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A SYSTEMATIC REVIEW OF LIMITATIONS IN EXISTING SATELLITE CONNECTIVITY SYSTEMS: TECHNICAL, ECONOMIC, AND REGULATORY PERSPECTIVES

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Abstract:

Satellite connectivity has emerged as a transformative technology for bridging the global digital divide, particularly in rural and remote regions underserved by conventional terrestrial infrastructure. Despite rapid advancements in Low Earth Orbit (LEO), Medium Earth Orbit (MEO), and Geostationary Orbit (GEO) satellite systems, existing deployments continue to face significant limitations across multiple dimensions. This paper presents a systematic review of the primary constraints inherent in current satellite connectivity systems, encompassing propagation latency, spectrum congestion, high user terminal costs, space debris accumulation, regulatory fragmentation, weather-induced signal degradation, security vulnerabilities, and power consumption challenges. Through a structured analysis of literature from 2018 to 2024, we identify critical gaps between the theoretical promise of global satellite coverage and its practical realization. Comparative evaluation of major constellation systems including Starlink, OneWeb, and Kuiper is presented alongside tabular and diagrammatic analyses. The findings of this review establish the foundational basis for future research directed toward developing enhanced frameworks for next-generation satellite connectivity. Our analysis reveals that no single existing system fully addresses the multi-dimensional challenge landscape, underscoring the need for an integrated, hybrid optimization approach.

Key Words: Satellite Connectivity, LEO Constellations, Digital Divide, Signal Latency, Spectrum Management, Space Debris, Rural Connectivity, Non-Terrestrial Networks

1. Introduction:

Satellite connectivity has undergone a paradigm shift over the past two decades, transitioning from expensive, low-bandwidth geostationary systems to dynamic, low-latency constellations deployed at lower orbital altitudes. This transformation has been driven by the convergence of declining launch costs, miniaturization of satellite hardware, advances in phased-array antenna technology, and the emergence of mega-constellation operators such as SpaceX's Starlink, OneWeb, and Amazon's Project Kuiper. Collectively, these developments have rekindled global optimism about achieving universal internet access a goal enshrined in the United Nations' Sustainable Development Goal 9 (SDG-9) on resilient infrastructure and universal digital inclusion. Despite this momentum, the practical realization of satellite connectivity at scale remains constrained by an array of persistent technical, economic, regulatory, and environmental limitations. These limitations are not merely incremental engineering challenges; they represent systemic barriers that collectively impede the equitable deployment of satellite-based services across diverse geographies and socio-economic contexts. The research objective underpinning this paper Objective 1 of the parent study on satellite connectivity is therefore to rigorously analyze these existing limitations in order to lay the evidentiary groundwork for proposing an enhanced framework in subsequent phases of the research program.

This paper systematically examines the constraint landscape through a structured review of peer-reviewed literature, technical reports, and empirical deployment data from 2018 to 2024. Section 2 provides the theoretical background on satellite orbital mechanics and system architecture. Section 3 presents a comprehensive taxonomy of limitations. Section 4 delivers a comparative analysis of major existing systems. Section 5 discusses cross-cutting implications, and Section 6 concludes with directions for future work.

2. Theoretical Background and System Architecture:

2.1 Satellite Orbital Classifications:

Satellite communication systems are fundamentally classified by orbital altitude, which governs key performance parameters including latency, coverage footprint, power requirements, and constellation size. Table 1 summarizes the three primary orbital regimes and their defining characteristics as established in the literature.

Table 1: Classification of Satellite Orbital Regimes and Key Parameters

Orbit Type	Altitude Range	Latency (ms)	Coverage Footprint	Representative Systems
LEO	500-2,000 km	20-40 ms	Regional (multi-sat coverage)	Starlink, OneWeb, Kuiper
MEO	2,000-35,786 km	100-600 ms	Continental	GPS, Galileo, O3b (SES)
GEO	~35,786 km	500-700 ms	Near-global (single sat)	Intelsat, Viasat, HughesNet
VLEO	< 500 km	< 20 ms	Narrow orbital strip	Emerging (experimental)

Sources: Rincon (2022) [14]; López et al. (2023); Chaoub et al. (2022) [2].

2.2 Satellite Network Architecture:

A complete satellite communication system consists of three principal segments: the space segment (the satellites and their payloads), the ground segment (gateway stations, network operations centers, and user terminals), and the control segment (command and control infrastructure). Inter-Satellite Links (ISLs) in modern LEO constellations such as Starlink's v2 satellites introduce a fourth dimension direct satellite-to-satellite communication which reduces dependence on ground infrastructure but introduces complexity in routing and synchronization.

3. A Taxonomy of Limitations in Existing Satellite Connectivity:

Based on a structured review of 25 peer-reviewed articles and technical reports from 2018-2024, this paper identifies eight primary limitation categories. These are organized into three overarching dimensions: Technical Limitations, Economic and Accessibility Limitations, and Regulatory and Environmental Limitations.

3.1 Technical Limitations:

3.1.1 Propagation Latency and Delay Constraints:

Latency remains one of the most fundamental and persistently discussed limitations in satellite communication. While LEO constellations have dramatically reduced round-trip times compared to GEO systems (from ~600 ms to approximately 20-40 ms), LEO latency still exceeds that of fiber-optic terrestrial connections (typically 5-15 ms for equivalent distances). López et al. (2023) empirically demonstrated in field tests spanning 250 km of rural terrain that even Starlink's LEO system failed to consistently achieve the 100 ms round-trip latency target required for real-time applications under high network load conditions. Furthermore, handover latency the time penalty incurred during satellite switching as the user terminal transitions between overhead LEO satellites introduces intermittent service disruptions that are particularly problematic for voice-over-IP (VoIP), gaming, and telemedicine applications requiring continuous low-latency streams.

For GEO satellites, the latency problem is effectively irreducible due to the physics of electromagnetic propagation across ~35,786 km of orbital distance. This fundamental constraint excludes GEO-based systems from real-time communication use cases, despite their superior single-satellite coverage footprint.

3.1.2 Spectrum Congestion and Radio Frequency Interference:

The radio frequency (RF) spectrum available for satellite communications is a finite, internationally regulated resource. As the number of operational satellites has grown exponentially the Union of Concerned Scientists' satellite database recorded over 9,000 active satellites by 2024 competition for Ka-band (26.5-40 GHz), Ku-band (12-18 GHz), and S-band (2-4 GHz) allocations has intensified severely. Furqan et al. (2022) documented that adjacent-satellite interference becomes statistically significant when satellite angular separation falls below 2 degrees in geostationary arc, a scenario increasingly common given the proliferation of competing GEO operators.

In LEO constellations, inter-constellation interference between Starlink, OneWeb, and Kuiper satellites operating in overlapping orbital shells poses a growing coordination challenge. The International Telecommunication Union (ITU) coordination mechanisms, while nominally governing spectrum use, are slow-moving regulatory instruments ill-suited to the pace of LEO constellation deployment.

3.1.3 Weather-Induced Signal Degradation:

Satellite signals operating in Ka-band frequencies are particularly susceptible to rain fade signal attenuation caused by precipitation in the tropospheric layer. Raúl Parada (2023) noted that in tropical and equatorial regions, where rainfall intensities regularly exceed 50 mm/hour, Ka-band path loss can exceed 20 dB during heavy precipitation events effectively interrupting service entirely. This limitation is especially problematic for disaster response applications, precisely the deployment scenarios where satellite connectivity is most critically needed.

Ku-band systems exhibit greater atmospheric resilience but offer lower bandwidth capacity, creating a performance trade-off that system designers must navigate depending on target geographic deployment. Additional atmospheric effects including ionospheric scintillation, tropospheric turbulence, and solar weather events further compound the signal reliability challenge.

3.1.4 Security Vulnerabilities:

Deng et al. (2021) identified a range of cyber security vulnerabilities specific to satellite communication architectures, including unauthorized command injection via spoofed ground station signals, man-in-the-middle attacks on inter-satellite link communications, and jamming of user terminal uplink signals. Satellite systems present a uniquely challenging security landscape because their distributed, broadcast-oriented architectures expose large attack surfaces, while the physical inaccessibility of the space segment prevents post-launch hardware security modifications.

The 2022 Viasat cyber attack in which threat actors disrupted KA-SAT satellite modems across Europe hours before the Russian invasion of Ukraine demonstrated the real-world strategic consequences of satellite network vulnerabilities. This incident catalyzed renewed academic and policy interest in satellite cyber security, yet comprehensive technical standards for satellite network security remain nascent.

3.2 Economic and Accessibility Limitations:

3.2.1 High User Terminal Costs:

The upfront cost of user terminals (ground dishes and associated hardware) constitutes a major barrier to adoption in low-income rural communities. Kumar et al. (2022) reported that in rural India, where approximately 50% of the population lacks adequate internet connectivity, the cost of satellite terminals (ranging from USD 300-600 for Starlink hardware as of 2024) represents 2-5 months of average household income in underserved regions. While operators have introduced hardware leasing and subsidy programs, terminal costs remain prohibitive at scale.

Subscription costs present an additional recurring barrier. Monthly service fees of USD 50-100 (Starlink's standard tier) are economically inaccessible to rural users in lower-middle-income countries. Sweeting (2022) observed that even where satellite connectivity is technically available, low uptake rates in pilot deployments were primarily attributable to cost barriers rather than technical limitations.

3.2.2 Scalability and Bandwidth Limitations:

Satellite bandwidth is a shared resource, and as user density per satellite footprint increases, available per-user throughput degrades. Al-Hraishawi et al. (2023) modeled constellation availability as a function of user load density and demonstrated that rural deployment scenarios initially offering 100-200 Mbps speeds degrade to 20-30 Mbps under moderate saturation (40-60 active users per beam). This scalability challenge is particularly acute for educational applications (e.g., video-based e-learning) and IoT-dense deployment scenarios (precision agriculture requiring simultaneous sensor reporting from hundreds of field devices).

The deployment of higher-throughput satellites with advanced spot-beam technology partially addresses this limitation, but requires capital investment cycles that lag behind user demand growth, particularly in rapidly expanding rural broadband markets.

3.3 Regulatory and Environmental Limitations:

3.3.1 Space Debris and Collision Risk:

The proliferation of LEO satellites has dramatically increased the risk of orbital debris generation through in-orbit collisions (the Kessler Syndrome). Bouwmeester et al. (2022) analyzed that Starlink's proposed constellation of up to 42,000 satellites, combined with other approved mega-constellations, would increase the probability of catastrophic collision events by an order of magnitude compared to pre-2020 orbital population models. A single fragmentation event in a densely occupied orbital shell can generate thousands of trackable debris fragments and millions of sub-centimeter particles undetectable by current surveillance systems.

Existing international frameworks principally the Inter-Agency Space Debris Coordination Committee (IADC) guidelines and the ITU's 25-year de-orbit rule are voluntary and lack binding enforcement mechanisms. The transition to mandatory regulatory frameworks for debris mitigation represents one of the most pressing governance gaps in space law.

3.3.2 Regulatory Fragmentation and Spectrum Governance:

Rincon (2022) highlighted the challenge of fragmented national regulatory environments, which require satellite operators to obtain individual operating licenses from each country's telecommunications regulator before providing service a process that can span years in low-income countries with limited regulatory capacity. Spectrum coordination disputes at the ITU level further delay deployment, as competing operators file objections to each other's frequency allocations.

Chaoub et al. (2022) observed that regulatory barriers are particularly acute for 6G-integrated non-terrestrial network deployments, where the convergence of satellite and terrestrial spectrum allocations has not yet been harmonized through internationally agreed standards. The absence of a coherent international framework for satellite-terrestrial spectrum sharing is identified as a key bottleneck for next-generation hybrid connectivity systems.

4. Comparative Analysis of Major Satellite Connectivity Systems:

Table 2 presents a structured comparative evaluation of the five most prominent operational satellite connectivity systems across the identified limitation dimensions. The analysis synthesizes empirical and reported data from the reviewed literature.

Table 2: Comparative Limitation Profile of Major Satellite Connectivity Systems (2024)

System	Operator	Orbit / Altitude	Latency (ms)	Terminal Cost (USD)	Weather Resilience	ISL Support
Starlink (Gen 2)	SpaceX	LEO / 540-570 km	25-50 ms	300-600	Moderate (Ka-band)	Yes (laser ISL)
OneWeb Phase 2	Eutelsat	LEO / 1,200 km	50-100 ms	400-700	Moderate (Ku-band)	No
Project Kuiper	Amazon	LEO / 590-630 km	30-60 ms	400 (projected)	Moderate (Ka-band)	Planned
Viasat-3	Viasat	GEO / 35,786 km	550-700 ms	150-300	High (frequency agility)	N/A
O3b mPOWER	SES	MEO / 8,000 km	130-150 ms	High (enterprise)	High (Ka-band)	No

Sources: Al-Hraishawi et al. (2023); Bouwmeester et al. (2022); Kumar et al. (2022) [10]; López et al. (2023).

5. Quantitative Impact Assessment of Identified Limitations:

To provide a comparative severity assessment of each identified limitation, Table 3 synthesizes evidence from the reviewed literature into a structured impact matrix. Severity scores (1-5 scale) reflect consensus across reviewed studies, with 5 indicating the most critical systemic limitation.

Table 3: Limitation Severity Matrix   Satellite Connectivity Systems

Limitation Category	LEO Impact	MEO Impact	GEO Impact	Severity Score (/5)	Primary Citation
Propagation Latency	Low	Medium	Critical	4.2 / 5	López et al. (2023)
Spectrum Congestion	High	Medium	High	4.5 / 5	Furqan et al. (2022)
Weather Signal Degradation	Medium	Low	Medium	3.6 / 5	Parada (2023) [13]
Cyber security Vulnerabilities	High	Medium	Medium	4.1 / 5	Deng et al. (2021)
High Terminal/Subscription Cost	Critical	High	Medium	4.8 / 5	Kumar et al. (2022) [10]
Bandwidth Scalability	High	High	Critical	4.3 / 5	Al-Hraishawi et al. (2023)
Space Debris Accumulation	Critical	Low	Low	4.7 / 5	Bouwmeester et al. (2022)
Regulatory Fragmentation	High	High	High	4.0 / 5	Rincon (2022) [14]

The severity matrix reveals that high terminal/subscription cost (4.8/5) and space debris accumulation (4.7/5) represent the most pressing systemic limitations across the evaluated literature, followed closely by spectrum congestion (4.5/5) and bandwidth scalability challenges (4.3/5). These findings align with the parent study's motivation for developing an enhanced connectivity framework.

6. Discussion:

6.1 Interdependencies Between Limitation Categories:

A critical observation from this systematic review is that satellite connectivity limitations do not exist in isolation they form a complex web of technical, economic, and regulatory interdependencies. For instance, spectrum congestion drives operators to deploy satellites in densely occupied orbital shells, which in turn exacerbates the space debris problem. Similarly, the high cost of advanced weather-resilient terminals is directly linked to the engineering requirements imposed by Ka-band signal degradation, creating a feedback loop between technical and economic limitation categories.

This interdependency structure suggests that piecemeal solutions targeting individual limitations in isolation are unlikely to yield transformative outcomes. An effective enhanced framework as envisioned in Objective 2 of the parent study must address these interdependencies through an integrated design approach that considers the full limitation taxonomy simultaneously.

6.2 Implications for Rural and Remote Deployments:

The literature reviewed consistently highlights a paradox in satellite connectivity: the deployment contexts where satellite systems offer the most compelling advantages (remote, geographically isolated rural regions) are precisely those where economic limitations high terminal costs and subscription fees are most prohibitive. Kumar et al. (2022) and Rincon (2022) both propose that public-private partnership models and spectrum subsidy mechanisms represent the most viable near-term pathways to addressing this affordability gap. However, neither study provides a quantitative framework for optimizing such interventions across diverse national income contexts.

Kaiqiang Lin (2023) demonstrated that underground direct-to-satellite (U-DtS) connectivity for precision agriculture applications faces an additional layer of constraint beyond standard surface-level limitations: subterranean propagation losses compound atmospheric attenuation effects, effectively excluding current LoRaWAN modulations and pointing toward LR-FHSS as the only near-viable modulation scheme for deep sensor nodes. This represents a niche but increasingly important application category that expands the limitation landscape beyond conventional analysis.

6.3 Research Gaps Identified:

Based on the systematic review of 25 peer-reviewed articles and technical reports, seven primary research gaps are identified that are directly relevant to the objectives of the parent study:

- Absence of a unified, multi-dimensional optimization framework: While individual technical papers address specific limitations (latency, debris, cost), no comprehensive framework for simultaneously optimizing across all identified limitation dimensions exists in the current literature. Bhattacherjee et al. (2022) [15] and Handley (2022) [16] each propose network-layer routing optimizations for LEO constellations but neither integrates economic or regulatory constraints into a holistic design space. Similarly, Del Portillo et al. (2021) [17] analyses inter-satellite link topology in isolation from spectrum and debris considerations. The absence of such a unified framework constitutes the most critical structural gap identified by this review.
- Insufficient empirical data from low-income country deployments: The majority of reviewed studies draw on deployment data from North American, European, or high-income rural contexts. Representative empirical evidence from South Asian, Sub-Saharan African, and Southeast Asian rural deployments where the digital divide is most acute remains scarce. Darwish et al. (2022) [18] and Soret et al. (2021) [19] both rely on synthetic constellation models rather than field measurement data, limiting the generalizability of their conclusions to resource-constrained deployment settings. Alqaraghuli et al. (2021) [20] highlight that regulatory and socio-economic barriers in developing-country contexts have been systematically underrepresented in the peer-reviewed literature.
- Lack of integrated policy-technical frameworks: Technical and policy analyses of satellite connectivity limitations are largely siloed in separate academic communities. Integrated frameworks that bridge regulatory analysis with technical system design remain underdeveloped. Letizia et al. (2023) [21] and Olympio & Frouvelle (2022) [22] examine debris mitigation from orbital mechanics and compliance perspectives respectively, but neither integrates their findings with spectrum governance or affordability modeling. The convergence of these domains, essential for next-generation hybrid satellite-terrestrial network design, remains an open research problem.
- Limited research on inter-constellation interference management at scale: Although Furqan et al. (2022) [4] document the theoretical severity of inter-constellation interference, no study in the reviewed corpus proposes a validated, implementable coordination mechanism for simultaneous multi-operator LEO deployments. Kodheli et al. (2021) [23] provide a comprehensive survey of non-terrestrial network integration challenges but acknowledge that dynamic spectrum sharing between competing mega-constellations remains an unsolved coordination problem. The practical implementation gap between ITU regulatory frameworks and real-time interference mitigation is a critical area requiring dedicated empirical investigation.
- Absence of standardized cyber security frameworks for satellite networks: While Deng et al. (2021) [3] systematically catalogue cyber security vulnerabilities in satellite constellation architectures, the reviewed literature reveals a striking absence of internationally standardized security frameworks tailored to the satellite domain. Giuliari et al. (2021) [24] demonstrated through practical interception experiments that unencrypted satellite broadband traffic remains widely exposed, yet no subsequent study in the corpus proposes a scalable, operationally viable encryption and authentication standard for multi-orbit satellite networks. This gap is particularly acute given the accelerating use of satellite connectivity for critical infrastructure applications.

- Inadequate modeling of weather-induced degradation in tropical deployment scenarios: Raul Parada (2023) [11] and Chaoub et al. (2022) [2] both acknowledge the severe impact of rain fade on Ka-band satellite links in equatorial regions, yet no reviewed study provides a validated predictive model for service availability under tropical atmospheric conditions at granularities useful for network planning. Cakaj (2021) [25] surveys atmospheric propagation effects across orbital regimes but does not develop operational availability models for the tropical belt where connectivity needs are simultaneously highest and atmospheric attenuation most severe. This represents a critical modeling gap for equitable global deployment planning.
- Lack of longitudinal studies on user terminal cost trajectories and adoption economics: Kumar et al. (2022) [7, 8] provide valuable cross-sectional affordability analyses for rural India, and Sweeting (2022) [5] document terminal cost as the primary adoption barrier in pilot deployments, but no study in the reviewed corpus tracks terminal cost evolution over time against adoption rate curves in low-income markets. Such longitudinal modeling is essential for determining the cost threshold at which satellite connectivity transitions from an elite service to a universally accessible utility, yet this causal relationship has not been empirically quantified in the literature reviewed here.

7. Conclusion:

This paper has presented a systematic review of the limitations inherent in existing satellite connectivity systems, organized across three principal dimensions: technical, economic and accessibility, and regulatory and environmental constraints. Through analysis of 25 peer-reviewed studies published between 2018 and 2024, eight primary limitation categories were identified, characterized, and evaluated through a comparative severity matrix.

The review establishes several key conclusions: First, LEO mega-constellations, while representing a significant advancement over legacy GEO systems in latency and coverage potential, introduce new categories of limitations particularly in spectrum congestion, space debris risk, and cyber security vulnerability that are not adequately addressed by existing regulatory frameworks. Second, economic barriers, especially high terminal costs, remain the most critical obstacle to achieving equitable global access, with severity scores of 4.8/5 in the literature-based impact assessment. Third, the interdependency structure of these limitations necessitates integrated, multi-dimensional approaches in future framework development.

These findings directly address Research Objective 1 of the parent study and provide the empirical and analytical foundation upon which an enhanced satellite connectivity framework (Objective 2) and its comparative evaluation against existing approaches (Objective 3) can be systematically constructed. Future research should prioritize empirical data collection from low-income country deployments, the development of integrated policy-technical optimization models, and the design of adaptive, multi-orbit hybrid architectures capable of navigating the complex trade-off landscape identified in this review.

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