Journal of Advanced Science and Optimization Research
April, 2025, Editions
www.ssaapublications.com
JASOR
Vol. 8, No.9, E-ISSN 3027-1983
P-ISSN 3027-2076
Sahara African Academic

OPTIMIZATION OF SATELLITE-BASED TELEMEDICINE NETWORKS FOR RURAL CONNECTIVITY: A CASE STUDY OF IGU VILLAGE, ABUJA

MARK ATNADU MORRIS[1], CAROLINE OMOANATSE ALENOGHENA[2], AND DAUDA UMAR SULEIMAN[3&1]
[1,2]Department of Telecommunications Engineering, Federal University of Technology, Minna, Niger State, Nigeria. [3]Department of Electrical and Electronics Engineering, Federal University of Technology, Minna, Niger State, Nigeria
Corresponding Author: morris.pg202318975@st.futminna.edu.ng
DOI: https://doi.org/10.70382/sjasor.v8i9.019

ABSTRACT:
Access to healthcare in rural areas is often limited by inadequate infrastructure and unreliable communication networks. This study optimizes satellite-based telemedicine networks to improve healthcare delivery, using Igu Village, Abuja, as a case study. A MATLAB-based simulation utilized NigComSat-1R, a geostationary satellite, as the backbone, with Particle Swarm Optimization (PSO) optimizing key network parameters such as modulation schemes and Convolutional forward error correction (FEC) codes. Performance metrics, including Signal-to-Noise Ratio (SNR), Bit Error Rate (BER), latency, and data throughput, were evaluated under various environmental conditions typical of Nigeria's climate. The optimized network achieved a 92.16% reduction in BER at 10 dB SNR in sunny conditions, and a 99.94% improvement at 15 dB SNR during rainy conditions. Latency was reduced to under 250 ms, while throughput increased from 761.32 Mbps to 1840.95 Mbps at 50 MHz. These improvements highlight the potential of satellite communication to enhance rural healthcare connectivity, supporting bandwidth-intensive services like video consultations and medical imaging. Future work should focus on the real-world implementation of this optimized network and explore the integration of advanced techniques such as reinforcement learning and edge computing to further improve scalability and resilience.

Keywords: Particle Swarm Optimization, NigComSat-1R, Signal-to-Noise Ratio, Bit Error Rate, Latency, Data Throughput, Rural Healthcare.

Introduction

Access to healthcare remains a persistent challenge in rural Nigeria, where traditional terrestrial infrastructure is lacking. While urban centers benefit from fiber optics and cellular towers, communities like Igu Village remain digitally excluded. Telemedicine, when supported by robust communication infrastructure, offers a solution. However, latency, bandwidth, and transmission reliability are critical barriers. This study proposes an optimized satellite-based network model that addresses these constraints by simulating a NigComSat-1R-powered system tailored for telemedicine under tropical weather conditions.

In recent years, telemedicine has emerged as a transformative solution to the widening disparity in healthcare access between urban and rural populations. The ability to deliver real-time consultations, diagnostics, and treatment recommendations via digital platforms offers a practical means of bridging this divide, particularly in low- and middle-income countries such as Nigeria. Despite its potential, the effective implementation of telemedicine in rural areas is impeded by the absence of high-quality, reliable communication networks. Terrestrial options, including mobile broadband and fiber-optic infrastructure, are often either unavailable or unsustainable due to economic, geographic, and environmental limitations in remote regions.

Satellite communication has gained considerable attention as a viable alternative for extending network coverage to underserved and geographically isolated areas. Unlike terrestrial systems, satellite networks do not rely on dense infrastructure and can provide wide-area coverage regardless of terrain. Nigeria's geostationary communication satellite, NigComSat-1R, offers such potential by delivering broadband services to areas where traditional connectivity is impractical. However, the use of satellite links for latency-sensitive and bandwidth-intensive applications such as telemedicine introduces new challenges, including signal degradation from atmospheric interference, high latency due to propagation delays, and fluctuating throughput under adverse weather conditions.

To address these challenges, network optimization becomes imperative. Advanced optimization techniques can significantly enhance the performance of satellite systems by fine-tuning parameters such as modulation schemes, power control, and error correction strategies. Among these techniques, Particle Swarm Optimization (PSO) has proven particularly effective in addressing multi-objective optimization problems, making it suitable for optimizing complex satellite-based networks where trade- offs between throughput, delay, and reliability must be carefully balanced.

This research explores the development of a PSO-optimized satellite-based telemedicine network tailored for rural environments, with a specific focus on Igu Village in Abuja, Nigeria. By simulating network conditions using MATLAB and evaluating performance under varying environmental conditions, the study aims to demonstrate how satellite communication, when properly optimized, can support real-time telemedicine applications in challenging terrains. The work further establishes a scalable framework that can be adapted for similar communities across sub-Saharan Africa and other regions facing comparable connectivity constraints. Through rigorous modeling and analysis, this study contributes to the body of knowledge on non-terrestrial networks (NTNs) for healthcare delivery, highlighting their role in achieving universal health coverage in resource-limited settings.

Theoretical Framework

Optimizing Connectivity in Igu Village: The Case for Satellite-Based Solutions

Igu Village, situated in Nigeria's Bwari Area Council (9°16′60″ N, 7°28′0″ E), exemplifies the persistent connectivity and infrastructural challenges affecting rural communities across developing regions. Its remote location, hilly terrain, and dense vegetation have rendered the deployment of conventional communication infrastructure—such as fiber-optic networks and cellular towers—technically difficult and economically unviable. Limited access to electricity, poorly maintained roadways, and inadequate healthcare and educational services further constrain the community's socio-economic development (Abaka et al., 2017; Rural Electrification Agency, 2018). These conditions have contributed to increasing rural-urban migration, especially among the youth, and underscore the need for scalable digital inclusion strategies.

In such environments, terrestrial communication systems often fall short. Fiber-optic deployment is prohibitively expensive and exposed to risks such as vandalism and environmental degradation, particularly in low-density regions where commercial incentives are weak. Cellular towers, which depend on line-of-sight transmission and stable backhaul infrastructure, are ineffective in topographically obstructed areas, providing minimal coverage at high operational costs. Consequently, rural communities like Igu Village remain excluded from vital services, including telemedicine.

To overcome these constraints, satellite communication presents a promising alternative. This study employs Nigeria's geostationary satellite, NigComSat-1R, as the core transmission backbone to support healthcare connectivity in Igu Village. Operating at an altitude of 35,786 km, NigComSat-1R offers nationwide coverage independent of terrestrial infrastructure (Lawal et al., 2022; Onyeka et al., 2022). Although Geostationary Earth Orbit (GEO) satellites inherently introduce latency due to signal propagation delays, this study integrates optimization techniques—such as adaptive modulation, forward error correction, and power control—to mitigate such limitations. These adjustments ensure reliable real-time communication suitable for bandwidth-intensive telemedicine services such as remote diagnostics, high-definition video consultations, and emergency care coordination.

Moreover, NigComSat-1R's proven success in previous rural deployment initiatives further justifies its selection. Prior use cases have demonstrated its capability to support internet access and eHealth services in underserved regions (Lawal et al., 2022), and its domestic ownership aligns with Nigeria's strategic goal of enhancing digital self-reliance.

In summary, the adoption and optimization of NigComSat-1R for telemedicine delivery in Igu Village offers a robust, cost-effective, and scalable solution to rural connectivity challenges. The approach reinforces the role of satellite communication in bridging the digital divide and promoting equitable access to healthcare and developmental opportunities in geographically marginalized areas.

Overview of Satellite Communication Systems

Satellite communication systems are essential for global connectivity, particularly in areas lacking terrestrial infrastructure. These systems utilize artificial satellites in orbit to relay signals, enabling data, voice, and video transmission over vast distances. A major advantage is the ability to offer broad coverage, making satellite communication ideal for remote and rural regions (Inmarsat, 2023).

Satellites are classified based on their orbital positions: Geostationary (GEO), Medium Earth Orbit (MEO), and Low Earth Orbit (LEO). GEO satellites provide continuous coverage by maintaining a fixed position relative to Earth's surface, though they suffer from higher latency due to their distance. In contrast, LEO satellites, which orbit closer to Earth, offer lower latency and better signal quality, though they require a constellation for continuous coverage (Leyva-Mayorga et al., 2020; Li et al., 2023). MEO satellites provide a balance between coverage and latency, making them suitable for high- throughput applications.

Key parameters in satellite communication include Signal-to-Noise Ratio (SNR), Bit Error Rate (BER), and latency. SNR indicates the clarity and reliability of transmitted data, while BER measures transmission errors. Latency is crucial for real-time applications like telemedicine.

Telemedicine Requirements in Rural Areas

Telemedicine offers significant potential for improving healthcare access in rural areas by using telecommunications technology. Its effectiveness depends on factors such as bandwidth, latency, and data reliability (Omaghomi et al., 2023).

High-bandwidth services, such as video consultations and remote diagnostics, require sufficient data capacity for high-resolution video and large transfers. Latency is a critical factor, as delays can hinder real-time communication between healthcare providers and patients.

In rural regions with limited traditional internet infrastructure, satellite communication is a viable solution, offering extensive coverage. However, optimizing satellite networks to meet telemedicine's demanding requirements necessitates addressing challenges like signal attenuation, bandwidth limitations, and high latency. A tailored approach is essential to ensure that satellite networks can effectively support telemedicine in underserved areas.

Optimization Techniques in Satellite Networks

Optimizing satellite networks involves techniques to enhance performance and meet telemedicine requirements. Key strategies include resource allocation, power control, and error correction.

Resource allocation ensures efficient distribution of bandwidth and power, utilizing techniques like Frequency Division Multiple Access (FDMA) and Time Division Multiple Access (TDMA). Machine learning can further enhance allocation by predicting traffic patterns and dynamically adjusting parameters. Power control maintains signal quality and minimizes interference. Techniques such as adaptive power control and beamforming optimize signal strength, improve SNR, and reduce BER, boosting overall network performance.

Error correction methods, such as Forward Error Correction (FEC) and Automatic Repeat Request
(ARQ), are employed to detect and correct transmission errors, ensuring data integrity (Sudha et al., 2022). MATLAB-based simulation tools are widely used to model network scenarios, evaluate performance, and identify optimization strategies.

Optimization Algorithms

Optimization algorithms are vital for designing satellite networks that meet the specific needs of telemedicine applications. These algorithms focus on improving SNR, BER, latency, and data throughput by optimizing parameters like modulation schemes, error correction, and power allocation. Commonly applied algorithms include Genetic Algorithm (GA), Particle Swarm Optimization (PSO), Simulated Annealing (SA), Linear Programming (LP), and Multi-Objective Optimization (MOO).

Review of Related Literature

Telemedicine has evolved as a pivotal tool in bridging the gap between healthcare providers and underserved populations, especially in rural and remote areas. The development of telemedicine systems has been significantly influenced by technological advancements, particularly in satellite and wireless communication technologies. Several studies have examined the role of telemedicine in improving healthcare access, as well as the challenges that must be addressed to optimize its effectiveness.

Lawal et al. (2022) investigated the use of satellite technology in addressing healthcare challenges for internally displaced persons (IDPs) in Nigeria, focusing on the integration of telemedicine in underserved regions. Utilizing the NIGCOMSAT-1R satellite, their study conducted a telemedicine outreach at the

New Kuchingoro IDP camp in Abuja, where 317 patients received healthcare over three days. The results demonstrated a reduction in patient waiting times and healthcare costs. However, challenges such as language barriers, limited medical supplies, and inadequate testing facilities were identified. Despite these limitations, the study highlighted the transformative potential of satellite-enabled telemedicine, offering a promising framework for expanding telemedicine services to underserved communities.

Expanding the scope of telemedicine, Nawaz et al. (2022) explored the potential of 5G and advanced telecommunication technologies in improving healthcare access for rural populations. Their systematic review emphasized that 5G could offer enhanced data transfer rates and lower healthcare costs, making specialized medical services more accessible to remote areas. They proposed a future telemedicine framework integrating Internet of Things (IoT), big data, and artificial intelligence (AI) to enhance healthcare delivery. However, the authors acknowledged that practical applications of 5G in telemedicine remain underexplored, with usability, connectivity, and data security emerging as key areas for further research.

Building on these advancements, Onyeka et al. (2022) investigated the role of satellite communication in enhancing the positioning control of dish antennas used for telemedicine in Nigeria. Their research focused on optimizing the performance of dish antennas mounted on distributed mobile telemedicine nodes communicating via Nigerian Communications Satellite 1R (NigComSat-1R). They developed a full-state feedback controller that improved transient and steady-state performance, demonstrating significant enhancements in response times, including a rise time of 0.39 seconds and a settling time of 1.31 seconds. This work emphasized the critical role of precise antenna positioning in maintaining reliable communication for telemedicine systems.

Further developments in eHealth systems were presented by (Alenoghena et al., 2022), who conducted a comprehensive survey on the evolution of eHealth and telemedicine technologies. They focused on wireless technologies, communication protocols, and Quality of Service (QoS) standards necessary for efficient telemedicine networks. The study identified challenges such as data security, network integration, and energy efficiency in wearable devices. The authors suggested that addressing these gaps would be crucial for improving the performance of telemedicine networks in rural settings.

In a subsequent study, Alenoghena et al., (2023) expanded on the earlier work, concentrating on the integration of wireless technologies, communication protocols, and QoS standards in telemedicine systems. Their review highlighted several communication methods, including Body Area Network (BAN), satellite, Wide Area Network (WAN), and Global System for Mobile Communications (GSM). The authors noted that the choice of communication technology depends on infrastructure availability, application requirements, and cost considerations. They also underscored the need for further research on data transmission standards, network integration, and security, particularly in the context of telemedicine systems deployed in rural areas.

The rapid evolution of telemedicine has also led to a broader exploration of connectivity solutions. Omaghomi et al. (2023) reviewed the impact of telemedicine in rural Africa, where isolation and poor infrastructure pose significant barriers to healthcare delivery. The authors highlighted how mobile technology and digital communication could improve healthcare access, reduce the need for extensive travel, and enhance diagnostic capabilities. Despite these benefits, the study identified barriers such as limited infrastructure and the digital divide, emphasizing the need for targeted investments and infrastructure development to fully realize telemedicine's potential.

As technology continues to advance, the integration of 6G networks into telemedicine systems is being explored. Vennapusa, (2023) examined the potential of integrating satellite and aerial networks within 6G systems to enhance global connectivity. This integration promises to provide improved coverage, reduced latency, and greater reliability, particularly for real-time applications like telemedicine. However, the author also acknowledged the challenges of high implementation costs, technological complexity, and regulatory hurdles that must be addressed to fully capitalize on the potential of 6G.

In recent years, advancements in satellite technology have further facilitated telemedicine systems, particularly in areas with limited terrestrial infrastructure. Kumar & Choudhary, (2024) reviewed recent innovations in satellite design, signal processing, and network architectures. Their study highlighted the role of low Earth orbit (LEO) constellations in providing low-latency, high-capacity connectivity, which is critical for telemedicine applications in remote areas. The authors also discussed challenges such as spectrum congestion and space debris, calling for collaborative efforts to overcome these obstacles and ensure the sustainability of satellite-based telemedicine systems.

Sadiq et al. (2024) further explored the role of unmanned aerial vehicles (UAVs) and Software-Defined Networks (SDNs) in enhancing telemedicine network capacity, management, and performance. Their review examined how UAVs could support telemedicine by expanding network coverage and facilitating real-time data communication. The authors also highlighted the integration of AI in telemedicine networks, which could enhance decision-making and optimize resource allocation. However, they noted that research gaps remain in optimizing UAV support for telemedicine, network security, and cost-effectiveness.

Finally, Elhachi et al. (2024) introduced an innovative approach to real-time video streaming for telemedicine through multi-access terrestrial and non-terrestrial networks (NTNs). Their study proposed using multipath QUIC extensions (MPQUIC) and multiple description coding (MDC) to improve video quality, addressing challenges such as dynamic topologies and high packet loss. The results demonstrated significant improvements in latency, data rate, and video quality, showcasing the potential of these technologies to enhance telemedicine services in rural areas.

These studies collectively demonstrate the growing potential of satellite-based telemedicine networks to bridge healthcare gaps in rural and underserved areas. However, they also reveal significant challenges in terms of network reliability, data security, and infrastructure development. Continued research and innovation are needed to optimize satellite communication technologies and ensure that telemedicine can effectively serve rural populations, as exemplified by the case study of Igu Village, Abuja.

Research Methodology

Network Design Approach

This section presents the design approach for a satellite-based network tailored to telemedicine services in rural areas. It incorporates critical network parameters, such as satellite configuration, signal-to-noise ratio (SNR), bit error rate (BER), latency, and data throughput, all aimed at optimizing network performance for telemedicine applications in regions like Igu Village, Abuja. Each parameter is explored to understand its role in ensuring efficient and reliable communication for telemedicine.

Satellite Network Configuration

The satellite network for this research leverages NigComSat-1R, Nigeria's dedicated geostationary communications satellite. Positioned at 42.5° East longitude, the satellite is strategically located to provide stable, high-throughput communication services across Nigeria, including remote areas like Igu Village. Its capability to offer reliable broadband internet, telephony, and broadcasting services makes it an ideal solution for supporting telemedicine.

The satellite network configuration is built around several key elements, starting with the satellite specifications. NigComSat-1R operates from a geostationary orbit at an altitude of 36,000 km above the Earth's surface, ensuring continuous and consistent coverage. Its beam coverage is particularly targeted at rural areas within Nigeria, optimizing connectivity for telemedicine applications. The satellite utilizes C-band and Ku-band frequency bands, which provide adequate bandwidth capacity and resistance to atmospheric interference, ensuring reliable communication under varying weather conditions.

The ground segment consists of a primary ground station, which manages communication between the satellite and telemedicine terminals. Portable satellite units, installed in Igu Village, serve as the user terminals, enabling telemedicine services in the area.

Regarding network characteristics, the configuration takes into account important factors that affect signal propagation, such as rain fade and attenuation, to improve signal reliability. The inherent latency of the system is considered, with an expected one-way delay of approximately 240 ms due to the geostationary orbit, but this is balanced by minimizing disruption to real-time telemedicine services. Optimized uplink and downlink communication links are designed to support video streaming and real- time data transmission, essential for telemedicine applications. To counteract data loss, error-correction mechanisms such as Hamming Code, Reed-Solomon, and Convolutional Code are implemented, ensuring robust communication even in challenging conditions.

This configuration enables a reliable satellite network that effectively supports the demanding needs of telemedicine services in rural areas, ensuring both consistency and quality in service delivery.

Signal-to-Noise Ratio (SNR)

SNR is a fundamental factor in the quality of communication, especially for telemedicine applications that require high-quality, uninterrupted data

transmission. A high SNR ensures that telemedicine services such as video conferencing and medical data transmission are reliable.
SNR can be quantified using Equation 1 (Kumar & Arnon, 2022):

[redacted] (1)

where P_{Signal} is the received power (w), P_{Noise} is the noise power (w). A higher SNR indicates better signal quality, which is crucial for telemedicine applications requiring high bandwidth for activities such as remote consultations.

Bit Error Rate (BER)

The Bit Error Rate (BER) measures the number of errors in data transmission, directly affecting the reliability of telemedicine applications. Minimizing BER is essential for ensuring that transmitted medical data is accurate and reliable. The BER can be calculated using Equation 2 (Choi, 2024):

[redacted] (2)

where[redacted] $_b$ is the energy per bit (J),[redacted] $_0$ is the noise power spectral density (W/Hz), Q (.) is the Q-function, which gives the tail probability of the Gaussian distribution. To reduce BER, error correction techniques like Forward Error Correction (FEC) are incorporated into the design, ensuring that data is transmitted with minimal errors.

Latency

Latency refers to the time delay between data transmission and reception, a crucial parameter for real- time telemedicine applications. High latency can disrupt critical interactions like video consultations.
The latency is calculated using Equation 3 (Choi, 2024):

[redacted] (3)

where d is the distance (d) between the satellite and the ground station, c is the speed of light
(3 × 108 ms), Processing Delay accounts for encoding, decoding, and any retransmission delays.

Ensuring that latency stays below 250 ms is crucial for seamless telemedicine interactions.

Data Throughput

Data throughput measures the rate at which data is successfully transmitted over the network, which is essential for high-bandwidth telemedicine services like video consultations and medical image transmission. Throughput can be calculated using Equation 4 (Choi, 2024):

[redacted] (4)

where B is the bandwidth (Hz) of the channel, SNR is the Signal-to-Noise Ratio. Optimizing throughput ensures that the network can handle large data volumes, facilitating the transmission of high-definition video and detailed medical images, essential for effective telemedicine.

Propagation and Power Control Models

This section focuses on the propagation and power control models employed in the satellite-based telemedicine network design. These models are crucial for ensuring reliable communication and signal quality across varying environmental conditions. The propagation model addresses how signals travel through space and atmospheric layers, while the power control model ensures optimal signal strength at the receiver. Additionally, the error correction techniques are implemented to mitigate transmission errors and enhance the overall reliability of the network, ensuring efficient delivery of telemedicine services.

Propagation and Power Control Models

This section delves into the propagation and power control models integral to the satellite-based telemedicine network design. These models are vital for ensuring signal reliability and quality, especially in rural areas where environmental factors, such as weather and topography, can significantly impact communication. The propagation model considers the factors that influence signal travel, while the power control model ensures that the received signal is strong enough for effective communication, even under varying environmental conditions. Additionally, error correction techniques are employed to minimize transmission errors and ensure a reliable and accurate delivery of telemedicine services.

Propagation Model

The propagation model defines how satellite signals travel through space and the Earth's atmosphere to reach the ground station. For this purpose, the Friis Transmission Equation was applied to estimate the received power at the receiver's end. This model is essential for determining the optimal satellite positioning and the necessary transmission power to ensure that the signal strength is sufficient for reliable communication, even in remote rural locations. The Friis Transmission Equation, given in Equation 5, calculates the received power based on several factors, including the transmitted power, antenna gains, wavelength, and the distance between the satellite and the ground station:

[redacted] (5)

where P_r is the received power (w), P_t is he transmitted power (w),G_t and G_r are the transmitter and receiver antenna gains, λ is the wavelength (m) of the signal, and d is the distance (m) between the satellite and the ground station. The Friis Transmission Equation provides a theoretical framework for determining how signals propagate through space and how satellite communication performance can be optimized. By incorporating this model, the design ensures that the telemedicine network can reliably operate under various environmental conditions, including those typical in rural areas.

Power Control

Adaptive Power Control (APC) is employed to optimize the transmission power in real time, ensuring that the satellite network's performance is consistently maintained despite changing environmental conditions. This approach dynamically adjusts the satellite's transmission power to meet the required Signal-to-Noise Ratio (SNR), enhancing communication efficiency while minimizing energy consumption. The primary objective is to maintain a stable SNR and to avoid over- or under- transmission, both of which can affect performance. The power control adjustment is achieved through the Equation 6:

[redacted] (6)

where P_{new} is the adjusted transmission power, $P_{initial}$ is the initial transmission power, SNR_{target} is the desired SNR for telemedicine, and $SNR_{measured}$ is the measured SNR at the receiver. This adaptive power control mechanism ensures that the satellite transmits at just the right power to achieve the desired SNR, improving both the reliability and energy efficiency of the communication system. By adjusting the transmission power based on real-time conditions, this technique also contributes to cost savings in operational energy usage.

Error Correction

Error correction is essential in maintaining the integrity and accuracy of transmitted data, particularly for sensitive medical information exchanged during telemedicine sessions. Forward Error Correction (FEC) techniques were implemented in this network design to detect and correct errors that occur during data transmission. By adding redundant bits to the transmitted data, FEC ensures that any errors introduced during transmission can be corrected without requiring retransmission, which is especially important for real-time services like telemedicine. The efficiency of FEC is represented by the following Equation 7:

$$R = \frac{k}{n} \quad (7)$$

where R is the code rate, k is the number of data bits, and n is the total number of bits (including redundant bits). By applying FEC, the system significantly reduces the Bit Error Rate (BER), ensuring that the transmitted data is received accurately. This error correction mechanism is particularly vital for telemedicine services, where reliable and error-free communication is critical to providing high-quality healthcare.

Application of PSO for Optimization

In this study, Particle Swarm Optimization (PSO) was utilized to optimize key performance metrics— latency, throughput, Signal-to-Noise Ratio (SNR), and Bit Error Rate (BER)—in a satellite-based telemedicine network. PSO, inspired by the swarm behavior of birds and fish, is a population-based metaheuristic algorithm known for its ability to efficiently explore complex, multidimensional solution spaces. It was chosen for this study due to its robustness in addressing optimization challenges in real- time communication systems, making it ideal for enhancing the performance of satellite-based networks in telemedicine applications.

Latency Optimization

Latency is a critical factor in real-time telemedicine applications such as video consultations and remote diagnostics, where delays can degrade the quality of service. To minimize latency, PSO was used to optimize satellite resource allocation, which includes transmission scheduling and power control. The PSO algorithm adjusted parameters such as time slot allocation in Time Division Multiple Access (TDMA) and transmission power to minimize propagation and queuing delays. The objective function for latency optimization is defined as Equation 8:

$$\text{Minimize } f1 = T_p + T_q + T_t \quad (8)$$

where T_p is propagation delay, T_q is queuing delay, and T_t is transmission delay. In this scenario, each particle in the PSO search space represented a combination of scheduling and power settings. The particles iteratively updated their positions based on the best observed configurations, converging toward the optimal set of parameters that minimized overall latency in the system.

Throughput Optimization

Throughput, or the data transmission rate, is a key factor in ensuring that telemedicine services, particularly video consultations and real-time diagnostics, can function smoothly without interruption. To maximize throughput, the PSO algorithm adjusted parameters such as modulation schemes, bandwidth allocation, and coding rates. The goal was to achieve the highest possible data rate while maintaining acceptable Bit Error Rates (BER). The fitness function for throughput optimization is defined as Equation 9:

$$\text{Maximize } f2 = \sum_{i=1}^{N} B_i \times \log_2(1 + SNR_i) \quad (9)$$

where B_i represents the allocated bandwidth for user ii and SNR_i is the signal-to-noise ratio. The particles in the PSO algorithm iteratively adjusted modulation schemes (16-QAM) and coding rates, selecting configurations that provided the highest throughput while ensuring that the BER remained within acceptable limits.

SNR Optimization

Maximizing the Signal-to-Noise Ratio (SNR) is essential for enhancing the link reliability and overall performance of the network. A higher SNR reduces transmission errors, leading to more stable and reliable communication. PSO was employed to optimize adaptive power control and beamforming techniques to maximize SNR. The optimization objective for SNR is given by Equation 10:

[redacted] (10)

where P_t is the transmit power, G_t and G_r are the antenna gains, N_0 is the noise power spectral density, and B is the bandwidth. In this optimization, PSO sought the optimal combination of power and antenna configurations that provided the best SNR while adhering to power constraints to avoid interference and excessive energy consumption.

BER Optimization

Minimizing the Bit Error Rate (BER) is critical for ensuring the accuracy of data transmission, particularly in telemedicine, where the integrity of medical data is paramount. PSO was used to optimize error correction coding schemes, such as Low-Density Parity-Check (LDPC) codes and Turbo codes, along with modulation schemes to achieve the lowest BER. The fitness function for BER optimization is given by Equation 11:

[redacted] (11)

where [redacted] is the energy per bit to noise power spectral density ratio and Q is the Q-function, which represents the tail probability of the standard normal distribution. PSO dynamically adjusted coding rates and modulation schemes based on channel conditions, ensuring an optimal trade-off between BER and throughput for reliable data transmission in telemedicine applications.

Standard Baseline Metrics for Telemedicine Applications

Telemedicine applications require reliable and efficient network performance to ensure high-quality medical services such as video consultations, remote diagnostics, and the transmission of medical images. Several international organizations, including the International Telecommunication Union (ITU-T), the World Health Organization (WHO), and the Federal Communications Commission (FCC), have established baseline standards to ensure these services meet the necessary quality requirements. The key metrics that define the performance of telemedicine networks include latency, signal-to-noise ratio (SNR), bit error rate (BER), throughput, and bandwidth.

Latency is the time delay in data transmission between sender and receiver, and it is critical for real- time applications like video consultations and diagnostics. Excessive latency can lead to communication lags, interrupting the flow of interaction between healthcare providers and patients. According to ITU- T G.114, video conferencing applications should have a maximum latency of 250 milliseconds, while

WHO recommends a latency of no more than 300 milliseconds for medical imaging (ITU-T G.114, 2003; WHO, 2022). Maintaining low latency is essential for the smooth operation of telemedicine networks.

Signal-to-Noise Ratio (SNR) is a measure of the strength of the transmitted signal relative to the background noise. A higher SNR results in clearer audio and video transmissions, essential for accurate medical data. The FCC and ITU-T standards specify a minimum SNR of 20 dB for video conferencing and a minimum of 30 dB for medical imaging (ITU-T H.264, 2007; Vaahteranoksa & Vuori, 2007). Insufficient SNR can lead to degraded quality, making it difficult to transmit clear video or high- resolution medical images.

Bit Error Rate (BER) represents the fraction of bits received in error compared to the total bits transmitted. A low BER is crucial for ensuring the accuracy of data transmission in telemedicine. High BER levels could lead to corrupted video, distorted voice communications, and errors in medical reports, impacting diagnoses and patient care. According to ITU-T and IEEE 802.11 standards, a maximum BER of 10^{-3} is acceptable for video conferencing, while medical imaging requires a BER of 10^{-6} (IEEE, 2021; ITU-T, 2021). Minimizing BER ensures that medical data is transmitted accurately, reducing the risk of misdiagnoses.

Throughput refers to the rate at which data is successfully transmitted over a network, and it is particularly important in telemedicine applications, where high data rates are needed for real-time interactions and large data transmissions like medical imaging. ITU-T H.264 specifies that high- definition video conferencing should have a minimum throughput of 1 Mbps, while the WHO and ITU- T Y.1541 recommend at least 5 Mbps for medical imaging (ITU-T H.264, 2007; ITU-T Y.1541, 2011; WHO, 2022). Low throughput can result in video buffering, long delays in uploading medical images, and poor user experiences during consultations.

Bandwidth is the maximum data capacity of a network, directly impacting the performance of telemedicine applications. According to ITU-T and WHO guidelines, a minimum bandwidth of 2 Mbps is recommended for video conferencing, and at least 10 Mbps is necessary for medical imaging (ITU- T, 2021; WHO, 2022). Bandwidth limitations, especially in rural areas with underdeveloped infrastructure, can lead to network congestion, affecting the quality and speed of telemedicine services.

Table 1 summarizes the standard baseline metrics for telemedicine applications.

Table 1: Summary of Standard Baseline Metrics

Metric	**Video Conferencing (Baseline)**	**Medical Imaging (Baseline)**	**References**
Latency	$\leq$ 250 ms	$\leq$ 300 ms	ITU-T G.114, WHO
SNR (dB)	$\geq$ 20 dB	$\geq$ 30 dB	FCC, ITU-T
BER	$\leq 10^{-3}$	$\leq 10^{-6}$	IEEE 802.11, ITU-T
Throughput	$\geq$ 1 Mbps (HD)	$\geq$ 5 Mbps	ITU-T Y.1541

These standards help guide the design and operation of telemedicine networks, ensuring that they meet the required performance levels for effective healthcare delivery, especially in remote and rural settings where reliable connectivity is paramount.

Analysis of Current Internet Connectivity in Igu Village

The analysis of internet connectivity in Igu Village reveals substantial gaps in coverage, highlighting the challenges faced by residents in accessing essential digital services, including telemedicine. While urban areas such as Bwari and Dutse benefit from dense network coverage, Igu Village, situated in the north eastern part of the Bwari area council, remains largely underserved by major telecom operators.

Airtel's network in the village is limited, with coverage primarily restricted to sparse 2G and 3G signals, offering basic voice services at best. The lack of 4G and 5G infrastructure further compounds the situation, rendering high-speed internet, which is crucial for telemedicine, inaccessible to residents.

Similarly, MTN's coverage in Igu Village is minimal, with only isolated 2G signals visible and no presence of 3G, 4G, or 5G networks. This limited connectivity hinders residents' ability to access the internet for essential services, highlighting the inadequacy of MTN's infrastructure in meeting the needs of rural communities.

9mobile's network in the area mirrors this pattern, with sparse 2G and 3G coverage, and the complete absence of 4G and 5G services. The limited availability of even basic internet connectivity exacerbates the challenges faced by residents in accessing modern digital services, further isolating the village from the benefits of advanced technology. Similarly, Glo's network coverage is characterized by a few scattered 2G signals and a near-total absence of 3G or higher network services. This insufficient network coverage further impedes the adoption of telemedicine and other digital applications, which rely on stable, high-speed internet access.

Smile, which specializes in data services, also falls short in Igu Village. Its network coverage is virtually nonexistent, further underscoring the lack of reliable internet access in the area. Unlike in urban hubs where Smile provides adequate service, Igu Village remains excluded from its offerings, preventing residents from benefiting from essential data-driven services.

The cumulative analysis of these networks highlights the digital divide between urban and rural areas, where Igu Village is left without reliable access to high-speed internet. With major telecom providers focused on urban centers, the need for alternative connectivity solutions, such as satellite-based communication systems, becomes evident. These systems could provide the necessary infrastructure to enable telemedicine and other digital services in underserved regions like Igu Village.

Results and Discussion

Bit Error Rate (BER) vs. Signal-to-Noise Ratio (SNR) Across Various Weather Conditions The reliability of satellite-based telemedicine networks is profoundly influenced by atmospheric conditions, which can significantly impair signal integrity. To assess this impact, we conducted a comprehensive analysis of the Bit Error Rate (BER) as a function of the Signal-to-Noise Ratio (SNR) under varying weather scenarios: sunny, rainy, cloudy, and stormy conditions. This evaluation encompassed both unoptimized and optimized network configurations, providing insights into how atmospheric variations influence communication quality.

Figure 1 presents the consolidated BER performance across the four weather conditions. Consistently, an inverse relationship between BER and SNR is observed; as SNR increases, BER decreases, indicating improved signal integrity. However, the extent of BER reduction varies with weather conditions and network optimization.

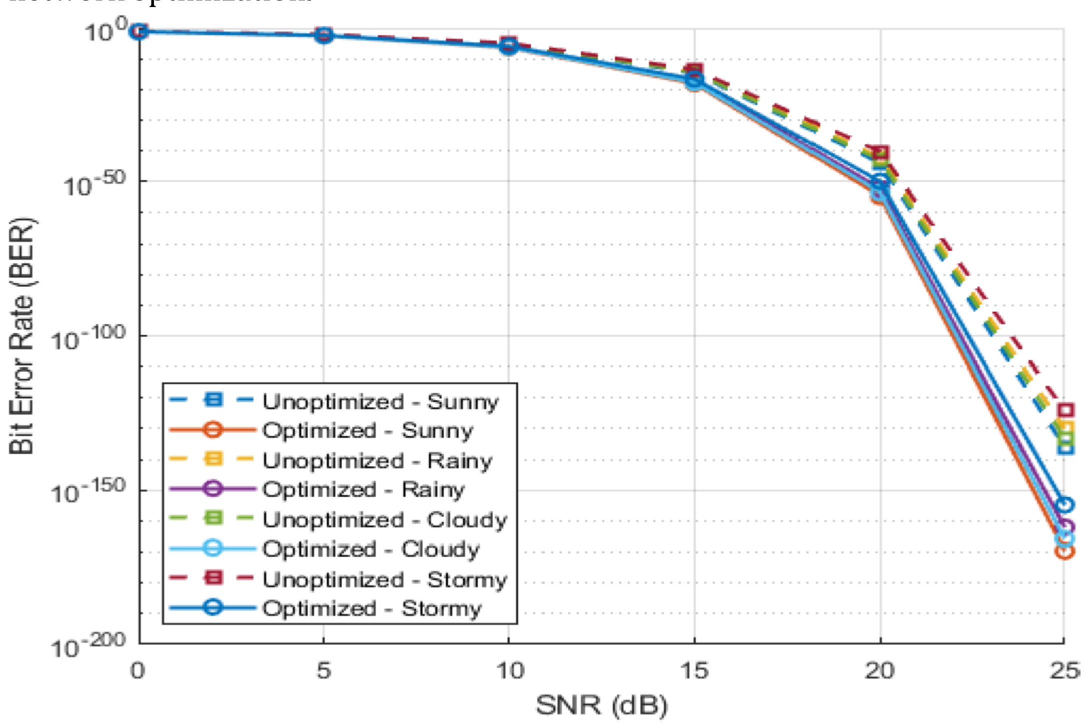

Figure 1: BER vs. SNR across Various Weather Conditions

Under sunny conditions, both network configurations exhibit optimal performance, with BER decreasing sharply as SNR increases. The optimized network demonstrates a more pronounced reduction, achieving near-zero BER at higher SNR levels. Rainy conditions introduce significant signal attenuation due to increased absorption and scattering by rain droplets, leading to higher BER values, especially in the unoptimized network. The optimized network, however, maintains a lower BER across all SNR levels, showcasing its resilience to rain-induced degradation.

Cloudy conditions result in moderate signal degradation. The optimized network consistently outperforms the unoptimized configuration, maintaining lower BER values across the SNR spectrum. Stormy conditions pose the greatest challenge, with severe atmospheric disruptions causing substantial signal degradation. Despite this, the optimized network exhibits superior performance, significantly reducing BER compared to the unoptimized network.

Table 2 provides a detailed comparison of BER values across varying SNR levels and weather conditions for both network configurations.

Table 2: BER vs. SNR across Weather Conditions

BER vs. SNR										
Weather Conditions ($\log_{10}$)										
SNR (dB)	Sunny			Rainy	Cloudy				Stormy	
	noptimize BER	Optimize d BER	d	noptimize BER	d Optimize BER	d Unoptimize BER	d Optimize	d	noptimize BER	Optimize d BER d
0	-1.23	-1.23	-1.20	-1.20	-1.21	-1.21	-1.17	-1.17		
5	-2.57	-2.57	-2.48	-2.48	-2.52	-2.52	-2.40	-2.40		
10	-5.31	-6.41	-5.11	-6.17	-5.21	-6.29	-4.92	-5.93		
15	-14.72	-18.13	-14.11	-17.36	-14.41	-17.74	-13.52	-16.63		
20	-43.99	-54.65	- 42.07		-52.25	-43.02	-53.43	-40.23	-49.96	
25	-169.00		-169.61		-129.95		-162.05		-132.95	-
165.78		-124.18		-154.82						

The data underscores the critical role of network optimization in enhancing communication reliability across diverse weather conditions. Implementing adaptive techniques and robust error correction mechanisms is essential for maintaining the integrity of satellite-based telemedicine services, particularly in regions susceptible to adverse weather phenomena.

Channel Capacity vs. SNR

Channel capacity serves as a critical metric in evaluating the efficiency of data transmission within communication systems. It defines the maximum achievable data rate of a channel, given a specific signal-to-noise ratio (SNR). Understanding the relationship between channel capacity and SNR is essential for optimizing communication performance, as higher SNR values typically enable more efficient transmission, leading to improved data rates. This relationship is visually represented in Figure 2.

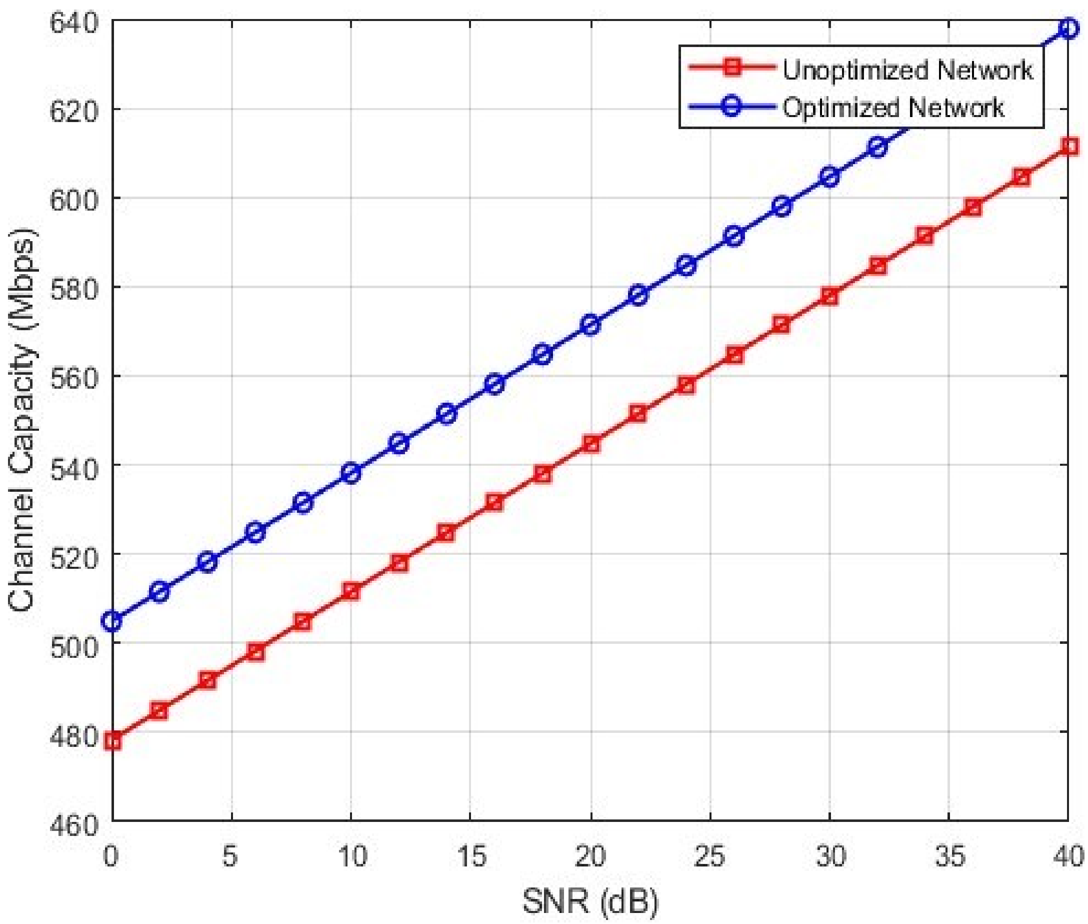

Figure 2: Channel Capacity vs. SNR

Table 3 further illustrates the numerical relationship between channel capacity and SNR for both unoptimized and optimized networks. It provides a comparative analysis of how optimization techniques impact the channel capacity at various SNR levels.

Table 3: Channel Capacity vs. SNR

Channel Capacity vs. SNR

SNR (dB)	Unoptimized Network Channel Capacity (Mbps)	Optimized Network Channel Capacity (Mbps)
0	478.36	504.97
10	511.58	538.19
20	544.80	571.41
30	578.02	604.63
40	611.24	637.84

The data presented in Table 3 reveals a consistent trend in the increase of channel capacity with the rise in SNR for both unoptimized and optimized networks. At an SNR of 0 dB, the unoptimized network achieves a channel capacity of 478.36 Mbps, while the optimized network performs better with a capacity of 504.97 Mbps. This reflects a notable improvement of 5.57% due to the applied optimization techniques.

At 10 dB SNR, the unoptimized network attains a channel capacity of 511.58 Mbps, while the optimized network reaches 538.19 Mbps, marking a 5.2% improvement. As the SNR increases to 20 dB, the unoptimized network's capacity rises to 544.80 Mbps, whereas the optimized network achieves 571.41 Mbps, showcasing a 4.89% enhancement.

Finally, at the highest observed SNR of 40 dB, the unoptimized network reaches 611.24 Mbps, whereas the optimized network achieves a higher capacity of 637.84 Mbps, corresponding to a 4.35% improvement.

These results consistently demonstrate the benefits of network optimization at all SNR levels, illustrating that optimization enhances the channel capacity and, by extension, the overall performance of communication systems. This optimization enables more efficient use of the available bandwidth, thereby ensuring higher data rates and improved network efficiency.

Latency vs. Distance

Latency, a key performance metric in communication networks, increases with distance. However, network optimization techniques can reduce latency, enhancing system responsiveness. Figure 3 illustrates the latency-distance relationship, showing a clear upward trend with distance, with the optimized network consistently outperforming the unoptimized one.

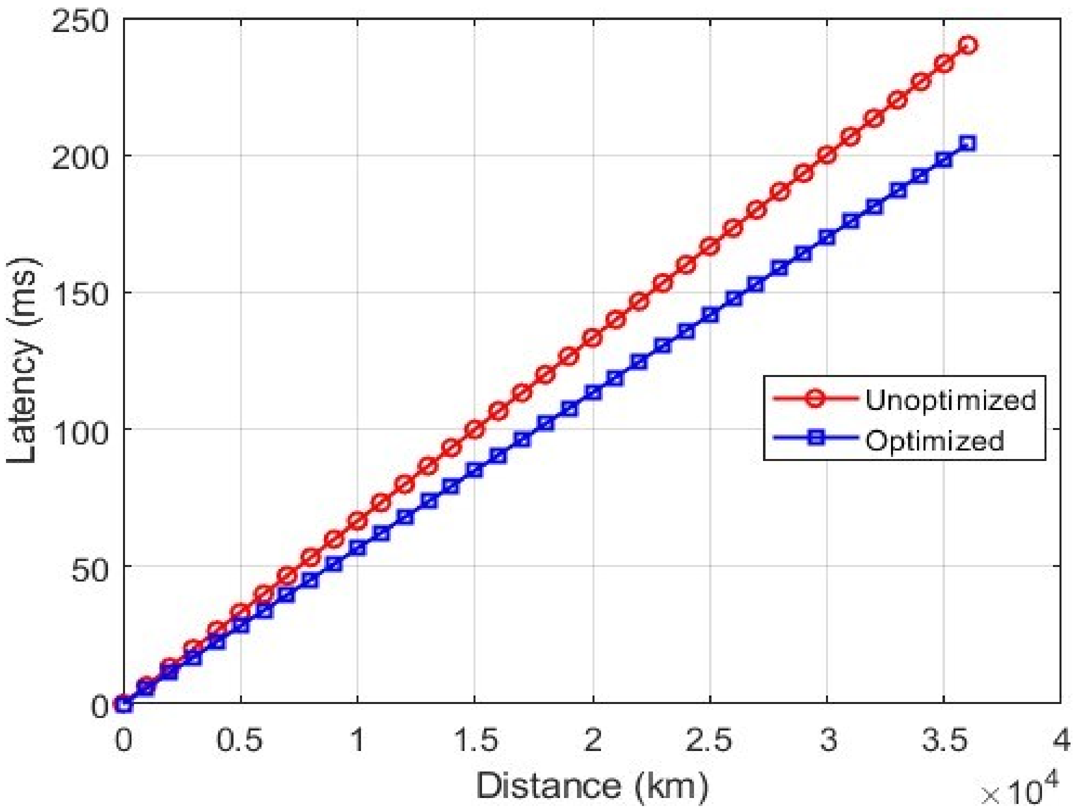

Figure 3: Latency vs. Distance

Table 4 presents latency values for both networks across various distances. The optimized network consistently exhibits lower latency, demonstrating improved performance even at greater distances.

Table 4: Latency vs. Distance

	Latency vs. Distance	
Distance (Km)	**Unoptimized Network Latency (ms)**	**Optimized Network Latency (ms)**
0	0	0
5,000	33.33	28.33
10,000	66.67	56.67
15,000	100.00	85.00
20,000	133.33	113.33
25,000	166.67	141.67
30,000	200.00	170.00
35,000	240.00	198.33

As depicted in Table 4, the latency increases with distance for both the unoptimized and optimized networks. However, the optimized network consistently demonstrates lower latency across all distance intervals. At 5,000 km, the unoptimized network has a latency of 33.33 ms, while the optimized network shows 28.33 ms, a 15% improvement. At 10,000 km, the unoptimized network's latency is 66.67 ms, reduced to 56.67 ms in the optimized network. At the maximum distance of 35,000 km, the unoptimized network reaches 240 ms, while the optimized network achieves 198.33 ms, an 18% improvement. This analysis demonstrates the significant benefits of optimization in reducing latency, thus enhancing the quality of service, especially in time-sensitive applications over long distances.

SIR vs. Link Quality

The Signal-to-Interference Ratio (SIR) is a key metric for assessing communication link quality. Higher SIR values indicate reduced interference and improved signal clarity. Figure 4 illustrates the relationship between SIR and link quality, highlighting the enhanced performance of optimized networks.

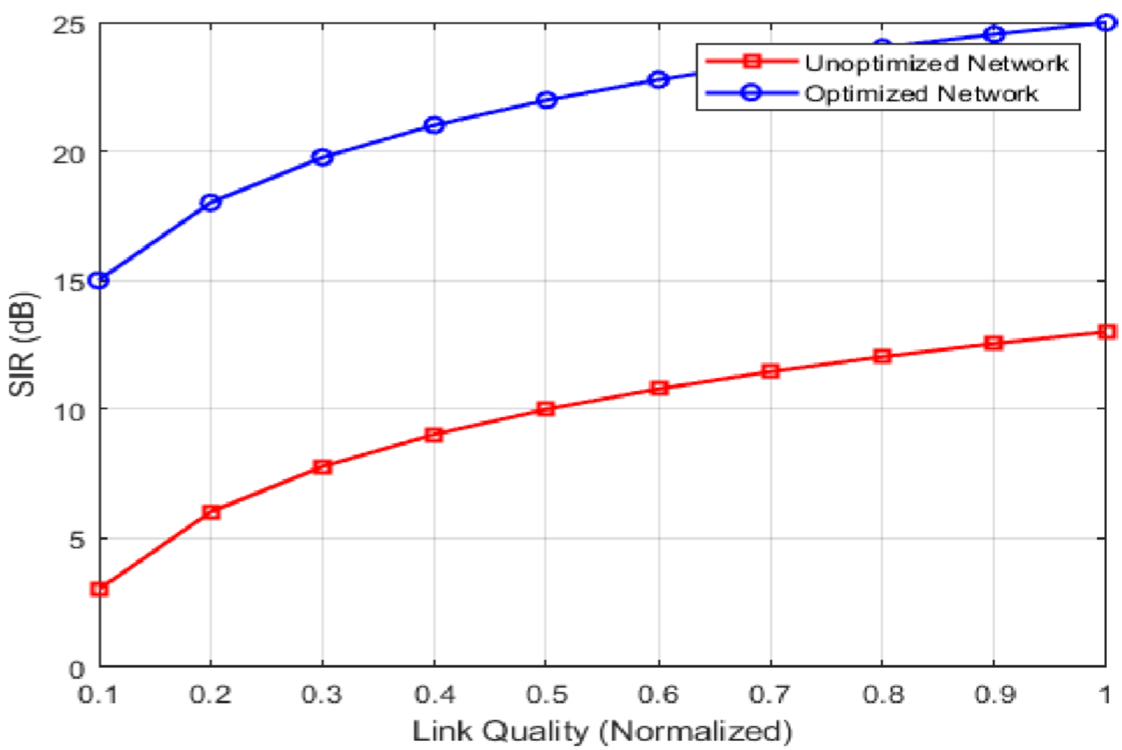

Figure 4: SIR vs. Link Quality

Table 5 compares SIR values for both unoptimized and optimized networks across various link quality levels. The optimized network consistently shows superior performance, with higher SIR values at every link quality.

Table 5: SIR vs. Link Quality

	SIR vs. Link Quality	
Link Quality (Normalized)	**Unoptimized Network SIR (dB)**	**Optimized Network SIR (dB)**
0.1	3.01	15.00
0.2	6.02	18.01
0.3	7.78	19.77
0.4	9.03	21.02
0.5	10.00	21.99
0.6	10.79	22.78
0.7	11.46	23.45
0.8	12.04	24.03
0.9	12.55	24.54
1.0	13.01	25.00

As depicted in the Table 5, for the unoptimized network, SIR starts at 3.01 dB when the link quality is 0.1 and steadily increases with better link quality, reaching 13.01 dB at a link quality of 1. However, the optimized network begins with a significantly higher SIR of 15 dB at a link quality of 0.1 and increases to 25 dB when link quality reaches 1. At a link quality of 0.5, the unoptimized network achieves an SIR of 10 dB, while the optimized network achieves 22.78 dB, showing a clear advantage of approximately 127% improvement. This trend continues across all link quality levels, with the optimized network providing significantly higher SIR values, ensuring better performance and reduced interference. This analysis demonstrates that optimization significantly enhances SIR across various link quality levels, offering substantial improvements in link reliability and communication clarity..

SNR vs. Distance

The Signal-to-Noise Ratio (SNR) is a key indicator of network performance, reflecting signal quality. As distance increases, both unoptimized and optimized networks experience a decrease in SNR due to signal attenuation. However, the optimized network consistently maintains higher SNR levels, highlighting its ability to sustain signal quality over longer distances. Figure 5 illustrates this relationship.

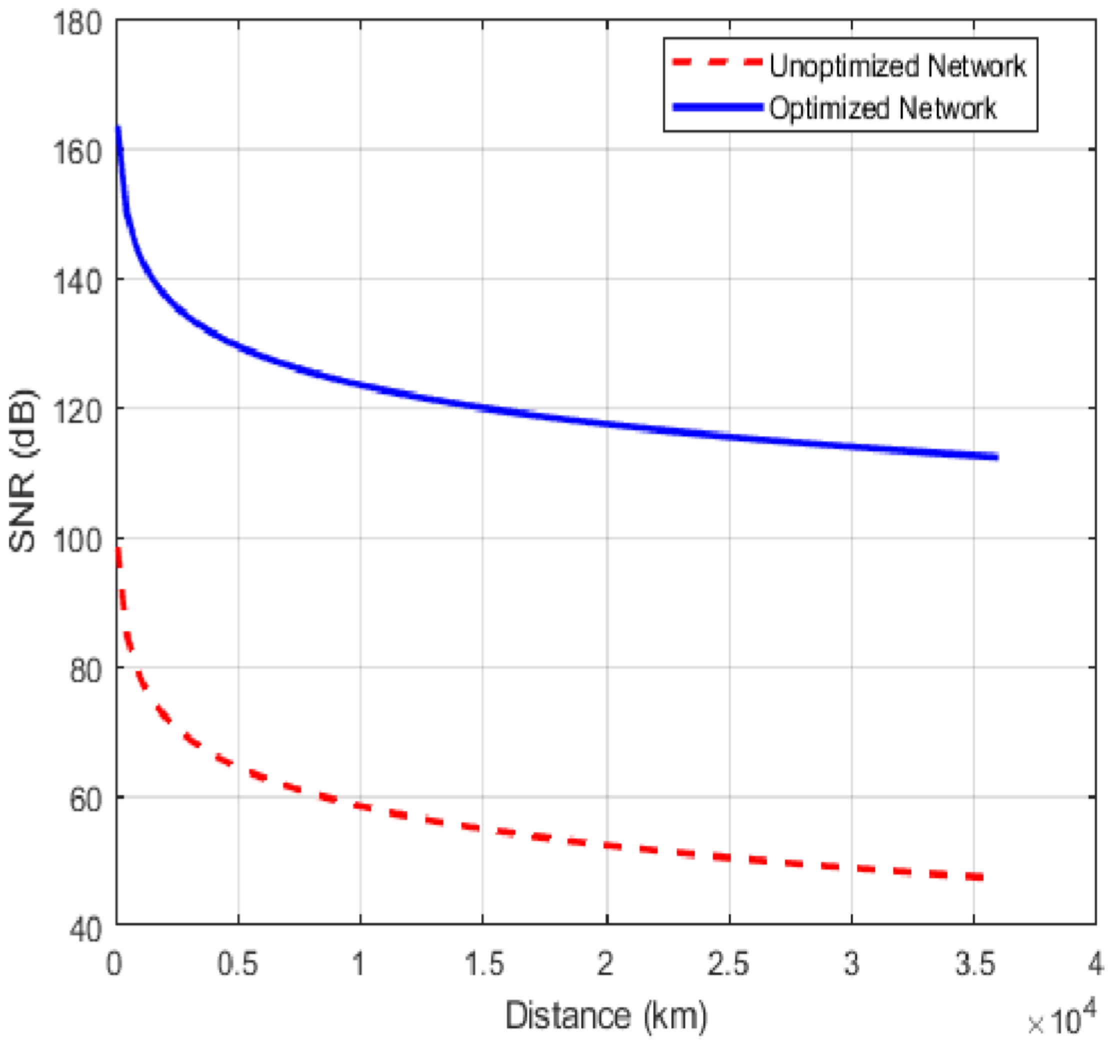

Figure 5: SNR vs. Distance

Table 6 provides the corresponding numerical data, clearly illustrating the superior performance of the optimized network in maintaining higher SNR values across various distances. The optimized network achieves this improvement by leveraging advanced techniques such as dynamic spreading factor adjustment and error correction mechanisms.

Table 6: SNR vs. Distance

	SNR vs. Distance	
Distance (Km)	Unoptimized Network SNR (dB)	Optimized Network SNR (dB)
100	98.39	163.39
5,176.77	64.11	129.11
9,890.91	58.48	123.48
14,967.7	54.89	119.89
20,044.4	52.35	117.35
25,121.2	50.39	115.38
29,835.4	48.89	113.89
35,274.7	47.44	112.44

Table 6 presents a clear trend: as the distance increases, the SNR values for both networks decline, which is expected due to the natural attenuation of signals over longer distances. At 100 km, the unoptimized network has an SNR of 98.39 dB, while the optimized network demonstrates a significantly higher SNR of 163.39 dB. This represents a 66% improvement in signal quality for the optimized network at this distance. As the distance increases, the SNR for both networks continues to decrease, but the optimized network consistently outperforms the unoptimized network, ensuring more reliable signal transmission even at larger distances.

These findings emphasize the importance of network optimization in maintaining high-quality communication over long distances, where signal degradation typically poses significant challenges. The optimized network's ability to preserve a higher SNR allows it to provide more reliable service and higher performance at greater distances.

Throughput vs. Bandwidth

The relationship between throughput and bandwidth is essential for understanding a network's data handling capacity. As bandwidth increases, both unoptimized and optimized networks show increased throughput, with the optimized network consistently outperforming the unoptimized one. Figure 6 illustrates this trend.

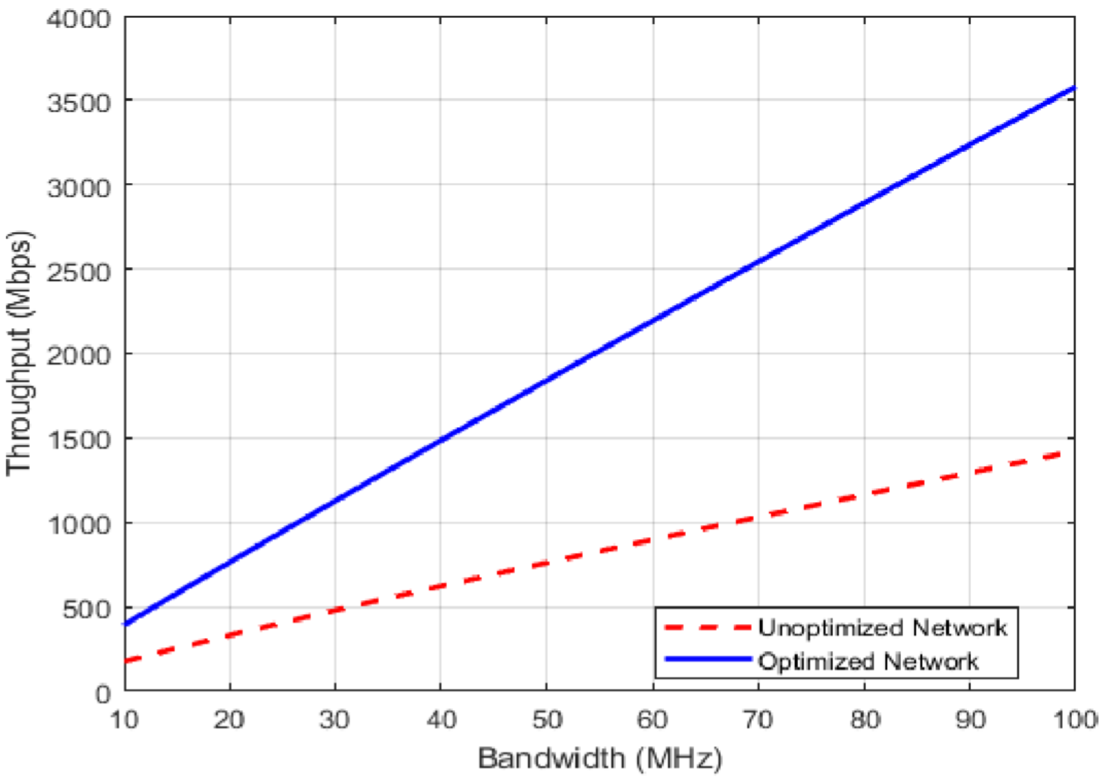

Figure 6: Throughput vs. Bandwidth

Table 7 supports these findings by presenting numerical values for throughput at varying bandwidth levels, demonstrating the optimized network's superior capacity to handle increased data rates efficiently.

Table 7: Throughput vs. Bandwidth

	Throughput vs. Bandwidth	
Bandwidth (MHz)	Unoptimized Network Throughput (Mbps)	Optimized Network Throughput (Mbps)
10	175.48	391.41
20	330.97	762.82
30	478.90	1126.68
40	621.94	1485.64
50	761.32	1840.95
60	897.80	2193.35
70	1031.87	2543.35
80	1163.87	2891.27
90	1294.06	3237.39
100	1422.65	3581.89

Table 7 illustrates the positive correlation between bandwidth and throughput for both networks. As bandwidth increases from 10 MHz to 100 MHz, both networks show significant throughput gains. At 10 MHz, the unoptimized network achieves 175.48 Mbps, while the optimized network achieves 391.41 Mbps, a 123.1% improvement. At 50 MHz, the unoptimized network reaches 761.32 Mbps, while the
optimized network delivers 1840.95 Mbps, a 141.7% increase. By 100 MHz, the optimized network outperforms the unoptimized network by 151.8%, with a throughput of 3581.89 Mbps versus 1422.65 Mbps. These findings demonstrate the significant benefits of optimization in improving throughput as bandwidth increases, enhancing data transmission capacity and network efficiency.

Throughput vs. SNR

The relationship between throughput and Signal-to-Noise Ratio (SNR) is essential for assessing network performance. As SNR increases, throughput improves for both unoptimized and optimized networks, with the optimized network consistently outperforming the unoptimized one. This highlights the optimized network's ability to maintain high data rates even in environments with lower signal quality, as shown in Figure 7.

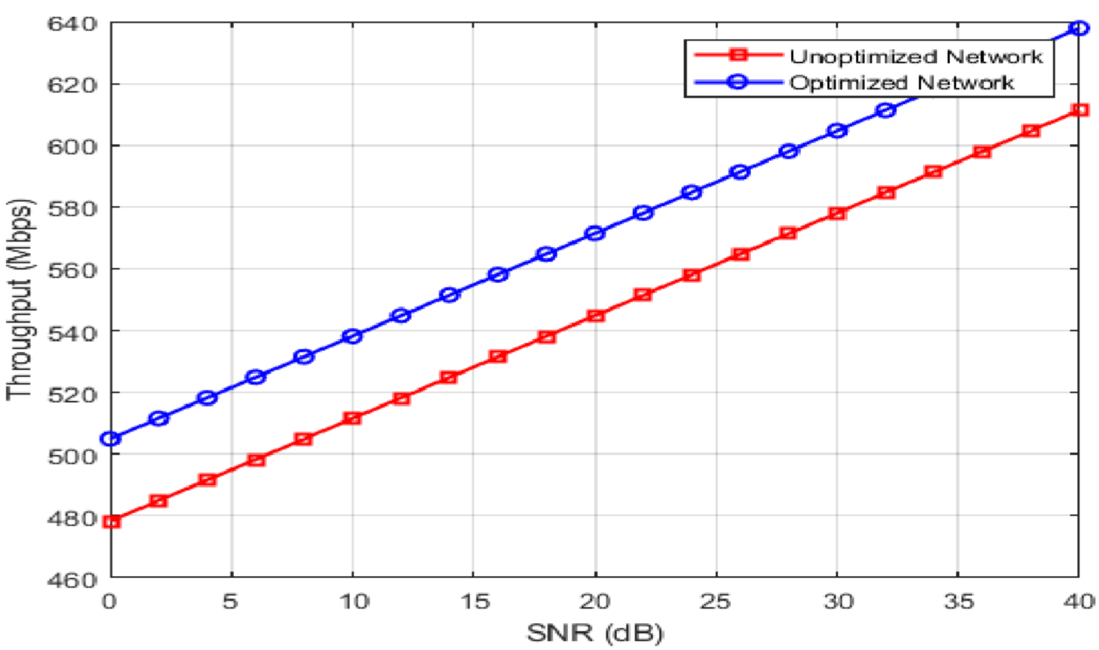

Figure 7: Throughput vs. SNR

Table 8 provides numerical data that highlights the throughput values for both networks at different SNR levels. The results clearly illustrate the optimized network's superior performance in maintaining higher data rates across all SNR values.

Table 8: Throughput vs. SNR

	Throughput vs. SNR	
SNR (dB)	Unoptimized Network Throughput (Mbps)	Optimized Network Throughput (Mbps)
0	478.36	504.97
10	511.58	538.19
20	544.80	571.40
30	578.01	604.63
40	611.24	637.84

Table 8 reveals the steady increase in throughput for both networks as SNR improves. As SNR increases, throughput steadily rises for both networks. At 0 dB, the unoptimized network achieves 478.36 Mbps, while the optimized network achieves 504.97 Mbps, a 5.57% improvement. At 20 dB, the unoptimized network reaches 544.80 Mbps, while the optimized network achieves 571.41 Mbps, a 4.88% improvement. At the highest tested SNR of 40 dB, the optimized network outperforms the unoptimized network by 4.36%, with a throughput of 637.84 Mbps compared to 611.24 Mbps.
These results demonstrate the benefits of network optimization, which ensures higher throughput even in low SNR conditions, contributing to improved reliability and performance in challenging environments.

SNR vs. Weather Conditions

Weather conditions play a crucial role in determining SNR, affecting the overall performance of communication networks. Sunny conditions lead to the highest SNR values, indicating clearer signal propagation, while stormy conditions result in the lowest SNR, reflecting the detrimental impact of adverse weather on signal strength. This demonstrates the susceptibility of signal quality to environmental factors and the importance of optimization in mitigating these effects. Figure 8 illustrates these trends.

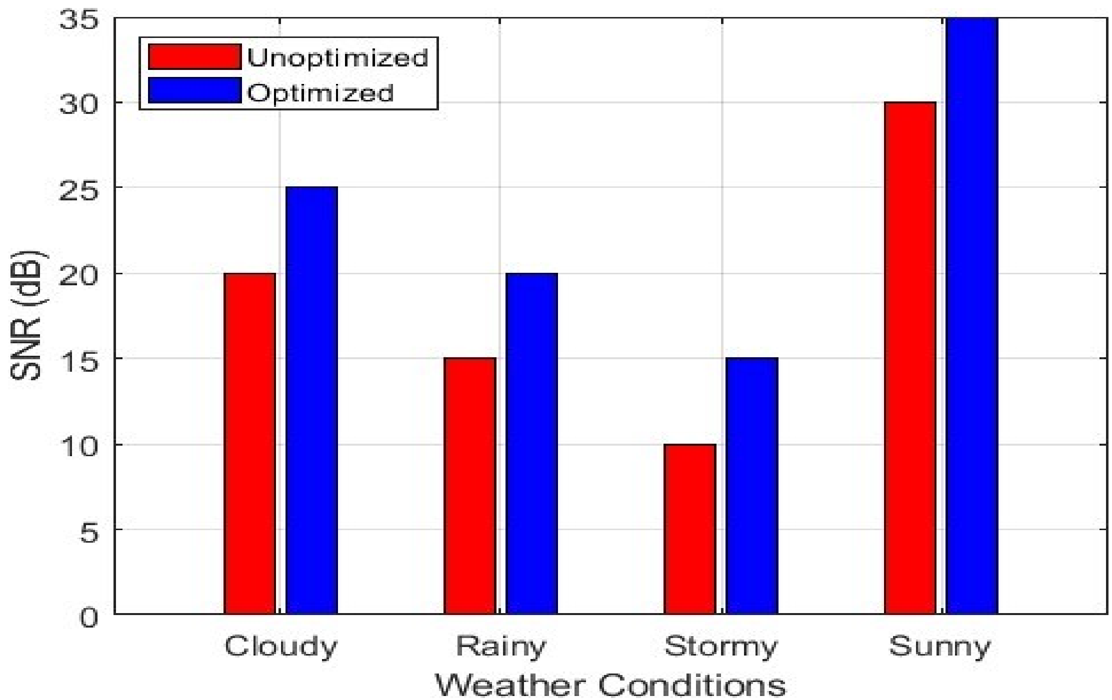

Figure 8: SNR vs. Weather Conditions

Table 9 presents the numerical data for SNR under different weather conditions, showcasing the consistent advantage of the optimized network over the unoptimized network.

Table 9: SNR vs. Weather Conditions

SNR vs. Weather Conditions		
Weather Conditions	**Unoptimized Network SNR (dB)**	**Optimized Network SNR (dB)**
Cloudy	20	25
Rainy	15	20
Stormy	10	15
Sunny	30	35

In stormy conditions, the optimized network shows a 50% improvement in SNR over the unoptimized one. This advantage continues across other weather conditions, ensuring the optimized network maintains higher signal quality and communication reliability.

BER vs. weather conditions

Weather conditions have a notable impact on the Bit Error Rate (BER), as reflected in the Figure 9 and Table 10. Sunny weather yields the lowest BER, indicating clear communication, while stormy weather results in the highest BER, signaling significant transmission errors. The optimized network consistently achieves lower BER values across all weather conditions, demonstrating its superior performance even in challenging environments.

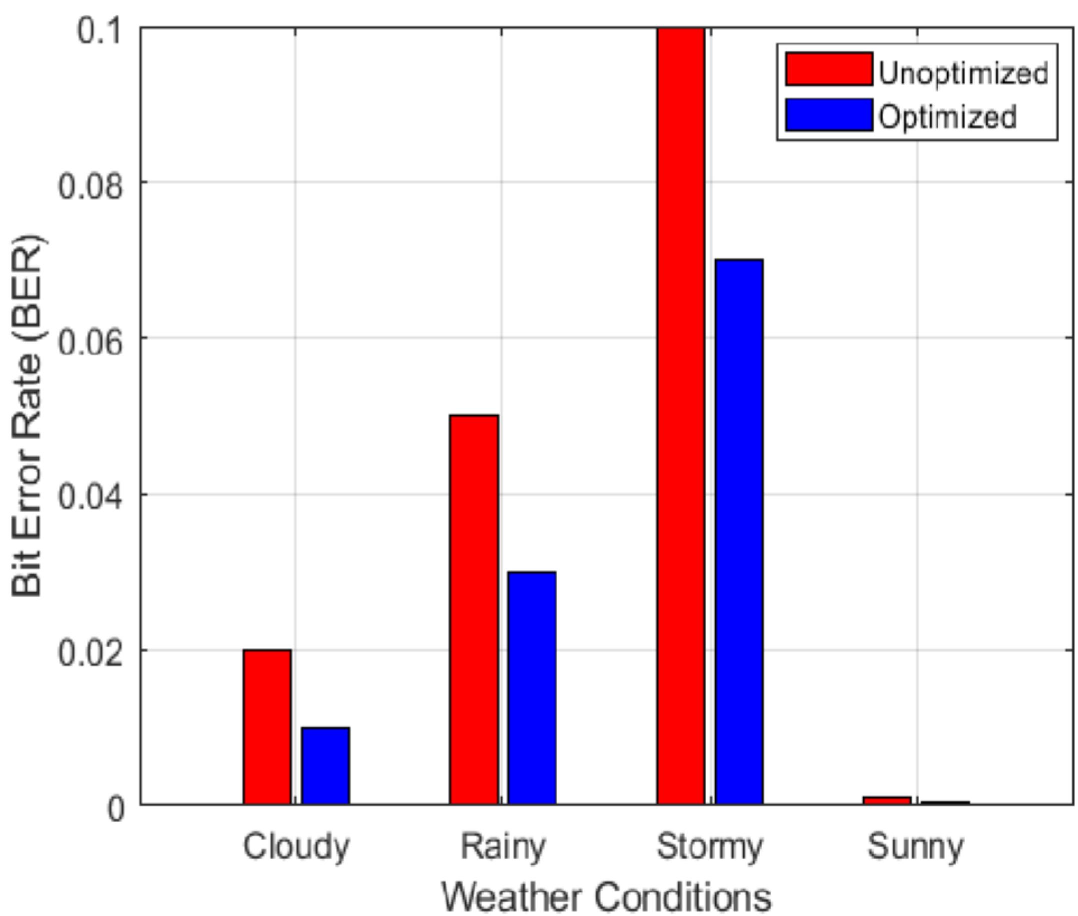

Figure 9: BER vs. Weather Conditions

Table 10 provides the corresponding BER values under various weather conditions, emphasizing the optimized network's superior performance in mitigating errors across different scenarios.

Table 10: BER vs. Weather Conditions

BER vs. Weather Conditions		
Weather Conditions	**$\log_{10}$ Unoptimized Network $\log_{10}$ Optimized BER**	**Network BER**
Cloudy	-1.70	-2.00
Rainy	-1.30	-2.52
Stormy	-1.00	-2.15
Sunny	-3.00	-3.30

In stormy conditions, the optimized network reduces BER by 30%, and under rainy conditions, it achieves a 40% improvement. Even in sunny conditions, where errors are minimal, the optimized network further enhances performance.

Throughput vs. weather conditions

Weather conditions significantly influence throughput, with sunny conditions delivering the highest throughput and stormy conditions resulting in the lowest. The optimized network consistently achieves higher throughput across all weather conditions, emphasizing its ability to maintain robust communication performance despite environmental challenges. Figure 10 illustrates this relationship.

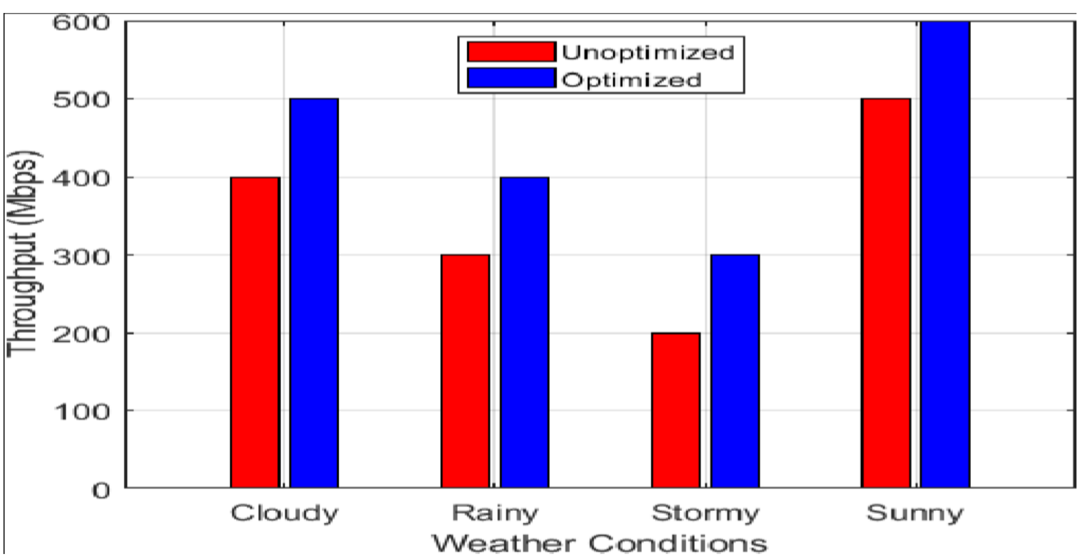

Figure 10: Throughput vs. Weather Conditions

Table 11 provides the numerical throughput values for both networks under different weather conditions, demonstrating the superior performance of the optimized network in various scenarios.

Table 11: Throughput vs. Weather Conditions

Throughput vs. Weather Conditions		
Weather Conditions	**Unoptimized Network Throughput Throughput (Mbps)**	**Optimized Network (Mbps)**
Cloudy Rainy	400	500
Stormy	300	400
Sunny	200	300
	500	600

In stormy conditions, the optimized network achieves 50% higher throughput than the unoptimized one. This performance advantage continues across all weather conditions, highlighting the optimized network's ability to maintain robust communication even in challenging environments.

Conclusion

This research addressed the pressing issue of inadequate healthcare connectivity in rural areas by optimizing satellite-based telemedicine networks, with Igu Village, Abuja, serving as the case study. A simulation model was developed, tailored specifically for telemedicine applications, leveraging NigComSat-1R as the satellite backbone. The study concentrated on key performance metrics, including Signal-to-Noise Ratio (SNR), Bit Error Rate (BER), latency, and data throughput.

The optimized network demonstrated significant improvements across varying weather conditions. Under sunny conditions, BER was reduced by 92.16% at 10 dB SNR and by 99.96% at 15 dB SNR. In rainy conditions, reductions were 91.25% at 10 dB SNR and 99.94% at 15 dB SNR. Cloudy conditions saw reductions of 91.71% at 10 dB SNR and 99.95% at 15 dB SNR. Latency was minimized to below 250 milliseconds, ensuring smooth real-time telemedicine consultations. Additionally, data throughput was significantly enhanced, making the network well-suited for bandwidth-intensive telemedicine services such as high-definition video and medical imaging.

These findings underscore the transformative potential of satellite communication in bridging healthcare gaps in rural areas. The study demonstrated that satellite-based networks, when optimized for key parameters, can reliably support telemedicine services even in adverse weather conditions, ensuring consistent service quality.

Recommendations

To build upon the findings of this study, future research should focus on implementing the optimized satellite-based telemedicine network in real-world rural healthcare facilities. This would allow for validation of the simulation results under practical conditions, addressing issues related to hardware constraints and environmental variability. Expanding the study to rural areas with diverse climatic and topographical conditions would provide insights into the model's adaptability and scalability.

Incorporating advanced optimization techniques, such as reinforcement learning or hybrid approaches that combine machine learning with traditional algorithms, could further enhance network efficiency and reliability. Collaborative efforts with policymakers and healthcare providers are essential to establish frameworks for deploying satellite-based telemedicine networks in underserved areas, ensuring alignment with national healthcare goals and regulatory standards. Assessing the broader societal and economic impact of these networks is also critical. Research should evaluate how implementing satellite-based telemedicine networks affects healthcare accessibility, patient outcomes, and cost-effectiveness, informing policy development aimed at equitable healthcare access.

Contributions to Knowledge

This study significantly advances the field of satellite-based telemedicine networks by developing a simulation model tailored to telemedicine applications using NigComSat-1R. The model achieved remarkable improvements in critical performance metrics, including SNR, BER, latency, and throughput. These outcomes establish a foundational framework for leveraging satellite communication to address healthcare connectivity challenges in underserved areas. The methodology, which integrates weather-dependent performance analysis, provides a replicable approach for designing robust telemedicine networks in diverse geographic settings. The findings also highlight the potential for applying satellite optimization techniques in broader contexts, contributing to the body of knowledge on sustainable and scalable telecommunication solutions for rural and remote areas.

In conclusion, this research presents a comprehensive framework for addressing healthcare connectivity challenges in underserved areas, paving the way for more reliable and accessible telemedicine services across Nigeria and beyond.

References

Abaka, J. U., Iortyer, H. A., & Ibraheem, T. B. (2017). Sizing and Economic Assessment of Photovoltaic and Diesel Generator for Rural Nigeria. *The International Journal of Engineering and Science (IJES)*, *6*(10), 10–17. https://doi.org/10.9790/1813-0610021017

Alenoghena, C. O., Ohize, H. O., Adejo, A. O., Onumanyi, A. J., Ohihoin, E. E., Balarabe, A. I., Okoh, S. A., Kolo, E., & Alenoghena, B. (2023). Telemedicine: A Survey of Telecommunication

Technologies, Developments, and Challenges. *Journal of Sensor and Actuator Networks*, *12*(2),

20. https://doi.org/10.3390/jsan12020020

Alenoghena, C. O., Onumanyi, A. J., Ohize, H. O., Adejo, A. O., Oligbi, M., Ali, S. I., & Okoh, S. A.

(2022). eHealth: A Survey of Architectures, Developments in mHealth, Security Concerns and Solutions. *International Journal of Environmental Research and Public Health*, *19*(20), 13071. https://doi.org/10.3390/ijerph192013071

Choi, C.-S. (2024). Modeling and Analysis of Downlink Communications in a Heterogeneous LEO Satellite Network. *IEEE Transactions on Wireless Communications*, *23*(8), 8588–8602. https://doi.org/10.1109/TWC.2024.3351876

Elhachi, H., Boumehrez, F., Aymen Labiod, M., Redadaa, S., & Mellouk, A. (2024). Smart cross-layer approach to multi-access terrestrial and non-terrestrial networks (NTNs): Real-time mobile-health use case. *International Journal of Communication Systems*, *November 2023*, 1–19. https://doi.org/10.1002/dac.5941

IEEE. (2021). IEEE Standard for Information technology–Telecommunications and information exchange between systems Local and metropolitan area networks–Specific requirements - Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications. *IEEE Std 802.11-2016 (Revision of IEEE Std 802.11-2012)*, 1–3534.

Inmarsat. (2023). *A Straightforward Introduction to Satellite Communications*. Inmarsat.

https://www.inmarsat.com/en/insights/corporate/2023/a-straightforward-introduction-to- satellite-communications.html

ITU-T. (2021). *ASN.1 Encoding Rules: Specification of Basic Encoding Rules (BER), Canonical Encoding Rules (CER) and Distinguished Encoding Rules (DER).* https://www.itu.int/rec/T-REC- X.690-202102-I/en

ITU-T G.114. (2003). One-way transmission time. In *One-way transmission time* (pp. 391–426). CRC Press. https://www.itu.int/rec/T-REC-G.114-200305-I/en

ITU-T H.264. (2007). Audiovisual and Multimedia Systems; Infrastructure of audiovisual services— Coding of moving video. H. 264. Advanced video coding for generic audiovisual services.

International Telecommunication Union. Version, *12*.

ITU-T Y.1541. (2011). Network performance objetives for IP-based services. *GLOBAL*

INFORMATION INFRASTRUCTURE, INTERNET PROTOCOL ASPECTS AND NEXT- GENERATION NETWORKS Internet Protocol Aspects – Quality of Service and Network Performance., 66. http://www.itu.int/rec/T-REC-Y.1541-201112-I

Kumar, R., & Arnon, S. (2022). SNR Optimization for LEO Satellite at Sub-THz Frequencies. *IEEE*

Transactions on Antennas and Propagation, *70*(6), 4449–4458. https://doi.org/10.1109/TAP.2022.3140217

Kumar, S., & Choudhary, N. (2024). *" Advancements in Satellite Communication Systems : Enabling Seamless " Advancements in Satellite Communication Systems : Enabling Seamless Connectivity in a Hyper Connected World ". June*, 0–10.

Lawal, L. S., Aibinu, A. M., Chris, C. R., Udoyen, U., Iheanacho, T., Jaafar, A., & Ibrahim, I. A. (2022). Overview of Satellite Communications and its Applications in Telemedicine for the underserved in Nigeria: A case study. *2022 International Conference on Electrical, Computer,*

Communications and Mechatronics Engineering (ICECCME), 1–10. https://doi.org/10.1109/ICECCME55909.2022.9988286

Leyva-Mayorga, I., Soret, B., Roper, M., Wubben, D., Matthiesen, B., Dekorsy, A., & Popovski, P.

(2020). LEO Small-Satellite Constellations for 5G and Beyond-5G Communications. *IEEE Access*, *8*, 184955–184964. https://doi.org/10.1109/ACCESS.2020.3029620

Li, Y., Wang, M., Hwang, K., Li, Z., & Ji, T. (2023). LEO Satellite Constellation for Global-Scale Remote Sensing With On-Orbit Cloud AI Computing. *IEEE Journal of Selected Topics in Applied*

Earth Observations and Remote Sensing, *16*, 9369–9381. https://doi.org/10.1109/JSTARS.2023.3316298

Nawaz, N. A., Abid, A., Rasheed, S., Farooq, M. S., Shahzadi, A., & Mubarik, I. (2022). Impact of telecommunication network on future of telemedicine in healthcare: A systematic literature review. *International Journal of Advanced and Applied Sciences*, *9*(7), 122–138. https://doi.org/10.21833/ijaas.2022.07.013

Omaghomi, T. T., Arowoogun, J. O., Akomolafe, O., Odilibe, I. P., & Elufioye, O. A. (2023).

Telemedicine in rural Africa: A review of accessibility and impact. *World Journal of Advanced*

Research and Reviews, *21*(2), 421–431. https://doi.org/10.30574/wjarr.2024.21.2.0475

Onyeka, E. B., Eze, P. C., Asiegbu, C. N., Olisa, S. C., & Udechukwu, C. F. (2022). Satellite dish antenna control for distributed mobile telemedicine nodes. *International Journal of Informatics and Communication Technology (IJ-ICT)*, *11*(3), 206. https://doi.org/10.11591/ijict.v11i3.pp206- 217

Rural Electrification Agency. (2018). *NIGERIA: THE NEXT BIG FRONTIER FOR RURAL*

ELECTRICITY ACCESS. https://rea.gov.ng/nigeria-next-big-frontier-rural-electricity-access/

Sadiq, B. O., Zakariyya, O. S., Buhari, M. D., & Shuaibu, A. N. (2024). Maximizing network capacity, control and management in designing a telemedicine network: A review and recent challenges. *Nigerian Journal of Technology*, *43*(1), 80–100. https://doi.org/10.4314/njt.v43i1.11

Sudha, K., Laxminarayan, G., & Soni, C. (2022). Study of Different Types of Error Detection and Correction Code in Wireless Communication. *International Journal of Scientific Research in*

Science, Engineering and Technology, 448–455. https://doi.org/10.32628/ijsrset2293138

Vaahteranoksa, M., & Vuori, T. (2007). Threshold value for acceptable video quality using signal-to- noise ratio. *Image Quality and System Performance IV*, *6494*, 649405. https://doi.org/10.1117/12.702995

Vennapusa, S. C. R. (2023). *Cutting-Edge Communication : Integrated Satellite-Aerial 6G Networks for Cutting-Edge Communication : Integrated Satellite-Aerial 6G Networks for Point-to-Point Connectivity*. *May 2023*.

WHO. (2022). a Guide To Telemedicine in Primary Healthcare. *Unicef*, *October*, 44.

https://www.unicef.org/romania/media/10891/file/A guide to telemedicine in primary healthcare.pdf