https://doi.org/10.31436/iiumej.v26i2.3653

LATENCY PERFORMANCE EVALUATION OF LEO STARLINK AND SES-12 GEO HTS NETWORK UNDER TROPICAL RAINFALL CONDITIONS

HAZRUL HAFIZ ABDUL SHUKUR, YASSER ASRUL AHMAD*, MUHAMMAD SHARIR FATHULLAH MOHD YUNUS, KHAIRAYU BADRON

Department of Electrical and Computer Engineering, Kulliyyah of Engineering, International Islamic University of Malaysia, Kuala Lumpur, Malaysia

**Corresponding author: yasser@iium.edu.my*

(Received: 17 March 2025; Accepted: 22 April 2025; Published online: 15 May 2025)

ABSTRACT: High Throughput Satellites (HTS) in geostationary Earth orbit (GEO) have been rapidly launched to meet the growing demand for high-speed data. However, the latency of HTS remains the same as that of conventional GEO satellites due to the characteristics of their orbit. Recently, Starlink HTS satellites in low Earth orbit (LEO) mega constellations have been operationalized globally, providing low-latency internet services compared to GEO HTS. Despite their high-speed benefits, Ku-band HTS systems are highly susceptible to rain-induced signal attenuation, particularly in regions with heavy rainfall, such as the tropics and equatorial countries. This phenomenon weakens the radio frequency signals and impacts real-time latency in the communication link. This research aims to determine the latency effect of the HTS satellite in LEO and GEO and evaluate its performance under heavy rainfall conditions. This study utilises real satellite link services from SES-12 GEO HTS and LEO Starlink for performance assessment. Continuous latency measurements are recorded over six months to analyse Ku-band performance in a heavy rainfall region. The results indicate that extreme rainfall in the tropical region significantly affects GEO satellite links, causing prolonged signal degradation due to fixed ground stations. In contrast, Starlink's LEO network experiences less impact from rain fade, as it dynamically switches between multiple satellites. The results show latency for the GEO terminal link ranges from 600 milliseconds (ms) to 3000 milliseconds (ms), whereas latency for the LEO Starlink terminal ranges from 20 milliseconds (ms) to 100 milliseconds (ms). Starlink provides higher satellite link availability at 99.6% onsite compared to 94% for the tropical region's SES-12 GEO HTS satellite services.

ABSTRAK: Satelit Jalur Lebar Berkapasiti Tinggi (HTS) dalam orbit geostasioner (GEO) berkembang pesat bagi memenuhi permintaan data berkelajuan tinggi. Namun, latensi HTS GEO kekal tinggi seperti satelit GEO tradisional. Sebaliknya, HTS dalam orbit bumi rendah (LEO) seperti Starlink menawarkan internet berlatensi rendah secara global.Walaupun berkelajuan tinggi, sistem HTS menggunakan jalur Ku terdedah kepada pelemahan isyarat hujan, terutamanya di kawasan tropika. Fenomena ini bukan sahaja melemahkan isyarat frekuensi radio tetapi juga menjejaskan latensi komunikasi masa nyata. Penyelidikan ini bertujuan untuk menentukan kesan latensi sistem satelit HTS di orbit LEO dan GEO serta menilai prestasinya dalam keadaan hujan lebat. Pengukuran latensi berterusan direkodkan selama enam bulan bagi menganalisis prestasi jalur Ku di kawasan beriklim hujan lebat.Kajian ini menilai kesan latensi HTS LEO dan GEO dalam keadaan hujan lebat menggunakan perkhidmatan satelit SES-12 GEO HTS dan LEO Starlink di Makmal Komunikasi Satelit IIUM. Keputusan menunjukkan hujan lebat memberi kesan besar kepada sambungan GEO kerana stesen bumi tetap, manakala rangkaian LEO Starlink kurang terjejas kerana boleh beralih antara satelit. Kelewatan GEO ialah 600ms–3000ms, manakala Starlink hanya 20ms–100ms. Starlink juga lebih stabil dengan 99.6% ketersediaan berbanding 94% bagi SES-12 GEO HTS di kawasan tropika menyebabkan degradasi isyarat berpanjangan.

KEYWORDS: *High Throughput Satellite, Ku Band, Starlink Satellite Latency, Tropical Regions, Rain Attenuation.*

1. INTRODUCTION

A high-throughput Satellite (HTS) is a type of satellite designed to handle large data communication links, offering high data throughput capabilities. Each spot beam reuses the frequencies in multiple transponders or carriers, which a single HTS can provide more than 100 Gbps of capacity, which is more than 100 times the capacity offered by conventional Ku-Band satellites [1].

A geostationary satellite (GSO) is an Earth-orbiting satellite at the same rate as the Earth's rotation, located approximately 36,000 km from the Earth's surface. This shows that the satellite appears stationary at a fixed point in the sky [2]. The first Ku GEO HTS launched was Thaicom in 2005, also known as IPSTAR, with 45 Gbps global capacity, and the launch of ViaSat 2 in 2017 with over 300 Gbps [3]. Furthermore, Geostationary satellite lifetimes are now extending to 15 years, and traffic demand changes are occurring rapidly during their operational period, affecting service areas and applications [4].

While for LEO, two major announcements were made in April 2019 where Amazon is planning an (HTS) constellation for broadband services with over 3,000 satellites in Low Earth Orbit (LEO) known as Project Kuiper in the year 2020 and subsequently SpaceX announced its HTS constellation known as Project Starlink and is going to launch nearly 1,600 satellites [5].

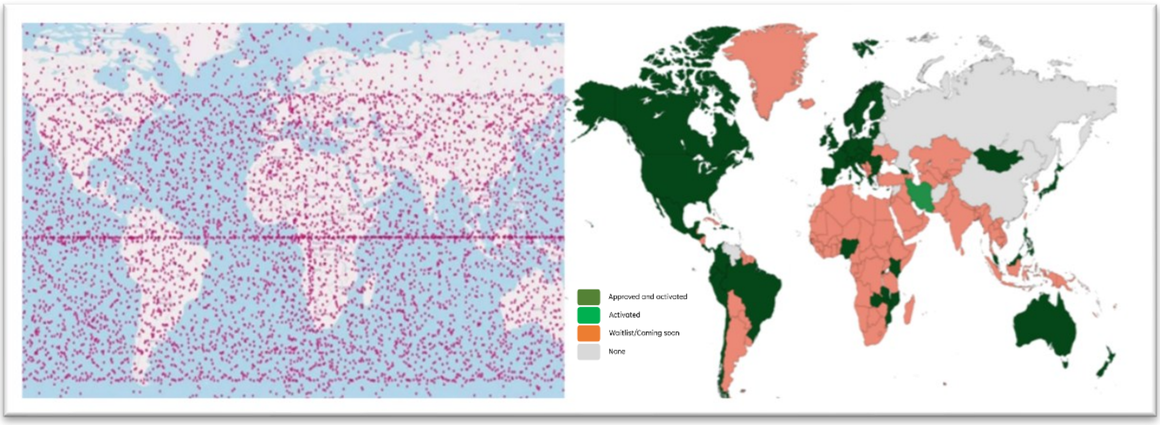


Figure 1. Starlink Satellite operation and distribution map[10]

Placing an HTS in LEO offers advantages such as lower latency, improved signal propagation, and enhanced data transmission speeds due to the satellite's proximity to Earth[6]. The satellite industry has experienced a rapid transformation to meet the ever-growing demand for high data throughput. Recently, Starlink has emerged as a prominent LEO satellite network service and entered the Malaysian market in 2023 [7]. SpaceX has received Class Assignment (CA) approval on a non-interference and non-protection basis to operate Starlink terminals using the Ku-band in Malaysia, with its gateway operating in the Ka-band at frequencies ranging from 12 to 40 GHz [8]. GEO HTS satellite services also utilise these frequency ranges, and they are particularly susceptible to rain attenuation [9]. Fig. 1 shows the Starlink satellite distribution in September 2024 from the Non-GEO Constellations Analysis Toolkit**,** with more than 6,000 active Starlink satellites [10]. The green code represents countries that have approved Starlink to operate, while the orange code indicates countries where SpaceX is obtaining approval**.**

Indirectly, those satellite signal link performances in Ku Band satellites operating beyond 10 GHz are subject to propagation loss, where rain attenuation is highly variable and, depending on the liquid water content, will impose a significant impact on signal link attenuation [11]. This propagation effect causes the receiving terminal signal level to be attenuated, causing the satellite link to suffer outages during rain [12].

Radio wave propagation is the process by which electromagnetic waves are transmitted from one point to another through the Earth's atmosphere or space. It exhibits reflection, refraction, diffraction, absorption, polarization, and scattering [13]. Atmospheric losses occur in the Earth's atmosphere due to energy absorption by the many atmospheric conditions, some of which are from adverse weather conditions. Weather-related losses are called atmospheric attenuation and absorption losses [14].

Annual precipitation data show that Peninsular Malaysia experiences the highest average annual rainfall compared to the neighbouring countries within the Asia Pacific region [15]. Malaysia experiences the highest rainfall rates in the world, frequently exceeding 200 mm/hr, attributed to its equatorial climate, which is characterized by high humidity and is further influenced by tropical monsoon patterns [16]. The climate results in a consistent rainfall distribution throughout the year, with heavy downpours often occurring in the afternoon due to the intense heat and moisture build-up during the day [17]. Two distinct monsoon seasons further shape the country's rainfall patterns. The Southwest Monsoon, which spans from late May to September, generally brings relatively lighter and less consistent rainfall. In contrast, the Northeast Monsoon, occurring between November and March, is associated with heavier and more sustained rainfall [16]. This monsoon primarily affects the eastern regions of Peninsular Malaysia, where heavy showers are known to occur in bursts, lasting an average of about an hour.

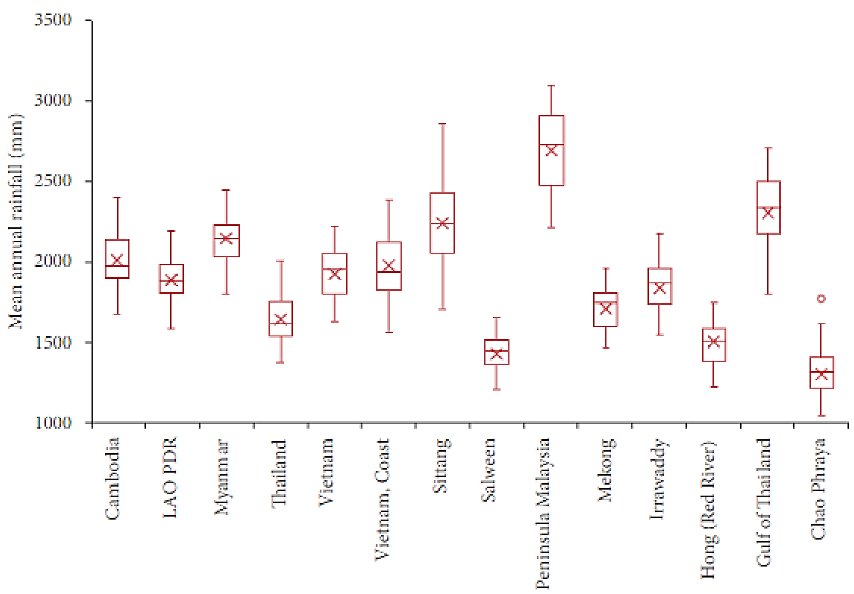


Figure 2. East and South Asia Precipitation Map [18]

Understanding rainfall patterns, specifically in tropical regions, is crucial for developing robust strategies to mitigate the effects of the intensity and frequency of rain, ensuring resilience in critical infrastructure and services in the face of this natural climatic phenomenon. However, research on Low Earth Orbit (LEO) satellite constellations remains limited, particularly in addressing their performance analysis in tropical regions. Most existing studies on rainfall effects have only focused on Geostationary Earth Orbit (GEO) satellites, largely due to their historical dominance in satellite communication services over the past decades.

Latency is often called round-trip time (RTT), the time it takes to receive and return data between two nodes. GEO satellites, positioned at approximately 36,000 km, experience inherently higher latency as little as 480 ms round-trip due to their extended transmission path, making them more susceptible to prolonged degradation during heavy rain events [19], [20]. In contrast, Starlink satellites orbiting in low Earth orbit are positioned much closer to Earth, at an altitude of approximately 550 km. Starlink network benefits from the reduced signal path loss, adaptive beamforming, and dynamic satellite handovers, which may mitigate rain-related latency fluctuations [19], [21].

This research aims to determine, compare, and evaluate the latency effect under heavy rain conditions in the equatorial region using the cumulative distribution function (CDF) for LEO HTS constellations versus GEO HTS, which provides a probabilistic view of exceedance times for different latency thresholds. The method uses real satellite link paid internet services from the Starlink terminal and the SES 12 GEO HTS very small aperture satellite (VSAT) terminal installed onsite at the International Islamic University Malaysia satellite communication lab to measure continuous latency measurements for 6 months. This setup measures latency in Ku-band link from both LEO and GEO HTS exposed under a heavy rainfall region. Table 1 shows a key comparison summary for both HTS GEO & LEO Starlink [8], [22], [23], [24].

Table 1. Comparison between SES12 and Starlink specifications

Satellite Name	Type	Frequency band	Satellite Count	Lifespan	Nominal Latency	Data Throughput
SES-12	Geostationary (GEO) HTS - Specific wide beam covers the entire Asia-Pacific region	Ku-band (VSAT Terminal) & Ka-band (Gateway)	1	15 years	500-700 ms	Download of 50-100 Mbps & Upload of 10-20 Mbps
Starlink	Low Earth Orbit (LEO) mega constellation - Global coverage focusing on underserved and remote areas.	Ku-band (Starlink Terminal) & Ka-band (Gateway)	> 3000	5 to 7 years	20-40 ms	Download of 100-250 Mbps & Upload of 20-40 Mbps

2. METHODOLOGY

This research methodology is structured into two key phases: (1) Onsite Measurement and Data Collection, and (2) Onsite Performance Analysis. Each phase focuses on distinct aspects to achieve the research objectives.

A critical aspect of the applied method is developing and implementing an automated monitoring system for LEO Starlink and SES-12 GEO HTS VSAT terminals to measure latency and ensure proper data storage accurately. This automated monitoring system enables continuous, consistent, and reliable data collection for six months, facilitating the analysis of latency trends across varying weather conditions.

2.1. Onsite measurement and data collection

LEO Starlink and SES-12 GEO HTS VSAT terminals are co-located and were installed at the satellite communication lab at the International Islamic University Malaysia (IIUM). This phase comprises setting up and testing satellite link services using Ku Band transmission from two different satellite systems: LEO Starlink and conventional SES-12 GEO HTS, a Geostationary Earth Orbit (GEO) satellite. A real-time gravity tipping bucket rain gauge is integrated into this setup to measure rainfall intensity accurately. It records data at one-minute intervals, providing high temporal resolution for detailed analysis. With a measurement resolution of 0.28 mm, the system ensures precise detection of even light rainfall events. Subsequently, satellite link latency was captured at 10 ms intervals and monitored continuously, serving as a primary parameter for understanding the behaviour of satellite communication links under tropical weather conditions. By implementing this automated monitoring approach, the methodology provides a comprehensive dataset for further analysis.

The LEO Starlink terminal is connected via the LEO Starlink Satellite network, as shown in Fig. 1, which is marked as an approved and activated region on the map. This LEO Starlink terminal is physically set up on a pole using a custom extended mount shown in Fig. 3. It performs an automatic alignment to locate and connect with Starlink satellites. The terminal will connect to the Starlink network and provide internet access. The Starlink terminal stays in a fixed position while tracking Starlink satellites using its advanced phased array antenna as shown in Fig. 3. Utilising a phased array antenna for electronically steered beam control, the Starlink terminal tracks satellites by its integrated a GPS receiver for its location with Starlink satellites' ephemeris data to predict satellite positions. Compared to a VSAT parabolic antenna, a phased array antenna scans faster due to electronic beam steering, while the parabolic antenna depends on the initial mechanical setup of its azimuth and elevation [25].

However, information regarding the azimuth and elevation angles of the Starlink terminal is not publicly available through its standard product dashboard. Therefore, the Starlink azimuth and elevation angles are obtained separately using the open-source Starlink-Grafana-Dashboard tool developed through outsourced scripting [26]. This tool was specifically created to capture the Starlink terminal's azimuth and elevation angles and to enable continuous monitoring of these parameters. Based on this setup for 6 months of observation, the azimuth and elevation angles measured in Kuala Lumpur, Malaysia, are approximately 4° and 76.5°, respectively.

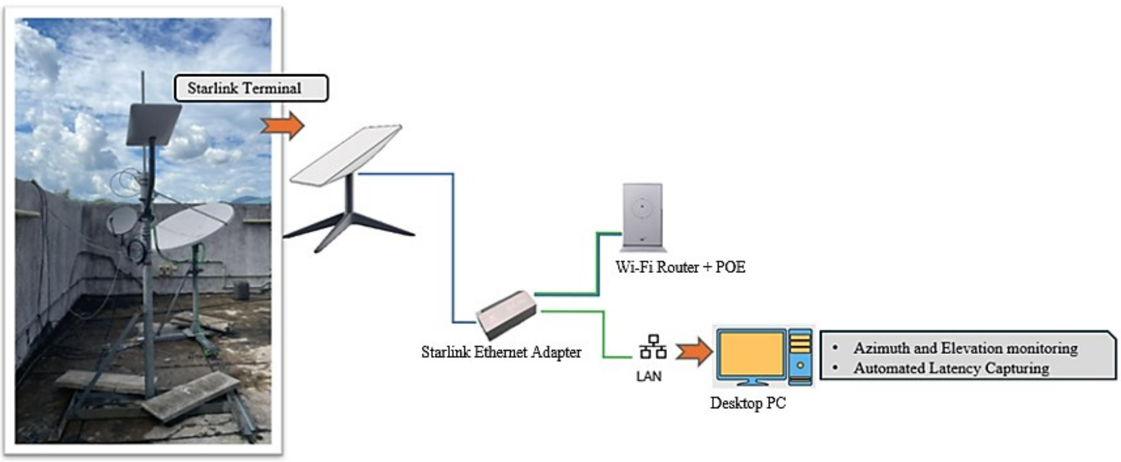


Figure 3. Onsite experimental arrangement for Starlink

Fig. 4 shows the SES-12 GEO HTS Ku-band terminal setup. The VSAT terminal is connected to the SES-12 Satellite, which is positioned in a Geostationary orbit at 95° East with a fixed azimuth of 244.35° and elevation of 81.20° [27].

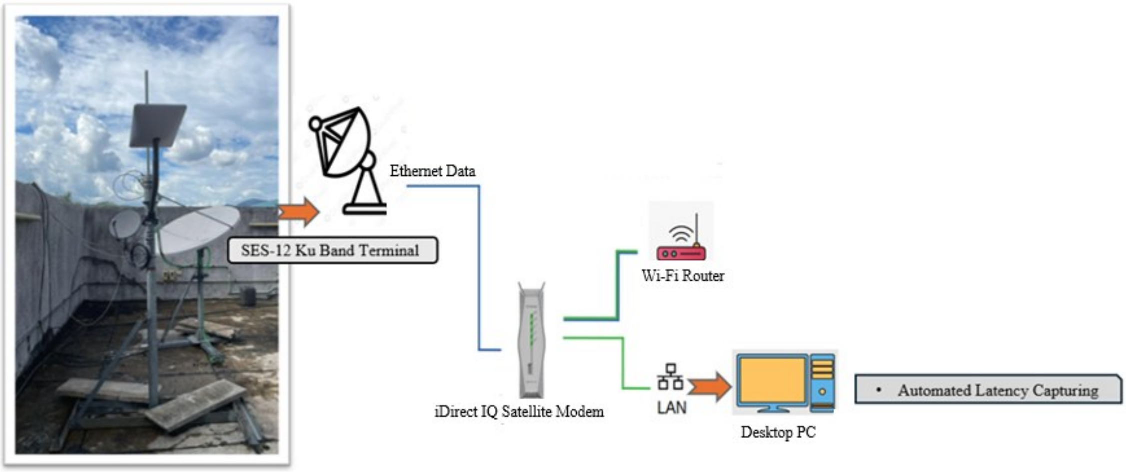


Figure 4. Onsite experimental arrangement for SES-12 GEO HTS

As shown in Fig. 5, this orbital slot allows it to provide coverage across the Asia-Pacific, specifically covering the Malaysian region in providing various communication services.

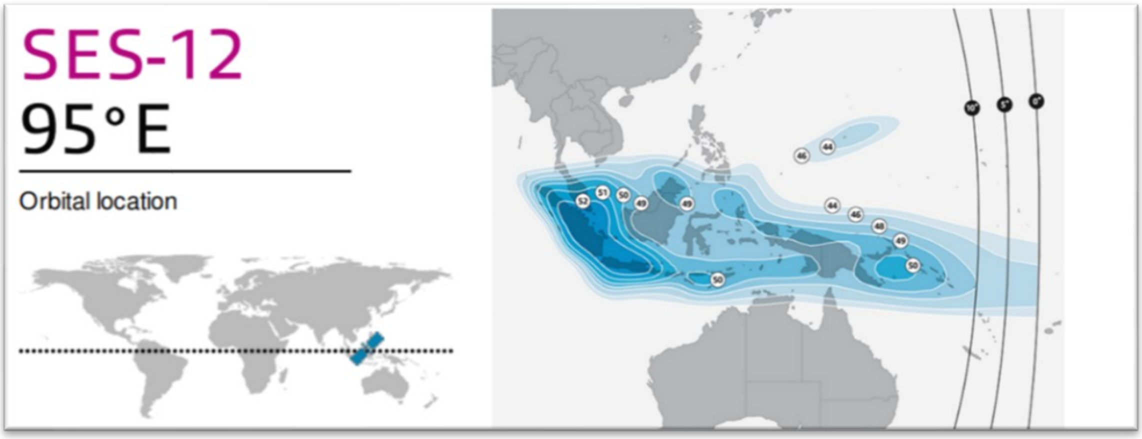


Figure 5. SES-12 GEO HTS satellite with Malaysian footprints [22]

A batch script was developed during this stage to automate the measurement of satellite link latency. The script was developed to ensure continuous operation, logging real-time data by sending ping requests to Google's DNS server (8.8.8.8) for both satellite links (SES-12 GEO HTS and LEO Starlink). An automated script runs continuously, measuring and recording latency results every 10 seconds. These results are saved in a file named ping_log.txt and are also displayed in real-time on the desktop PC, allowing users to monitor the data as it updates. Fig. 6 shows a simplified block diagram of the automated script process, where results are stored in Google Cloud Storage in a structured format for future analysis.

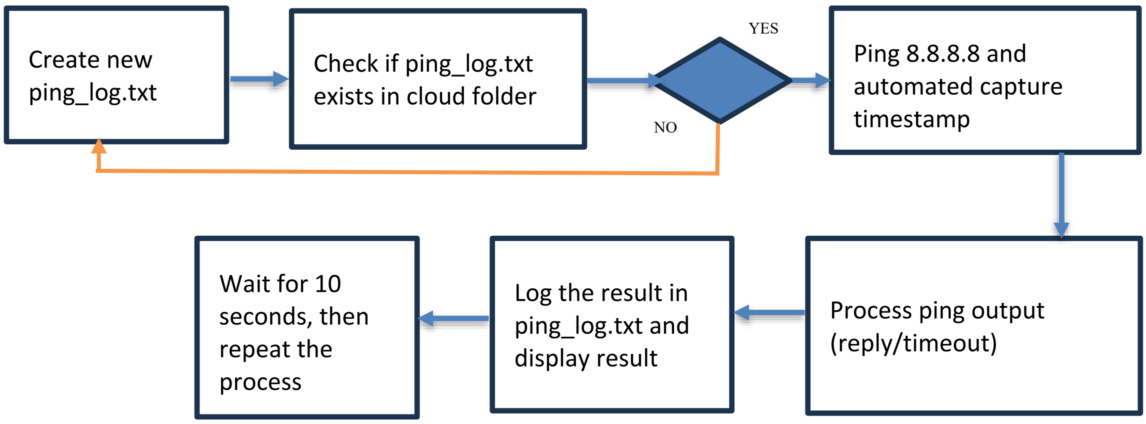


Figure 6. Flow Chart for Automated Latency Script

2.2. Data Analysis

This section focuses on the performance evaluation methodology of the new Low Earth Orbit (Starlink) HTS technology compared to the satellite communication HTS technology of Geostationary Earth Orbit (GEO). Empirical data collected were evaluated with respect to their critical parameters, such as latency and rainfall rate impact, resulting in their communication signal link reliability.

The study starts with data preprocessing, which involves cleaning and organizing the collected data, including rainfall intensity and satellite link delay (latency). Next, an analysis is done to find patterns between the rainfall and latency over time, and to create Cumulative Distribution Functions (CDFs) for both rainfall rates and latency for the LEO Starlink and GEO SES-12 satellite systems. Finally, the performance of both satellite links is evaluated by comparing their latency and connection timeouts during different rain conditions. The CDFs are used to calculate useful statistics that help compare how each satellite system handles heavy rain and how reliable they are overall. Given the tropical region's high rainfall intensity and frequency, the empirical observations provide insights into these technologies' operational limits and resilience under adverse conditions.

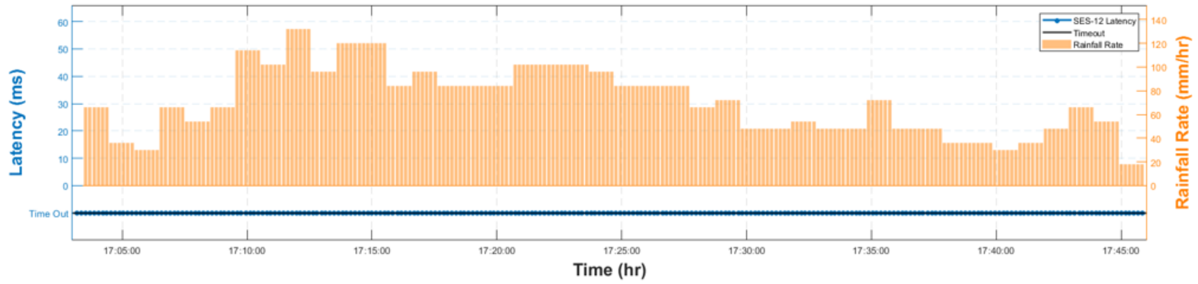
These three phases provide a comprehensive performance analysis, highlighting the strengths and limitations of SES-12 GEO HTS and LEO Starlink satellite technologies, specifically in tropical environments. Additionally, this analysis establishes a foundation for future research and the development of region-specific recommendations for satellite communication in high-rainfall areas.

3. EFFECTS OF RAIN ON LATENCY

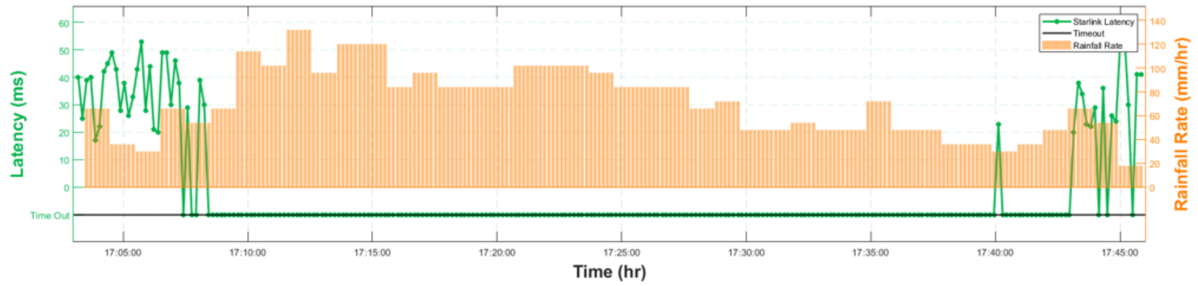
This section analyzes the performance of the SES-12 GEO HTS and LEO Starlink satellite services during rain events, focusing on how precipitation affects signal latency and discussing the experimental findings in detail. This section also discusses the correlation between rainfall rate and latency based on experimental data collected under various weather conditions. The study aims to evaluate the impact of rainfall intensity on the Starlink satellite internet system's latency, focusing on signal degradation caused by rain fade.

3.1. Rain conditions

The graph consists of two subplots, each analyzing the latency performance of SES-12 GEO HTS and LEO Starlink under various rainfall conditions on August 22, 2024. Fig. 7(a) and 7(b) highlight the significant impact of heavy rainfall on the latency performance of Starlink and the SES-12 GEO HTS satellite services. High rainfall rate caused the SES-12 GEO HTS VSAT terminal to become fully disconnected at Fig.7(a). Rainfall rates consistently exceeded 100 mm/hr, peaking at 120 mm/hr, causing disconnections and latency spikes above 60ms, occasionally exceeding 100ms from the LEO Starlink terminal. This is attributed to raindrops' scattering and absorption of satellite signals, highlighting the vulnerability of LEO satellite links to rain fade (Fig.7 (b)).

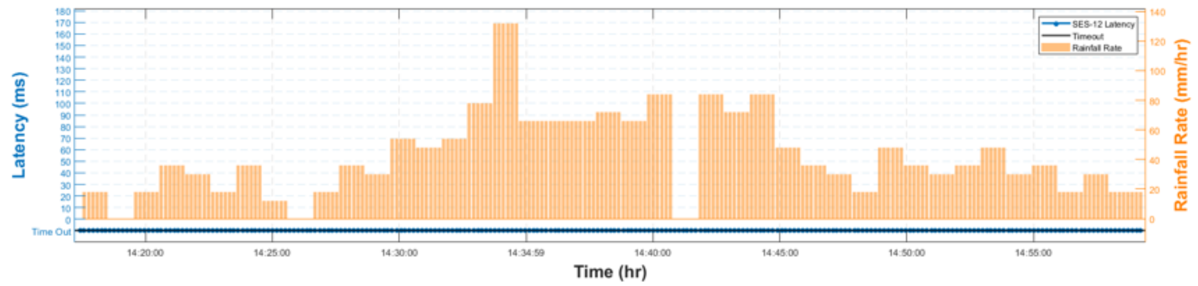


(a) SES-12 GEO HTS

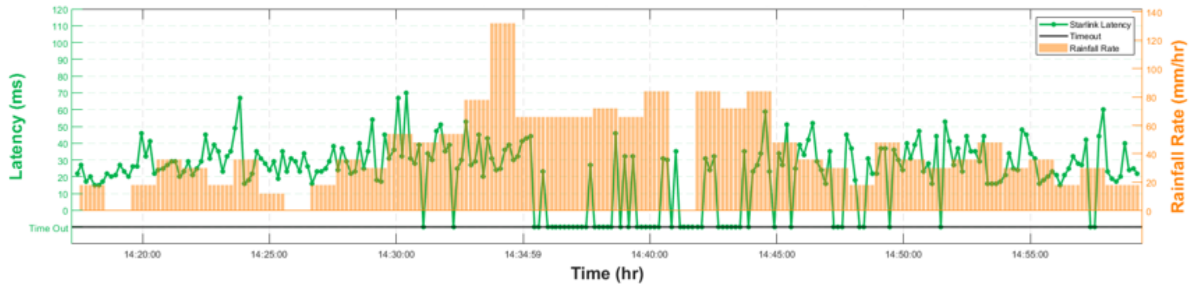


(b) LEO Starlink

Figure 7. A Rain Event occurred on 22 August 2024



(a) SES-12 GEO HTS



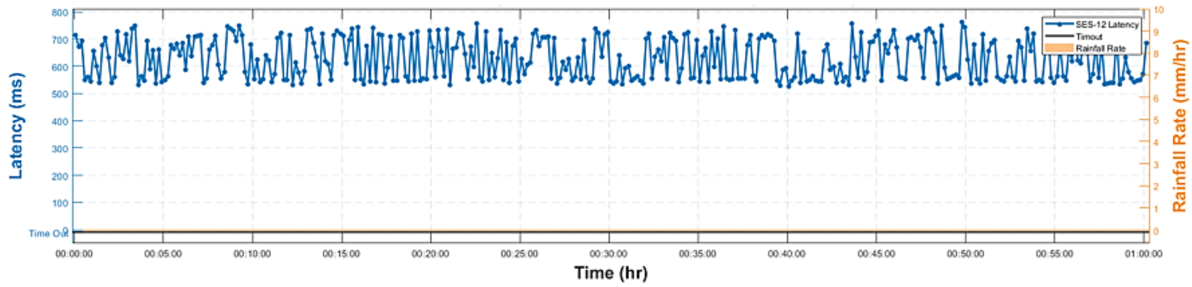
(b) LEO Starlink

Figure 8. A Rain Event occurred on 23 August 2024

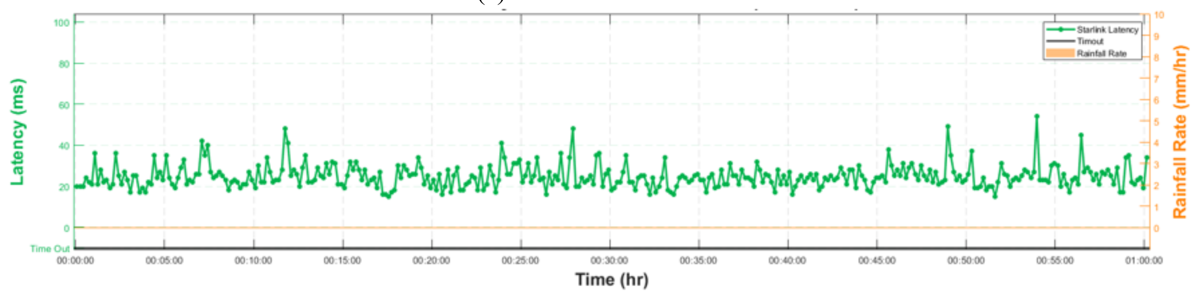
Fig.8(a) and 8(b) illustrate an August 23, 2024, event featuring prolonged medium to heavy rainfall with multiple peaks exceeding 100 mm/hr for SES-12 GEO HTS and LEO Starlink VSAT Terminal. During this period, as shown in Fig. 8(a), the SES-12 GEO HTS VSAT terminal still suffered a total loss of connectivity. The LEO Starlink satellite system experienced only a few disconnects during this period, as shown in Fig. 8(b). In summary, multiple rainfall rate conditions and rain events demonstrate a strong correlation between rainfall intensity and higher latency, highlighting the susceptibility of high-frequency satellite systems to adverse weather. These findings also confirm the vulnerability of Ku-band frequencies to high-intensity rainfall, even in a LEO satellite system mega-constellation closer to Earth. Rain fade causes signal degradation and higher latency. However, the LEO Starlink terminal maintained link availability at certain rainfall rates below 60 mm/hr. In contrast, the SES-12 GEO satellite system experienced complete disconnection.

3.2. Clear sky

The analysis in Fig. 9(b) highlights the stable performance of the Starlink satellite system during no rain events, where rainfall rates consistently remained near 0 mm/hr, indicating clear weather conditions. During these periods, latency for the LEO Starlink terminal showed minimal variability, remaining within a predictable range between 25ms and 35ms. This stable performance reflects the system's ability to operate optimally without atmospheric disturbances, with no signal attenuation or interference caused by rain fade. Compared to the GEO satellite services, which range between 550ms and 750ms in Fig. 9(a), Starlink demonstrates greater latency stability under clear skies, showcasing its robustness in favourable weather conditions.



(a) SES-12 GEO HTS

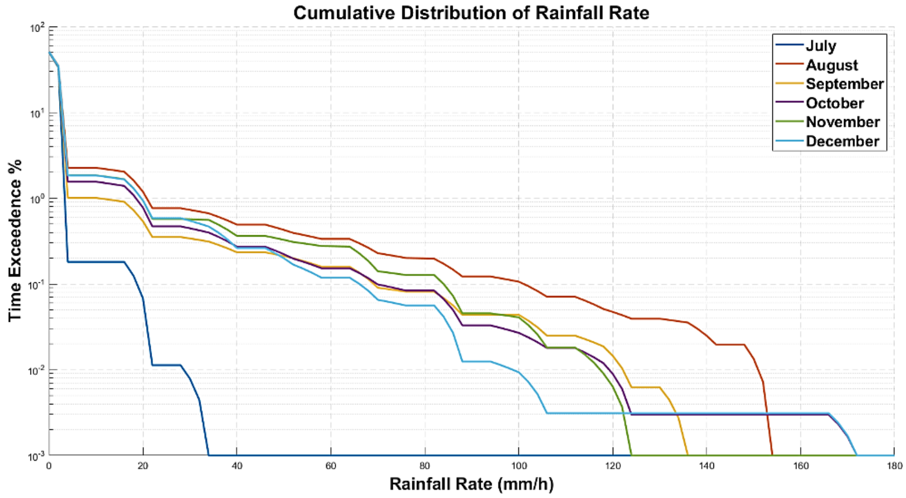


(b) LEO Starlink

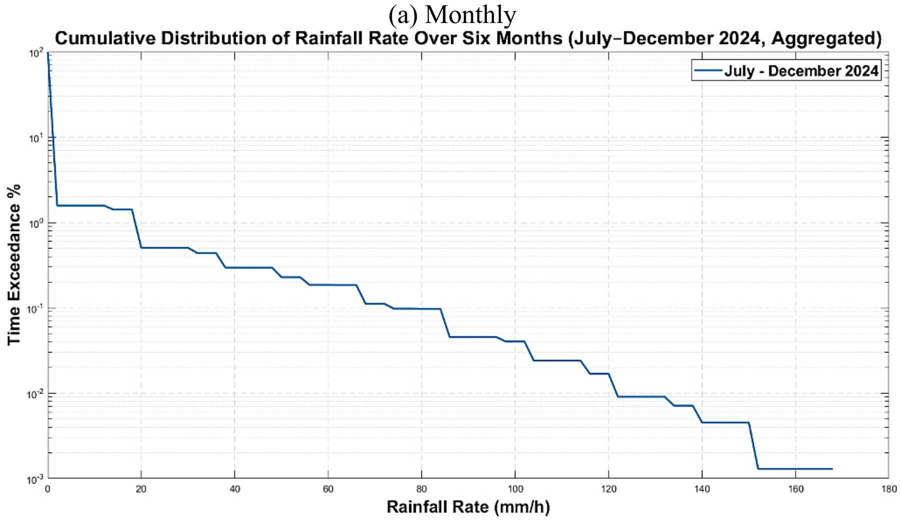
Figure 9. A clear sky event occurred on 5 December 2024

3.3. Cumulative distribution function (CDF) analysis of rain rate

The CDF analysis of rainfall, illustrated in Fig. 10(a) and 10(b), provides a detailed statistical evaluation of the distribution and frequency of rainfall rates across six months (July to December 2024) and accumulated. This analysis examines the percentage of time that specific rainfall rates are exceeded, offering insights into the occurrence and intensity of precipitation during the data collection period. Each month's rainfall distribution is represented by a distinct line, with the x-axis indicating rainfall rates (in mm/hr) and the y-axis showing the percentage of time exceedance.



(a) Monthly



(b) Aggregated

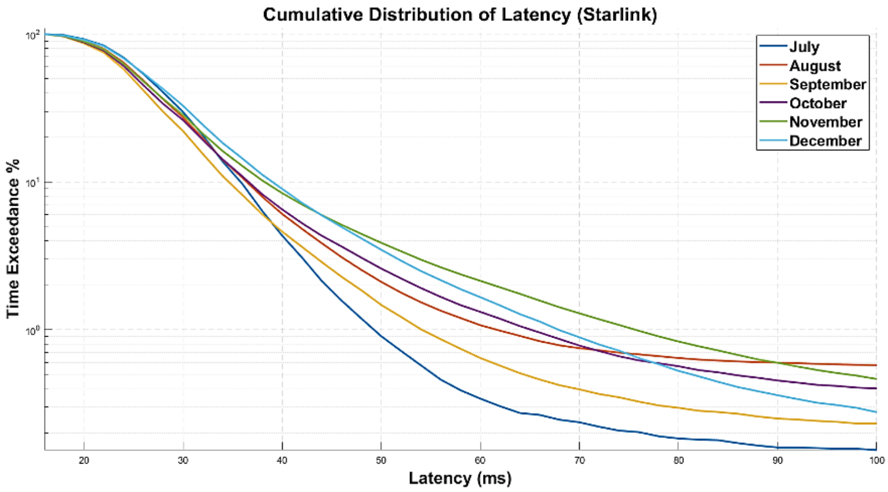
Figure 10. CDF Analysis of Rainfall Rate

The cumulative distribution function (CDF) of the rainfall rate in Fig. 10(a) highlights seasonal variations in rainfall intensity. July experiences mostly light to moderate rainfall, with minimal heavy rain. From August to November, the probability of moderate-to-heavy rainfall increases, likely due to the monsoon season, as seen in the closely aligned curves. December records the highest extreme rainfall events, exceeding 160 mm/h, but these are rare. Most of the time, rainfall remains in the light-to-moderate range. Overall, September to November shows the most frequent heavy rain, while December, despite occasional extremes, has a lower time exceedance for intense rainfall. These seasonal variations directly impact Starlink's performance, particularly in the Ku-band range, as increased rainfall can cause signal attenuation, leading to higher latency, reduced data rates, and potential service disruptions during heavy rain periods. Though infrequent, heavy rainfall events above 100 mm/hr significantly degrade performance, leading to substantial signal attenuation and increased latency. Moderate rainfall, ranging between 40 and 100 mm/hr, also introduces signal degradation, but connectivity remains mostly intact. In contrast, light rainfall below 40 mm/hr has minimal impact, allowing for stable network performance.

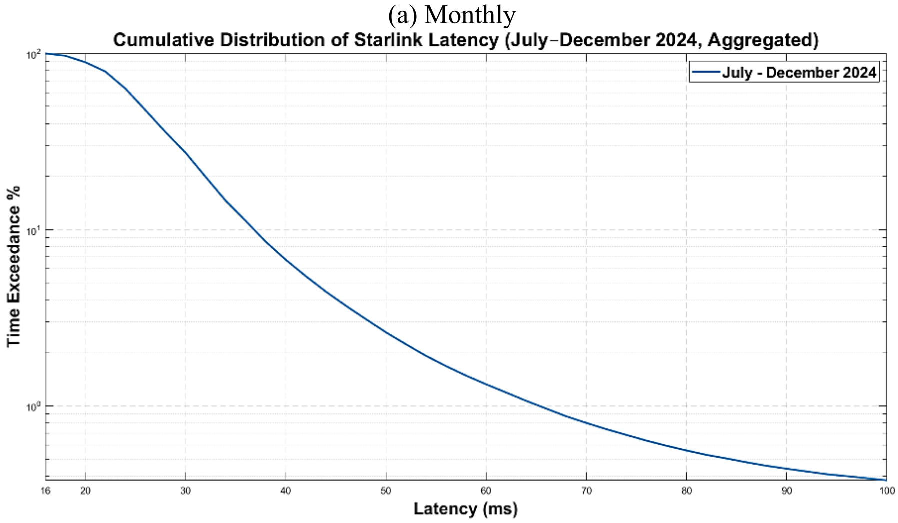
The data collected over six months is not to be directly comparable to ITU-R standards, which are based on long-term averages. However, since the data was gathered during the monsoon season, when rainfall is most intense, it still offers valuable insight. Therefore, the result shown estimated $R_{0.01}$ value from Fig. 10(b), ranging between 110–130 mm/h, is slightly higher than the value shown by the ITU-R P.837-7 model, which generalizes Malaysia's 0.01% exceedance rainfall rate as 100 mm/h [23]. This suggests that the measured data may reflect localised variations in rainfall intensity that exceed the ITU-R's generalised value. The study emphasises the importance of using tools like CDF to quantify the likelihood of various rainfall intensities and their correlation with signal degradation. Integrating CDF insights with latency data enables a comprehensive understanding of the relationship between rainfall intensity and Starlink system performance.

3.4. Cumulative distribution function (CDF) analysis of latency

The Cumulative Distribution Function (CDF) analysis of latency, as depicted in Fig. 11(a) and (b), provides a comprehensive evaluation of the percentage of time that specific latency thresholds were exceeded over a six-month period (July to December 2024). This analysis is crucial for assessing the variability and consistency of the Starlink satellite internet system's latency performance under different conditions. By examining the CDF curves, trends in latency distribution across multiple months can be identified, highlighting periods of increased or reduced network delays.



(a) Monthly



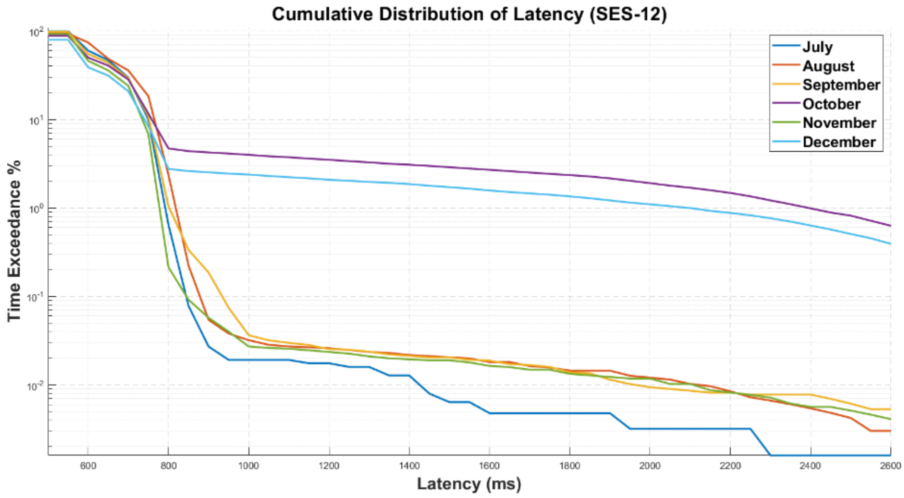
(b) Aggregated

Figure 11. CDF Analysis of Latency for LEO Starlink

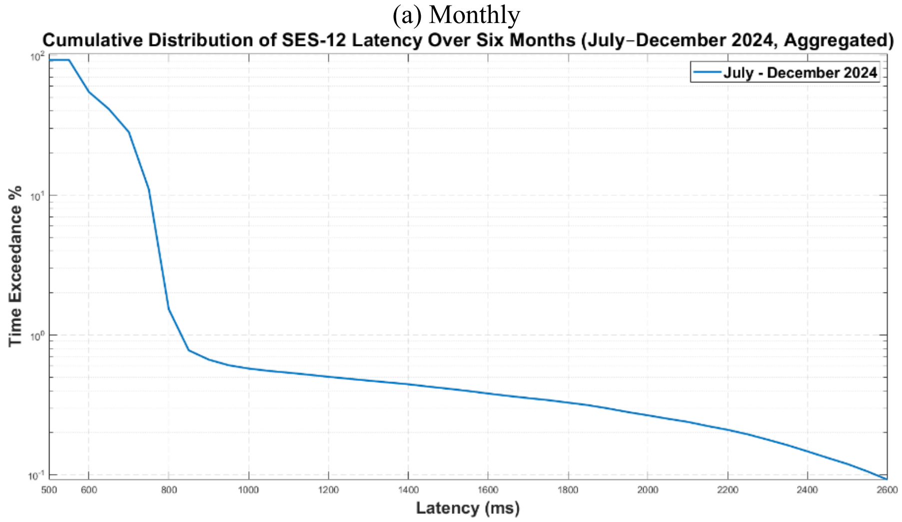
https://doi.org/10.31436/iiumej.v26i2.3653

Furthermore, this analysis helps to establish a correlation between latency fluctuations and environmental factors, specifically rainfall intensity. The CDF analysis highlights in Fig. 11(a) monthly trends in Starlink's latency performance, showing that latency averaged at 20ms about 90% of the time between July and August. From September to November, latency performance increases closer to 40ms at 90% of the time. These changes in latency performance align with higher rainfall intensities observed in the same period, where rain fade likely caused significant signal attenuation and increased latency.

December recorded the highest latency, with latency surpassing other months. Overall, the aggregated data show in Fig. 11(b) that average latency remained below 40ms for 90% of the time, highlighting the reliability of the Starlink system under varying weather conditions. Understanding these variations is essential for optimising Starlink's quality of service (QoS), predicting network behaviour, and improving system reliability for real-time applications.



(a) Monthly



(b) Aggregated

Figure 12. CDF Analysis of Latency for SES-12 GEO HTS

Meanwhile, for SES-12 GEO HTS, as shown in Fig. 12(a) and 12(b), the latency averages around 600ms for approximately 90% of the time across the observed six-month period. The cumulative distribution function (CDF) curves in Fig. 12(a) indicate that the latency remains below 1,000ms during most months, suggesting relatively stable performance under normal conditions. However, higher latency values exceeding 1,500ms are occasionally recorded, particularly in October and December, where the curves gradually deteriorate beyond this threshold. Notably, in December, the latency remains persistently high, with a significant portion exceeding 2,000 ms, likely due to the extensive rainy season causing network congestion and signal degradation in the GEO satellite link.

Overall, the findings established a clear correlation between rainfall intensity and latency performance, emphasising the vulnerability of high-frequency satellite signals to rain fade. The insights gained from this chapter provide a strong foundation for future research to enhance the resilience and reliability of satellite internet systems in varying environmental conditions.

3.5. Performance comparison

Fig. 13 shows a performance comparison graph between the SES-12 GEO HTS and LEO Starlink satellite systems, analyzing the timeout occurrences and site availability from July to December. The timeout percentage, represented by bars, indicates that Starlink in blue bars consistently experiences minimal timeouts across all months. In contrast, the SES-12 GEO HTS VSAT terminal in red bars shows significantly higher timeout occurrences, particularly in August, November, and December.

Onsite availability performance, represented by solid and dashed lines, shows that Starlink, in the solid blue line, maintains above 99% availability throughout the period, highlighting its reliability. In contrast, in the dashed red line, the SES-12 GEO HTS VSAT terminal exhibits a downward trend in its site availability, with a notable decline in December, when it drops below 90% due to heavy rain events.

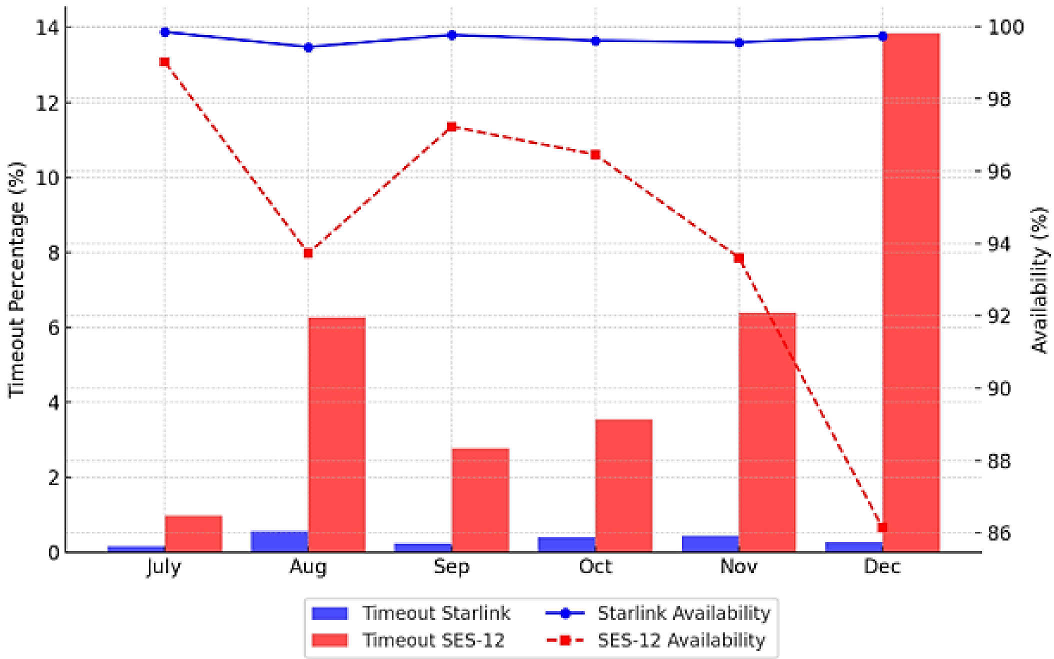


Figure 13. Monthly timeout and site availability

Table 2 summarizes the overall performance analysis, indicating that LEO Starlink satellite services maintain superior stability and availability despite using similar Ku-bands. In contrast, SES-12 GEO HTS Satellite services experience higher disruptions, especially during extreme weather. The LEO Starlink terminal shows temporary latency spikes but recovers quickly, whereas the SES-12 GEO HTS VSAT terminal suffers from persistent signal degradation due to rain events. Additionally, the LEO Starlink terminal has much lower latency, captured at 20ms to 100ms, compared to the SES-12 GEO HTS VSAT terminal, which is 550ms to 1000ms, further emphasising its advantage in responsiveness. The mean site availability for the LEO Starlink terminal remains close to 100%. In comparison, the SES-12 GEO HTS VSAT terminal fluctuates significantly to 94% for 6 months of the analysis, highlighting its vulnerability to network disruptions in this tropical region.

Table 2. Summary of performance

Parameters	LEO Starlink terminal	SES-12 GEO HTS VSAT terminal
Measured Latency	~20-100ms	~550 -1000ms
Effect of Rain	Temporary spikes, but recovers fast	Persistent degradation
Site Availability	99.63% (6 months average)	93.99% (6 months average)

4. CONCLUSION

This study analyzed the impact of rainfall on Starlink's signal latency compared to the GEO satellite link signals. Over six months, heavy rainfall exceeding 120 mm/hr was recorded. This extreme weather condition resulted in significant signal degradation for both GEO and LEO satellite services, highlighting the susceptibility of satellite communications to intense precipitation. The findings emphasize the need for advanced mitigation strategies to enhance signal reliability during severe weather conditions. Latency performance evaluation shows that Starlink demonstrates superior satellite link availability, achieving 99.6% uptime onsite compared to 94% for SES-12 GEO HTS satellite services in the tropical region. This higher availability highlights Starlink's resilience and reliability, particularly in areas where consistent connectivity is critical. The difference in uptime suggests that LEO Starlink's satellite network is less susceptible to weather-related disruptions and signal latency issues that can impact traditional geostationary (GEO) satellite services like SES-12. Further analysis is required to develop a latency model that accounts for the effects of rain in tropical regions, particularly for the LEO Starlink satellite network.

ACKNOWLEDGEMENT

This project's funding comes from the International Islamic University Malaysia (IIUM) sponsored research project's grant number SPI24-224-0224.

REFERENCES

[1] O. Vidal, B. Roy, S. Dimitrov, R. Barrios, D. Giggenbach, and A. Le Kernec, "Next generation high throughput satellite system based on optical feeder links," *https://elib.dlr.de/*, 2015.

[2] F. Geng, D. B. Gomez, Y. Guan, and J. H. Saleh, "Monte-Carlo value analysis of high-throughput satellites: Value levers, tradeoffs, and implications for operators and investors," *PLoS One*, vol. 14, no. 9, 2019, doi: 10.1371/journal.pone.0222133.

[3] A. García Zaballos, W. Wagner, and R. Brazil David, *The Provision of Satellite Broadband Services in Latin America and the Caribbean*. 2016. doi: 10.18235/0012642.

[4] S. E. Hobbs, J. P. Sanchez, and J. Kingston, "Extended lifetime Laplace plane Geo SAR mission design," in *IET Conference Publications*, 2015. doi: 10.1049/cp.2015.1489.

[5] Jason Rainbow, "Amazon gets key FCC approval for more than 3,000 LEO broadband satellites," *Spacenews*, Feb. 08, 2023.

[6] S. Agnelli, P. Feltz, P. F. Griffiths, and D. Roth, "Satellite's role in the penetration of broadband connectivity within the European Union," in *2014 7th Advanced Satellite Multimedia Systems Conference and the 13th Signal Processing for Space Communications Workshop, ASMS/SPSC 2014*, 2014. doi: 10.1109/ASMS-SPSC.2014.6934560.

[7] Reuters, "Malaysia issues license to Musk's Starlink to bring internet services to remote areas," Reuters. Accessed: Mar. 09, 2025. [Online]. Available: https://www.reuters.com/technology/malaysia-issues-license-musks-starlink-bring-internet-services-remote-areas-2023-07-20/

[8] Alexander Wong, "MCMC says co-existence study not done for Starlink before green light given to operate," *Malay Mail*, Kuala Lumpur, Sep. 08, 2023.

[9] Y. Guan, F. Geng, and J. H. Saleh, "Review of high throughput satellites: Market disruptions, affordability-Throughput map, and the cost per bit/second decision tree," 2019. doi: 10.1109/MAES.2019.2916506.

[10] Christopher Baugh, "SpaceX Starlink and Amazon Kuiper look set to dominate the satellite connectivity market," https://www.analysysmason.com/research/content/articles/starlink-kuiper-connectivity-nsi040/. Accessed: Sep. 07, 2024. [Online]. Available: https://www.analysysmason.com/research/content/articles/starlink-kuiper-connectivity-nsi040/

[11] "ITU-R P.839-4," *Rain height model for prediction methods* , 2013.

[12] J. S. Mandeep and S. I. S. Hassan, "Slant-path rain attenuation predictions in tropical regions," *J Atmos Sol Terr Phys*, vol. 68, no. 8, 2006, doi: 10.1016/j.jastp.2006.01.009.

[13] Ajayi Taiwo Seun, "Mobile Satellite Communications," Blekinge Institute of Technology, 2007.

[14] "ITU-R P618.14," *Propagation data and prediction methods required for the design of Earth-space telecommunication syste*, vol. 8, 2023.

[15] M. Edirisinghe, N. Alahacoon, M. Ranagalage, and Y. Murayama, "Long-Term Rainfall Variability and Trends for Climate Risk Management in the Summer Monsoon Region of Southeast Asia," *Advances in Meteorology*, vol. 2023, pp. 1–12, Oct. 2023, doi: 10.1155/2023/2693008.

[16] N. H. H. Khamis, J. Din, and T. A. Rahman, "Rainfall rate from meteorological radar data for microwave applications in Malaysia," in *2005 13th IEEE International Conference on Networks jointly held with the 2005 7th IEEE Malaysia International Conference on Communications, Proceedings*, 2005. doi: 10.1109/ICON.2005.1635660.

[17] I. Shayea, T. Abd Rahman, M. Hadri Azmi, and M. R. Islam, "Real Measurement Study for Rain Rate and Rain Attenuation Conducted over 26 GHz Microwave 5G Link System in Malaysia," *IEEE Access*, vol. 6, 2018, doi: 10.1109/ACCESS.2018.2810855.

[18] UN Office for the Coordination of Humanitarian Affairs (OCHA), "Asia Pacific Regional Reference Map: Annual Precipitation." Accessed: Mar. 09, 2025. [Online]. Available: https://reliefweb.int/map/world/asia-pacific-regional-reference-map-annual-precipitation

[19] J. Conde, G. Martínez, P. Reviriego, and J. A. Hernández, "Round Trip Times (RTTs): Comparing Terrestrial and LEO Satellite Networks," in *2024 27th Conference on Innovation in Clouds, Internet and Networks (ICIN)*, IEEE, Mar. 2024, pp. 42–46. doi: 10.1109/ICIN60470.2024.10494421.

[20] M. Beyaz, "Satellite Communications with 5G, B5G, and 6G: Challenges and Prospects," *International Journal of Communications, Network and System Sciences*, vol. 17, no. 03, pp. 31–49, 2024, doi: 10.4236/ijcns.2024.173003.

[21] Starlink, "Satellite Technology." Accessed: Feb. 22, 2025. [Online]. Available: https://www.starlink.com/technology

[22] "SES-12 at 95 degree East," https://www.ses.com/our-coverage#/explore/satellite/365.

[23] Y. A. Ahmad, A. F. Ismail, M. N. A. Abdul Hamid, and M. F. Jamlos, "Area-Based Rainfall Rate Model for Specific Attenuation in the Equatorial Region," *IIUM Engineering Journal*, vol. 25, no. 2, pp. 287–298, Jul. 2024, doi: 10.31436/iiumej.v25i2.3279.