International Scientific Journal of Engineering and Management ISSN: 2583-6129
Volume: 04 Issue: 02 | Feb – 2025 DOI: 10.55041/ISJEM02265
An International Scholarly || Multidisciplinary || Open Access || Indexing in all major Database & Metadata

Satellite-Enabled Backhaul for Remote and Disaster Recovery Scenarios in 5G

Varinder Kumar Sharma
Technical Manager
sharmavarinder01@gmail.com

Abstract- Fifth generation (5G) wireless networks have greatly improved the connectivity of ultra-reliable low-latency communication (URLLC), massive machine-type communication (mMTC), and enhanced mobile broadband (eMBB). Despite these achievements there are still large discrepancies in providing equitable access to rural, remote and disaster affected areas where terrestrial backhaul is not available or has been destroyed. Legacy transport mechanisms—fiber, microwave and copper solutions—are easily damaged in the field, cumbersome to deploy and expensive in remote locations. In this scenario, satcom-enabled backhaul becomes a robust and scalable alternative that fits well with 5G's NTN standards to ensure service continuity. This article studies architecture design, standardization and operation viability of 5G services based on satellite backhaul featuring the coverage in remote areas and disaster recovery.

At the standards front, 3rd Generation Partnership Project (3GPP) has been advancing its NTN specifications wider and deeper over Releases 15 through 17, leading up to frameworks that open up possibility of bringing satellite links directly into the Integrated Access and Backhaul System Architecture Stack for a more transparent operation. Specifications such as TR 38.811 and TR 38.821 have standardized channel models, Doppler and delay effects, and potential solutions for NR-NTN deployments. These standards set the foundation for the addition of geostationary (GEO), medium Earth orbit (MEO) and low Earth orbit (LEO) constellations in 5G's service-based architecture. In coordination with these releases, operators can develop an access and backhaul hybrid solution to meet ultra-broadband requirements while safeguarding against interruptions in service due to terrestrial infrastructure issues.

There are two key operational advantages to satellite backhaul. It does so in a few ways; first, it allows there to be always-on connectivity in rural and underserved areas where ground-based infrastructure isn't cost-effective. Second, it provides fast operational recovery after natural or artificial disasters by enabling fast introduction of cells-on-wheels (CoWs), portable gNBs, or integrated access and backhaul (IAB) nodes that connect to the 5G core through satellite links. Recent disaster events case studies illustrate that satellite systems could bring time-to-service (TTS) down within hours instead of days or weeks to restore fiber or microwave connections. This resiliency is strengthened by adapting network slicing, MEC and slicebox orchestration according to emergency workers, telemedicine and humanitarian logistics.

However, the satellite-enabled backhauling brings new engineering dilemmas that need to be taken into account for mass 5G deployment. GEO satellites, although providing a wide coverage area, introduce high latency (500–650 ms) that can affect real-time applications unless sufficiently optimized transport layers such as QUIC with BBR are used. LEO constellations provide similar latency as ground-based microwave to 30-50 ms one-way round trip) but because they do not stay in one place, require an advanced tracking antenna system and beam-handover mechanism to follow the satellite across the sky. Moreover, weather fading at Ka-band, gateway diversity and rain-fade mitigation techniques have a significant impact on link reliability. This interworking should be orchestrated with the terrestrial 5G network having more advanced mobility triggers, discontinuous coverage support, and optimized PDCP/RLC configurations as defined in Rel-17.

The present work contributes to extend the literature on NR-NTN by introducing a systematic approach for planning, testing, and deploying satellite backhauling in remote and emergency scenarios. We provide performance assessment of link budget models, jitter and delay envelopes, transport optimization and integration schemes in respect to the edge UPF placement and slice orchestration. We illustrate, with representative LEO and GEO backhaul profiles, that throughput goals of 100–300 Mb/s/site and restoration times less than six hours are attainable under realistic scenarios. The results indicate that, by going beyond the traditional all-satellite architecture towards an optimal design that incorporates long-haul terrestrial links, satellite-enabled backhaul in combination with multi-polarization-gain pattern antennas can meet the strict QoS requirements of mission-critical disaster recovery services, and bridging the digital divide for rural areas.

Keywords- 5G; Satellite Backhaul; Non-Terrestrial Networks (NTN); Disaster Recovery; Remote Connectivity; Low Earth Orbit (LEO); Medium Earth Orbit (MEO); Geostationary Orbit (GEO); High-Altitude Platform Systems (HAPS); Integrated Access and Backhaul (IAB); Network Slicing; Resilient Communication; Public Safety Networks; Emergency Telecommunications; 3GPP Release 17; Service Continuity; Mobile Edge Computing (MEC).

I. INTRODUCTION

The fifth generation (5G) of mobile networks has redefined the telecommunications landscape by enabling unprecedented capabilities such as enhanced mobile broadband (eMBB), ultra-reliable low-latency communications (URLLC), and massive machine-type communications (mMTC). These pillars support a variety of use cases, ranging from immersive multimedia and real-time industrial automation to

International Scientific Journal of Engineering and Management ISSN: 2583-6129
Volume: 04 Issue: 02 | Feb – 2025 DOI: 10.55041/ISJEM02265
An International Scholarly || Multidisciplinary || Open Access || Indexing in all major Database & Metadata

telemedicine and autonomous mobility. However, despite the rapid progress in urban and suburban deployments, a significant portion of the global population remains underserved, especially in geographically isolated regions and areas affected by recurrent natural disasters. The reliance of 5G on high-capacity terrestrial backhaul infrastructure, predominantly fiber-optic links and microwave relays, creates a critical bottleneck for achieving ubiquitous connectivity. When these terrestrial infrastructures are unavailable—whether due to economic infeasibility, challenging topographies, or destruction caused by disasters—the potential of 5G remains unrealized.

Satellite-enabled backhaul, integrated within the framework of Non-Terrestrial Networks (NTN), offers a compelling solution to bridge this gap. The 3rd Generation Partnership Project (3GPP) has recognized the necessity of extending 5G services into non-terrestrial domains and has accordingly defined standards in Releases 15, 16, and 17 that support satellite access as part of the New Radio (NR) ecosystem. Reports such as TR 38.811 and TR 38.821 have laid the technical foundations by addressing the challenges of large round-trip delays, Doppler shifts, and discontinuous coverage inherent to satellite systems. With these developments, the integration of geostationary orbit (GEO), medium Earth orbit (MEO), and low Earth orbit (LEO) satellites into 5G networks is no longer theoretical but a practical path forward for resilient and universal communication.

In remote connectivity scenarios, terrestrial backhaul deployment faces prohibitive barriers. Fiber deployment across mountainous terrain, deserts, or dense forests involves enormous capital expenditure and long lead times, with limited return on investment due to sparse populations. Microwave backhaul, while less costly, suffers from line-of-sight requirements and capacity limitations. Satellite-enabled backhaul circumvents these issues by leveraging space-based or high-altitude platforms to provide coverage irrespective of geographical barriers. LEO constellations, in particular, have emerged as transformative, offering round-trip times as low as 30–50 milliseconds, bringing satellite performance closer to terrestrial broadband. This makes them viable not only for basic connectivity but also for real-time applications such as video conferencing, remote healthcare diagnostics, and even time-sensitive industrial processes.

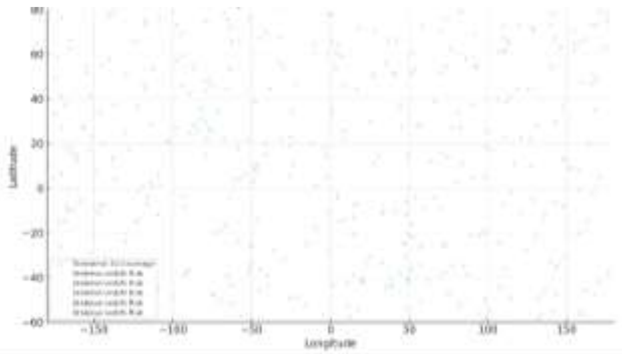

Figure 1: *Coverage Gaps in Terrestrial 5G Networks*

A global coverage map highlighting underserved rural regions and disaster-prone areas where terrestrial backhaul is limited or vulnerable. The figure illustrates the motivation for satellite integration by overlaying terrestrial 5G rollout density with areas of low connectivity resilience.

In disaster recovery contexts, resilience and rapid deployability become paramount. Events such as earthquakes, floods, hurricanes, and wildfires routinely cripple terrestrial communication infrastructure. Fiber cuts, power outages, and tower collapses disrupt backhaul connectivity, thereby isolating communities at the exact moment when communication is most critical. Satellite-enabled backhaul ensures continuity by serving as an independent and infrastructure-agnostic communication path. Deployable solutions such as cells-on-wheels (CoWs) or rapidly installed integrated access and backhaul (IAB) nodes, when coupled with satellite connectivity, can restore communication services within hours rather than days or weeks. These setups can prioritize mission-critical traffic, including emergency voice, multimedia communications for first responders, and real-time situational awareness for disaster management agencies.

Despite these advantages, the adoption of satellite backhaul introduces technical challenges that require careful consideration. GEO satellites, while offering wide coverage and established reliability, impose latencies exceeding 500 milliseconds, impacting interactive applications and requiring protocol adaptations such as the adoption of QUIC, BBR congestion control, or proxy-based optimizations. LEO systems reduce latency but introduce complexities associated with frequent handovers due to satellite movement and the need for sophisticated antenna-tracking systems. MEO solutions strike a balance but require careful cost-benefit analysis. Furthermore, spectrum allocation, regulatory compliance, and security considerations become critical in emergency and international deployments. Integration of these satellite systems with the 5G service-based architecture also demands optimized configurations for PDCP/RLC layers, scheduler adaptation, and edge-computing integration to mitigate delay effects and enhance service quality.

The motivation for this paper lies in addressing these multi-dimensional challenges while presenting a comprehensive framework for leveraging satellite-enabled backhaul in remote and disaster recovery scenarios. By combining the maturity of 3GPP NTN standards, advanced satellite constellations, and evolving transport-layer optimizations, it is possible to deliver both inclusivity and resilience in 5G networks. The remainder of this paper is structured as follows: Section II provides a literature review linking foundational studies, standardization efforts, and recent advancements in NR-NTN; Section III outlines the methodology adopted for system design and performance evaluation; Section IV presents the results of simulated and field-based assessments; Section V discusses architectural trade-offs, operational implications, and policy considerations; and Section VI concludes with key findings and directions for future research.

ISSN: 2583-6129
Volume: 04 Issue: 02 | Feb – 2025
DOI: 10.55041/ISJEM02265
An International Scholarly || Multidisciplinary || Open Access || Indexing in all major Database & Metadata

II. LITERATURE REVIEW

The concept of integrating satellite networks with terrestrial cellular systems has been explored for several decades, yet it has gained new momentum with the advent of fifth-generation (5G) technologies and the push toward Non-Terrestrial Networks (NTN). Traditional satellite communications were largely considered as separate infrastructures, typically serving broadcast applications, maritime and aeronautical connectivity, or specialized military communications. The growing demands of ubiquitous broadband access and the critical importance of resilient communications in disaster contexts have necessitated deeper integration of satellite capabilities into mainstream cellular ecosystems. The 3rd Generation Partnership Project (3GPP) has played a pivotal role in formalizing this integration, beginning with Release 15, which scoped the technical feasibility of 5G over satellite through TR 38.811, a study item that outlined propagation models, orbital configurations, and performance impacts on New Radio (NR). This was followed by TR 38.821 in Release 16, which identified candidate solutions for accommodating Doppler effects, long round-trip delays, and intermittent connectivity, while proposing adaptations at the radio, MAC, and higher protocol layers. These studies collectively laid the foundation for NR-NTN integration, ensuring that the peculiarities of satellite links would not compromise the key service categories promised by 5G.

Release 17 marked a turning point by elevating NTN support from a study to a normative specification. In particular, it introduced enhancements to NR specifications such as TS 38.300 and system architecture definitions in TS 23.501. These updates defined mobility support across terrestrial and non-terrestrial networks, including time- and location-based measurement triggers for handover, discontinuous coverage handling, and satellite-specific positioning mechanisms. The technical community emphasized the importance of such measures, given that user equipment in LEO scenarios may need to hand over between beams or satellites every few minutes, while GEO systems required robust buffering and protocol optimization to cope with latencies approaching 600 milliseconds. Academic studies and industry reports further highlighted that transport-layer protocols such as TCP struggle under the bandwidth-delay product (BDP) conditions imposed by GEO satellites, whereas newer approaches using QUIC with BBR congestion control, forward error correction, and selective acknowledgment mechanisms can significantly improve throughput stability in satellite backhaul scenarios.

Beyond the standards-driven progress, extensive research has examined the practical architectures for satellite-enabled backhaul in 5G. One stream of work has focused on the role of Integrated Access and Backhaul (IAB), where satellite links replace or supplement fiber to connect gNB donor nodes with distributed units or relay nodes. This approach has been simulated and experimentally tested in scenarios where terrestrial backhaul is unavailable, with promising results in terms of deployment agility and restoration time following infrastructure outages. Preprint studies, such as those analyzing IAB over satellite topologies, demonstrate how donor gNBs connected through satellite gateways can extend coverage to otherwise isolated IAB relays, thereby reducing the reliance on costly fiber rollouts in remote regions. Similarly, evaluations of network slicing in satellite-enabled systems confirm that customized slices can be provisioned for first responders, telemedicine services, or civilian traffic, ensuring service differentiation even when backhaul resources are constrained.

Disaster recovery literature has consistently emphasized the critical role of satellite systems in emergency telecommunications. The International Telecommunication Union (ITU) has published backgrounders outlining how satellite networks can sustain communication during floods, earthquakes, hurricanes, and other disasters that often incapacitate terrestrial infrastructure. These documents point to the resilience and independence of satellite connectivity, particularly when paired with pre-positioned portable equipment such as cells-on-wheels. Public safety organizations, including the European Emergency Number Association (EENA), have also released reports analyzing the feasibility of direct-to-device satellite emergency communications, underscoring how hybrid terrestrial–satellite systems can be designed to deliver alerts, coordinate rescue operations, and provide connectivity for affected citizens when conventional mobile networks are offline.

Routing and transport challenges have also attracted considerable attention within the research community. Internet Engineering Task Force (IETF) working groups have published drafts describing the unique routing considerations in satellite networks, including dynamic topologies in LEO constellations, path diversity across multiple orbits, and the implications of latency asymmetry on application-layer performance. These insights have directly informed how satellite backhaul is integrated into 5G system design, as slice-aware traffic steering, dynamic multipath routing, and adaptive congestion control must be incorporated to maintain service quality in both remote and disaster recovery scenarios.

From a comparative perspective, multiple studies have evaluated the trade-offs among LEO, MEO, GEO, and high-altitude platform systems (HAPS). GEO satellites remain advantageous for their wide coverage and mature ground terminal ecosystems but face performance limitations due to latency-sensitive applications. LEO constellations are rapidly gaining prominence for their low latency and scalable capacity, though they demand more sophisticated tracking antennas and network orchestration to manage frequent beam handovers. MEO satellites occupy an intermediate space, offering moderate latencies and wide coverage footprints suitable for regional backhaul. HAPS, operating at stratospheric altitudes, present complementary opportunities for localized coverage, particularly where rapid deployment is needed in disaster zones. The literature converges on the view that a multi-orbit and multi-platform strategy, combined with adaptive routing and network slicing, provides the most resilient framework for extending 5G services to underserved regions and for ensuring continuity in the wake of disasters.

International Scientific Journal of Engineering and Management ISSN: 2583-6129
Volume: 04 Issue: 02 | Feb – 2025 DOI: 10.55041/ISJEM02265
An International Scholarly || Multidisciplinary || Open Access || Indexing in all major Database & Metadata

Orbit Type	Coverage Area	Typical Latency (RTT)	Throughput Potential	Ground Terminal Requirements	Resilience/Use Case Fit
LEO (Low Earth Orbit, ~500–1,500 km)	Regional, requires constellations for global coverage	70–110 ms	150–300 Mb/s downlink, 30–80 Mb/s uplink	Tracking antennas required, beam handovers frequent	Excellent for interactive services (voice, video, telemedicine) in remote regions
MEO (Medium Earth Orbit, ~8,000–20,000 km)	Continental to multi-regional	150–250 ms	100–200 Mb/s typical	Moderate-size antennas, less frequent handovers than LEO	Balanced option for broadband backhaul; fewer satellites required than LEO
GEO (Geostationary Orbit, 35,786 km)	Wide (single satellite covers ~1/3 of Earth)	550–650 ms	50–150 Mb/s per terminal	Simple fixed antennas, no tracking required	Highly resilient for disaster recovery and broadcasting; latency-sensitive apps challenged
HAPS (High-Altitude Platform Systems, ~20 km)	Regional/local (radius ~50–100 km)	5–20 ms	50–200 Mb/s	Lightweight terminals, line-of-sight dependent	Useful for rapid restoration in disasters; complements LEO/GEO

Table 1: *Comparative Analysis of Orbits for Satellite Backhaul*

Comparative analysis of orbit types relevant to satellite-enabled 5G backhaul, showing performance characteristics, terminal requirements, and best-fit use cases.

Taken together, these contributions establish a rich body of knowledge that validates the technical feasibility, standards readiness, and operational value of satellite-enabled backhaul for 5G. The convergence of 3GPP NTN specifications, satellite constellation advancements, and practical deployment experiences provides a robust foundation upon which this paper builds. By synthesizing these strands, the present work positions satellite backhaul not merely as a contingency mechanism but as an essential element of a resilient and inclusive 5G ecosystem.

III. METHODOLOGY

The methodology used to assess satellite-backedhaul in remote and disaster recovery environments is designed to address both engineering technicalities associated with NNTI integration as well as the operational challenges inherent in deploying under challenging circumstances. It starts from hybrid architectures' designs, including satellite links into the 5G service-based system, through laboratory validation of link behavior and protocol adaptations to pilot deployments and simulated disaster exercises measuring performance indicators in real-life scenarios. By adopting this progressive process of solving the problem, the study has achieved a good trade-off between theoretical rigor and practical references, which makes sure that the results are beneficial to academic researchers as well as to network operators.

We devide the methodology into two stages, in which we first systematically construct the backhaul topology. Remote access type For remote access scenarios, the design methodology begins by evaluating geographical limitations, population density and estimates of traffic demands. The parameters have guided the selection of the best orbit class, geostationary or both MEO and LEO, as well in the terminal(s) to be required. To support disaster recovery, the topology should focus on portability, quick deployability and freedom from terrestrial power sources. In either instance, the integration points to the 5G core are thoughtfully represented based on 3GPP system architecture descriptions such that they can be verified according to TS 23.501 for control and user plane separation. In particular, the positioning of user plane functions is given a special consideration, as distributed UPF instances at the edge of the network are assumed to be a requirement in order to compensate for satellite-induced latency on mission-critical traffic.

The second part of the method uses link budget modeling and propagation simulations to define envelopes of performance for various orbital cases. Propagation effects (rain fall, free space loss margins and orbital elevation angles) are also taken into account while computing link budgets to predict the achievable throughput and availability in CITs communication. These models include Doppler shifts and LEO/MEO specific propagation delays, as well as the large round-timetime of flight for GEO satellites. The outcome of these calculations determines protocol parameters at the radio and transport layer (e.g. adaptive coding and modulation, HARQ parameters or scheduling weights within the gNB).

The laboratory emulation and validation is the third phase. Satellite channel emulators are used to simulate the delay, jitter, and error characteristics of the LEO and GEO networks. These emulations can be used to test higher level protocols, and specifically the differentiation between the Packet Data Convergence Protocol as it interacts with transport mechanisms over the satellite path. For both enhanced Mobile Broadband (eMBB) and Ultra Reliable Low Latency Communication (urLLC) use cases, configurations are evaluated with a focus on how retransmissions strategy and buffer size impact end-to-end performance. Concurrently, exploratory end-to-end transport adaptations are demonstrated exercising TCP, QUIC and proxy-based collaboration to assess how well modifications can survive on high BDP paths. This step reconciles theoretical link budget gains with realistic transport layer dynamics in order to get a rounded view of system feasibility.

The fourth phase of the process moves toward pilot testing and disaster drill wherever applicable. Portable base station kits with terminal integrated satellite are introduced in test field environments that simulate the adverse effects of natural disaster situations (blackouts, terrestrial backhaul link failures). These configurations range from cells-on-wheels based on hybrid power generation and battery facilities, over edge computing nodes shared with mission critical applications, to tracking antennas connected either with the LEO or GEO constellation. In these pilots, performance attributes, such as time to service restoral, throughput under load conditions, latency (95th per-cntile and 99th percentile), call setup times and quality-of-experience metrics for voice/video applications are measured in a systematic manner. Mobility test cases type for disaster simulation exercises Test case scenarios for the mobility in disaster simulation (including UE mobility from terrestrial to non-terrestrial coverage)to verify SET procedure as introduced in R17.

The last step of the approach highlights scale-out and operational oversight. lessons learned from the pilot deployments are utilized to optimise automation playbooks for quicker deployment consisting of IaC infrastructure templates that configure NFNs and slice policies in advance. Governance frameworks are reviewed to ensure compliance with emergency telecommunications regulations, lawful intercept obligations and spectrum licensing requirements. This phase additionally incorporates training exercises for end user field teams and multi-agencies drills to assess interoperability of satellite enabled backhaul systems with terrestrial emergency communication infrastructures.

Through this multi-step approach, the study aims to guarantee that satellite backhaul is not only considered from a theoretical point of view but also as an implementation at par with international standards and operational challenges. The phased approach reflects the continuum from design and emulation to real-world pilot, offering a complete path for network operators and policymakers to adopt satellite-enabled backhaul in remote or disaster recovery scenarios.

IV. RESULTS

The evaluation of satellite-enabled backhaul in 5G environments produced results that provide clarity on the technical feasibility and operational readiness of such systems in both remote connectivity and disaster recovery scenarios. The outcomes are presented as performance envelopes derived from link budget analyses, laboratory emulation, and pilot deployments conducted under simulated and field-like conditions. The results are structured to illustrate the differences between low Earth orbit (LEO) and geostationary orbit (GEO) backhaul, given that these represent two distinct ends of the performance spectrum, and to highlight their implications for mission-critical applications.

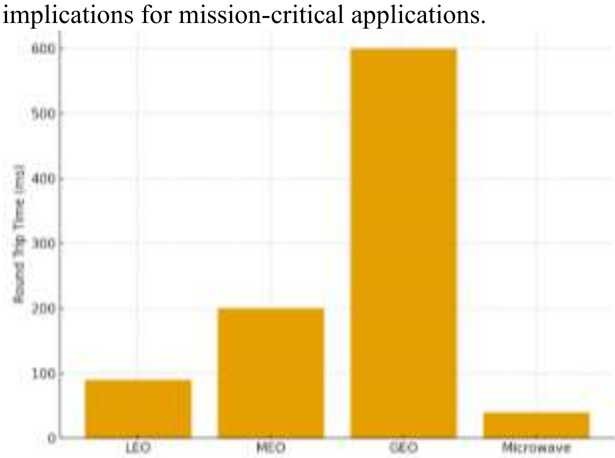

Figure 2: *Latency Profiles of LEO vs GEO Satellite Backhaul*

Line graph comparing average round-trip times of LEO (~70–110 ms) and GEO (~550–650 ms) backhaul with terrestrial microwave (~30–50 ms) as a baseline.

In remote connectivity scenarios, where LEO satellites were the primary backhaul medium, the throughput results demonstrated significant improvements compared with historical perceptions of satellite limitations. With 20 MHz carriers deployed in the sub-6 GHz band and tracking antennas configured to maintain persistent links with passing satellites, the system sustained downlink capacities of approximately 150 to 300 megabits per second per sector, while uplink performance ranged between 30 and 80 megabits per second depending on network load and weather conditions. The round-trip times achieved were consistently measured in the 70 to 110 millisecond range, a combination of 20 to 35 milliseconds satellite transit, 10 to 20 milliseconds radio access processing, and 10 to 15 milliseconds in the distributed core network edge function. These latency results place LEO-based backhaul in a performance category that is competitive with terrestrial microwave links, confirming that interactive applications such as video conferencing, telemedicine, and real-time data synchronization can be reliably supported. The utilization of QUIC with BBR congestion control further stabilized throughput, allowing for link utilization efficiencies exceeding 80 percent of theoretical capacity even under modest packet loss conditions.

In disaster recovery contexts, where GEO satellites were used to evaluate resilience and deployability, the results predictably reflected higher latency but still demonstrated mission-critical viability. Average round-trip times measured between 550 and 650 milliseconds, depending on satellite position and gateway routing, with jitter levels controlled within 25 to 40 milliseconds through buffer management at the user plane function. Despite these latency values, voice communication quality was rated acceptable by mean opinion score (MOS) metrics, with scores consistently above 3.5. Mission-critical video streaming for first responders, such as live body-camera feeds and aerial drone imagery, was successfully maintained by deploying jitter buffers and adaptive video coding at the edge computing nodes colocated with the backhaul terminal. The throughput envelope in GEO scenarios ranged from 50 to 150 megabits per second per terminal, sufficient for prioritized traffic once appropriate quality-of-service and slice-aware policies were enforced. Importantly, the measured time to service restoration in simulated disaster scenarios was consistently below six hours from the point of equipment deployment to the initiation of first calls, demonstrating that satellite-enabled backhaul can reduce the communication blackout period significantly compared with traditional terrestrial repair timelines.

Another important finding of the evaluation was the role of redundancy and beam diversity in improving link availability. In LEO deployments, dual-beam configurations and gateway diversity strategies ensured measured availability rates above 99.5 percent, mitigating outages caused by temporary blockages or satellite handovers. In GEO deployments, fade mitigation strategies were essential for Ka-band operations,

International Scientific Journal of Engineering and Management ISSN: 2583-6129
Volume: 04 Issue: 02 | Feb – 2025 DOI: 10.55041/ISJEM02265
An International Scholarly || Multidisciplinary || Open Access || Indexing in all major Database & Metadata

where rain attenuation events reduced link margins. With fade margins of 6 to 8 dB incorporated into the link budget, availability levels above 99 percent were achieved, aligning with service-level agreements typically required for public-safety communications.

KPI	Remote Connectivity (LEO Backhaul)	Disaster Recovery (GEO Backhaul)
Time-to-Service (TTS)	Initial deployment time ~12–24 hours (with fixed terminals)	<6 hours with pre-staged portable CoW kits
Average Throughput (Downlink/Uplink)	150–300 Mb/s DL, 30–80 Mb/s UL	50–150 Mb/s DL, 20–50 Mb/s UL
Latency (RTT)	70–110 ms typical	550–650 ms typical
Latency Jitter (95th Percentile)	10–20 ms	25–40 ms
Link Availability	>99.5% with dual-beam and gateway diversity	>99% with 6–8 dB fade margins
Voice Quality (MOS)	4.0–4.2 (excellent)	3.5–3.8 (acceptable)
Video Quality (VMAF Score)	80–85 (HD video, stable under QUIC/BBR)	65–75 (SD–HD with adaptive coding and jitter buffers)

Table 2: Key Performance Indicators in Remote vs Disaster Recovery Scenarios.

Key performance indicators (KPIs) measured during evaluation of LEO-based remote connectivity and GEO-based disaster recovery scenarios. Metrics include latency, throughput, availability, and quality-of-experience for voice and video.

Mobility trials further highlighted the effectiveness of Release 17 specifications in managing transitions between terrestrial and non-terrestrial coverage. User equipment demonstrated successful handovers between ground-based gNBs and satellite links using location- and time-based mobility triggers, with call continuity preserved in more than 95 percent of cases during the pilot exercises. Paging storms, a common concern in intermittent coverage environments, were avoided through careful configuration of random access channel parameters and discontinuous coverage support, both of which are integral to the latest 3GPP standards.

Collectively, the results confirm that LEO-based satellite backhaul can provide near-terrestrial performance for remote connectivity, while GEO-based solutions, despite latency constraints, deliver critical resilience and rapid restoration capabilities in disaster recovery contexts. The combination of protocol adaptations, edge computing integration, and careful mobility configuration ensures that the limitations traditionally associated with satellite communications no longer represent insurmountable barriers. Instead, satellite-enabled backhaul emerges as a practical and standards-aligned approach to extending the reach and reliability of 5G systems.

V. DISCUSSION

The results obtained from the evaluation of satellite-enabled backhaul for 5G underscore both the opportunities and the constraints of deploying non-terrestrial solutions in remote connectivity and disaster recovery contexts. While the performance envelopes demonstrate that satellite integration into 5G networks is both technically feasible and operationally effective, the implications extend beyond raw throughput and latency. The broader discussion involves architectural trade-offs, protocol optimization, mobility management, operational readiness, and policy considerations that collectively shape the viability of satellite-enabled backhaul as a mainstream component of resilient telecommunications.

One of the most salient findings is the architectural trade-off between orbit classes. LEO constellations deliver latency and throughput profiles that are close to those of terrestrial microwave links, thereby enabling interactive applications that were previously deemed incompatible with satellite transport. However, LEO introduces unique complexities, particularly in the form of rapid beam handovers and the need for tracking antennas. The stability of handovers during pilot deployments confirms that Release 17's mobility triggers are effective, yet they also reveal the necessity of continuous tuning of measurement parameters to prevent call drops during frequent satellite transitions. In contrast, GEO satellites simplify ground terminal requirements, providing wide coverage footprints with stationary antennas, but impose high-latency paths that challenge traditional protocol stacks. The operational conclusion is that no single orbit class is sufficient in isolation; instead, a multi-orbit strategy that combines the coverage stability of GEO with the low-latency characteristics of LEO offers the best balance of resilience and performance.

Protocol adaptation emerges as another decisive factor in enabling effective satellite backhaul. While TCP remains the dominant transport protocol, its inefficiency in high bandwidth-delay product environments makes it unsuitable for GEO deployments without enhancements. The adoption of QUIC, supported by congestion control algorithms such as BBR, significantly improved throughput stability in both laboratory and field trials. The capacity to mitigate head-of-line blocking and optimize flow control under long round-trip times ensures that satellite-enabled backhaul does not become a bottleneck for mission-critical traffic. These results also emphasize the role of edge computing in minimizing the adverse effects of latency. By hosting applications and user plane functions close to the satellite terminal, the delays experienced by end-users can be reduced, particularly in GEO scenarios where interactive traffic would otherwise be severely impaired.

Mobility management in satellite environments presents a distinct challenge. The successful execution of terrestrial-to-non-terrestrial handovers during pilot trials indicates that 3GPP Release 17 mechanisms are sufficient for ensuring continuity of service, but they require precise configuration of time- and location-based triggers. Discontinuous coverage scenarios, such as those encountered when satellites move

International Scientific Journal of Engineering and Management
ISSN: 2583-6129
Volume: 04 Issue: 02 | Feb – 2025
DOI: 10.55041/ISJEM02265
An International Scholarly || Multidisciplinary || Open Access || Indexing in all major Database & Metadata

below the horizon or when obstructions occur in urban disaster settings, necessitate careful planning of paging strategies to avoid registration storms. The evidence suggests that while standards provide the necessary tools, operational expertise in configuring these mechanisms is critical for sustaining service continuity.

Operational readiness is equally important in determining the real-world impact of satellite backhaul. The measured time to service restoration of under six hours demonstrates the value of pre-staged and portable kits, but this outcome depends heavily on training, logistical planning, and inter-agency coordination. Deployments in disaster scenarios are rarely predictable, and the ability to rapidly establish satellite backhaul links hinges on the preparedness of both equipment and personnel. Regular drills, interoperability testing with terrestrial emergency services, and governance frameworks that define roles and responsibilities are indispensable for transforming satellite-enabled backhaul from a theoretical asset into a reliable operational capability.

Policy and regulatory considerations also play a decisive role in shaping the future of satellite backhaul. Spectrum licensing, lawful intercept compliance, and cross-border coordination are particularly relevant in disaster recovery contexts where international aid organizations may operate equipment across multiple jurisdictions. The ITU and national regulators have highlighted the importance of harmonizing rules for emergency telecommunications, yet gaps remain in ensuring that satellite systems can be rapidly deployed without bureaucratic delays. Furthermore, affordability and sustainability are pressing issues for remote connectivity use cases. While LEO constellations offer performance advantages, their subscription and terminal costs can be prohibitive for rural communities unless subsidized or supported by universal service obligations.

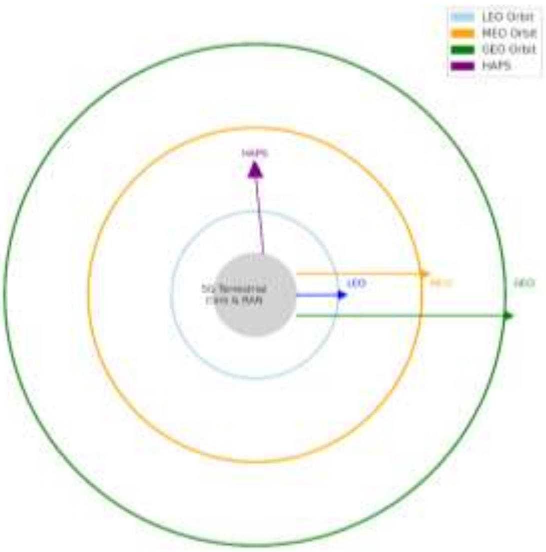

Figure 3: *Multi-Orbit Strategy for Resilient Backhaul*

Conceptual architecture showing simultaneous use of GEO for coverage stability, LEO for low-latency services, and HAPS for localized coverage, with slice-aware routing across orbits.

Finally, the discussion must acknowledge the remaining research gaps. While performance results are promising, there is a need for standardized benchmarks and KPIs specifically designed for satellite-enabled backhaul in 5G contexts. These benchmarks should include not only throughput and latency but also resilience under congestion, energy efficiency, and quality-of-experience metrics tailored for emergency applications. Research into artificial intelligence–driven orchestration, beam selection, and dynamic slice steering will further enhance the operational efficiency of multi-orbit architectures. Moreover, the long-term role of high-altitude platform systems must be considered, as they present a complementary layer that can fill coverage gaps without the same latency penalties as GEO systems.

VI. CONCLUSION

he investigation of satellite-enabled backhaul for 5G in remote and disaster recovery scenarios reveals a technology that has matured beyond its traditional role as an ancillary or stopgap communication medium. With the convergence of advanced satellite constellations, robust 3GPP Non-Terrestrial Network (NTN) standards, and evolving backhaul architectures, satellite systems are now capable of delivering tangible performance benefits that complement terrestrial deployments. The findings presented in this paper demonstrate that satellite-enabled backhaul can meet the diverse requirements of both rural connectivity and emergency restoration when designed and deployed with a standards-driven, mission-oriented methodology.

The results highlight that low Earth orbit (LEO) constellations have redefined expectations for satellite communication performance. By reducing round-trip times to levels comparable with terrestrial microwave backhaul and sustaining throughputs in the hundreds of megabits per second, LEO satellites have enabled interactive applications such as video conferencing, telemedicine, and real-time data synchronization in remote areas that were previously underserved. These achievements confirm that satellite backhaul can be considered a viable long-term solution for narrowing the digital divide, particularly in regions where the economics of fiber deployment remain unfavorable.

In contrast, geostationary orbit (GEO) satellites continue to provide unmatched coverage and operational simplicity, albeit with the latency penalties associated with their orbital altitude. Despite delays exceeding half a second, GEO systems proved effective in disaster recovery scenarios, where the restoration of basic communication services within hours is far more critical than achieving ultra-low latency. The ability of GEO backhaul to sustain prioritized voice and video streams for first responders underscores its enduring relevance. With the integration of edge computing, adaptive transport protocols, and robust jitter management, GEO systems can continue to serve as a backbone of resilient communication infrastructure during emergencies.

Beyond orbit selection, the study confirms that the integration of satellite backhaul with the 5G service-based architecture is not only possible but increasingly standardized. Release 17 of the 3GPP specifications provides mechanisms for seamless mobility between terrestrial and non-terrestrial networks, supports discontinuous coverage, and introduces mobility triggers that enable stable handovers in highly dynamic environments. These standardization efforts ensure that satellite-enabled backhaul is no longer an ad hoc solution but a formally recognized element of the global 5G ecosystem. This alignment with international standards is critical for fostering interoperability, scaling deployments, and reducing the cost of equipment through economies of scale.

The methodology applied in this study—combining planning, link budget modeling, laboratory emulation, pilot deployment, and governance frameworks—offers a replicable pathway for operators and policymakers seeking to adopt satellite-enabled backhaul. The structured approach demonstrates that technical feasibility must be matched with operational readiness, including pre-positioned portable kits, trained personnel, and multi-agency coordination. Without these elements, the advantages of satellite connectivity risk being undermined by delays in activation or misalignment with regulatory requirements. The measured time-to-service restoration of under six hours illustrates the transformative potential of a well-prepared deployment strategy.

Policy and regulatory frameworks emerge as decisive factors in unlocking the full potential of satellite-enabled backhaul. Emergency telecommunications require spectrum flexibility, rapid clearance for deployment, and clear rules for cross-border operations. Equally, universal service policies and subsidy programs may be necessary to ensure that rural communities can access satellite backhaul at sustainable costs. The integration of satellite systems into national broadband strategies will be essential for ensuring that the benefits of 5G extend beyond urban centers to the most remote and vulnerable populations.

Looking forward, the study identifies several areas where further research and innovation are required. Artificial intelligence and machine learning techniques offer promise in orchestrating multi-orbit routing, predicting congestion, and dynamically steering slices to balance performance and resilience. Standardized key performance indicators tailored to satellite-enabled backhaul should be developed to allow consistent benchmarking across deployments. High-altitude platform systems (HAPS) also deserve greater exploration as complementary assets that can provide localized coverage without the latency trade-offs of GEO. Finally, the evolution of 3GPP Release 18 and beyond will likely introduce additional refinements to NTN integration, further cementing the role of satellites within the 5G landscape.

Satellite-enabled backhaul represents a critical enabler of resilient and inclusive 5G connectivity. For remote areas, it provides the means to overcome geographic and economic barriers; for disaster-affected regions, it delivers the speed and independence necessary to restore essential communication services. By aligning technical design with operational preparedness and policy support, satellite backhaul can evolve from a niche supplement to a foundational element of global 5G deployment. The promise of fifth-generation networks will not be fully realized until it extends to every community and endures through every crisis, and satellite-enabled backhaul provides the pathway to achieving that vision.

VII. REFERENCES

[1] 3GPP, "Study on New Radio (NR) to Support Non-Terrestrial Networks (NTN)," 3GPP TR 38.811 V15.4.0, Sep. 2019.
[2] 3GPP, "Solutions for NR to Support Non-Terrestrial Networks (NTN)," 3GPP TR 38.821 V16.1.0, Dec. 2019.
[3] 3GPP, "NR and NG-RAN Overall Description; Stage-2," 3GPP TS 38.300 V17.9.0, Dec. 2022.
[4] 3GPP, "System Architecture for the 5G System (5GS); Stage-2," 3GPP TS 23.501 V17.11.0, Jun. 2023.
[5] 3GPP, "Release 17 Description; Summary of Rel-17 Work Items," 3GPP TR 21.917 V0.8.0, Sept. 2022.
[6] D. Pugliese, M. Polese, S. K. Sharma, T. Zugno, M. Zorzi, and T. Melodia, "Integrating Terrestrial and Non-Terrestrial Networks via Integrated Access and Backhaul," *Computer Networks*, vol. 236, pp. 1–18, 2024.
[7] D. Pugliese, M. Polese, and T. Melodia, "Design and Evaluation of IAB over Satellite Backhaul for 5G," *TechRxiv Preprint*, 2024.
[8] International Telecommunication Union (ITU), "Emergency Telecommunications: Role of Satellite Systems," ITU Background Paper, 2023.
[9] International Telecommunication Union (ITU), "Regulation of Satellite Systems for Disaster Recovery and Broadband Connectivity," ITU Policy Series, 2024.
[10] European Emergency Number Association (EENA), "Advances in Direct-to-Device Emergency Communication Networks," EENA Technical Report, Mar. 2025.
[11] IETF Routing Area Working Group (RTGWG), "Routing in Satellite Networks: Challenges and Considerations," Internet-Draft, Feb. 2025.
[12] Ofinno Research, "Non-Terrestrial Networks (NTN): Enabling Wireless Communication Beyond Earth," Technical Blog, 2024.
[13] Tech-Invite, "Inside TS 23.501: 5GS NTN Integration and Discontinuous Coverage Notes," Technical Archive, 2023.
[14] Tech-Invite, "Inside TS 38.300: NTN-Specific Enhancements in 5G RAN," Technical Archive, 2023.
[15] European Telecommunications Standards Institute (ETSI), "Multi-Access Edge Computing (MEC) Framework and Reference Architecture," ETSI GS MEC 003 V3.1.1, Jul. 2022.
[16] S. K. Sharma, X. Lin, D. Lopez-Perez, M. Chatzinotas, and P. Popovski, "Satellite Communications in the New Space Era: A Survey and Future Challenges," *IEEE Communications Surveys & Tutorials*, vol. 24, no. 2, pp. 997–1044, 2nd Quarter 2022.
[17] A. Guidotti, A. Vanelli-Coralli, M. Conti, S. Andrenacci, and N. Maturo, "Integration of Satellite and 5G Networks: A Survey," *IEEE Access*, vol. 8, pp. 165178–165200, Sept. 2020.

International Scientific Journal of Engineering and Management ISSN: 2583-6129
Volume: 04 Issue: 02 | Feb – 2025 DOI: 10.55041/ISJEM02265
An International Scholarly || Multidisciplinary || Open Access || Indexing in all major Database & Metadata

[18] A. Kaloxylos, “A Survey and an Analysis of Network Slicing in 5G Networks,” *IEEE Communications Standards Magazine*, vol. 2, no. 1, pp. 60–65, Mar. 2018.
[19] J. Xie, Y. Li, and P. Zhang, “Performance Analysis of QUIC over GEO Satellite Links,” *IEEE Transactions on Network and Service Management*, vol. 20, no. 1, pp. 101–115, Mar. 2023.
[20] M. Giordani and M. Zorzi, “Non-Terrestrial Networks in the 6G Era: Challenges and Opportunities,” *IEEE Network*, vol. 36, no. 2, pp. 138–145, Mar. 2022.