

Dynamic LEO Satellite Communication Systems for 6G Networks: A Survey of Modeling Techniques and Performance Evaluation

Prateek Anand

M Tech Scholar

Dept. of Electronics and Communication
Oriental Institute of Science and Technology, Bhopal, India

Rishi Sharma

Asst. Professor

Dept. of Electronics and Communication
Oriental Institute of Science and Technology, Bhopal, India

Abstract- The rapid evolution toward sixth-generation (6G) wireless communication networks has accelerated the integration of Non-Terrestrial Networks (NTNs) with terrestrial communication infrastructures to achieve seamless global connectivity, ultra-low latency, and high data rates. Among various NTN technologies, Low Earth Orbit (LEO) satellite communication systems have emerged as a promising solution due to their low propagation delay, high throughput capability, and extensive worldwide coverage. Modern LEO mega-constellations such as Starlink and OneWeb demonstrate the practical feasibility of satellite-assisted broadband communication for future intelligent networks. However, the high mobility of LEO satellites introduces several challenges including severe Doppler shifts, dynamic channel variations, frequent handovers, interference management, and resource allocation complexity.

This survey paper presents a comprehensive review of recent advancements in LEO satellite communication systems for 6G networks. The paper discusses the architecture of LEO-enabled NTN systems, orbital dynamics, Doppler-aware channel modeling, mobility management techniques, handover optimization strategies, and integration with terrestrial 6G infrastructures. Furthermore, MATLAB-based simulation methodologies for modeling satellite movement, user mobility, time-varying channels, and link performance are explored in detail. A comparative analysis of recent literature is also presented based on performance metrics such as latency, throughput, packet delivery ratio, handover delay, spectral efficiency, and Doppler impact. The survey identifies major research gaps including real-time Doppler compensation, AI-driven mobility management, intelligent beamforming, and integrated NTN-terrestrial resource optimization. Finally, future research directions and a proposed framework for dynamic LEO satellite communication system evaluation are discussed to support the development of reliable and scalable 6G communication networks.

Keywords: 6G, LEO satellites, Non-Terrestrial Networks (NTN), Doppler shift, MATLAB simulation, mobility management, handover optimization, satellite communication etc.

I. INTRODUCTION

The exponential growth of wireless devices, Internet of Things (IoT) applications, autonomous systems, immersive multimedia services, and intelligent transportation networks has accelerated the development of sixth-generation (6G) wireless communication systems. Future 6G networks are expected to provide ultra-high data rates, massive connectivity, ultra-low latency, high reliability, and seamless global coverage beyond the capabilities of existing fifth-generation (5G) systems [1]. However, terrestrial communication infrastructures alone are insufficient to provide reliable connectivity in rural areas, maritime regions, deserts, mountainous terrains, and disaster-affected environments. To overcome these limitations, researchers and industries are increasingly focusing on the integration of Non-Terrestrial Networks (NTNs) with terrestrial wireless systems [2].

Among various NTN technologies, Low Earth Orbit (LEO) satellite communication systems have emerged as one of the

most promising solutions for future 6G communication networks. LEO satellites operate at altitudes ranging from approximately 500 km to 2000 km above the Earth's surface, significantly reducing propagation delay compared to Geostationary Earth Orbit (GEO) satellites positioned at around 36,000 km [3]. Due to their lower altitude, LEO satellite systems can provide end-to-end latency in the range of 20–50 ms, making them suitable for delay-sensitive applications such as autonomous driving, telemedicine, augmented reality, remote industrial automation, and emergency communication systems [4].

Recent advancements in satellite technology and reusable launch systems have accelerated the deployment of large-scale LEO mega-constellations. Companies such as Starlink, OneWeb, Amazon Kuiper, and Telesat Lightspeed are actively developing broadband satellite networks capable of supporting global internet connectivity [5]. These satellite constellations utilize hundreds or even thousands of interconnected satellites equipped with advanced phased-array antennas, inter-satellite links (ISLs), onboard processing capabilities, and adaptive beamforming technologies [6]. Such developments are transforming satellite communication from conventional broadcasting systems into dynamic broadband communication infrastructures suitable for 6G applications.

Despite the significant advantages offered by LEO satellite systems, several technical challenges remain unresolved. One of the primary challenges is the high orbital velocity of LEO satellites, which can exceed 7.5 km/s. This rapid movement introduces severe Doppler frequency shifts, frequent beam switching, and continuous handover events between satellites and ground terminals [7]. The Doppler effect can significantly impact synchronization, carrier frequency recovery, channel estimation, and communication reliability, especially at high-frequency bands such as Ka-band and millimeter-wave frequencies [8].

The Doppler shift generated in LEO satellite communication systems can be expressed as:

$$f_d = \frac{v}{c} f_c \cos(\theta)$$

where (f_d) represents the Doppler frequency shift, (v) denotes the relative velocity between the satellite and user terminal, (c) is the speed of light, (f_c) is the carrier frequency, and (θ) is the elevation angle between the satellite and the receiver [9]. Accurate Doppler compensation techniques are therefore essential for maintaining reliable communication links in highly dynamic satellite environments.

Another major challenge in LEO satellite communication systems is mobility management and handover optimization. Unlike terrestrial cellular networks, handovers in LEO systems occur primarily due to satellite movement rather than user

mobility. As satellites continuously move across orbital paths, user terminals frequently switch communication links between adjacent satellites and spot beams [10]. Inefficient handover mechanisms may result in increased signaling overhead, packet loss, latency, and service interruption. Consequently, intelligent handover algorithms based on Artificial Intelligence (AI), Machine Learning (ML), and Deep Reinforcement Learning (DRL) are being actively investigated to improve network performance and Quality of Service (QoS) [11].

Channel modeling in LEO satellite communication systems is also considerably more complex than terrestrial wireless communication. Time-varying propagation characteristics, atmospheric attenuation, rain fading, shadowing effects, and dynamic line-of-sight conditions significantly influence communication performance [12]. Furthermore, the integration of satellite communication with terrestrial 6G infrastructures introduces additional challenges related to interference management, spectrum sharing, resource allocation, synchronization, and network orchestration [13].

To address these challenges, simulation and modeling tools such as MATLAB and Simulink are extensively used for analyzing orbital dynamics, Doppler effects, user mobility, handover performance, and link budget evaluation in LEO satellite networks. MATLAB provides flexible frameworks for implementing satellite orbit generation, time-varying channel models, adaptive beamforming algorithms, and performance evaluation metrics including throughput, latency, Signal-to-Noise Ratio (SNR), packet delivery ratio, and spectral efficiency [14].

This survey paper presents a comprehensive review of LEO satellite communication systems for 6G networks with emphasis on system architectures, Doppler-aware channel modeling, mobility management, handover optimization, and MATLAB-based simulation methodologies. Additionally, the paper provides a comparative analysis of recent research contributions, identifies major research gaps, and discusses future directions for developing reliable and scalable satellite-assisted 6G communication systems.

II. LITERATURE SURVEY

Recent advancements in sixth-generation (6G) wireless communication systems have accelerated the development of Low Earth Orbit (LEO) satellite communication technologies to achieve seamless global connectivity, ultra-low latency, and high data throughput. Researchers have extensively investigated Non-Terrestrial Networks (NTNs), dynamic channel modeling, Doppler compensation, mobility management, beamforming techniques, and AI-driven handover optimization for integrating LEO satellite systems with terrestrial 6G infrastructures.

K. Ntontin et al. [15] presented a comprehensive vision and roadmap toward space communications in the 6G and beyond era. The authors discussed the integration of satellite networks with terrestrial communication systems and highlighted the importance of intelligent network orchestration, inter-satellite links (ISLs), and software-defined satellite communication architectures. The study emphasized the role of artificial intelligence and machine learning in future satellite communication systems. However, the work mainly focused on architectural perspectives and provided limited analysis of

Doppler-aware communication and dynamic mobility management.

E. Lagunas, S. Chatzinotas, and B. Ottersten [16] investigated the role of Low Earth Orbit satellite constellations in providing global communication network connectivity. Their work analyzed the advantages of LEO systems including reduced propagation delay, high-speed communication, and extensive worldwide coverage compared to traditional Geostationary Earth Orbit (GEO) systems. The authors also discussed deployment challenges associated with mega-constellations such as interference management, scalability, and spectrum sharing. However, detailed MATLAB-based simulation models and adaptive handover mechanisms were not considered in the study.

W. Zhang [17] proposed a two-ray channel model with Doppler effects for LEO satellite communications. The study focused on analyzing Doppler frequency shifts and their impact on communication reliability under dynamic satellite movement conditions. The author developed channel models considering antenna characteristics, elevation angles, and time-varying propagation effects. The results indicated that adaptive antenna tracking significantly improves communication performance in high-mobility environments. Nevertheless, the research mainly concentrated on physical layer channel modeling without considering network-level mobility management and handover optimization.

A. Guidotti et al. [18] discussed key technical challenges associated with satellite integration into future wireless communication systems. The authors highlighted major issues related to synchronization, interference mitigation, propagation delay, resource allocation, and interoperability between terrestrial and satellite networks. Their study emphasized the need for efficient channel modeling and adaptive resource management strategies to support next-generation communication systems. However, the work lacked detailed implementation methodologies and real-time simulation analysis for LEO satellite systems.

The study presented in [19] investigated inter-beam handover schemes for LEO satellites in integrated 5G satellite-terrestrial networks. The authors analyzed handover probability, user mobility patterns, and beam switching mechanisms under dynamic communication environments. Simulation results demonstrated that efficient handover strategies significantly reduce packet loss and service interruption probability. However, the proposed framework did not utilize artificial intelligence or machine learning techniques for adaptive decision-making in highly dynamic scenarios.

S. Seeram et al. [20] explored handover challenges in disaggregated Open Radio Access Network (O-RAN) architectures for LEO satellite systems. The study focused on the trade-off between onboard processing complexity and handover latency in dynamic satellite communication environments. The authors showed that edge processing and onboard intelligence can considerably improve handover performance and reduce communication delays. Despite these advantages, the proposed architecture introduced additional computational complexity and increased implementation costs.

M. Mendonça et al. [21] proposed a Deep Q-Learning-based handover framework for spectral coexistence between feeder

and user links in LEO satellite networks. The authors utilized Deep Reinforcement Learning (DRL) algorithms to optimize handover decisions and minimize interference under varying traffic conditions. Simulation results demonstrated improvements in spectral efficiency, packet delivery ratio, and handover reliability compared to traditional approaches. However, the proposed DRL-based system required extensive training datasets and high computational resources for practical deployment.

J. Wu et al. [22] introduced an accelerated handover mechanism for mobile satellite communication systems. The study proposed predictive synchronization and mobility-aware handover techniques to minimize service interruption during satellite switching operations. Experimental results showed substantial reductions in handover latency and packet loss. However, the proposed solution was evaluated mainly under prototype conditions and lacked large-scale network implementation analysis.

F. Wang et al. [23] discussed the evolution and future directions of Non-Terrestrial Networking for 6G systems. The authors emphasized the importance of integrated terrestrial-space-air-sea communication architectures for achieving ubiquitous connectivity and ultra-reliable communication services. Their work also explored future technologies including AI-enabled network optimization, satellite edge computing, intelligent beamforming, and digital twin-based NTN simulation frameworks. However, practical implementation strategies and real-world validation remained limited.

A. Ramírez-Arroyo et al. [24] conducted a measurement-driven assessment of Starlink and OneWeb Non-Terrestrial

Networks integrated with terrestrial 5G systems. The authors analyzed real-world performance metrics including latency, throughput, packet loss, and communication reliability under practical deployment conditions. The study demonstrated that LEO satellite systems can provide low-latency broadband communication suitable for future 6G applications. Nevertheless, issues related to real-time Doppler compensation and efficient mobility management under dense user conditions still require further investigation.

Recent studies indicate that LEO satellite communication systems have significant potential for enabling future 6G communication networks. Existing research primarily focuses on NTN integration, Doppler-aware channel modeling, mobility management, handover optimization, and AI-driven communication techniques. However, several research gaps still exist, including real-time adaptive Doppler compensation, low-complexity intelligent handover mechanisms, integrated MATLAB-Simulink simulation frameworks, energy-efficient satellite communication architectures, and efficient beam tracking techniques for highly dynamic communication environments.

TABLE 1. Comparative Analysis of Existing Literature on LEO Satellite Communication Systems for 6G Networks.

Author(s)	Technique Used	Parameters Used	Major Contribution	Limitations
K. Ntontin et al. (2025) [15]	Survey and roadmap analysis for 6G space communication	Scalability, NTN integration, ISLs, network architecture	Proposed comprehensive roadmap for integrating space communication with 6G networks	Limited practical implementation and Doppler analysis
E. Lagunas, S. Chatzinotas, and B. Ottersten (2024) [16]	LEO constellation communication analysis	Coverage, latency, throughput, scalability	Demonstrated advantages of LEO constellations for global broadband communication	Lack of mobility management and handover optimization
W. Zhang (2024) [17]	Two-ray Doppler-aware channel modeling	Doppler shift, fading, antenna gain, elevation angle	Developed Doppler-aware channel model for dynamic LEO communication	No network-level performance or handover analysis
A. Guidotti et al. (2019) [18]	Satellite-terrestrial integrated architecture analysis	Synchronization, interference, propagation delay, resource allocation	Identified key challenges in integrating satellites with future wireless systems	Limited real-time simulation framework
Physical Communication Study (2024) [19]	Inter-beam handover scheme using mobility models	Handover probability, QoS, packet loss, beam switching	Reduced service interruption and improved handover efficiency	No AI-based adaptive optimization
S. Seeram et al. (2025) [20]	Open RAN-based handover optimization	Handover delay, onboard processing, latency	Improved handover performance using onboard intelligence	Increased computational complexity
M. Mendonça et al. (2025) [21]	Deep Q-Learning-based handover optimization	Spectral efficiency, packet delivery ratio, interference	Enhanced handover reliability using Deep Reinforcement Learning	Requires extensive training data and computational resources

J. Wu et al. (2024) [22]	Predictive synchronization and accelerated handover	Handover latency, packet loss, synchronization delay	Achieved faster handover with reduced service interruption	Prototype-level validation only
F. Wang et al. (2024) [23]	NTN evolution and AI-enabled networking framework	Connectivity, AI optimization, edge computing	Proposed integrated terrestrial-space-air-sea communication framework	Limited experimental implementation
A. Ramírez-Arroyo et al. (2025) [24]	Measurement-driven performance assessment	Throughput, latency, packet loss, reliability	Evaluated practical performance of Starlink and OneWeb systems	Limited Doppler compensation and mobility analysis

III. PROBLEM IDENTIFICATION AND RESEARCH GAP

The rapid growth of sixth-generation (6G) wireless communication systems has increased the demand for global, high-speed, low-latency, and highly reliable communication infrastructures. Low Earth Orbit (LEO) satellite communication systems are emerging as an important component of Non-Terrestrial Networks (NTNs) due to their capability to provide worldwide coverage, reduced propagation delay, and broadband communication services. Modern LEO mega-constellations such as Starlink and OneWeb demonstrate the practical feasibility of satellite-assisted communication for future intelligent

networks. However, several technical challenges still limit the efficient integration of LEO satellite systems with 6G communication architectures.

One of the major problems in LEO satellite communication systems is the high orbital velocity of satellites, which produces significant Doppler frequency shifts and rapidly varying channel conditions. These Doppler effects severely affect carrier synchronization, channel estimation, signal detection, and communication reliability, particularly at higher frequency bands such as Ka-band and millimeter-wave frequencies. Existing Doppler compensation techniques are often computationally complex and may not provide accurate real-time adaptation under highly dynamic communication scenarios.

Another important issue is frequent handover occurrence caused by continuous satellite movement. Unlike terrestrial communication systems where handovers mainly depend on user mobility, LEO satellite systems require constant switching between satellites and spot beams even for stationary users. Frequent handovers increase signaling overhead, packet loss probability, latency, and service interruption. Current handover mechanisms still face challenges related to adaptive decision-making, efficient mobility prediction, and seamless communication continuity in dense user environments.

Dynamic channel modeling is also a critical challenge in LEO satellite communication systems. Existing channel models often consider simplified assumptions and fail to accurately

represent real-world propagation conditions including atmospheric attenuation, rain fading, shadowing effects, beam misalignment, and time-varying mobility conditions. Furthermore, most existing studies focus either on physical layer channel analysis or network-level performance independently, resulting in insufficient cross-layer optimization for practical NTN deployments.

Artificial Intelligence (AI) and Machine Learning (ML)-based optimization techniques have recently been introduced for mobility management, beamforming, and resource allocation in satellite communication systems. However, many AI-based approaches require extensive training datasets, high computational resources, and large processing overhead, making real-time implementation difficult in practical LEO satellite environments. Additionally, the integration of AI-enabled algorithms with MATLAB-based dynamic simulation frameworks remains limited.

Another major research problem is the lack of comprehensive MATLAB-Simulink-based frameworks capable of jointly modeling orbital dynamics, Doppler effects, user mobility, handover mechanisms, and communication performance under realistic LEO satellite communication scenarios. Most existing works evaluate only specific parameters such as throughput, latency, or Doppler shift independently rather than providing an integrated system-level performance evaluation.

Based on the literature survey, several important research gaps have been identified:

A. Existing Doppler compensation methods are insufficient for highly dynamic and high-frequency LEO communication environments.

B. Limited research has been conducted on low-complexity adaptive handover mechanisms for seamless mobility management.

C. Most channel models do not accurately represent real-time dynamic propagation characteristics in practical LEO satellite systems.

D. AI-based optimization techniques require high computational complexity and lack real-time implementation feasibility.

E. Integrated MATLAB-Simulink simulation frameworks for joint evaluation of orbital dynamics, Doppler effects, mobility, and handover performance are still limited.

F. Efficient beam tracking and interference management techniques for dense LEO mega-constellations remain underdeveloped.

G. Existing research provides limited experimental validation using practical Starlink and OneWeb communication scenarios.

H. Energy-efficient and sustainable satellite communication techniques for future green 6G networks require further investigation.

Therefore, there is a strong need to develop an intelligent and comprehensive MATLAB-based LEO satellite communication framework capable of modeling dynamic satellite movement, Doppler-aware communication, adaptive handover optimization, and realistic NTN-terrestrial integrated communication scenarios. The proposed work aims to address these research gaps by developing a dynamic simulation model for evaluating latency, throughput, Doppler impact, packet delivery ratio, and handover performance in next-generation 6G LEO satellite communication systems.

IV. LEO SATELLITE COMMUNICATION ARCHITECTURE FOR 6G NETWORKS

Low Earth Orbit (LEO) satellite communication systems are expected to become one of the major enabling technologies for

sixth-generation (6G) wireless communication networks due to their capability to provide global connectivity, low propagation delay, high data rates, and reliable broadband communication services. Unlike traditional Geostationary Earth Orbit (GEO) satellites, LEO satellites operate at lower orbital altitudes ranging from approximately 500 km to 2000 km above the Earth's surface, significantly reducing end-to-end communication latency and improving communication efficiency [25].

The architecture of LEO satellite communication systems for 6G networks mainly consists of three major segments: the space segment, the ground segment, and the user segment. The space segment includes multiple interconnected LEO satellites organized into mega-constellations capable of providing continuous global coverage. These satellites are generally equipped with advanced phased-array antennas, regenerative payloads, onboard processing units, and inter-satellite links (ISLs) for high-speed communication between satellites [26]. Modern mega-constellations such as Starlink and OneWeb utilize thousands of satellites operating in coordinated orbital planes to achieve uninterrupted communication coverage across the globe [27].

The ground segment consists of gateway stations, network operation centers, terrestrial base stations, and satellite control centers responsible for traffic routing, network management, synchronization, and resource allocation. Gateway stations serve as communication interfaces between satellite networks and terrestrial communication infrastructures [28]. In future 6G systems, intelligent edge computing and cloud-assisted processing are expected to play an important role in optimizing communication performance and reducing latency in satellite-terrestrial integrated networks.

The user segment includes mobile users, IoT devices, autonomous vehicles, maritime communication systems, airborne communication terminals, and handheld satellite-enabled devices. Future 6G-enabled user equipment will support direct satellite-to-device communication for achieving seamless connectivity even in remote and underserved areas [29].



Fig 1 A typical LEO satellite communication architecture for 6G networks

One of the important features of LEO satellite systems is the use of inter-satellite links (ISLs), which enable satellites to communicate directly with neighboring satellites without routing traffic through ground stations. ISLs significantly reduce communication delay and improve routing efficiency in global communication networks [30]. Optical inter-satellite communication technologies are also being

investigated to support ultra-high-speed data transmission in future 6G NTN architectures.

Beamforming and beam steering technologies are critical components of LEO satellite communication architectures. Satellites dynamically generate multiple spot beams to efficiently allocate communication resources and improve spectral efficiency [31]. Adaptive beam management techniques help maintain reliable communication links under high mobility conditions and varying traffic demands.

Despite the advantages of LEO satellite architectures, several technical challenges still exist. High orbital velocity causes frequent topology changes, dynamic link variations, and complex mobility management issues. Additionally, efficient spectrum sharing, interference mitigation, synchronization, and energy-efficient communication remain important research areas in satellite-assisted 6G systems [32].

Therefore, the development of intelligent and adaptive LEO satellite communication architectures is essential for supporting next-generation 6G communication requirements including ultra-reliable low-latency communication (URLLC), massive machine-type communication (mMTC), and enhanced mobile broadband (eMBB).

V. DOPPLER EFFECTS AND MOBILITY MANAGEMENT IN LEO SATELLITE NETWORKS

One of the major challenges in Low Earth Orbit (LEO) satellite communication systems is the high relative velocity between satellites and ground users, which introduces severe Doppler frequency shifts and dynamic mobility management problems. Since LEO satellites move at speeds exceeding 7.5 km/s, the communication links continuously experience rapid variations in frequency, propagation delay, and channel characteristics [33]. These effects significantly influence synchronization, carrier recovery, signal detection, and communication reliability in future 6G satellite communication systems.

At higher carrier frequencies such as Ka-band and millimeter-wave bands, Doppler shifts become more severe and can significantly degrade communication performance [34]. Accurate Doppler estimation and compensation techniques are therefore essential for maintaining reliable communication links in highly dynamic satellite environments.

Several researchers have proposed Doppler-aware channel models for analyzing time-varying propagation characteristics in LEO satellite systems. Two-ray channel models, stochastic fading models, and adaptive channel estimation techniques are widely used for evaluating communication reliability under varying orbital conditions [35]. Adaptive antenna tracking and beam steering methods have also been introduced to minimize Doppler-induced communication degradation.

Mobility management is another critical issue in LEO satellite communication networks. Unlike terrestrial communication systems, handovers in LEO satellite systems occur primarily due to satellite movement rather than user mobility [36]. As satellites continuously move across orbital paths, user terminals frequently switch communication links between neighboring satellites and spot beams. Frequent and overs increase signaling overhead, packet loss, latency, and service interruption probability.

Efficient mobility management techniques are required to ensure seamless connectivity and uninterrupted communication services. Recent studies have introduced Artificial Intelligence (AI) and Machine Learning (ML)-based handover optimization methods for improving Quality of Service (QoS) and reducing handover latency [37]. Deep Reinforcement Learning (DRL)-based approaches dynamically predict user mobility and optimize handover decisions under varying traffic conditions.

Predictive mobility management techniques using user trajectory estimation and satellite visibility prediction have

also been proposed to minimize unnecessary handovers and improve communication reliability [38]. Furthermore, edge-assisted processing and onboard intelligence are being investigated for reducing communication delays and enabling autonomous network management in future 6G satellite systems.

Although significant progress has been achieved in Doppler compensation and mobility optimization, several challenges remain unresolved. Real-time Doppler estimation under ultra-high mobility conditions, low-complexity adaptive handover algorithms, and efficient beam tracking techniques continue to be major research challenges in LEO satellite communication systems.

The integration of NTN with terrestrial communication systems aims to overcome coverage limitations of conventional cellular networks and support communication in remote, rural, maritime, and disaster-affected regions [40]. Future 6G communication systems are expected to utilize integrated terrestrial-space-air-sea architectures for achieving seamless global connectivity and ultra-reliable communication services.

3GPP Release 17 and beyond have introduced NTN support for future wireless communication systems. These standards focus on satellite-based communication, mobility management, synchronization mechanisms, and interoperability between terrestrial and non-terrestrial communication infrastructures [41].

HANDOVER MANAGEMENT IN LEO SATELLITE SYSTEMS

Handover management ensures seamless connectivity as satellites, beams, gateways and orbits change.

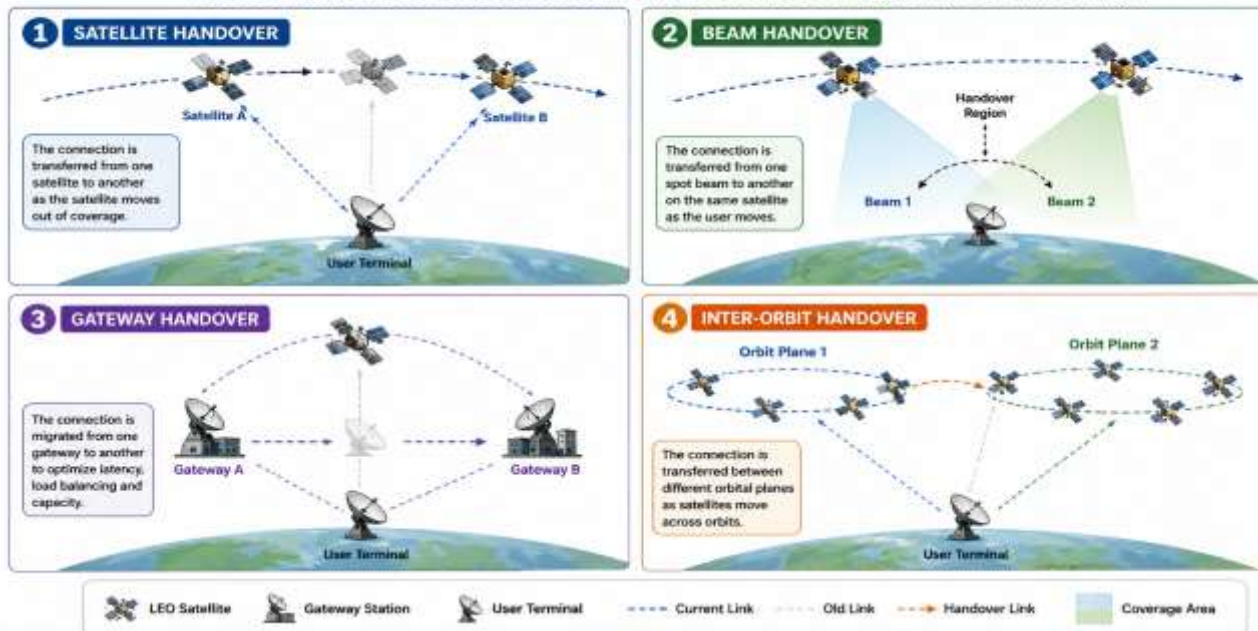


Fig 2 Handover Management

VI. NON-TERRESTRIAL NETWORK (NTN) INTEGRATION IN 6G SYSTEMS

Non-Terrestrial Networks (NTNs) are emerging as a fundamental component of sixth-generation (6G) wireless communication systems due to their capability to provide ubiquitous connectivity, extended coverage, and resilient communication services. NTNs integrate satellite communication systems, aerial platforms, unmanned aerial vehicles (UAVs), high-altitude platform stations (HAPS), and terrestrial communication infrastructures into a unified communication framework [39]. Among these technologies, LEO satellite systems play a major role in enabling global broadband communication and supporting future intelligent network applications.

Efficient integration of NTNs with terrestrial 6G systems requires intelligent network orchestration and adaptive communication management strategies. Artificial Intelligence (AI), Machine Learning (ML), and Software-Defined Networking (SDN) are being actively investigated to optimize network resource allocation, beam management, mobility control, and interference mitigation in integrated NTN environments [43].

Edge computing and cloud-assisted communication architectures are also important components of NTN-enabled 6G systems. Satellite edge computing enables local data processing near communication sources, thereby reducing latency and improving real-time communication performance [44]. Additionally, digital twin-based NTN simulation frameworks are being explored for real-time monitoring and optimization of satellite communication networks.

Recent real-world deployments such as Starlink and OneWeb demonstrate the practical feasibility of integrated NTN-terrestrial communication systems for future broadband services [45]. These systems provide low-latency internet access and support large-scale communication applications across geographically diverse environments.

Although NTN integration has significant potential for future 6G networks, several research challenges remain unresolved. Efficient cross-layer optimization, low-complexity AI-driven communication management, dynamic spectrum allocation, and energy-efficient communication techniques continue to be active research areas in satellite-assisted 6G communication systems.



Fig 3 Key Applications of NTN 6G Networks

V. PERFORMANCE EVALUATION METRICS AND COMPARATIVE ANALYSIS

Performance evaluation plays a crucial role in analyzing the efficiency, reliability, and scalability of Low Earth Orbit (LEO) satellite communication systems integrated with sixth-

generation (6G) wireless networks. Due to the highly dynamic nature of LEO satellite systems, several communication parameters must be evaluated to ensure stable and seamless connectivity under varying channel and mobility conditions. Researchers utilize different performance metrics to analyze

communication quality, handover efficiency, Doppler impact, spectral utilization, and overall network reliability.

A. Latency

Latency is one of the most critical performance metrics in LEO satellite communication systems. It represents the total communication delay between the transmitter and receiver, including propagation delay, processing delay, queuing delay, and transmission delay. Since LEO satellites operate at lower altitudes compared to Geostationary Earth Orbit (GEO) satellites, they significantly reduce propagation delay and support ultra-low latency communication suitable for real-time applications such as autonomous vehicles, remote surgery, industrial automation, and immersive virtual reality systems.

The communication latency can be represented as:

$$D_{total} = D_{propagation} + D_{processing} + D_{queue} + D_{transmission}$$

Where:

- D_{total} = Total communication latency
- $D_{propagation}$ = Propagation delay
- $D_{processing}$ = Processing delay
- D_{queue} = Queuing delay
- $D_{transmission}$ = Transmission delay

B. Throughput

Throughput measures the amount of successfully transmitted data over the communication channel within a specific period of time [52]. High throughput is essential for supporting broadband multimedia services, IoT communication, cloud applications, and high-speed internet connectivity in 6G-enabled NTN systems.

The throughput equation is expressed as:

$$T = \frac{\text{Total Data Received}}{\text{Transmission Time}}$$

Where:

- T = Throughput
- Total Data Received = Amount of successfully received data (bits/bytes)
- Transmission Time = Total communication time

LEO satellite systems generally provide higher throughput compared to conventional satellite systems due to reduced propagation losses and advanced beamforming techniques.

C. Handover Delay

Handover delay represents the time required to transfer an active communication session from one satellite, beam, or gateway to another without communication interruption. Since LEO satellites continuously move across orbital paths, efficient handover mechanisms are essential for maintaining seamless communication.

The handover delay is generally expressed as:

$$H_d = t_{completion} - t_{initiation}$$

Where:

- H_d = Handover delay
- $t_{completion}$ = Time at which handover process is completed
- $t_{initiation}$ = Time at which handover process starts

Minimizing handover delay improves Quality of Service (QoS), reduces packet loss, and enhances user experience.

D. Packet Delivery Ratio (PDR)

Packet Delivery Ratio represents the ratio of successfully received packets to the total transmitted packets. It indicates communication reliability and network stability under dynamic communication conditions.

The PDR is calculated using:

$$PDR = \frac{\text{Packets Received}}{\text{Packets Sent}} \times 100$$

Where:

- PDR = Packet Delivery Ratio (%)
- Packets Received = Number of packets successfully received
- Packets Sent = Total number of transmitted packets

A higher PDR indicates better network performance and reliable communication.

E. Signal-to-Noise Ratio (SNR)

Signal-to-Noise Ratio measures the strength of the received signal relative to background noise. High SNR values improve communication quality, modulation efficiency, and data transmission reliability.

The SNR is expressed as:

$$SNR = 10 \log_{10} \left(\frac{P_{signal}}{P_{noise}} \right)$$

Where:

- SNR = Signal-to-Noise Ratio (dB)
- P_{signal} = Signal power
- P_{noise} = Noise power

F. Spectral Efficiency

Spectral efficiency indicates how efficiently the available bandwidth is utilized for data transmission. It is an important parameter in integrated NTN-terrestrial communication systems where efficient spectrum sharing is required.

The spectral efficiency equation is:

$$\eta = \frac{R}{B}$$

Where:

- η = Spectral Efficiency (bits/s/Hz)
- R = Data rate or throughput (bits/s)
- B = Bandwidth (Hz)

VI. CONCLUSION

Low Earth Orbit (LEO) satellite communication systems are emerging as a fundamental component of future sixth-generation (6G) wireless communication networks due to their capability to provide global connectivity, reduced latency, high throughput, and seamless broadband communication services. The integration of Non-Terrestrial Networks (NTNs) with terrestrial communication infrastructures enables reliable communication in remote, rural, maritime, and disaster-affected regions where conventional terrestrial networks are insufficient.

This survey paper presented a comprehensive review of LEO satellite communication systems for 6G networks with emphasis on system architecture, Doppler effects, mobility management, handover mechanisms, NTN integration, and performance evaluation metrics. Various research

contributions related to Doppler-aware channel modeling, intelligent handover optimization, AI-enabled communication frameworks, beamforming techniques, and satellite-terrestrial integrated architectures were analyzed and comparatively discussed. Important performance parameters including latency, throughput, Doppler frequency shift, handover delay, Packet Delivery Ratio (PDR), Signal-to-Noise Ratio (SNR), and spectral efficiency were also reviewed for evaluating communication reliability and network performance.

The literature analysis indicates that although significant advancements have been achieved in LEO satellite communication technologies, several challenges still remain unresolved. High Doppler frequency shifts, frequent handovers, dynamic channel variations, synchronization issues, interference management, and computational complexity continue to affect communication performance in highly dynamic satellite environments. Furthermore, existing AI-based optimization approaches often require high computational resources and extensive training datasets, limiting their real-time implementation capability.

This research also highlighted the growing importance of MATLAB-based simulation frameworks for modeling orbital dynamics, mobility management, Doppler compensation, and communication performance analysis in realistic LEO satellite environments. Emerging technologies such as Artificial Intelligence (AI), Machine Learning (ML), Software-Defined Networking (SDN), edge computing, and adaptive beamforming are expected to play crucial roles in improving the efficiency and scalability of future NTN-enabled 6G communication systems.

Overall, LEO satellite communication systems have the potential to revolutionize next-generation wireless communication by enabling intelligent, reliable, and globally accessible broadband connectivity. Future research should focus on developing low-complexity adaptive Doppler compensation techniques, intelligent mobility management algorithms, energy-efficient communication architectures, real-time NTN simulation platforms, and efficient spectrum-sharing mechanisms for large-scale deployment of integrated 6G satellite-terrestrial communication networks.

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