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Microwave Link Planning for USO/N3T Telecommunication Sites Using Atoll Radio Planning Software

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A B S T R A C T

Microwave backhaul is a key solution for extending telecommunication connectivity in rural, frontier, and outermost (N3T) regions where fiber deployment is limited by terrain, cost, and accessibility. This study proposes a KPI-driven microwave link planning framework using Atoll radio planning software combined with field line-of-sight (LOS) verification. The methodology includes identifying multiple far-end (FE) candidates, conducting terrain-based LOS analysis, performing link budget simulations, and evaluating received signal level (RSL), fade margin, and link availability. The results show that although all candidate links satisfy basic LOS requirements, only selected configurations meet long-term reliability targets when assessed using availability and fade margin criteria. An 11 GHz microwave link over a medium-distance path achieves link availability above 99.99% with adequate fade margin, offering a balanced trade-off between performance and propagation robustness. Field LOS verification confirms strong agreement with simulation results. These findings demonstrate that Atoll-based, KPI-oriented planning supported by selective field validation provides an effective and practical approach for microwave backhaul deployment in N3T environments, contributing actionable insights for reliable and sustainable telecommunication infrastructure planning

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INTRODUCTION

The rapid advancement of information and communication technology has significantly transformed modern society, as evidenced by the increasing sophistication of smartphones, the widespread adoption of artificial intelligence across various sectors, the rapid growth of e-commerce, and the expansion of digital services. These technological developments are highly dependent on reliable telecommunication networks, which serve as the fundamental infrastructure for information exchange, internet access, and digital connectivity. Without adequate network coverage and signal availability, access to emerging technologies such as mobile communication systems, cybersecurity platforms, digital services, and the Internet of Things (IoT) would not be feasible (Al-Fuqaha et al., 2015; Ullah et al., 2024).

To support the growing demand for high-speed and reliable communication, telecommunication infrastructure must be designed to ensure optimal connectivity and network performance. Communication systems generally employ various transmission media, including optical fiber, microwave radio links, satellite communication, and infrared transmission. Each transmission medium has specific advantages and limitations depending on factors such as geographical conditions, deployment cost, scalability, and maintenance requirements. Consequently, selecting an appropriate transmission medium plays a crucial role in ensuring efficient signal propagation and enhancing the overall quality of cellular communication networks (Poornima et al., 2023; Sanjivani Munot, 2024).

In remote and geographically challenging regions, such as rural, frontier, and outermost areas, the deployment of optical fiber infrastructure is often limited by complex terrain, high installation costs, and restricted accessibility. In such environments, microwave radio communication has emerged as a practical and cost-effective solution for network backhaul deployment. Microwave backhaul systems enable rapid installation and flexible network expansion by connecting cellular base stations through high-frequency wireless links, particularly in areas where fiber-based solutions are not economically or technically viable (Kristiadi & Nashiruddin, 2019; Mohsan & Amjad, 2021; Simanihuruk, 2018; Zakaria, 2023).

Microwave communication systems typically operate in a point-to-point configuration and require a clear line-of-sight (LOS) between transmitting and receiving antennas to achieve optimal performance. However, maintaining LOS conditions in mountainous or densely vegetated regions remains challenging due to terrain irregularities, buildings, and natural obstacles, which may degrade signal quality through attenuation and fading effects (Forsido et al., 2024; Sadin et al., 2022). Therefore, accurate microwave link planning is essential to ensure reliable transmission, sufficient fade margins, and high link availability.

In this study, microwave link planning is conducted using Atoll radio planning software, an industrial-grade tool widely adopted for radio network design and performance evaluation. The planning process focuses on link budget analysis to predict link feasibility and reliability prior to deployment. Key factors influencing link budget performance include transmission distance, operating frequency, rain attenuation, propagation loss, system noise, and environmental conditions(Sanjivani Munot, 2024). Through simulation-based planning, this research aims to provide practical insights into microwave backhaul deployment to enhance telecommunication connectivity in remote regions of Indonesia.

Despite the growing body of research on microwave backhaul planning and performance evaluation, most existing studies predominantly focus on urban or suburban environments with relatively flat terrain and well-established infrastructure. These conditions significantly differ from those found in rural, frontier, and outermost (N3T) regions, where complex topography, limited accessibility, and the absence of fiber-optic backbone networks present unique challenges for telecommunication deployment. As a result, findings from conventional microwave planning studies may not be directly applicable to N3T scenarios.

Moreover, previous works often emphasize theoretical link budget analysis or generic simulation models without incorporating industrial-grade radio planning tools that are commonly used by network operators in real-world deployments. There is limited empirical research that integrates Atoll-based microwave link simulation with key performance indicators such as line-of-sight (LOS) clearance, received signal level (RSL), fade margin, and link availability under challenging geographical conditions typical of N3T areas. Additionally, comparative evaluation among multiple far-end (FE) candidates to determine the most reliable and cost-effective backhaul configuration remains insufficiently explored in the existing literature.

Therefore, a clear research gap exists in the systematic planning and performance analysis of microwave links for N3T telecommunication sites using industry-standard planning software. This study addresses this gap by conducting a comprehensive Atoll-based microwave link planning and evaluation in a real N3T deployment scenario, combining simulation results with field line-of-sight verification and KPI-based decision criteria. The findings are expected to contribute practical insights for network operators and policymakers in designing reliable and scalable telecommunication infrastructure for remote and underserved regions.

This study contributes to the existing body of telecommunication network planning research by providing a practical, KPI-driven framework for microwave backhaul design in N3T regions, integrating Atoll-based simulation, comparative far-end (FE) evaluation, and field line-of-sight validation to support reliable and cost-effective deployment decisions.

LITERATURE REVIEW

Microwave Backhaul in Remote and N3T Areas

Microwave backhaul has long been recognized as a practical solution for extending mobile network connectivity in remote and underserved regions. In rural, frontier, and outermost (N3T) areas, the deployment of fiber-optic infrastructure is frequently constrained by rugged terrain, sparse population density, high civil-work costs, and limited accessibility. As a result, wireless backhaul technologies, particularly microwave links, remain essential for providing reliable connectivity and supporting mobile broadband services (Abdelmoaty et al., 2023; Bhardwaj et al., 2024; Song et al., 2020).

Recent studies highlight that microwave backhaul continues to play a critical role in current and future mobile networks, including 4G LTE and beyond, due to its rapid deployment capability, scalability, and cost efficiency compared to fiber-based solutions(Zakaria, 2023). In the context of N3T regions, microwave links enable network operators to establish connectivity between base stations without extensive ground infrastructure, making them suitable for mountainous and remote environments. However, the effectiveness of microwave backhaul in such regions strongly depends on careful planning to ensure sufficient link reliability, capacity, and availability under challenging geographical and environmental conditions(Tran et al., 2025; Zhou et al., 2023).

Propagation and Rain Effects on Microwave Links

Propagation impairments significantly influence the performance of microwave communication systems, especially in frequencies above 10 GHz. In tropical and subtropical regions, rain attenuation is a dominant factor that can severely degrade signal strength and reduce link availability if not properly accounted for during the planning stage. Several recent studies emphasize that rainfall intensity, climatic variability, and path length are key parameters that must be incorporated into link budget calculations to ensure robust microwave link performance(Budalal & Islam, 2023; Matondo & Owolawi, 2024, 2025).

Beyond rain attenuation, environmental factors such as terrain irregularities, vegetation, and man-made structures can obstruct the line-of-sight (LOS) path, leading to diffraction losses and multipath fading. These effects are particularly pronounced in N3T regions characterized by mountainous landscapes and dense vegetation. Consequently, modern microwave planning approaches increasingly rely on simulation-based propagation models that integrate terrain and clutter data to more accurately predict real-world link behavior (De & Maitra, 2024). Accurate modeling of these propagation impairments is therefore essential to minimize service degradation and ensure stable connectivity.

Link Budget and Availability Metrics

Link budget analysis is a fundamental component of microwave backhaul planning, as it provides a quantitative assessment of whether a communication link can meet predefined performance requirements. Key performance indicators (KPIs) commonly evaluated in microwave planning include received signal level (RSL), fade margin, and link availability. These parameters collectively determine the robustness and reliability of a microwave link under varying environmental and operational conditions (Sanjivani Munot, 2024).

Recent literature emphasizes the importance of availability-based design, particularly for links deployed in challenging environments. High availability targets (e.g., ≥ 99.99%) require adequate fade margins to compensate for signal fluctuations caused by fading and attenuation effects. Studies conducted in developing and rural network deployments demonstrate that systematic KPI-driven evaluation enables more informed decision-making when comparing multiple candidate links or far-end (FE) options (Zakaria, 2023)Such an approach is especially relevant in N3T scenarios, where network reliability directly impacts access to essential digital services.

Atoll-Based Microwave Link Planning

Simulation-based radio planning tools have become integral to modern telecommunication network design, enabling engineers to evaluate link feasibility and performance prior to physical deployment. Atoll is widely recognized as an industry-standard radio planning and optimization platform, offering comprehensive capabilities for microwave link design, including terrain-based LOS analysis, link budget computation, and KPI evaluation (Benosman et al., 2024; Elbagir & Bilal, 2014; Prymak & Karpinsky, 2022).

Recent industrial and academic works highlight that the use of professional planning tools such as Atoll enhances planning accuracy by integrating high-resolution digital elevation models, clutter data, and propagation models within a unified simulation environment (Savini et al., 2020). Despite its widespread adoption in industry, empirical studies that document Atoll-based microwave planning for remote and N3T regions, particularly those combining simulation results with comparative far-end analysis and field LOS verification, remain limited in the open literature. This gap underscores the need for applied research that demonstrates how industrial-grade tools can be effectively utilized to support reliable microwave backhaul deployment in underserved regions.

METHODOLOGY

Research Design

This study adopts a quantitative and simulation-based research design to evaluate the feasibility and performance of microwave backhaul links in an N3T (rural, frontier, and outermost) telecommunication deployment scenario. The methodology combines microwave link simulation using industrial-grade radio planning software with analytical link budget evaluation and field line-of-sight (LOS) verification. This integrated approach enables systematic comparison among multiple far-end (FE) candidates to identify the most reliable and cost-effective microwave backhaul configuration.

Study Area and Network Scenario

The study is conducted on a microwave backhaul planning case in a N3T region characterized by hilly and mountainous terrain, which poses significant challenges for line-of-sight clearance and signal propagation. The network scenario involves a new network element (NE) site that requires backhaul connectivity to existing far-end (FE) sites. Three FE candidates are considered, each with different distances, frequency bands, and configuration options. This scenario reflects a realistic deployment condition faced by mobile network operators when extending coverage to underserved areas.

Microwave Link Planning Using Atoll

Microwave link planning is performed using Atoll radio planning software, which provides comprehensive tools for terrain-based simulation, LOS analysis, and link budget calculation. Digital elevation models (DEM) and clutter data are utilized to evaluate path profiles and identify potential obstructions along each candidate link. The simulation process includes:

1. LOS Analysis: Determination of line-of-sight clearance between the NE and each FE candidate based on antenna height configuration and terrain profile.
2. Frequency and Configuration Selection: Selection of operating frequency bands (e.g., 11 GHz and 23 GHz) and antenna configurations (1+0) in accordance with regulatory guidelines and link distance criteria.
3. Link Budget Simulation: Estimation of key performance parameters, including free space loss, effective isotropic radiated power (EIRP), isotropic received level (IRL), and received signal level (RSL).

This simulation-based planning enables early identification of feasible and non-feasible links before physical deployment.

Link Budget and KPI Evaluation

Link performance is evaluated using standard microwave link budget metrics and key performance indicators (KPIs). The primary KPIs considered in this study include:

1. Received Signal Level (RSL): Used to assess whether the received signal exceeds the receiver sensitivity threshold.
2. Fade Margin: Indicates the system's resilience against signal degradation caused by fading and attenuation.
3. Link Availability: Represents the percentage of time the link is expected to operate reliably under normal environmental conditions.

Availability targets are defined based on industry practice, with a minimum acceptable availability of 99.99% for backhaul links in remote deployments. Links that fail to meet these KPI thresholds are excluded from further consideration.

Comparative Evaluation of Far-End Candidates

A comparative analysis is conducted to evaluate the performance of each FE candidate. The comparison is based on LOS clearance, link distance, operating frequency, RSL, fade margin, and total link availability. By comparing these parameters, the study identifies the FE candidate that provides the best balance between performance reliability and deployment practicality. This comparative approach supports objective decision-making and reduces deployment risks in N3T environments.

Field Line-of-Sight Verification

To validate the simulation results, field LOS verification is conducted for the selected FE candidate. Field survey data are collected to confirm LOS conditions between the NE and FE sites and to identify any discrepancies between simulated and real-world conditions. This step enhances the reliability of the planning results by ensuring that simulation assumptions are consistent with on-site observations.

Research Workflow

The overall research workflow consists of the following stages:

1. Identification of the study area and network requirements.
2. Selection of candidate FE sites.
3. Atoll-based LOS and link budget simulation.

4. KPI-based evaluation and comparative analysis.
5. Field LOS verification.
6. Final selection of the optimal microwave backhaul configuration.

This structured workflow ensures that the proposed microwave backhaul solution is technically feasible, reliable, and aligned with real deployment constraints in N3T regions.

RESULTS

Line-of-Sight (LOS) Analysis Results

In this study, three far-end (FE) candidates, referred to as FE1, FE2, and FE3, are evaluated as potential microwave backhaul termination points for the new network element (NE). FE1 represents a far-end site integrated with fiber-optic transport infrastructure, while FE2 and FE3 are microwave-based transport nodes with different link distances and operating frequency configurations. These candidates are selected to reflect realistic deployment alternatives commonly encountered in N3T network expansion scenarios.

The initial stage of the analysis focuses on evaluating the line-of-sight (LOS) conditions between the NE and each FE candidate. Based on Atoll-based terrain and clutter profile simulations, all candidate links demonstrate clear LOS conditions when the NE antenna height is set to 30 meters, in accordance with operator requirements. The simulation results indicate that terrain elevation and surrounding obstacles, such as vegetation and buildings, do not cause critical obstructions along the propagation paths.

Although all candidates satisfy the LOS requirement, differences are observed in terrain clearance margins. FE1 and FE3, which are located at distances exceeding 5 km, exhibit tighter clearance margins compared to FE2 due to the presence of hilly terrain. This observation highlights the importance of detailed terrain-based simulation, as LOS feasibility alone does not guarantee optimal link reliability. Therefore, LOS analysis serves as a necessary but insufficient criterion for final link selection and must be complemented by link budget and KPI evaluation.

Link Budget and KPI Performance Evaluation

Following LOS verification, link budget simulations are conducted to evaluate key performance indicators (KPIs), including received signal level (RSL), fade margin, and total link availability. The simulation results show that all evaluated links meet the minimum KPI thresholds defined for microwave backhaul deployment, namely RSL above −40 dBm, fade margin greater than 30 dB, and availability exceeding 99.99%.

Among the evaluated candidates, FE2 achieves the highest RSL and fade margin values due to its shorter link distance and higher operating frequency. However, higher frequencies are generally more susceptible to rain attenuation, which can negatively affect long-term reliability in tropical environments. In contrast, FE1 and FE3 operate at 11 GHz, which offers a more favorable balance between propagation robustness and capacity for medium-distance links.

FE1 demonstrates a received signal level of −36.86 dBm with a fade margin of 45.14 dB, resulting in a total link availability of 99.9952%. These values indicate a strong resilience against fading and attenuation effects, making the link suitable for reliable backhaul operation in N3T environments. Although FE3 shows comparable performance, its slightly lower fade margin suggests a higher sensitivity to environmental variations compared to FE1.

Comparative Analysis of Far-End Candidates

A comparative evaluation is performed to identify the most suitable FE candidate by considering LOS clearance, KPI performance, and deployment practicality. While FE2 offers superior signal strength, its reliance on higher-frequency operation introduces increased vulnerability to rain-induced attenuation. Moreover, FE2 and FE3 are both microwave-based transport nodes, which raises the potential risk of frequency congestion and interference in dense microwave deployments.

FE1 is distinguished by its integration with fiber-optic transport infrastructure, which reduces dependency on microwave-only backhaul chains and mitigates the risk of cumulative interference. From an operational perspective, FE1 also provides sufficient tower capacity for antenna installation and meets all KPI requirements with adequate safety margins. These factors position FE1 as the most balanced and reliable option among the evaluated candidates.

This comparative analysis demonstrates the effectiveness of a KPI-driven framework in supporting objective decision-making, particularly in N3T deployments where infrastructure reliability and maintenance accessibility are critical considerations.

Validation Through Field LOS Survey

To validate the simulation outcomes, a field line-of-sight survey is conducted for the selected FE1 candidate. The survey results confirm the presence of unobstructed LOS between the NE and FE1 sites, consistent with Atoll simulation predictions. No significant discrepancies are observed between simulated terrain profiles and real-world conditions, reinforcing the accuracy of the planning approach.

The decision to limit field verification to FE1 is driven by operational considerations, including the avoidance of potential frequency interference and unnecessary survey overhead. The strong agreement between simulation and field observations supports the reliability of using Atoll-based simulation as a primary planning tool for microwave backhaul deployment in remote regions.

Discussion in Relation to Research Gap

The findings of this study directly address the identified research gap concerning microwave backhaul planning in N3T regions. Unlike prior studies that focus on theoretical or urban-centric scenarios, this work demonstrates a practical, industry-aligned planning framework that integrates Atoll-based simulation, KPI evaluation, and field verification. The results confirm that systematic KPI-based analysis enables effective comparison among multiple FE candidates and supports informed deployment decisions under challenging geographical conditions.

Furthermore, the selection of FE1 illustrates how performance metrics alone are insufficient without considering transport integration and operational sustainability. This insight is particularly relevant for policymakers and network operators seeking scalable and resilient telecommunication solutions for underserved areas.

Microwave Link Planning Workflow

The microwave link planning process in this study follows a structured workflow to ensure systematic evaluation and reliable decision-making. The workflow begins with the preparation and input of required planning data into the Atoll radio planning software, including site coordinates, antenna parameters, frequency bands, and terrain information.

The next stage involves identifying potential far-end (FE) candidate sites that can provide backhaul connectivity to the new network element (NE). If no feasible FE candidate is available due to line-of-sight (LOS) constraints or excessive path loss, a repeater site is considered to restore link feasibility and ensure signal continuity. Once feasible FE candidates are identified, link budget analysis is performed to evaluate key performance indicators such as received signal level (RSL), fade margin, and link availability.

Following the analytical evaluation, a field line-of-sight (LOS) survey is conducted for the selected candidate link to validate the simulation results and confirm real-world feasibility. The workflow is completed once the microwave configuration satisfies the predefined KPI requirements and field verification confirms unobstructed LOS conditions. This structured workflow ensures that the final microwave backhaul design is technically feasible, reliable, and suitable for deployment in N3T environments.

KPI Summary

Overall, the results indicate that all evaluated links meet the minimum KPI thresholds for microwave backhaul deployment; however, FE1 consistently provides the most balanced performance, achieving a received signal level above −40 dBm, a fade margin exceeding 45 dB, and total link availability above 99.99%, making it the most reliable and operationally sustainable option for N3T deployment.

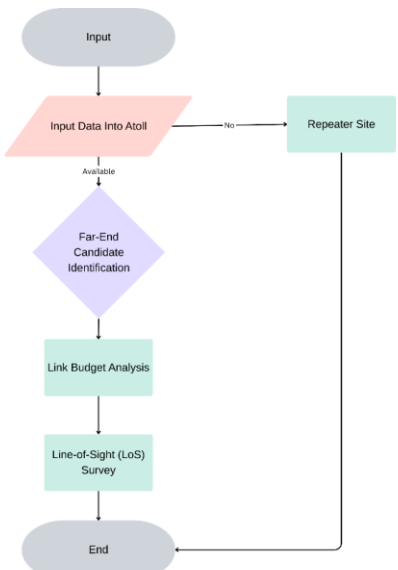

Figure 1. Microwave Link Planning Workflow

DISCUSSION

The results of this study demonstrate that systematic microwave link planning using an industry-grade simulation tool can effectively support backhaul deployment decisions in N3T regions. Although all evaluated far-end (FE) candidates satisfy the basic line-of-sight (LOS) requirement, the analysis confirms that LOS feasibility alone is insufficient to guarantee long-term link reliability. Instead, a combination of link budget performance, fade margin, and availability must be jointly considered to ensure robust operation under challenging environmental conditions.

From a KPI perspective, the comparative evaluation reveals that shorter links operating at higher frequencies tend to provide stronger received signal levels (RSL) and larger fading margins. However, this apparent advantage must be interpreted cautiously in tropical and mountainous regions, where higher frequencies are more susceptible to rain attenuation. In this context, the results support existing findings that medium-frequency microwave bands, such as 11 GHz, offer a more balanced trade-off between capacity and propagation robustness for medium-distance links in remote environments. The performance achieved by the selected FE configuration demonstrates that sufficient availability can be attained without excessive reliance on high-frequency bands that may compromise resilience.

The decision to prioritize FE candidates with fiber-optic transport integration further highlights an important operational insight. While KPI metrics provide a quantitative basis for link selection, infrastructure integration and long-term maintainability play a critical role in N3T deployments, where access for maintenance and upgrades is limited. By selecting a far-end site supported by fiber transport, the overall backhaul architecture reduces dependency on multi-hop microwave chains and mitigates the risk of cumulative interference and cascading failures. This finding underscores that optimal microwave planning extends beyond radio performance metrics to include network topology and operational sustainability.

The strong agreement between Atoll-based simulation results and field LOS verification confirms the reliability of simulation-driven planning when supported by accurate terrain and clutter data. This validation strengthens confidence in using industrial planning tools as a primary decision-support mechanism, particularly in early deployment stages where field surveys may be costly or logistically challenging. Nevertheless, the results also reaffirm the importance of selective field validation to ensure that simulation assumptions align with real-world conditions.

In relation to the identified research gap, this study contributes empirical evidence that applied, KPI-driven microwave planning using Atoll is both feasible and effective for N3T scenarios. Unlike prior studies that predominantly focus on theoretical models or urban deployments, this work demonstrates how comparative FE analysis and field validation can be integrated into a practical planning framework. These insights are valuable for network operators and policymakers seeking scalable and reliable solutions to extend telecommunication services to underserved regions.

Overall, the discussion highlights that reliable microwave backhaul deployment in N3T areas requires a holistic approach that integrates radio performance analysis, environmental considerations, and infrastructure strategy. The findings emphasize that simulation-based planning, when combined with KPI evaluation and targeted field verification, can significantly enhance the quality and sustainability of telecommunication infrastructure in remote and challenging environments.

CONCLUSIONS AND RECOMMENDATIONS

This study has demonstrated that microwave backhaul planning using an industry-grade radio planning tool can effectively support telecommunication deployment in rural, frontier, and outermost (N3T) regions. Through Atoll-based simulation, KPI-driven link budget analysis, and field line-of-sight (LOS) verification, the feasibility and performance of multiple far-end (FE) candidates were systematically evaluated.

The results confirm that while all evaluated links satisfy basic LOS requirements, reliable backhaul deployment in N3T environments requires a comprehensive assessment of key performance indicators, including received signal level (RSL), fade margin, and link availability. The selected microwave link configuration operating at 11 GHz achieved a favorable balance between propagation robustness and performance reliability, meeting availability targets above 99.99% with sufficient fade margin under challenging terrain conditions.

Furthermore, the integration of microwave backhaul planning with existing fiber-optic transport infrastructure proved to be a critical factor in ensuring long-term network stability and operational sustainability. The close agreement between simulation outcomes and field LOS verification also validates the effectiveness of simulation-based planning as a reliable decision-support approach for early-stage deployment in remote areas.

Overall, the findings address the identified research gap by providing empirical evidence that applied, KPI-based microwave link planning using Atoll can deliver reliable and scalable backhaul solutions tailored to N3T scenarios

Recommendations

Based on the outcomes of this study, several recommendations can be proposed for future deployment and research:

1. ***Operational Deployment***
   Network operators deploying microwave backhaul in N3T regions should adopt KPI-driven planning frameworks that integrate LOS analysis, link budget evaluation, and availability assessment to ensure long-term reliability.
2. ***Frequency Selection Strategy***
   Medium-frequency bands, such as 11 GHz, are recommended for medium-distance links in tropical and mountainous regions due to their balanced performance between capacity and resistance to rain attenuation.

3. ***Infrastructure Integration***
   Whenever possible, microwave backhaul planning should prioritize far-end sites with existing fiber-optic transport to reduce dependency on multi-hop microwave chains and minimize interference risks.
4. ***Simulation and Field Validation***
   Industrial-grade simulation tools should be complemented by selective field LOS verification to validate planning assumptions and enhance deployment confidence.
5. ***Future Research Directions***
   Future studies may extend this work by incorporating long-term performance monitoring data, climate-specific attenuation modeling, and the evaluation of adaptive modulation or protection schemes to further improve link resilience in N3T environments.

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