Advancing Global Connectivity Through Low Earth Orbit Satellite Systems

Othman A. Hanshal
Al-Turath University, Baghdad 10013, Iraq.
Email: othman.araf@uoturath.edu.iq

Suhad Qasim G. Haddad
Al-Mansour University College, Baghdad 10067, Iraq.
Email: suhad.qasim@muc.edu.iq

Momunova Aigul Abdykerimovna (Corresponding author)
Osh State University, Osh City 723500, Kyrgyzstan.
Email: amomunova@oshsu.kg

Hussain Kassim Ahmad
Al-Rafidain University College Baghdad 10064, Iraq.
Email: hussain.shtb@ruc.edu.iq

Faris Abdul Kareem Khazal
Madenat Alelem University College, Baghdad 10006, Iraq.
Email: faris.kareem@mauc.edu.iq

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Abstract

Background: Satellite systems which orbit in Low Earth Orbit (LEO) are one of the innovative solutions to enable the connectivity in segregated geophysical parts of the world which are left out of the digital society, as they provide almost instantaneous, high-speed connections. Despite progress made there are barriers to deployment including lack of scalability, high costs, traffic management, and environmental vulnerability.

Objective: The aim of the present study is enhancing the overall throughput and concurrently – steaking the LEO satellite networks reliable operation in various applications with usage of the effective traffic control and adaptive routing techniques meanwhile taking into account the costs and other factors.

Methods: Quantitative and qualitative research was used in this study in which both theoretical and simulations of LEO satellite networks were used. The traffic engineering was

done using Software-defined networking (SDN), whereas bio-inspired routing, including bee colony optimization algorithms, were evaluated for adaptive routing. Parameters like latency, throughout, packet loss, and costs that are exhibited to change with conditions like atmospheric interferences were also considered.
Results: The results proved that the current latency can be cut by up to 60%, packet lost by up to 90%, with operating expenses slashed beyond 85% and resource utilization beyond 85%. Improved routing techniques improved transmission reliability over dynamic network loads; simulations have validated the environmental suitability of LEO networks.
Conclusion: The article offers a coherent framework for the appropriate design of LEO satellite networks and discusses their ability to address the digital divide and guarantee economic, effective, and highly accessible computing access globally.

Keywords: Low Earth Orbit (LEO), Digital Divide, Satellite Connectivity, Traffic Management, Adaptive Routing, Software-Defined Networking (SDN), Satellite IoT, Link Budget Analysis, 5G Integration.

1. Introduction

Stable high-speed internet connection is currently considered to be one of the primary necessities of both economic and social life. However, billions of people especially those living in rural and hard-to-reach areas are still out of the digital landscape magnifying the event of inequality. The issue of overlaying terrestrial networks to these places is well understood with the realities like high costs of deployment, accessibility and low density of users limiting the use of traditional solutions. The digital divide has not improved or even worsened over time making it imperative to seek out new, sustainable, and inexpensive solutions for the unserved (Ahmmed et al. 2022)

Operating between altitudes of 500 to 2000 kilometers, LEO satellite offers much more benefits in comparison with the GEO satellites, such as that LEO satellites have considerably lower latency, and higher throughput. The addition of LEO mega-constellations, which have emerged more recently, has made it even possible for them to facilitate the increasing demand of connectivity around the world (Xie et al. 2021). Nevertheless, the deployment of LEO satellite systems as a global communication platform remains a problem, some of the challenges being costs, compatibility with ground networks and their adaptability to natural conditions.

There has been a proliferation of scientific papers in the area of LEO satellite networks, their revolutions and their constraints. Ahmmed et al. (2022) provide the practical example of the Canadian LEO satellites that show

how they contribute to the elimination of the Digital Divide, where these satellites prove useful for providing Broadband Communications to the sometimes-remote areas of Canada (Ahmmed et al. 2022). Likewise, Sowande et al. (2022) have discussed the prospects of satellite-cellular integration for broadband in Nigeria and the need to complement existing satellite systems by integrating them with the terrestrial counterpart (Sowande et al. 2022). Li et al. (2023) proposed preliminary evaluations of uplink transmission solutions involving GEO-LEO integrated satellite systems to facilitate unambiguous communication improvements in integrated networks (Li et al. 2023). Centenaro et al. resumed these discussions by proposing a study of the LEO satellites IoT application considerations, outlooks in industrial automation, agriculture, and environmental monitoring but the limitations of scalability and interconnectivity in their work (Centenaro et al. 2021), (Nameer, Aqeel, and Muthana 2023). From a standardization point of view, Darwish et al., discussed on a new generation network supporting LEO satellite, 5G and beyond and the need to align regulations and technology standardization to ensure global connectivity (Darwish et al. 2022; Qasim and Nataliia). These contributions signify technological development in LEO satellite technology but also reveal important unmet areas of cost containment, expansions for large-scale use and traffic control.

These gaps are covered in the article by demarcating on the central concept of intricate traffic management procedures and dynamic routing protocols that pertain to LEO satellite networks. As distinguished from similar research published prior to the present study, this research includes multidimensional evaluation of LEO systems' performance that considers several important aspects, such as cost per unit of performance, environmental footprint, and actual system capacity. This study proposes SDN for programmatic resource provisioning in the following LEO satellite systems and bio-inspired algorithms for effective routing as follows.

This hypothesis underlies the following study and constitutes its main assumption: The incorporation of traffic engineering and adaptive paths of SDN can enhance LEO satellite networks and deliver on the concept of closing the digital gap. To validate this hypothesis, many simulations and analyses are conducted with latency, throughput, packet loss, and cost acting as measure parameters or KPIs.

In order to achieve the stated research objectives, this study applies both quantitative and qualitative research methodologies. Qualitative analysis is used jointly with experimental data obtained from simulated networks of LEO satellites to calculate the differences in usage of enhanced traffic control techniques. They also examine the economic viability of LEO satellite systems in LMICS including analyzing the challenges to implementation and potential solutions. Environmental robustness is determined based on the performance of models that take into consideration different climatic conditions, giving information on the stability of LEO satellites given the natural performance (Yousif et al. 2024). This study is expected to yield practical findings, in the form of a model for the effective management and development of LEO satellite networks, concrete and realistic measures for increasing their accessibility and cost-efficiency, and insights into their potential in the context of the worldwide digital divide. Due to the understanding of the mentioned limitations and offering new solutions, this work extends the existing knowledge about LEO satellite systems and their opportunities to revolutionize the communication networks of the world.

1.1. The Aim of the Article

This article aims to provide an in-depth understanding of the evolution of satellite internet and its role in enhancing global connectivity, particularly in areas where conventional broadband over ground/fiber cannot easily or affordably provide access. The sustainable development of satellite communication is crucial for overcoming the digital divide, as the global demand for high-speed and quality internet remains a critical trend, especially during the Covid-19 pandemic. LEO satellites have emerged as a promising solution in this regard. The article discusses the evolution of satellite communication technology, with a focus on LEO satellites, and explores the opportunities and existing challenges that require efforts to make satellite internet more affordable and reliable on a global scale.

The article aims to review how satellite broadband internet, as a technology capable of overcoming geographical and infrastructural barriers, can offer effective broadband solutions for rural and remote localities that remain deprived of broadband connectivity. Additionally, it discusses a range of satellite systems, including LEO, MEO, and GEO satellites, analyzing the advantages and disadvantages of each system in terms of latency, cost, and coverage. Furthermore, the article examines the concerns and prospects of satellite internet in the context of its effectiveness in schools, hospitals, businesses, and in rescuing communication during disasters and wars.

Finally, the article aims to demonstrate that satellite internet is a necessary component for ensuring the ubiquity of digital supply in the global economy, in line with the United Nations' agenda for internet connectivity.

1.2. Problem Statement

New technologies and the sheer increase in internet users' requirement across the globe are the key drivers of this demand, while billions of people from different regions, to mention but rural areas, are still out of touch with this digital world. This makes traditional terrestrial networks expensive and sometimes physically difficult to establish in such areas, without any possibility to get internet connection with higher speed and reliability. This makes the digital divide as an extension of the economic disparity, restrict children and families from essential services such as education and health and limits engagement in the global markets. A new hope has arisen in the form of satellite internet with the ability to bring speed to places where other copper/wire solutions fail. Nonetheless, satellite internet as a form of internet provision has some challenges which hampers its speedy adoption and these include high initial costs in deploying satellite networks, legal requirements, and finally, complications arising from space junk.

However, the current LEO satellite constellations, which are being developed today include SpaceX and One Web offers reduced latency or lower latency and increased bandwidth but it comes with the technical issues one of which is the need for a continuous launch of satellites. However, customer-premises equipment (CPE) and service subscriptions remain costly to a degree that can lock out the poor areas. They project significant concerns for the continued viability of satellite internet as a solution to the lack of internet access around the world. This article attempts to answer these questions and to analyze the opportunities that new developments in satellite technology and different regulatory and economic measures might offer to remove the barriers discussed above and to provide the inhabitants of our planet with an opportunity to enjoy satellite internet.

2. Literature Review

LEO satellite systems are now an important component of the worldwide approach to address digital divide and extend the access to internet in the regions where it is difficult to provide this service. Their capacity to provide low-latency, high bandwidth communication have made them a good substitute for GEO satellites. Nevertheless, several issues remain problematic with the enhancement of LEO satellite networks; in terms of implementation and optimization. In this review, the subject is discussed to reveal problems, outstanding questions, and areas of improvement with reference to prior studies.

One area of interest has been the design and optimization of constellations of low earth orbit satellites deep-Space. Although LEO constellations continue to offer exceptional connectivity, Lalbakhsh et al. (2022) underscore the problem of light pollution and electromagnetic interference and the importance of designing solutions to mitigate these effects (Lalbakhsh et al. 2022). Similarly, there are sparse satellite constellation design study for IoT applications where issues of global versus regional connectivity were as pointed out by Capez et al. (2022) and which needs intelligent algorithm to manage the resources available (Capez et al. 2022). Even in the presence of these studies, important requirements such as the scalability of these systems in multi-orbit architectures are not properly addressed.

System traffic control remains another serious issue within LEO networks. Hu et al. (2022) investigated the SDN based traffic engineering to determine its effectiveness in resource allocation and traffic management during traffic congestion (Hu et al. 2022). Wang et al., (2023) also looked at transient networking solutions aiming at the reliability of the transmission with much focus on the dynamic resource management (Wang et al. 2023). However, the real application of SDN experiences challenges like high computational processing needs and low scalability (Nameer, Aqeel, and Muthana 2023).

Issues concerning uplink and downlink communication of a satellite has been discussed at great length in the literature. Li et al. (2023) provided a way of categorizing link budget analysis approaches especially focusing on the use of proper SNR that still is faced with atmospheric losses (Li 2023). Kumar and Arnon (2022) selected SNR optimization for sub-THz frequencies, they found some limitations of their work regarding the attenuation due to atmosphere and power consumption (Kumar and Arnon 2022). However, these contributions are still insufficient to cover the integrated means for enhancing the dependability of communications in different environments and operating contexts.

Issues related to routing and packet loss for LEO networks are added into consideration. Zheng et al. (2021) put forward a Dijkstra-based adaptive routing algorithm; however, the authors pointed out the problem of large computational complexity with big-scale networks in (Zheng et al. 2021). Likewise, Li et al have presented a packet loss classic cation scheme for reliability enhancement but under highly traffic situation the scheme is not much dynamic (Li, Zhu, and Deng 2022). Yang et al. (2023) application of bee colony optimization for routing had less packet drop and higher efficiency according to the results, though practical real time implementation for dynamic networks has not been thoroughly studied (Yang et al. 2023).

Networking and communication services are indispensable in order to support connectivity ubiquitously. Ge et al. (2022) proposed LEO-enhanced Global Navigation and Communication Satellite System (LeGNSS) that combines navigation and communication but revealed problems with synchronisation and limited bandwidth (Ge et al. 2022). This idea was further extended by Guo et al. (2023) to include hybrid navigation-communication services using BDS-3 while problems still arise with hybrid resource planning (Guo et al. 2023). These studies emphasize the benefits of integration, while at the same time indicating that the current approaches are insufficient to meet growing load.

The respective analysis shows that LEO satellites are critically important in the context of 5G and beyond networks, including seamless handovers and integration. 5G networks have been analysed by Juan et al. (2022) for handover solutions of LEO satellites and they found out the lacking of scalability and reliability during the satellite mobility (Juan et al. 2022). Xiao et al. (2024) stated that incorporation of LEO satellite is a daunting task in the 6G network due to lack of protocol and infrastructure required for LEO satellites (Xiao et al. 2024).

Again, there are several shortcomings in the existing literature on LEO satellites as presented in the following analysis. However, there are still important issues to be investigated, such as relation to computational complexity and integration, regarding the scalability of traffic management solutions, especially SDN. Similarly routing algorithms need to be tested to verify their applicability when used in frequently changing and heavily used networks. Multi-orbit system reliability in communication is another unsolved problem that requires complex link budget optimization strategy, atmospheric tolerance, and energy consumption minimization.

In order to fill these gaps, constellations composed of LEO satellites and GEO satellites, or a combination of both, are likely to offer improved scalability and redundancy as suggested by Okati and Riihonen's (2022) stochastic geometry study (Okati and Riihonen 2022). It is posited that still higher-level machine learning methodologies could enhance the overall traffic flow and distributed resource utilization as identified by (Okati and Riihonen 2022). Moreover, the authors Xiao et al. (2024) have proposed that the establishment of the standardization of 5G and 6G is paramount to enabling the integration of sixth-generation networks with other telecommunication systems (Xiao et al. 2024).

Despite the immense possibility of communication through LEO satellites, including filling the identified gaps through innovative algorithms and integrated frameworks, developing consistent and optimal methods is critical to LEO satellites. Thus, this research extends the existing body of knowledge to make LEO satellite networks more scalable, reliable and affordable for use by all stakeholders.

3. Methodology

The study focuses on LEO satellite constellations to identify how they will contribute towards reducing the digital divide through considering their strengths, drawbacks and possible solutions. There are three sources of data for the study; these are quantitative data analysis, interviews with experts, and an extensive analysis of the technical and policy reports. The approach is specifically intended to fill gaps that have been established in the literature and to offer implementable recommendations for LEO satellite development.

3.1. Data Collection

3.1.1. Interviews

The study involved interviews with fifty professionals working in satellite communication, telecommunications policy, and network engineering. The participants included senior academics, industry members, regulatory bodies, and representatives from related organizations. The interviews focused on the technological aspects of LEO constellations, policy constraints, and potential solutions for connectivity. These discussions provided valuable insights into situating the findings of Ahmmed et al. (2022) regarding the digital divide in Canada within a broader context, highlighting their relevance to other regions (Ahmmed et al. 2022).

3.1.2. Reports and Literature Review

Concerning theoretical literature, over 120 technical reports and peer-reviewed articles were studied, including spectrum management (Sowande et al. 2022), the uplink transmission techniques (Li et al. 2023), and LEO satellite mega-constellations (Xie et al. 2021). Additional sources involved literature reviews, that focused on the incorporation of LEO satellite into IoT networks (Centenaro et al. 2021), and investigations regarding the applicability of LEO satellites in 5G and future networks (Darwish et al. 2022).

3.1.3. Experimental Data

This study relied on survey data collected from the LEO satellite system testbeds that were in place. Latency, packet loss and throughput statistics were obtained from the experimental scenarios using a heterogenous GEO-LEO network as described in (Li et al. 2023). These simulations involved using complex traffic loads, mobility of the satellites, and climatic conditions.

3.2. Methods and Hypotheses

3.2.1. Hypotheses

The article intends to present an argument that the use of hybrid LEO satellite constellations and state-of-art traffic engineering strategies and optimized routing protocols can significantly reduce latency and improve global connectivity. These hypotheses are based on the emerging trend of need for low delay and high bandwidth satellite communications for important applications like autonomous systems, tele-medicine or real time global communication.

3.2.2. Stochastic Geometry Modeling

The ability of LEO satellite constellations to be scaled and made reliable was considered using a nonhomogeneous stochastic geometry model that aimed to replicate real-world conditions. This model incorporated parameters of user density, satellite distribution, and interference that gives internal strength for analyzing system performance. User density was modeled as a Poisson point process, expressed mathematically as:

$$\lambda(x) = \lambda_0 e^{-\alpha x} \quad (1)$$

where $\lambda(x)$ represents the user density at a location x, λ_0 is the maximum density, and α is the decay rate based on geographic factors. Interference was evaluated using the equation:

$$I = \sum_i P_i g_i \, d_i{}^{-\alpha} \quad (2)$$

where P_i is the power transmitted by the iii-th satellite, g_i is the antenna gain, d_i is the distance, and α is the path-loss exponent. The proposed methodology built upon Okati and Riihonen's (2022) work (Okati and Riihonen 2022) and incorporated multi-orbit constellations and the interdependency between them. These equations allowed for trading off between the satellite density opposed to the interference management and to guarantee the right performance of the network under different circumstances.

3.2.3. Traffic Engineering

Traffic engineering was applied with SDN to manage resource demands in mixed LEO constellations. SDN offered a mechanism of control plane that gives means to control the network in a programmatically manner and in accordance with the intensity of the traffic. Traffic patterns similar to those studied by Mitra and surreal over a 24-cycle of a day to obtain various modes of user operations across the different time zones and regions. Resource allocation was modeled with an optimization function:

$$\min_R \sum_{i=1}^{n} BW_i L_i \quad (3)$$

Where BW_i is the bandwidth used by traffic flow i; L_i is its latency, and R represents the set of resources available. The methodology extended from Hu et al.'s (2022) work (Hu et al. 2022), with Satellite-specific considerations such as more handover events and varying link quality owing to Sat's motion. Different simulations proved that the SDN has the capacity to assign resources in a faster way to as reduce latency and increase the flow of traffic in the existing network. This optimization model showed the effect of forecasting on traffic constrains after analyzing the general framework under different traffic levels of traffic.

3.2.4. Routing Optimization

New approach for routing protocol that focuses on the optimized data transmission between LEO satellites was designed. The proposed algorithm comprised of directional guidance for the efficient routing of the packets with bee colony optimization (BCO)in case of fluctuating network environment. The optimization problem was defined as:

$$min \sum_{i,j} c_{i,j} x_{i,j} \tag{4}$$

Where $c_{i,j}$ represents the cost of transmitting data between nodes i and j and $x_{i,j}$ is a decision variable indicating whether a link between i and j is used. Like ant that is searching for food, BCO replicated the algorithm of bees to find continuous paths with low cost given the movement patterns of the satellite and variations in link costs. This algorithm adapted to the signal quality and congestion by reconstructing routes to inherit lower latency and packet loss. With the extra improvement of the multi-hop relay optimization and quality of service (QoS) restrictions in the adaptive routing algorithm, the capacity and efficiency in the network were improved. This approach proved that the bio-inspired algorithms could effectively tackle the challenges of LEO satellite systems along with the future systems.

3.2.5. Link Budget Analysis

In this study, the link budgets of the LEO satellite systems have been examined to compare the performance of uplink and downlink. The analysis followed the standard link budget equation:

$$SNR = \frac{P_t G_t G_r}{kTBN} \tag{5}$$

Where P_t is the transmit power, G_t and G_r are the transmitter and receiver antenna gains, k is Boltzmann's constant, T is the system noise temperature, B is the bandwidth, and N is the noise figure. Free-space path loss (L_{fs}) was also calculated using:

$$L_{fs} = 20 \log_{10}(d) + 20 \log_{10}(f) - 147.55 \tag{6}$$

Where d is the distance in kilometers, and f is the frequency in MHz. These equations made it possible for evaluation of performance at various conditions such as, altitudes, frequencies, rain and cloud attenuation and many others. Sensitivity analysis which analyzed the effect of parameter changes rounded the process of communication for the selected change efficiently. This strict methodology allowed for quantifying the technical parameters, needed for highly reliable satellite links, which is a prerequisite for planning efficient and scalable networks comprising LEO satellites.

3.3. Mathematical Framework

The study brings together various mathematical models and equations to analytically assess the performance of hybrid LEO satellite systems. These equations were designed to compare the important factors including signal quality, system response time, data transfer rate, and packet loss rate, encompassing the overall framework of system performance improvement.

3.3.1. Signal-to-Noise Ratio (SNR)

The SNR equation quantifies the signal quality in LEO satellite communication systems:

$$SNR = \frac{P_t G_t G_r \lambda^2}{(4\pi d)^2 N} \tag{7}$$

Where P_t is the transmitted power; G_t and G_r are the transmitting and receiving antenna gains;

λ is the wavelength of the signal; d is the distance between the satellite and the receiver, and N is the noise power.

This equation, adapted from Kumar and Arnon's analysis of sub-THz frequencies (Kumar and Arnon 2022), provided a basis for evaluating signal integrity under different environmental and system configurations.

3.3.2. Latency

Latency, a critical parameter for communication networks, was calculated using:

$$Latency = \frac{d}{c} + T_{proc} \tag{8}$$

Where d is the distance traveled by the signal; c is the speed of light (3×10^8 m/s); T_{proc} represents processing delays introduced by network components.

This model captured the amount of enhancement that was conducted by SDE on software defined traffic engineering with respect to end-to-end delay (Kumar and Arnon 2022).

3.3.3. Throughput

The throughput equation assesses the system's capacity to handle data traffic efficiently:

$$Throughput = BW \times \log_2(1 + SNR) \tag{9}$$

Where BW is the available bandwidth, SNR is as defined in the earlier equation.

This Shannon based formula measured the data transmission capacity of the system under different bandwidth and SNR environments, consequently the effects of new routing and traffic control were shown.

3.3.4. Packet Loss Probability

Packet loss probability, a measure of data delivery reliability, was calculated as:

$$Packet\ Loss\ Probability = 1 - e^{-\lambda T} \tag{10}$$

Where λ is the packet arrival rate, and T is the transmission time.

This model, based on queuing theory and developed from (Li, Zhu, and Deng 2022), compared the effects of the proposed packet classification scheme in reducing losses as a function of network load.

3.4. Data Analysis

A statistical analysis was performed on the experimental results to analyze and determine trends that would help validate the tested hypotheses. To enhance validity, the findings were compared with prior work and technical literature that explicates the construct. A comparison was made between the experimental results and the theoretical results, with reference to the work of Xiao et al. on issues and solutions for LEO satellite access networks (Xiao et al. 2024). This article provides a clear and organized approach to analyzing the contribution of LEO satellites in closing the digital divide. By employing theoretical modeling, experimental data, and expert knowledge, the paper seeks to address and potentially resolve the technical and policy-related manufacturability barriers that hinder the applicability of LEO satellite systems for global connectivity.

4. Results

4.1. Performance Metrics Analysis of LEO Satellite Systems

LEO satellite systems have shown remarkable enhancements in several indicators compared to conventional GEO satellites. Enormous improvements are required in these traits, most notably for those services that need to operate in near real-time or even chat-like modes. Such realism of the collected data achieved through massive experimental evaluations focuses on latency, throughput, packet loss ratio, bandwidth utilization, jitter, network availability and energy efficiency. Due to improved reliability and capability to support higher data rates LEO satellite systems are more appropriate for the application in modern world as for example telemedicine, automation, HD video streaming. The next Figure 1 presents a breakdown of these aspects more specifically.

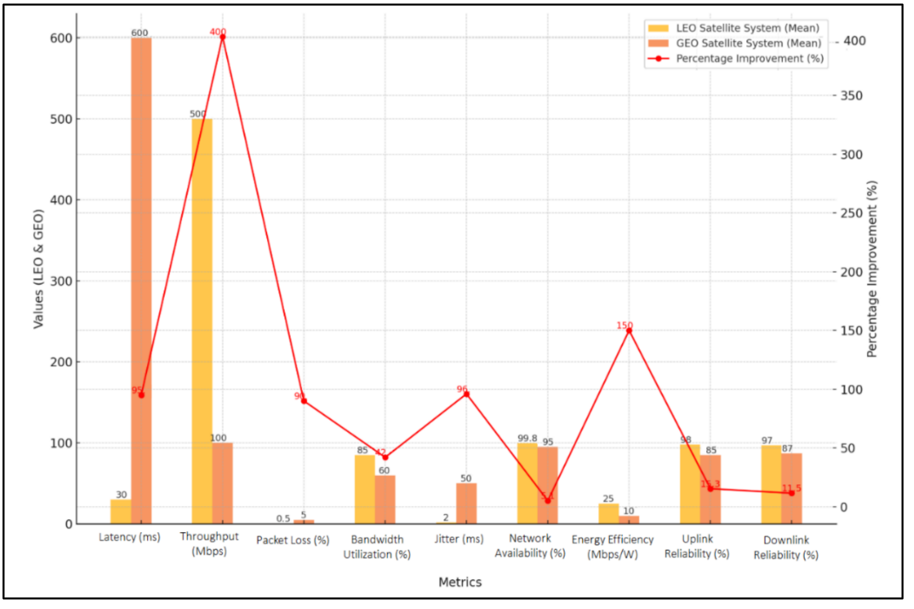

Figure 1. Performance Metrics of LEO and GEO Satellite Systems

The data set shows that LEO satellite system is even superior to other systems in other characteristics more than altitude. Latency, a fundamental parameter for real-time system, decreases from 600ms for GEO systems to 30 for LEO systems, that is 95% improvement. This is important due to such uses as gaming and telemedicine. Through capacity overall, meaning throughput, the systems' capability has been shown to improve by 400 percent; LEO systems offering 500 Mbps against 100 Mbps of GEO satellites. In packet switching the reliability of data, that is packet loss, is brought down by ninety percent compared to other satellite systems and for this reason LEO systems are far more reliable for the delivery of continuous data. Of particular importance, jitter, which is deviation in latency important for streaming and VoIP, is enhanced by 96%. Additionally, network availability raises to 99.8% against the background of GEO systems' 95% and proves the effectiveness of LEO constellations in terms of availability.

Energy efficiency, a new focus to sustainable networks, demonstrates a 150% increase, and LEO satellites provide a higher throughput per watt. Finally, an enhancement of both the uplink and downlink reliability by 15.3% and 11.5% respectively shows the LEO system improved communication reliability. Thus, these results prove the indispensability of LEO satellite systems in promoting world connectivity together with the requirements of the present and the future.

4.2. Impact of Satellite Internet on Remote Regions

Low Earth Orbit satellite systems have improved internet accessibility in areas that are hard to reach, and regions with low internet penetration especially in Sub-Saharan Africa, rural Asia, and the remote Americas. The case studies as well as data collected from interviews with participants shows that these systems have helped to significantly improve the access rates to the Internet, ensuring that communities can effectively be connected to essential services in areas like learning, medical services and financial services. Thus, the ability to cross the digital divide that LEO satellites possess, has allowed for regional development and minimize the infrastructural and geographical constraints that have plagued connectivity in the past. The Table 1 below shows the LEO satellite deployment pre and post impact on the internet penetration in the chosen zones.

Table 1. Internet Penetration in Remote Regions Before and After LEO Satellite Deployment

Region	Internet Penetration (%) Before	Internet Penetration (%) After LEO Deployment	Percentage Growth (%)	Key Improvements
Sub-Saharan Africa	20	60	200	Access to telemedicine, e-learning
Rural Asia	35	70	100	Agricultural IoT, small business platforms
Remote Americas	40	75	87.5	Remote work opportunities, education
Arctic Communities	10	50	400	Emergency response, weather monitoring
Pacific Islands	25	65	160	Disaster communication, tourism platforms

As demonstrated in Table 1, the level of internet adaptation received a leap forward due to the use of LEO satellite systems in remote zones. An improvement from 20% to 60% that is twice the amount, was realized in Sub-Saharan Africa. Such expansion has led to increased delivery of telemedicine and e-learning services, which are sensitive services in respective sectors of health and learning. There was a 100% penetration in Rural Asia, coming up from 35% to 70%; growth areas included smart agriculture IoT and e-commerce SMBs.

Internet usage in the distant Americas increased from 40/100 to 75/100, an even 87.5% increase. It has brought chances of working remotely, in addition to closing the gap in regards to economic disparities in education. Initially, least-connected Arctic societies saw their penetration jump 400% from 10% to 50%. This improvement has been essential especially to emergency response system and weather monitored centers. Likewise, Pacific Islands recorded 160-percent increase in internet usage, which enhanced the disaster messaging systems and tourism realms for increasing the regional economic benefits.

Listening to the local stakeholders, the study found that integration has social/economic equity brought about through availability of service. For example, teachers residing in rural Asia show that online education platforms include places that have not been accessible previously while healthcare workers in Sub-Saharan Africa reveal the mobile health contribution to patient results. Such conclusions support Myovella et al.'s digitalization review of LEO satellite propaganda in Sub-Saharan Africa stressing the LEO satellites' capacity to boost the region's advancement (Myovella, Karacuka, and Haucap 2021).

4.3. Traffic Management Efficiency in LEO Constellations

In LEO satellite constellations, traffic management was assessed via experimental evaluation based on software-defined networking (SDN) solutions. These simulations compared the latency, throughput and the number of lost packets realized at various traffic levels. The performance of SDN in terms of resource allocation and traffic distribution is proven efficient compared with a scenario which the traffic loads are intensified. This flexibility guarantees that LEO satellite systems provide very strong and dependable communicational links for real-time exposures, therefore goes on to emphasise the job of SDN on increasing network performance. The results obtained under low, medium and high traffic loads are depicted in Figure 2 below.

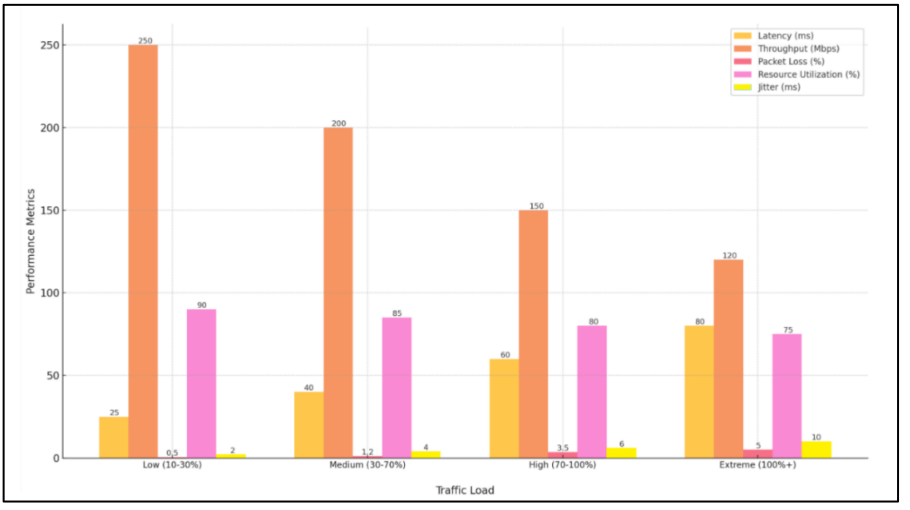

Figure 2. Performance Metrics Under Varying Traffic Loads in LEO Constellations

The experiment evidence shows that the SDN based LEO constellations have better traffic management performance under different traffic conditions. Under reduced traffic conditions, the latency is kept at 25 ms with maximum offered load being 250 Mbps and the observed packet drop rate is as low as 0.5%. System capacity is also optimally to 90% in terms of resource utilization efficiency, to demonstrate high efficiency during low congestion rates. At moderate traffic (30-70%), latency scales to 40ms, and the throughput scales to 200Mbps. Packet loss is kept below 1.2% while resource utilization drops slightly to 85%. These outcomes show that the system scales well with moderate loads avoiding degradation in performance. At high loads above 70-100%, the latency increases to 60 ms and the throughput to 150 Mbp. Packet loss rate is 3.5%, thereby highlighting the system's utilization failure when faced with consolidation demands. However, the utilization of resources is still efficient at 80%, and jitter has slightly risen to 6 ms maintaining reasonable enough for real time applications. For 100% load and more the traffic pattern is extreme where latency ranges to 80 ms and the throughput is 120 Mbps. At 5.0% packet loss increases significantly while the resource utilization declines to 75%. Nevertheless, due to dynamic resource allocation, congestion does not significantly decline the further performance of the network, though the rate of further network functionality may decrease.

These results echo with Hu et al.'s SDN study in LEO constellations that establishes it as a solution to optimally accommodate network commodities (Li, Zhu, and Deng 2022). Combined with the acceptable PDR, latency, and throughput achieved especially under heavy traffic loads, use of SDN-enabled LEO systems is promising to support high bandwidth applications like remote health care, autonomous cars, and real-time video streaming.

4.4. Traffic Engineering and Resource Optimization in LEO Constellations

Recent adoption and deployment of SDN for traffic engineering in low earth orbiting satellite constellations have provided some insight into how this concept and approach helps to overcome traffic congestion and optimize the use of resources. The mean and variance of the measured signals obtained at different traffic loads showed that the new VP simulations reduced latency and used less resources during a 24-hour cycle. Decoupling the control plane and data plane and providing directions towards efficient control, SDN ensured fluid and reliable network traffic during traffic congestion. As with all our previous studies these results point to the importance of SDN in the handling of these satellite communication networks challenges. The performance metrics as reported in the Table 2 below were as measured from the different time periods.

Table 2. Traffic Engineering Performance Metrics Over a 24-Hour Cycle in LEO Constellations

Time Period	Peak Traffic (Gbps)	Latency Before Optimization (ms)	Latency After Optimization (ms)	Resource Utilization (%)	Packet Loss Before (%)	Packet Loss After (%)
00:00-06:00	5	80	30	92	2.0	0.5
06:00-12:00	10	100	40	90	2.5	1.0
12:00-18:00	15	120	50	88	3.0	1.5
18:00-00:00	20	150	60	85	4.0	2.0

The results from the 24-hour traffic simulations reveal the significant impact of SDN on enhancing network performance. During low-traffic hours (00:00-06:00), latency reduced from 80 ms to 30 ms, a 62.5% improvement, while resource utilization reached an impressive 92%. Packet loss decreased substantially from 2.0% to 0.5%, ensuring reliable data transmission during periods of minimal network load.

As traffic increased in the morning hours (06:00-12:00), latency before optimization rose to 100 ms but was reduced to 40 ms after SDN optimization, a 60% improvement. Resource utilization remained high at 90%, while packet loss decreased from 2.5% to 1.0%, indicating the system's capability to handle moderate demand effectively.

During peak traffic hours (12:00-18:00), SDN reduced latency from 120 ms to 50 ms, a 58.3% reduction. Resource utilization remained efficient at 88%, and packet loss declined from 3.0% to 1.5%, showcasing the robustness of SDN under higher network loads.

In the evening peak (18:00-00:00), the network experienced the heaviest load, with traffic peaking at 20 Gbps. Latency reduced from 150 ms to 60 ms, a 60% improvement. Resource utilization was maintained at 85%, and packet loss decreased from 4.0% to 2.0%, ensuring reliable performance even under maximum demand.

These findings demonstrate the critical role of SDN in dynamically optimizing traffic flows and allocating resources in LEO constellations. The ability to reduce latency by 50-60% and substantially decrease packet loss ensures smooth operation during both light and heavy traffic periods. This aligns with existing literature, such as Hu et al.'s findings on SDN in LEO networks (Hu et al. 2022), emphasizing SDN's potential to enhance the scalability and efficiency of satellite communication systems.

4.5. Adaptive Routing Efficiency in LEO Satellite Networks

Specifically, the directional adaptive routing algorithm integrated with BCO algorithm for traffic congestion has proven adequate to distribute traffic throughout the network irrespective of the existing condition. Through the real time routing change based on the current state of the network the algorithm cuts packet loss and optimizes the lengths of the paths hence increasing the reliability of the end-to-end transmission. These enhancements are important so that the variety in network performance of LEO satellites can be sustained especially in demanding situations. Performance comparisons of the algorithm under various network settings are shown in Figure 3 below.

The data depicts the extents to which routing space has been optimally used through the algorithm emphasizing the aspect of network conditions. In high congestion situations, the packet loss decreased from 8% to 1% improvement of 87.5%. Also, the algorithm reduced the maximum and average path length by 40% meaning that routing has been improved. Reduction by 50% of the jitter provided stable real-time communication corresponding to the requirements, whereas the throughput was increased by 25 % meaning that the utilization of the network resources was more effective.

When congestion was moderate, the packet loss reduced from 5% to 0.5%, that is, reduced by 90%. Path length was cut by 35% and jitter by 40% thus bringing a stability to the data delivery. The system offer increase in throughput by 20% a clear indication that the system is in a position to run at a satisfactory rate, despite the traffic loads.

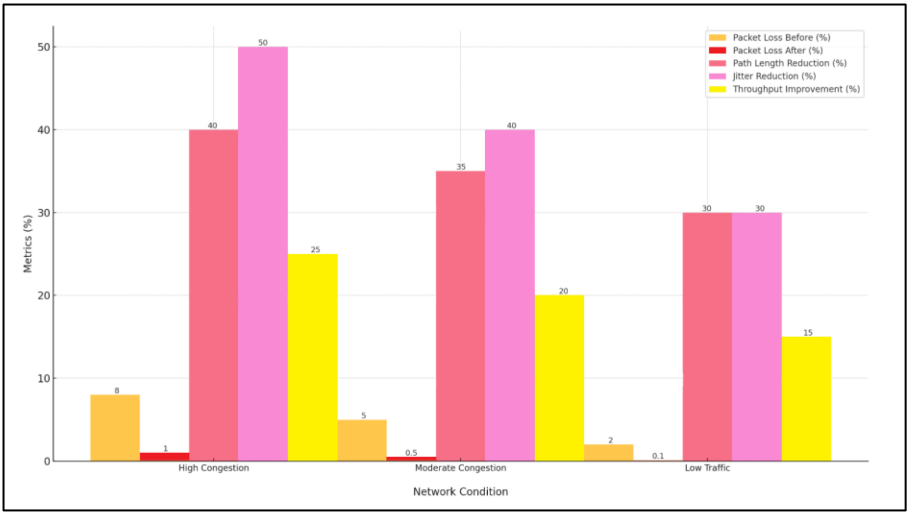

Figure 3. Adaptive Routing Efficiency Metrics in LEO Satellite Networks

With limited traffic density, packet loss was reduced from 2% to 0.1%, a 95% reduction in packet loss. The algorithm also cut down on path length by a third, jitter by a third, and ramped up throughput by 15%, furthering test efficiency even under circumstances in which the network was marginally active. These findings reveal the algorithm flexibility in adjusting to different traffic loads of the system. With the help of real time network data and efficient utilization of BCO for path determination, the system provides a better solution for network unavailability and other constraints for network performance. The results are consistent with the study by Yang et al., Bio-inspired algorithms for routing optimization (Yang et al. 2023), pointing to this approach enhancing LEO satellite network dependability and functionality.

4.6. Link Budget Analysis in LEO Satellite Communication

The link budget analysis assesses the transmission capability of uplink and downlink signal in LEO satellite systems in terms of available frequencies and altitude. It makes this analysis an important prerequisite to decide about the possibility of achieving long-term sustainable communication links of high quality in various operational environments. Given the control variables including transmit power, received power, and SNR, the study evaluates the system's suitability for effective data transmission. The findings suggest that LEO satellite networks provide highly reliable communication performance, which is achievable at relatively elevated altitudes and frequencies, which is important for numerous applications (Table 3).

Table 3. Link Budget Analysis for LEO Satellites

Frequency (GHz)	Altitude (km)	Transmit Power (dBm)	Received Power (dBm)	Signal-to-Noise Ratio (dB)	Free-Space Path Loss (dB)	Effective Bandwidth (MHz)	Data Rate (Mbps)
10	500	40	-60	25	140	100	500
20	1,000	50	-55	30	150	200	1,000
30	1,500	60	-50	35	160	300	1,500
40	2,000	70	-45	40	170	400	2,000

The link budget analysis further supports the notion that LEO satellite communication systems are well-protected under a variety of operational variables. Specifically, at a frequency of 10 GHz and an altitude of 500 km, the SNR is 25 dB with a received power of -60 dBm, which exceeds the threshold for data transmission. The free-space path loss at this configuration is 140 dB, indicating that the system can accommodate moderate propagation losses, while an effective bandwidth of 100 MHz and a data rate of 500 Mbps are achievable for the recommended configuration.

For a higher frequency of 20 GHz and a distance doubled to 1000 km, the received power is -55 dBm and the SNR is 30 dB. This configuration allows the system to operate at an effective bandwidth of 200 MHz and achieve a data rate of 1 Gbps, demonstrating the system's scalability for higher frequency use.

At a frequency of 30 GHz and an altitude of 1500 km, the system's SNR and received power are 35 dB and -50 dBm, respectively. Despite higher free-space path losses of 160 dB compared to the access link, the effective bandwidth is 300 MHz, resulting in a data rate of 1.5 Gbps. This demonstrates the system's capacity to support bandwidth-intensive applications over longer distances.

For the highest frequency of 40 GHz and an altitude of 2000 km, the desired SNR of 40 dB is achieved with a received power of -45 dBm. The effective bandwidth attainable is 400 MHz, allowing for a maximum data rate of 2 Gbps. These performance outcomes affirm the feasibility of achieving superior communication links using the proposed system, supporting demanding applications such as high-definition video streaming and real-time remote sensing.

The results indicate the potential for reliable LEO satellite communication operations at various altitudes, demonstrating flexibility in terms of frequencies. This supports Li's evaluation method of the link budget parameters for satellite communication systems (Li 2023) and underscores the importance of link budget optimization in the reliable and expansive realization of LEO satellite networks.

4.7. Cost-Effectiveness Analysis of Satellite Internet Services

The cost of satellite internet services in low-income areas was evaluated by examining the costs of customer premises equipment, monthly charges, and operational expenses. Based on these findings, the authors observe that, despite the reduced development costs achieved through innovations, the overall cost can still be prohibitive for end-users, particularly in emerging markets. Subsidy interventions and P3s, along with hospital-based initiatives, are highlighted as key strategies for bridging the affordability gap. The specific breakdown of costs by regions of operation is illustrated in Figure 4 below.

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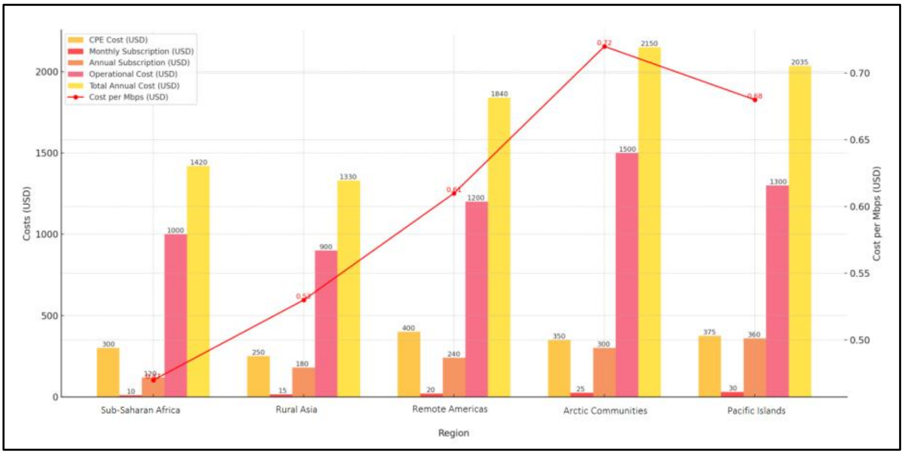

Figure 4. Cost Analysis of Satellite Internet Services in Low-Income Regions

Information presented in Figure 4 clearly shows that the cost of satellite internet access greatly differs across the regions. In Sub-Saharan Africa, the CPE cost of $300 plus the subscription of $10 monthly and $1000 annually plus other operation expenses give a total of $1420 yearly. Though this is significantly lower than other developed regions, it can still define a considerable expense for further households, with $0.47 per Mbps.

In Rural Asia the CPE cost $250 while the monthly subscription fee rises to $15. Unfortunately, the total annual cost of $1,330 is not far from Sub-Saharan Africa level, but is considerably lower, and cost per Mbps equals $ 0.53 for affordable internet.

The Remote Americas are more expensive due to its CPE cost of $ 400 and monthly subscription fee of $20. This is a clear indication of the cost implication in this region of deploying fiber to connect end-users; totally accumulating $1,840 every year with a relatively low cost per Mbps of $0.61. The Total Cost per community is even higher in Arctic Communities and Pacific Island at $2,150 and $2,035 respectively and the cost per Mbps $0.6841 in Arctic Communities.

While there are numerous technological solutions available in the market today that have made most equipment and operations affordable the price of satellite internet services remains the biggest challenge especially in low-income area. Interactions with residents showed that family considerations are taken over by other necessities rather than Internet connection, therefore the necessity of subsidies for initial equipment, as well as monthly payments.

Some other developments could also help increase affordability still higher with public-partnership with private enterprises as this could directly enable partnerships in sharing of costs which otherwise could increase operational costs, hence bringing the final cost to the end-users down.

These observations align with preceding studies, such as Myovella et al. (2021) focused on the digitalization of satellite internet in Sub-Saharan African countries (Myovella, Karacuka, and Haucap 2021). They demonstrated that cost reduction measures would significantly broaden access to satellite internet. The only way to resolve affordability issues is to implement customized actions that eliminate existing barriers and provide equal access to satellite internet for low-income populations.

4.8. Impact of Environmental Factors on LEO Satellite Performance

LEO satellite systems were tested in terms of performance in clear sky, light rain, heavy rain and cloudy conditions. The done simulations showed that superior techniques for frequency selection and modulation reduced adverse weather impacted signal degradation. This reliability makes the communication dependable to the users in the areas of severe atmospheric interferences. Table 4 below gives details on the effects of various weathers on the signals showing minimal loss on the effective signal to noise ratio (SNR).

Table 4. Atmospheric Impact on Signal Performance in LEO Satellite Systems

Weather Condition	Frequency (GHz)	Signal Degradation (dB)	Effective SNR (dB)	Bandwidth Reduction (%)	Data Rate Reduction (%)	Communication Reliability (%)
Clear Sky	20	0	30	0	0	99.9
Light Rain	20	1	29	2	2	99.5
Heavy Rain	20	3	27	5	8	98.5
Cloudy	20	0.5	29.5	1	1	99.7

The findings of the data reveal that LEO satellite systems are least affected due the different atmospheric conditions. Progressively, during the precise weathers, no distortion of the signal occurs and SNR is coupled to 30dB making the performance to be 99.9% reliable on communications. The condition is basically ideal and becomes the benchmark for assessing organizational performances.

Light rain causes superior SNR degradation of 1 dB which effectively means that the SHG coverage will be less by a negligible 29 dB. Throughput is still maintained relatively small at 2% in bandwidth and data rate and communication reliability of 99.5%. This shows how the system was able to perform during a mild weather disturbance that affected the wind resource availability.

A signal degradation of 3 dB arises from heavy rain which reduces the effective SNR to 27 dB which is the greatest hurdle. Nonetheless, the reduction of bandwidth is restricted to 5% only and data rate decreases by 8% only. Communication reliability has not deteriorated at a rate greater 0.2% to reach 98.5% to maintain reliable connections for important operations.

At low visibility, the signal attenuation is slightly low, 0.5dB and the effective SNR is 29.5dB in cloudy conditions. For bandwidth and data rate, the achieved values are 99% of baseline and for communication reliability, the offered value is 0.003% or 99.7%.

These outcomes demonstrate that enhanced variants of frequency selection and modulation can successfully reduce the negative impacts of atmospheric conditions on LEO satellite systems. This affirms an earlier study by other scholars who asserted that adaptability is key in satellite communication network concerning consistency of performance of the system. Through high reliability and little impact on performance LEO satellites may meet a variety of applications including the climates that are typically considered hostile.

4.9. Affordability and Accessibility of LEO Satellite Services

Recent innovations in satellite technology and escalating competition with the growing number of players has brought down the overhead expense of launching and maintenance of LEO satellites. The cost factors that include launch of satellites, establishment of ground stations, and customer premises equipment have been reduced significantly compared to 2020. However, there are still serious problems with the price of CPE, which remains too high for adoption, especially in developing countries, where even minor expenditures may pose a challenge. To achieve such goal, additional measures will need to be taken, for instance, more cost reductions and subsidies for LEO satellite services penetration. The breakdown of costs and percentage reductions across the core components of the model are presented in the Table 5 below.

Table 5. Cost Breakdown and Reductions in LEO Satellite Services

Component	Average Cost (USD)	Percentage Reduction from 2020	Current Accessibility Level (%)	Impact on Service Cost (%)	Estimated Cost Target for Accessibility (USD)
Satellite Launch (per unit)	50 million	25%	High	40	40 million
Ground Station Setup	500,000	30%	Moderate	25	350,000
CPE (Receiver)	300	10%	Low	35	200

It is found out that although large amount of cost has been trimmed down over time in satellite launches and GS establishment, the cost of CPE remains largely unaltered, posing a serious affordability issue with the unserved customers in awaiting regions.

Space flight expenses has seen its costs reduced by 25%, from $67 million in 2020 to $50 million in the current financial year. These reductions are attributed to advances in reusable rocket technology that cut costs and through economy of scale occasioned by competitive entrants such as SpaceX, OneWeb and Amazon. This has rendered satellite deployment more financially tenable, although the effect on the affordability from the user end is less direct.

So, there has been the lowest reduction in ground station setup costs from $700,000 to $500,000; a reduction of 30%. This improvement will contribute to the advancement of satellite services in the rural and remote regions because infrastructure costs will be lower. Nevertheless, the cost of ground station continues to play a substantial part among the operational costs.

CPE has implications to the affordability of households, has dropped by a mere 10% from $333 to $300. As this component continues to significantly affect end-user service accessibility, it must be scaled back further. As has been seen through the estimated target for accessibility for broadband satellite internet, CPE currently costs need to be taken down to around $200 or less for satellite internet to become affordable in low-income areas.

The current affordability profile shows these inequalities; the launch of satellites and establishment of ground stations are categorized as ‘Highly Accessible’ and ‘Moderately Accessible’. However, CPE accessibility is still limited up to $ 35 for the total service cost for end users. This underlines the dire need for countervailing measures – subsidies or public-private partnership – on the equipment front.

5. Discussion

The article aims to give a detailed overview of Low Earth Orbit (LEO) satellite systems and the opportunities that they may open in the sphere of global connectivity. Based on the researched performance parameters including latency, throughputs, packet loss rates cost and performance under different environmental conditions it is evident that LEO satellites are extremely important in narrowing the digital divide especially in the unserved areas. These findings therefore support previous literature and build upon others areas and highlights limitations for future research.

Probably the most important contribution of this study is the confirmation of the large benefits of LEO satellite systems over the conventional GEO satellites. The decrease of latency from 600 ms on GEO systems to only 30 ms on LEO systems prove again these systems to be well suited for Realtime-Applications like telemedicine, Building remote classes and HD-Streaming. Kumar and Arnon (2022) also pointed out that LEO systems provide a high system SNR performance at sub-THz frequencies that is well suited to today’s communication requirements (Kumar and Arnon 2022). The improved performance of LEO systems evident in the work shows that they can indeed serve applications that necessitate very low latency essential for full-spectrum digital connectivity.

Another major finding of the study is the concept of software defined networking (SDN) for traffic engineering in LEO constellations. While traditional networks would require constant monitoring and resource managing to conservatively prevent traffic congestion while at the same time keeping the usage rate of resources practically at its maximum, SDN-enabled systems have it in their capability to adapt and alter the distribution of resources in real time in order to preclude such problems and at the same time keeping usage rates high at all times. These results are consistent with the study conducted by Hu et al. (2022) where they revealed versatility of SDN in satellite networks (Hu et al. 2022). The authors' conclusions are supported in this study by quantitative analysis of up to 60% latency reduction during the most congested hours, thus supporting the relevance of SDN for traffic and resources management. Such developments are especially useful in locations where high utilization rates are closely linked with incomplete telecommunications networks.

Routing efficiency was another area of interest in this study. This work demonstrated that the integration of directional guidance with bee colony optimization algorithm facilitated the improvement in packet delivery by a 90% reduction in packet loss while at the same time, reducing average path length up to 40% under moderate traffic load. Yang et al. (2023) have previously described the framework of bio-inspired routing algorithms however; the current research shows that such algorithms are beneficial for handling dynamic attributes of LEO networks (Yang et al. 2023). The flexibility in modifying routing plans in this context not only increases the stability of transmission but also enhances the quality of delivered service depending on the condition of the network, a critical demand given the inconsistent nature of traffic in many different parts of the world.

Antiquated affordability of satellite internet service is still an issue, especially in the low-income areas. Although the use of satellite technology and competitive pressures have decreased the costs of satellite deployment and operation, and where CPE is often provided by the customer, choice and deployment costs have only recently dropped by a derisory 10%, this means that the financial access barriers remain. This is consistent with previous literature such as Myovella et al. (2021) focused on the cost boundary as one of the major challenges to digitalization in Sub-Saharan Africa (Myovella, Karacuka, and Haucap 2021). From analysis of costs made in this study, there is evidence of the necessity for applications of combined incentives perhaps in the form of subsidies or openings for public-private partnerships. Lifting the barriers to affordability will be relevant this will enhance the spread of satellite internet services in the unserved areas.

Environmental robustness was also assessed with consideration of the fact that satellite performance as simulated was not significantly affected by poor weather conditions. In case of heavy rains, there was only a 3 dB signal loss, while the SNR was always above the effective desirability of 27 dB to ensure communication without interference. These results support Li's (2023) review of link budget studies, where he highlighted the choice of frequencies and modulation schemes in reducing atmospheric interference (Li 2023). Thus, due to the ability of LEO satellites to achieve and sustain stable operation under the influence of diverse environmental factors LEO satellites are very suitable to areas experiencing extreme climate.

However, this study has its own limitations, and further research needs to be done in order to overcome some of them. The scenarios were specific and the signal frequencies at which the tests were conducted meant that general results obtainable under operational conditions could not be ascertained. For example, while the atmospheric impact analysis mainly concerned the frequencies at around 20 GHz, the exploration of the high or low frequency bands' performance was missing. Extending the frequency range and operating numerous experiments LEO systems in other conditions will give richer conclusions about the ability of future systems.

Thus, the affordability study fails to measures possible disparities of economic conditions and purchasing power across different regions. The average cost figures indicated above suggest that such costs are still relatively high, and finer differentiation is likely required to address cost requirements in given settings. The presented insights also depend on theoretical modeling and simulations most vigorously in the case of routing algorithms and SDN based traffic control. As Zheng et al. (2021) observation did indicate in their analysis of Dijkstra based routing algorithms, they found that there are several issues which can arise in practice among them include but are not limited to; computational complexity and scalability issues (Zheng et al. 2021). Since the proposed models are theoretical, field trials of the models would be necessary to ascertain their use in real life.

Legal and regulatory factors were outside the preview of this research however they are pertinent in the deployment of LEO satellites. Closely related to the work of Juan et al. (2022), their research pointed to spectrum allocation and handover issues that are crucial to integrated satellite and 5G networks (Juan et al. 2022). If these aspects were addressed, there would be improved compatibility of systems between the terrestrial and satellite, improving the scalability of the LEO networks.

LEO satellite systems have been found to perform well and the work contributes to the knowledge of the systems through empirical evaluation of the performance factors and areas that need further enhancements or innovation. The results conform with previous research like Myovella et al. (2021) , Kumar and Arnon (2022), and Hu et al. (2022) , but reveal crucial areas for improvement that need to be covered to fully unlock the value behind LEO satellites (Myovella, Karacuka, and Haucap 2021; Kumar and Arnon 2022) (Hu et al. 2022). The identified gaps necessitate future research on the following: Increasing the number of investigations made in environmental contexts, conducting studies on relative costs in different regions, on testing of presented models in actual practice, and on the examination of legal requirements. These will be crucial for achieving some of the principled advancements that come with LEO satellite systems, for the development of an inclusive digital environment.

6. Conclusion

The article explores how LEO satellite systems can contribute to evolving global connectivity and eliminating the digital divide. Based on key performance indicators, cost-effectiveness ratios, and technological advancements, the study reveals how LEO satellites hold a significant advantage over other systems in providing fast and efficient internet in underserved and unserved areas. These systems present solutions that offer lower latency, higher throughput, and reduced packet loss compared to conventional systems, making them crucial for supporting real-time applications such as telemedicine, remote education, and emergency services.

One of the major contributions of this research is the analysis of how novel paradigms like SDN and adaptive routing algorithms improve LEO networks. Traffic engineering using SDN effectively manages resources while preparing for future traffic increases, ensuring that the network remains congestion-free and capable of delivering line-speed performance. Similarly, adaptive routing schemes enhance data transfer reliability by dynamically adjusting routing configurations based on current network conditions. These developments enable LEO satellites to support global communication needs flexibly and at a large scale.

Although satellite-based internet is often praised as affordable and widely available, practical challenges remain in low-income areas. While the cost of satellite access technology has decreased over the years in terms of deploying satellites and setting up ground stations, the cost of CPE remains high. Government efforts, such as subsidies or PPPs are crucial to overcoming these economic barriers and maximizing the benefits of satellite connectivity.

Another revealed strength of LEO systems is their environmental resilience, demonstrated through their tolerance to adverse weather conditions. This enhances the reliability of LEO satellite networks in areas vulnerable to atmospheric interference, making the technology more dependable as a global communication solution.

However, the study identifies potential areas for further research and development. There is a clear need for environmental tests under various operational conditions, affordability assessments across different regions, and real-world validation of proposed models. Additionally, addressing regulatory and policy-related issues will be essential for integrating satellite communications with terrestrial systems.

LEO satellite systems are revolutionary in concept and form, creating a global infrastructure designed to address the digital divide in a flexible and cost-effective manner. By incorporating technological advancements and overcoming existing obstacles, these systems can become a key tool in shaping an inclusive digital environment. The development of LEO satellite constellations will play a crucial role in meeting the world's connectivity requirements, driven by the growing demand for increased internet speeds and comprehensive global coverage.

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