690. https://doi.org/10.63125/2hqejb24
[107]. Tchana, Y., Ducellier, G., & Remy, S. (2019). Designing a unique Digital Twin for linear infrastructures lifecycle management. *Procedia CIRP*, *84*, 545-549.
[108]. Tuinema, B. W., Rueda Torres, J. L., Stefanov, A. I., Gonzalez-Longatt, F. M., & van der Meijden, M. A. (2020). Cyber-physical system modeling for assessment and enhancement of power grid cyber security, resilience, and reliability. In *Probabilistic Reliability Analysis of Power Systems: A Student's Introduction* (pp. 237-270). Springer.
[109]. Wang, K., Hu, Q., Zhou, M., Zun, Z., & Qian, X. (2021). Multi-aspect applications and development challenges of digital twin-driven management in global smart ports. *Case Studies on Transport Policy*, *9*(3), 1298-1312.
[110]. Wu, X., Wang, H., Jiang, G., Xie, P., & Li, X. (2019). Monitoring wind turbine gearbox with echo state network modeling and dynamic threshold using SCADA vibration data. *Energies*, *12*(6), 982.
[111]. Yitmen, I., Alizadehsalehi, S., Akıner, İ., & Akıner, M. E. (2021). An adapted model of cognitive digital twins for building lifecycle management. *Applied Sciences*, *11*(9), 4276.
[112]. Yu, G., Wang, Y., Mao, Z., Hu, M., Sugumaran, V., & Wang, Y. K. (2021). A digital twin-based decision analysis framework for operation and maintenance of tunnels. *Tunnelling and underground space technology*, *116*, 104125.
[113]. Yu, G., Zhang, S., Hu, M., & Wang, Y. K. (2020). Prediction of highway tunnel pavement performance based on digital twin and multiple time series stacking. *Advances in Civil Engineering*, *2020*(1), 8824135.
[114]. Zang, T., Gao, S., Liu, B., Huang, T., Wang, T., & Wei, X. (2019). Integrated fault propagation model based vulnerability assessment of the electrical cyber-physical system under cyber attacks. *Reliability Engineering & System Safety*, *189*, 232-241.
[115]. Zhang, Y., Huang, T., & Bompard, E. F. (2018). Big data analytics in smart grids: a review. *Energy informatics*, *1*(1), 8.
[116]. Zhang, Y., Wang, L., Xiang, Y., & Ten, C.-W. (2015). Power system reliability evaluation with SCADA cybersecurity considerations. *IEEE Transactions on Smart Grid*, *6*(4), 1707-1721.
[117]. Zhou, C., Xu, J., Miller-Hooks, E., Zhou, W., Chen, C.-H., Lee, L. H., Chew, E. P., & Li, H. (2021). Analytics with digital-twinning: A decision support system for maintaining a resilient port. *Decision Support Systems*, *143*, 113496.
[118]. Zhu, W., Han, M., Milanović, J. V., & Crossley, P. (2020). Methodology for reliability assessment of smart grid considering risk of failure of communication architecture. *IEEE Transactions on Smart Grid*, *11*(5), 4358-4365.
[119]. Zografopoulos, I., Ospina, J., Liu, X., & Konstantinou, C. (2021). Cyber-physical energy systems security: Threat modeling, risk assessment, resources, metrics, and case studies. *IEEE access*, *9*, 29775-29818.