COMPARATIVE ANALYSIS OF STARLINK AND CELLULAR SERVICE IN INDONESIA: CASE STUDY OF WEST JAVA

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By

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Approved and authorized to fulfil one of the requirements of
Program of Master of Electrical-Telecommunication Engineering
School of Electrical Engineering
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Bandung, 11th August, 2025

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11th August, 2025
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ABSTRACT

This thesis presents a comparative study of Starlink's Low Earth Orbit (LEO) satellite service and terrestrial cellular networks (4G/5G) in Indonesia, using West Java as a case study. The research explores how these distinct technologies can complement one another to bridge the digital divide between urban and rural areas. It hypothesizes that 5G will perform best in high-density urban settings due to its low latency and high throughput, while Starlink will offer more reliable connectivity in remote regions where terrestrial infrastructure is lacking.

Field measurements were conducted across four distinct regions in West Java—Dense Urban (Bandung City), Urban (Bandung Regency), Suburban (Karawang Regency), and Rural (Garut Regency) to evaluate the performance of Starlink and cellular networks (4G/5G). Key Quality of Service (QoS) metrics collected include download and upload throughput, latency, jitter, packet loss, and availability. These metrics were then analyzed through technical evaluation, link budget modeling, and capacity estimation using the Shannon formula. Economic analysis involved assessing service affordability relative to regional minimum wages and mapping business models from the perspectives of users, providers, regulators, and national stakeholders. Regulatory analysis examined Indonesia's telecommunications and data protection laws, highlighting the importance of infrastructure localization and digital sovereignty enforcement.

The findings show that 5G delivers ultra-low latency (17.96 ms) and minimal packet loss in urban areas, while Starlink provides high stability and 100% availability in rural regions, making it a strong candidate for expanding rural connectivity. However, Starlink remains economically inaccessible for low-income users (up to 48.96% of annual minimum wage), unlike cellular services that fall below the 24% affordability threshold. The study recommends a sovereignty-based hybrid deployment strategy, emphasizing local infrastructure requirements (gateway and NOC) and regulatory enforcement to ensure both secure and inclusive national broadband development.

Keywords: Comparative Analysis, Starlink, Cellular Service.

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PREFACE

Alhamdu lillahi rabbil 'alamin. All praise is due to Allah, the Most Gracious and the Most Merciful. By His mercy and guidance, the author has successfully completed this thesis entitled "**COMPARATIVE ANALYSIS OF STARLINK AND CELLULAR SERVICE IN INDONESIA: CASE STUDY OF WEST JAVA**". This thesis is submitted as part of the requirements for the completion of the Master's Degree Program in Electrical-Telecommunication Engineering at the School of Electrical Engineering, Telkom University.

The author sincerely welcomes any suggestions or constructive feedback for the improvement of this thesis. It is the author's hope that this work will continue to be developed and may provide valuable contributions to readers, particularly in advancing telecommunication education and research in Indonesia in the future.

Bandung, 11th August, 2025

FAIDAH MAISAROH ZAHRAH

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LIST OF ABBREVIATION

LEO	:	Low Earth Orbital
4G	:	Fourth Generation
5G	:	Fifth Generation
QoS	:	Quality of Service
STD	:	Standard Deviation

CHAPTER 1
INTRODUCTION

1.1 Background

The global communication technology boom has led to a steadily rising user base, with predictions of a significant decrease in unconnected populations within the next five years [1], [2]. This underscores the critical role of high-speed internet and digital technologies in national advancement across various sectors [2]. However, Indonesia faces a persistent digital divide between urban and rural areas. While urban centers benefit from advanced 4G and emerging 5G infrastructure, many remote and hard-to-reach areas remain underserved, limiting access to critical online services [3]. Traditional internet service providers (ISPs) have played a significant role in increasing connection throughout the nation, but large geographic distances and inadequate infrastructure continue to be significant barriers, particularly in rural and isolated areas [4]. Furthermore, rural and distant areas telecommunications and internet infrastructures are falling behind their urban counterparts due to low population and economic conditions. This necessitates urgent research into rural wireless access, coverage, cost, and dependability [2].

To address these disparities, both Fourth Generation (4G) and Fifth Generation (5G) cellular networks provide wireless networks for both mobile and fixed service applications and services. Additionally, geostationary earth orbit (GEO) and low earth orbit (LEO) satellites are especially useful for Internet connectivity in rural and isolated places, and there are clear-sky outdoor nodes nearby [2]. Recognizing this potential, the Indonesian Business Competition Supervisory Commission (KPPU) recommends focusing Low-Earth Orbit (LEO) satellite internet services, like Starlink, in underdeveloped and remote 3T regions to bridge digital inequality. Starlink's advanced technology is seen as ideal for areas beyond the reach of conventional providers [5]. Wayan Toni Supriyanto, Acting Director General of Digital Ecosystem at the Ministry of Communication and Digital Economy, emphasized the need for diverse infrastructure solutions, including satellites, cables, and radio, with technology prioritization guided by detailed competitive analysis considering technical, and societal impacts [5].

In response to these connectivity challenges, the Indonesian government officially facilitated the entry of Starlink into the retail internet market in 2024 [6].

PT Starlink Services Indonesia, the local legal entity of Starlink, was established and completed the necessary licensing processes for ISP and VSAT services. According to the Ministry of Communication and Informatics (Kominfo), Starlink's user equipment passed national standardization, and its operational feasibility testing was conducted in Ibu Kota Nusantara after Eid 2024. This policy development followed the removal of satellite-based internet services from the Negative Investment List (DNI), which allows full foreign ownership in the sector and reflects the state's commitment to expanding internet access through non-terrestrial infrastructure. Initially introduced through a business-to-business collaboration with Telkomsat, Starlink has since expanded its services to individual users in Indonesia, with a particular focus on rural and industrial areas where terrestrial networks remain limited. Kominfo has emphasized the importance of maintaining fair competition and protecting consumer interests, requiring Starlink to comply with national regulations concerning business practices and service quality.

Starlink, a network established by SpaceX, offers internet services through satellite technology. The concept of an internet solution was initially introduced by SpaceX in 2015. By 2019, the first batch of 60 Starlink satellites was launched into orbit [7]. LEO satellite networks, like Starlink, differ from conventional cellular networks in that they use unique connectivity and communication technology. In contrast to cellular networks, which depend on base stations on land, Starlink uses a constellation of satellites to function. A satellite links to a user-side dish and then interacts with a ground station. The Internet receives and sends data through these ground stations. Starlink requires a line-of-sight between satellites and user equipment. Satellite communications may be obstructed with by obstructions like trees or towering structures. As a result, Starlink performs better in open and rural locations. On the other hand, heavily populated locations are ideal for cellular networks since a dense base station deployment guarantees dependable connectivity. Furthermore, the two types of networks can have very different performance and coverage characteristics because of their different deployment methodologies and, consequently, service availability [8].

Prior research on Starlink's impact on ISP competition in Indonesia highlights its potential for improving remote internet access while addressing challenges for conventional ISPs [7]. A related study published in the CoNEXT Companion '23 also highlights these complementary strengths and weaknesses. The research compared the performance and coverage of Starlink's low-earth-orbit (LEO) satellite networks with cellular networks across five U.S. states [8]. The findings revealed that Starlink outperforms cellular networks in rural areas, providing better throughput and coverage, while cellular networks excel in urban areas due to higher capacity and more stable infrastructure. The synergistic integration of Starlink and cellular networks is proposed as an effective strategy to enhance connectivity across diverse geographic conditions [8]. This concept is relevant to Indonesia, where both satellite and terrestrial networks could complement each other to ensure reliable internet access nationwide.

This paper aims to comprehensively analyze and compare the performance of Starlink satellite service and traditional terrestrial cellular networks (4G/5G) across diverse geographical settings in West Java, Indonesia: specifically, in densely populated urban areas and sparsely populated rural regions. We hypothesize that although Starlink, as a satellite technology, may exhibit higher latency compared to cellular networks, Starlink has great potential to effectively address the persistent digital divide in Indonesia, especially in rural and remote areas where conventional cellular infrastructure is often unavailable or inadequate. Through an in-depth exploration of the trade-offs in performance between these two technologies, including throughput, latency, jitter, packet loss, and network availability, this study aims to determine whether Starlink can serve as a viable alternative or a synergistic complementary solution to traditional cellular networks in bridging the connectivity gap in remote locations across the Indonesian archipelago. The findings of this study are expected to provide crucial empirical insights for policymakers, telecommunications service providers, and other stakeholders in formulating more effective and efficient network deployment strategies to achieve national broadband access equity.

1.2 Problem Identification

Indonesia has adopted various technologies, including 4G, 5G, and Low Earth Orbit (LEO) satellites, to improve connectivity and support digital growth. However, a significant digital divide persists between urban and rural areas. While cities benefit from advanced 4G and emerging 5G networks, many remote and underserved regions still lack reliable internet access, limiting their ability to engage in essential online services like education, healthcare, and e-commerce. To mitigate this challenge, it is essential to conduct a study of the technical, economic, and regulatory aspects on how 5G can be utilized in urban areas and Starlink can help improve connectivity in rural regions, ultimately enabling more equitable access to digital resources across Indonesia.

1.3 Objectives

Based on the background and problem identification that form the foundation of this thesis, the objective of this research is to deliver a study on how Starlink and 5G can complement each other in specific areas, leveraging their distinct characteristics. The objectives can be described as follows.

1. Technical Analysis to evaluate key performance metrics such as throughput, latency, jitter, packet loss, network availability, link budget, and capacity analysis for Starlink and cellular networks in different environments.

2. Economic Analysis to assess the affordability of each service relative to regional minimum wages, and to examine the business model by identifying key stakeholders involved, including users, regulators, and national operators.

3. Regulatory Analysis to review the legal and regulatory frameworks affecting the coexistence of both technologies, and to provide actionable policy recommendations that support secure and equitable integration.

1.4 Scope of Work

To maintain focus and clarity in this thesis research, several limitations and assumptions have been established. The scope of the study is outlined as follows:

1. This research adopts a case study approach based on four distinct geographical categories: Dense Urban (Bandung City), Urban (Bandung Regency), Suburban (Karawang Regency), and Rural (Garut Regency).

2. Cellular focusing on 5G network. In rural areas where 5G infrastructure is not yet available, 4G data is used as a reference to assess connectivity.

3. The analysis considers key Quality of Service (QoS) indicators, including throughput, latency, jitter, packet loss, and network availability.

4. Capacity analysis is conducted using the Shannon capacity formula, applied to Starlink's Ku Band downlink frequency (10.7–12.7 GHz). The bandwidth used in this analysis is assumed as follows: Starlink 240 MHz, 5G 100 MHz, and 4G 20

5. The regulatory analysis focuses on Indonesia's national telecommunications policies and concludes with a policy brief that outlines recommendations to support the coexistence of Starlink and 5G in Indonesia.

1.5 Hypothesis

This research hypothesizes that the coexistence of Starlink and 5G networks in Indonesia will be most effective when each technology is deployed in areas that align with its inherent strengths and characteristics. Specifically, 5G is expected to perform optimally in densely populated urban environments that demand high bandwidth and low latency, while Starlink is anticipated to provide more reliable internet connectivity in rural or remote regions where terrestrial 5G infrastructure is limited or unavailable.

1.6 Research Methodology

1. **Literature Study** This phase involves reviewing relevant theories and concepts related to Starlink and 5G networks. Theoretical references are obtained from scholarly books, peer-reviewed journals, conference proceedings, and official publications to build a solid conceptual framework for the study.

2. **Data Collection** Data collection includes both primary and secondary data to support the analysis. Secondary data sources include population data from Badan Pusat Statistik (BPS) for West Java and official documents from Starlink and Telkomsel. Primary data are collected through field measurements and observations conducted in four different area types: dense urban, urban, suburban, and rural. The key network performance metrics gathered include throughput, latency, jitter, packet loss, and network availability.

3. **Technical Analysis** This step analyzes the performance of Starlink and 5G networks using the Quality of Service (QoS) indicators obtained from field testing. The evaluation includes throughput, latency, jitter, packet loss, and availability. Furthermore, link budget to determine the SNR and capacity analysis is conducted using the Shannon capacity formula to estimate the theoretical capacity of each technology based on bandwidth and signal quality in various geographic scenarios.

4. **Economic Analysis** Economic Analysis to assess the affordability of each service relative to regional minimum wages and to analyze the business models from the perspectives of user, regulator, and national.

5. **Regulatory Analysis** This step involves examining the national regulatory framework and policies relevant to the coexistence of Starlink and 5G in In-

donesia. The objective is to identify regulatory challenges, potential opportunities, and broader policy implications associated with the deployment of both technologies. The analysis concludes with the development of a policy brief that offers actionable recommendations for policymakers to support effective and secure technological coexistence.

1.7 Methodology

1. CHAPTER I – INTRODUCTION

   This chapter, will includes the introduction, research background, problem identification, objectives, scope of work, hypothesis, research methodology, and writing systematics.

2. CHAPTER II – LITERATURE REVIEW

   This chapter, presents theoretical studies that will support and underpin this research. The theory that will be conducted is about satellite communications and 5G.

3. CHAPTER III – RESEARCH METHODOLOGY

   This chapter will discuss the research scheme that will be carried out the process of data collection and analysis.

4. CHAPTER IV – RESULT AND DISCUSSION

   This chapter will give the result of the technical, economic, regulatory analysis, and policy brief is presented.

5. CHAPTER V – CONCLUSION, RECOMMENDATION AND FUTURE WORKS

   This chapter describes the conclusion of technical and regulatory analysis. It will then draw conclusions, recommendations and future research.

CHAPTER 2
LITERATURE REVIEW

This chapter presents the theoretical foundations and relevant background information necessary to support the research. It includes an overview of the fundamental concepts, architectures, and technologies related to 5G cellular networks and the Starlink low Earth orbit satellite system. The chapter also discusses previous studies, key performance metrics, and regulatory aspects.

2.1 Satellite Communication System

The foundation of satellite communication is a line-of-sight (LOS) one-way or two-way radio frequency (RF) transmission system, which consists of a transmitting station using an uplink channel, a space-borne satellite system serving as a signal regeneration node, and one or more receiving stations keeping an eye on a downlink channel to gather data. Both endpoint stations are capable of sending and receiving in a two-way scenario can be seen in Fig. 2.1

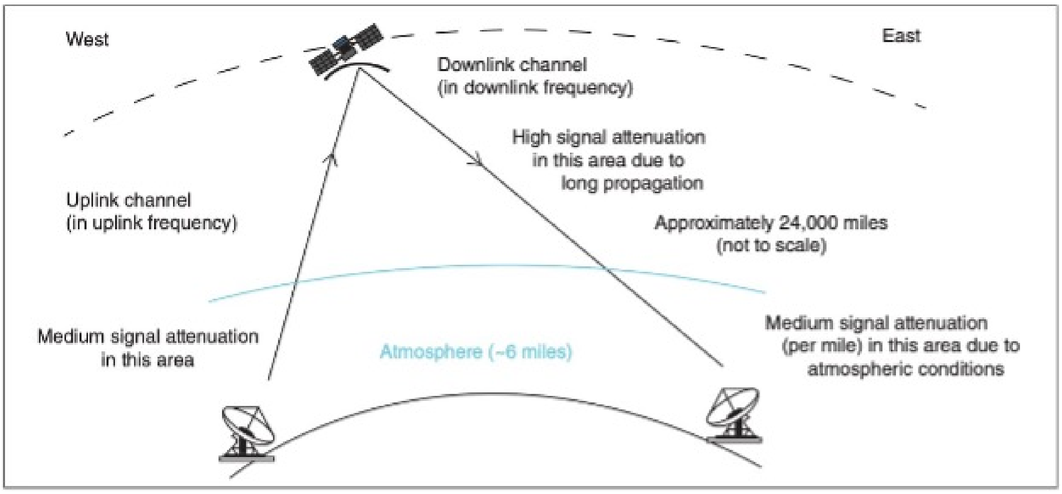

Fig. 2.1 Satellite Communication System

Numerous near-earth orbits are possible for satellites to occupy. Located 35,786 kilometers (22,236 miles) above the earth's surface (42,164 kilometers from the earth's center, with a radius of 6,378 kilometers), the geostationary orbit (GSO) is a concentric circular orbit in the plane of the earth's equator. In the GSO, a geosynchronous (GEO) satellite orbits the planet in the same direction and at the same speed as its revolution. When viewed from the earth's surface, the satellite in this equatorial plane essentially seems to be fixed, therefore an antenna aimed at it won't need to be tracked or have its position (major) adjusted on a regular basis. Other orbits, such the low Earth orbit (LEO) and the medium Earth orbit (MEO), are also feasible [8].

2.1.1 Low Earth Orbital (LEO)

Unlike GEO and MEO, LEO satellites typically orbit between 500 and 2000 kilometers in height. There are two fundamental network designs for LEO satellite communication systems [9], [10]. One is the design of a ground-based network, in which satellite transponders are visible. Any data exchange between two users must pass via the ground gateways. Consequently, a large number of ground infrastructures need be installed worldwide to ensure worldwide coverage. The other is the space-based network architecture, which is made up of two subnetworks: one in space and one on the ground [10], [11].

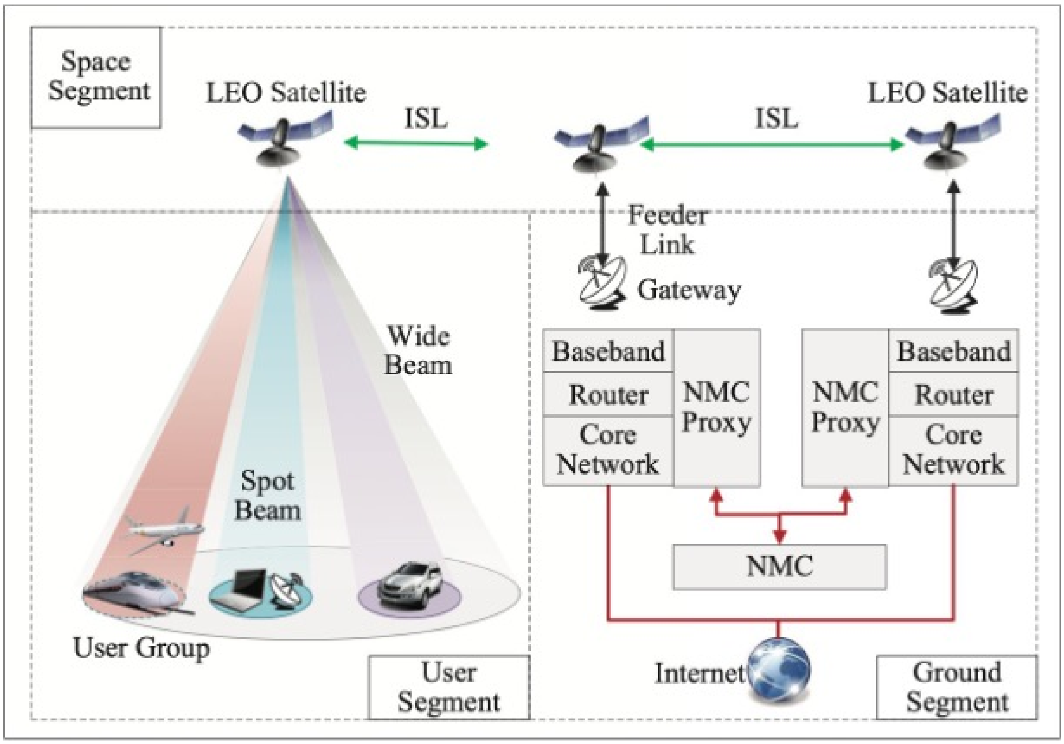

Fig. 2.2 LEO System

As shown in Fig. 2.2, this system is separated into three segments: space, ground, and user, as seen in Fig. 2.2 ISLs link the satellites carrying OBP payloads in the space segment. Satellites may implement air interface protocols, including physical layer protocols and even layer 2 protocols like medium access control

(MAC) and radio link control (RLC), thanks to OBP payloads. As a result, the satellites serve as space base stations and give consumers radio access. Gateways and a network management center (NMC) are part of the ground segment. Antennas, baseband processing units, routers, and core network components make up the gateway. It has the ability to establish feeder linkages with several visible satellites at the same time. A virtual private network, or VPN, connects each gateway, and the NMC is in charge of them. The whole satellite communication system is operated, managed, and controlled from the NMC. Network planning and scheduling radio resources are NMC's two most crucial responsibilities. Frame, frequency and bandwidth, transmitting power, and beam steering are all dynamically scheduled by the NMC to optimize the allocation of radio resources based on user location distribution, QoS requirements, and channel circumstances. Lastly, there are a range of UTs in the user sector, including both stationary and mobile terminals [10].

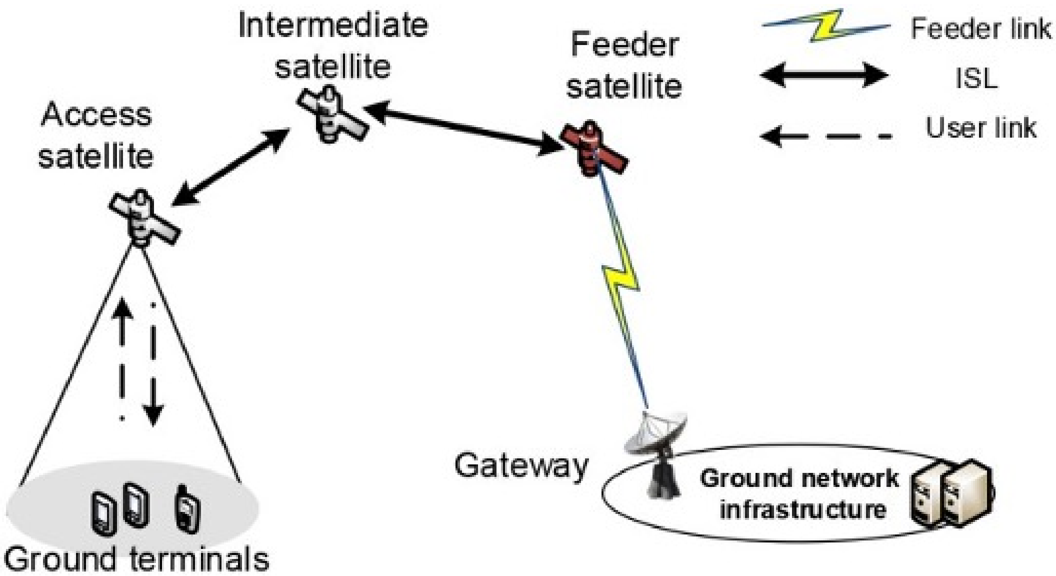

Fig. 2.3 Space Segment

As seen in Fig. 2.3, the space segment serves as the ground core network's extended access network in an integrated space–ground network [12]. Gateway serves as the link between the terrestrial and space segments. Feeder satellites are those that use Sat-GW links to interact directly with the gateway, while access satellites are those that use Sat-User links to communicate directly with ground users. Intermediate satellites are not necessary when the same satellite serves both the gateway and the ground terminals; the access satellite may also serve as the feeder satellite. The access satellite gathers data packets from ground users, which are subsequently transmitted to the ground network through the feeder satellite and gateway [7]. One or more ISL relays are needed to provide access to the gateway if the user and the gateway are not served by the same satellite (i.e., the feeder and access satellites are separate). One hop is the definition of each ISL relay. It takes a lot of hops to get to a gateway when the access satellite is far away. The gateway can be reached over the same ISL hops as the matching feeder satellite. Following their arrival at the gateway, packets are transmitted in the same manner as in a conventional ground network. As a result, rather than discussing an end-to-end connection, this article primarily concentrates on the communication between the satellite and gateway. The data that is returned takes the opposite route from the packet's bidirectional transmission. This article just examines the transmission from the user to the gateway in order to simplify the issue.

2.2 Starlink Satellite

SpaceX subsidiary Starlink launched the first batch of 60 low-Earth orbit (LEO) communication satellites in May 2019. The spacecraft' effulgent, noticeable size is a result of processing very low orbits after launch and then grouping into trains. In order to put its 42,000 Starlink LEO communication satellites into orbit, the U.S. Federal Communications Commission (FCC) approved the Starlink project [10]. The FCC file states [13] that the Starlink constellation will be separated into five shells. The first, at 540 km, is divided into 72 orbital planes, each with 22 satellites. The second, at 550 km, similarly has 72 orbital planes with 22 satellites. The third and fourth at 560 km have six and four planes, respectively, with 58 and 43 satellites per plane. The fifth at 570 km has 36 orbital planes, each with 20 satellites. As of June 26, 2025, there are approximately 7,875 Starlink satellites in orbit. Of these, 7,855 are reportedly working.

2.2.1 System Architecture

Starlink system architecture consists of three segments: space segment, ground segment, user segment [14]. Space segment consists of a number of satellites in Lower Earth Orbit (LEO). These are small, low-cost satellites weighing around 260 kg, operating in the Ku-band and Ka-band, and with a lifespan of 5-7 years. These satellites enabled the user to connect to the internet. Since there are numerous satellites, satellites communicate with one another via inter-satellite links (ISL). It employs phase array antennas for uplink/downlink and laser communication in the ISL link. CPE-Satellite communication employs Ku band frequencies, while Ground Station-Satellite communication uses Ku band for downlink and Ka band for uplink. Since Starlink satellites are substantially closer to the ground, they produce ultra-small spot size beams. Starlink's ground segment includes various facilities that run the network and offer internet connectivity to the satellites. These, also known as Ground Stations or Starlink Gateways, are strategically situated around the world to give coverage to distant and underserved areas with poor internet connectivity. The ground station is connected to the Internet Service Provider via Fiber. The User Segment includes areas where individuals use internet services via Starlink CPE. This CPE comprises of a satellite dish mounted on a rooftop or on the ground with a clear view of the sky, a router power supply, and a WiFi router. The dish is made up of a phased antenna array with stacked honeycomb structure that automatically aligns with the available satellite. The router provides communication via a Gigabit Ethernet port and Wi-Fi. The satellite dish is connected to the router, and both are powered by Power over Ethernet. One router can support up to 128 devices at once. It is powered by a 56 V DC source given via PoE. The router complies with the IEEE 802.11 standard and runs at 2.4 and 5 GHz.

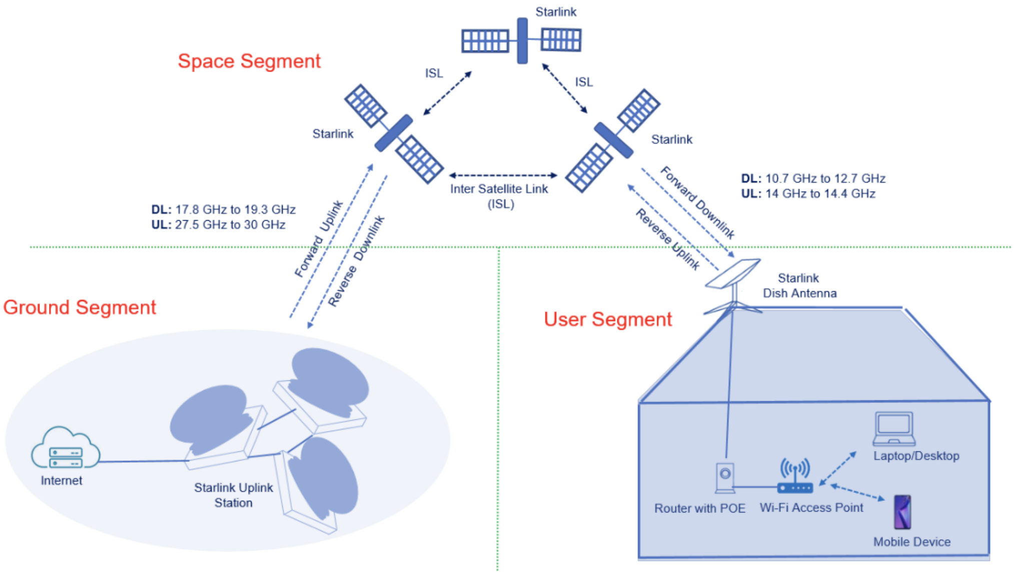

Fig. 2.4 Starlink Architecture

2.2.2 Frequency Allocation

Starlink satellites use higher frequency bands for communication, such as Ku-band (10.7-12.7 GHz and 14.0-14.5 GHz), Ka-band (17.7-20.2 GHz and 27.5-30.0 GHz), V-band (37.5-51.4 GHz), and E-band (71.0-76.0 GHz and 81.0-86.0 GHz), to transmit and receive data with ground stations and users [15]. Starlink uses Orthogonal Frequency Division Multiplexing (OFDM) for its Ku-band downlink signal modulation, a method extensively utilized in current wireless communications like

Wi-Fi and 5G for its spectral efficiency and stability [16], [17]. Table 2.1 shows frequency allocation and modulation type of Starlink satellite [18], [19].

Characteristic	Uplink	Downlink
Frequency (GHz)	14.0-14.5	10.7-12.7
	27.5-29.1	17.8-18.6
	29.5-30.0	18.8-19.3
	47.2-52.4	37.5-42.5
Modulation Type	BPSK	OQPSK
	QAM	QAM

Table 2.1 Starlink Frequency Allocation and Modulation Type

2.2.3 Multi Beam

According to publicly available information such as FCC filings, AMAs, and other articles, each satellite has four Ku-band ESAs, one for uplink and three for downlink, with each antenna capable of projecting eight beams in two polarizations (RHCP/LHCP), for a total of 48 downlink beams and 16 uplink beams. This delivers a 75/25 downlink/uplink split ratio. Starlink's maximum capacity in Ku band is 8x 250 MHz downlink channels (total 2 GHz) and 8x 62.5 MHz uplink channels (total 500 MHz) [20], [21].

2.2.3.1 Ku Band User Beams

Ku band (down 10.70-12.75/up 14.0-14.8 GHz) [22] is used; The terminal that customers utilize at their location will only connect to satellites at an elevation angle of at least 40 degrees. All Ku-band downlink spot beams on all SpaceX satellites can be steered independently of one another over the whole earth's field of vision. This implies that any operational satellite at a height of roughly 1,150 km will cover an area of about 5 million square kilometers, or a radius of 1,060 km, from boresight for up to 40.46 degrees [22].

2.2.3.2 Ka Band User Beams

Ka-band (down 17.3-20.2/up 27.5-30.0 GHz) [23] is similar to the Ku band user beams, SpaceX satellites's gateway downlink spot beams can be autonomously guided over the whole field of view from the ground. The utilization terminals and gateways would only be able to communicate with satellites at an ascension angle of at least 40 degrees, meaning that all spacecraft would be fortified by gateways situated only up to a specified limit away from boresight, which barely varies by operational altitude. Each satellite will have the ability to send two beams at the same frequency using the right- and left-hand circular polarization, for a total of eight co- frequency beams. A maximum of four satellites will be able to beam transmissions to the gateway position [23].

2.3 Cellular Network

2.3.1 Mobile Technology Evolution

The mobile communication system has witnessed a significant transformation since the first wireless network was established over forty years ago. The demand for more connections globally was heightened by the spontaneous increase in the need for effective communication systems and the introduction of the first-generation mobile network in the early 1980s, which accelerated the development of mobile communications. Thus, wireless communications have evolved to become a substantial component of contemporary society. It has also significantly altered the way society functions, particularly following the introduction of satellite communications, television (TV), and radio transmission [24].

- First Generation (1G)

  The first generation of mobile networks (1G) was introduced in the 1970s and 1980s. This technology was analog and operated similarly to a landline phone.. However, 1G technology had numerous disadvantages, despite its primary function of voice communication. Neither the sound quality nor the coverage were satisfactory. It did not deliver system compatibility or migration between operators. Furthermore, the absence of call encryption with 1G resulted in exceedingly inadequate security, as any eavesdropper could effortlessly access the message during transmission.

- Second Generation (2G)

  Unlike previous technologies, 2G was the first digital system to provide mobile voice communication that was preferable to 1G. In 1991, it was initially made accessible. Speeds of up to 1 Mbps were feasible during the 2G era. Voice is transmitted via digital signals, and it operates at a rate of 64 kbps. 2G supports a bandwidth of 30–200 kHz. Only a few of the services that 2G provides include photo messaging, multimedia messaging, and short message services (SMS). The digital techniques employed are Time Division Multiple Access (TDMA) and Code Division Multiple Access (CDMA). Global

System for Mobile Communications (GSM) is the most prevalent 2G mobile standard.

- Third Generation (3G)

  The 3G was introduced in 2001 to standardize the network protocol that manufacturers employ. The standardization of the ”data packets” that facilitate web connectivity enables 3G technology users to access data from any location on the planet. The improved data transmission capabilities of 3G have led to an increase in the popularity of new services, including video streaming and Voice over Internet Protocol (VoIP). 3G systems were designed to offer data speeds of 384 kbps, with a wide coverage area and a restricted coverage area of 2 Mbps.

- Fourth Generation (4G)

  The 4G technology known as Long-Term Evolution (LTE) was introduced in 2009. Many millions of users were able to transmit high-quality videos after it was introduced, and it became extensively used. The high-speed mobile web connection of 4G enables static users to access up to 1 gigabit per second, thereby enabling the use of high-definition media, gaming services, and video conferences. By transitioning all communication services to all-IP (Internet Protocol), it was feasible to establish a unified platform for all existing technologies. 4G technology's terminal mobility is a critical feature that enables automatic roaming between other wireless networks.

- Fifth Generation (5G)

  The new 5G generation of mobile communication was introduced around the end of 2010. Unlike the last generations that arrived to boost the flow, 5G is not a straightforward continuation of 4G. It is regarded as a revolutionary technology that needs to adapt to the rapid growth of data usage. Since one in five users will use 200 GB per month by 2025, the primary goal of 5G is to prevent network saturation in densely populated regions like stations and airports [9]. 5G technology will be able to provide more energy efficiency, lower latency, faster data rates, and larger capacity than earlier generations of mobile cellular technologies [25]. The 5G vision is based on the significant transformation of the infrastructure of telecommunications networks and the technologies they use. More people or devices requesting Internet connectivity with varying performance requirements as well as an incredibly large number of applications and use cases will need to be strengthened by 5G technology. The available spectrum won't be sufficient to meet such a massive demand if it is anticipated that data traffic requests will increase by up to 1000 times by the end of 2020. It will become necessary to employ much smaller cells where resources may be habituated effectively in time and space [26]. Additionally, a number of methods will be used to improve the capacity, including precoding, high-frequency reuse, and Multiple Input/Multiple Output (MIMO) antennas. Furthermore, 5G systems will need to meet critical performance metrics like reduced latency, high security, massively concurrent connectivity, and coherent quality of accommodation. It is predicted that 5G will offer users bit rates up to 10 Gbps and minute round trip times ranging from 1 to 10 ms for specific applications [26]. According to International Telecommunication Coalescence M-2083, there are three distinct 5G scenarios [25], [27].

1. Enhanced Mobile Broadband (eMBB): Seen as a crucial component of the upcoming generation of consumer devices.
2. massive Machine-Type Communications (mMTC): Astute meters and environmental sensors are examples of low-potency, low-involution devices that can be connected via the huge internet of things.
3. Ultra-Reliable Low Latency Communications (URLLC): This includes failsafe features like factory automation and conveyance-to-conveyance communication.

2.3.2 Frequency Spectrum

Radio frequency spectrum refers to the range of invisible frequencies that travel through the air, enabling wireless communication. Spectrum is categorized based on frequency, which is measured in hertz (Hz). One hertz represents a single wave passing a fixed point in one second. A kilohertz (kHz) equals 1,000 hertz, one megahertz (MHz) is equivalent to 1,000 kHz, and one gigahertz (GHz) equals 1,000 MHz [28].

The ITU separates the radio frequency spectrum into nine frequency band spans, ranging from 3 kHz to 3000 GHz, and groups them constantly [19]. The Indonesian Telecommunication Regulator has singled out the frequency bands which may be used for IMT-2020 or 5G. Table 2.2 constricts the Indonesian candidates for 5G frequency bands. The bands were selected on several considerations. The main consideration is the existing world frequency band testing ecosystem and the equipment used by MNOs [29].

Table 2.2 Frequency spectrum

NR operating band	Frequency band (MHz)	Potential bandwidth (MHz)
n28	700	90
n40	2300	90
n41	2600	190
n77	3300	100
n78	3500	200
n258	26000	2750
n257	28000	2500

Bands with higher frequencies were found to be good candidates for 5G spectrum. The abundance of spectrum accessible to facilitate transmission at ultrahigh data rates is a defining characteristic. This frequency range, which spans from 3 to 300 GHz, is commonly known as mm- wave bands. Not every mm-wave spectrum, meanwhile, is suitable for mobile communications. The spectrum selection is influenced by three things [30].

First, the allocations of spectrum administrations and regulators, as well as the primary/coprimary services for the allocations, are critical factors in the selection of prospective spectrum. The 28-GHz band, specifically the 24.25–29.5-GHz band, is a global allocation for mobile service on a coprimary basis, with the exception of the 24.25–25.25 GHz band, which is only allocated in Region 3 [14]. Similar circumstances apply to the E-band, which spans 71–76 GHz and 81–86 GHz. The possibility of creating a globally standardized spectrum distribution for these bands is high. Second, a contiguous spectrum with several hundred megahertz or even a few gigahertz is ideal. Administrations and regulators may find it easier to manage the spectrum allocation plan with such a continuous spectrum. Additionally, it may provide mobile network operators greater freedom in how they use their spectrum resources. Third, the selected spectrum's propagation properties ought to be conducive to the delivery of mobile communication services. The candidate spectrum selection should take into account a number of channel propagation issues, including severe path loss, the impact of weather and atmosphere, Doppler with even slow movement due to higher carrier frequency, and NLOS channels, since the propagation characteristics of the mm-wave bands can differ significantly from those of the frequency bands below 6 GHz. Preliminary research has indicated that NLOS coverage for mm-wave bands in cellular communications is possible.

2.3.3 5G NSA Network Architecture

3GPP defines NSA and SA architectures, and the two architectures have been standardized. Option 3x for NSA and Option 2 for SA are widely accepted in the business. SA is the intended architecture, however the NSA ecosystem will lead it for 6 months. The NSA can easily establish a 5G network to enable eMBB services and over time upgrade to SA software [31].

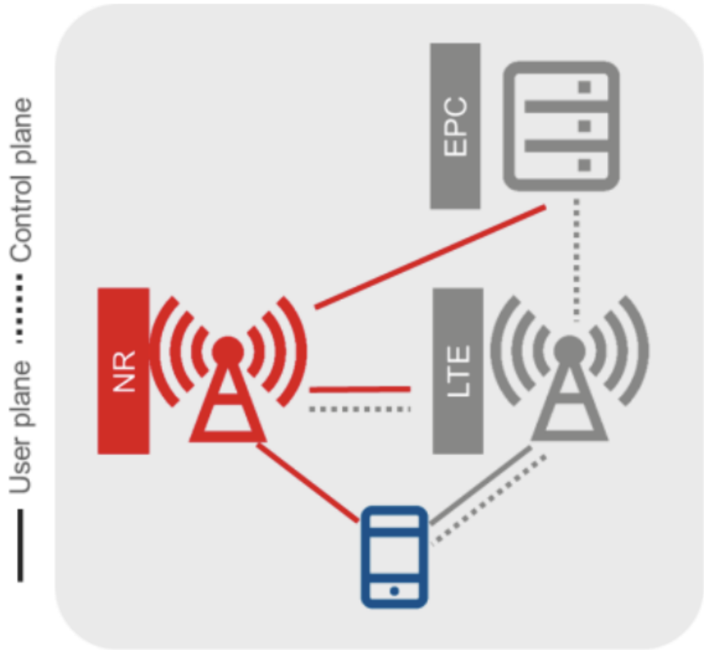

Fig. 2.5 Option 3

Option 3 is an NSA scenario that ensures the network continues to employ LTE with NR radio access while only delivering control signals via LTE's EPC core. This option uses LTE as the control plan anchor for NR, with both LTE and NR used for user data traffic (User Plan). It could also be referred to as non-Standalone (NSA) NR in the Evolved Packet System [32].

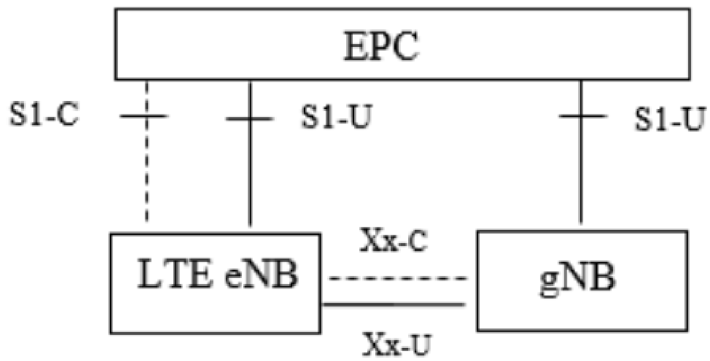

Fig. 2.6 Option 3x

Option 3x is a combination of 3 and 3a, therefore both S1 and X2 interfaces are available for the User plan, allowing traffic to be split based on S1-U's backhaul capacity. Option 3x delivers excellent coverage at higher frequencies while aggregating the peak data rates of LTE and 5G at lower frequencies. Option 3x offers nearly insignificant interrupt time for LTE-5G mobility. Option-3x permits voice over LTE without the use of RAT fallback. This configuration can be utilized in circumstances when LTE coverage extends beyond than NR, allowing EPC to be used [32].

2.4 Technical Aspects

Several technical parameters must be considered a calculated in a network based on a satellite communication system. The analysis which is used in technical aspect analysis consists of network performance such as throughput, latency, and jitter, packet loss, network availability, and capacity analysis.

2.4.1 QoS Parameter

2.4.1.1 Throughput

Throughput is the actual bandwidth measured over a specific period under certain network conditions for transferring files of a particular size. It represents the total data transfer speed across all terminals within a network [29].

$$Throughput = \frac{Amountofdata}{Time} \tag{2.1}$$

2.4.1.2 Latency

Delay, or latency, is the time it takes for data to move from one place to its destination [3]. In Equation (1), t1 represents the delay or latency, measured in milliseconds. This value indicates the time it takes for a data packet to travel from the source to the destination. The variable ts denotes the timestamp at the moment the data is sent from the source, while te refers to the timestamp when the data is received at the destination.

$$t1 = te - ts \tag{2.2}$$

2.4.1.3 Jitter

Jitter is the variation in delay between packet arrivals. It is influenced by changes in traffic load and packet collisions (network congestion). Jitter impacts network performance and must be assessed alongside delay. While high jitter can be mitigated if delay remains low, network performance deteriorates significantly when both jitter and delay values are high [3].

$$J = \frac{1}{N-1} \sum_{i=1}^{N-1} |D_{i+1} - D_i| \tag{2.3}$$

In this equation, J represents the average jitter, N is the total number of packets observed, and Di denotes the delay experienced by the ith packet. The formula calculates the average of the absolute differences in delay between consecutive packets. A lower value of J indicates more consistent packet delivery times, which is essential for maintaining a smooth and uninterrupted network experience.

2.4.1.4 Packet Loss

Packet loss metric (L_p) is calculated by dividing the total number of transmitted packets (N_p) by the number of received packets with error (N_e). The achievable SNR or SINR, the maximum allowable packet loss for a service, and the channel bandwidth all have a direct impact [2].

$$Lp = \frac{Ne}{Np} \tag{2.4}$$

2.4.1.5 Network Availability

Availability is the percentage of time that the system was available and functioning correctly. Availability reflects how reliable a system is over a given period of time. A higher A_v means the system was operational and available more often. A lower A_v means the system experienced more downtime, making it less reliable.

$$Av = \frac{T_c}{T_o} = \frac{T_c}{T_c + T_o} \times 100\% \tag{2.5}$$

Table 2.3 represents the standard parameters of 5G technology as defined by 3GPP (3rd Generation Partnership Project). These parameters, including throughput, latency, jitter, packet loss are outlined in key 3GPP technical specifications such as TS 23.501, TS 22.261, and TS 29.513. These standards ensure that 5G networks meet the performance requirements for three main usecases, such as enhanced Mobile Broadband (eMBB) to ultra-Reliable Low-Latency Communication (URLLC) and massive Machine-Type Communication (mMTC). It also presents the ideal 4G network performance parameters based on 3GPP TS 36.300, ITU-R M.2134, and ITU-T G.114. Table 2.3 also presents the target values for the Starlink network's performance. Starlink parameters were sourced directly from the official Starlink website, which provides up-to-date and accurate information regarding the network's capabilities.

Table 2.3 QoS Standard Parameter

Parameter	4G	5G	Starlink
Download Speed	≥10 Mbps	≥100 Mbps	90-240 Mbps
Upload Speed	≥5 Mbps	≥50 Mbps	13-29 Mbps
Latency	<10 ms	<1 ms	33-62 ms
Jitter	<30 ms	<10 ms	10-30 ms
Packet Loss	<1%	<0.1%	<1%
Availability	≥99.99%	≥99.99%	≥95%

2.4.2 Link Budget Analysis

The link budget is the calculations of power between the transmitter (Tx) and the receiver (Rx), taking into account the output power of Tx and the gains and losses to calculate the power received at the Rx [27]

1. Antenna Gain

   An antenna gain is the antenna ability to focus the radiated energy to a specific direction [33]. In calculating the antenna gain, the frequencies, antenna diameter, and the antenna efficiency will be considered. The antenna efficiency refers to the antenna losses due to the differences between power delivered to the antenna input and the power radiated by the antenna [34]. Below is the formula to calculate the gain [35].

$$G = 10 \times \log\left(\eta\left(\frac{\pi D}{\lambda}\right)^2\right) \tag{2.6}$$

Where:

G : Antenna gain (dBi)

f : Frequency (Hz)

D : Antenna diameter (m)

λ : Wavelength (m)

η : Antenna efficiency (%)

For a phased-array antennas, the antenna gain calculations uses the following formula [36].

$$G = 20 \times \log\left(\frac{4\pi\eta a\sqrt{m^2/3}}{\lambda}\right) \tag{2.7}$$

Where:

G : Antenna gain (dBi)

$\eta\mathbf{a}$: Antenna efficiency (%)

m^2 : Area of the antenna (m^2)

λ : Wavelength (m)

2. Free Space Loss

   Free Space Loss (FSL) is the signal strength loss because of the distance from the transmitter via free space [33]. FSL can be calculated using formula below.

$$\mathrm{FSL} = 20 \times \log(f) + 20 \times \log(d) + 92.45 \tag{2.8}$$

3. Effective Isotropical Radiated Power

Effective Isotropical Radiated Power (EIRP) is the total power that antenna radiates if it has the gain in all directions [37]. EIRP can be calculated using the following formula.

$$\text{EIRP} = P_{\text{tx}} + G_{\text{tx}} - L_{\text{cable}} \tag{2.9}$$

Where:

EIRP : Effective Isotropic Radiated Power (dBm or dBW)

$P_{\mathbf{tx}}$: Transmit power of the transmitter (dBm or dBW)

$G_{\mathbf{tx}}$: Gain of the transmitting antenna (dBi)

$L_{\mathbf{cable}}$: Losses due to cables or connectors (dB)

4. Noise (N0)

   Noise power spectral density, denoted as N_0, represents the amount of thermal noise per unit bandwidth in the communication system. This noise is primarily caused by random motion of electrons, known as Johnson-Nyquist noise, and is inherent in all electronic systems [18].

   The noise power spectral density is calculated using the following equation:

$$N_0 = k \cdot T \tag{2.10}$$

Where:

N_0 : Noise power spectral density (W/Hz)

k : Boltzmann's constant (1.3806×10^{-23} J/K)

T : System noise temperature (Kelvin)

5. Azimuth Angle Calculation

   The azimuth angle is measured from true north in an eastward direction to the projection of the satellite path onto the local horizontal plane. Equation is expressed as follows [38]:

$$\cos(\gamma) = \cos(L_e) \cdot \cos(l_s - l_e)] \tag{2.11}$$

Where:

L_e : Latitude of the earth station (°)

l_s : Longitude of the satellite (°)

l_e : Longitude of the earth station (°)

6. Slant Range Calculation

   The slant range is between the ground station and the satellite is the distance measured from the ground station pulled straight towards the satellite position. The slant range equation is expressed as follows [38]:

$$d = r_s \cdot \sqrt{1 + \left(\frac{r_e}{r_s}\right)^2 - 2 \cdot \left(\frac{r_e}{r_s}\right) \cos(\gamma)} \tag{2.12}$$

   Where:

   d : Slant range (km)

   r_e : Earth radius (km)

   r_s : Distance from Earth's center to the satellite, i.e., $r_s = r_e + h$ (km)

7. SNR Estimation

   Signal-to-Noise Ratio (SNR) is a critical metric in evaluating the quality and performance of a communication link. It represents the ratio of the received signal power to the total noise power present in the system. In satellite communications, the dominant source of noise is thermal noise, often modeled using Johnson-Nyquist noise [18]. The SNR in its linear form is expressed as:

$$\mathrm{SNR} = \frac{P_{rx}}{k \cdot T \cdot B} \tag{2.13}$$

   Alternatively, when both the received power and noise power are expressed in decibel-watt (dBW), the SNR in decibel (dB) form is given by:

$$\mathrm{SNR}_{dB} = P_{rx(dBW)} - N_{(dBW)} \tag{2.14}$$

   Where:

   SNR : Signal-to-noise ratio (unitless)

   SNR_{dB} : Signal-to-noise ratio in decibels (dB)

   P_{rx} : Received signal power (W)

   $P_{rx(dBW)}$: Received power in decibel-watt (dBW)

$N_{(dBW)}$: Noise power in decibel-watt (dBW)

k : Boltzmann's constant (1.3806×10^{-23} J/K)

T : System noise temperature (Kelvin)

B : Channel bandwidth (Hz)

2.4.3 Capacity Analysis

The most crucial aspect of a communication system is capacity analysis, which involves estimating the system's capacity. A theoretical method may be used to calculate the capacity. The Shannon Capacity theorem is used in this theoretical method [39]. The formula can be seen in equation (2.10)

$$C = B \cdot \log_2 (1 + \mathrm{SNR}) \tag{2.15}$$

2.5 Economic Aspects

2.5.1 Affordability Analysis

Affordability of ICT services refers to the cost of a minimum combination of telecommunications services, such as Internet data, voice calls, and text messaging, compared to a given income. The United Nations Broadband Commission for Sustainable Development's Broadband Advocacy Target 2 aims to make broadband affordable by 2025, with entry-level services in low and middle-income countries costing less than 2% of monthly GNI per capita. Affordability formula can be seen in equation (2.11)

$$\text{Affordability} = \frac{\text{Annual Cost}}{\text{Annual Income}} \times 100\% \tag{2.16}$$

2.6 Regulatory Aspects

2.6.1 Law No 36 of 1999 concerning Telecommunication

1. Articles 2 and 3

   These articles set forth the principles and objectives of telecommunications provision, including the principles of benefit, justice, security, and supporting public welfare, economic life, and governance.

2. Article 4

   This article affirms that telecommunications are controlled by the state, and their development is managed by the government through policy, regulation, supervision, and control.

3. Article 8

   This article specifies who is authorized to provide telecommunication networks and services, including state-owned enterprises, private entities, cooperatives, and others.

4. Article 10

   This article prohibits monopolistic practices and unfair business competition within the telecommunications sector.

5. Article 11

   This article regulates the licensing for telecommunications provision, which must be obtained from the Minister through simple, transparent, and non-discriminatory procedures.

6. Articles 16 and 17

   These articles outline the obligations of providers to contribute to universal service and the principles of fair, efficient, and standard-compliant service delivery.

7. Articles 19 and 20

   These articles address the freedom of users to choose networks and the priority of transmitting vital information related to national security, public safety, disasters, and epidemics.

8. Articles 23-25

   These articles regulate the numbering system and the rights and obligations of interconnection among telecommunications network providers.

9. Article 30

   This article governs the provision of specialized telecommunications services in underserved areas and related permit requirements.

10. Articles 45-48

    These articles detail the administrative and criminal sanctions for violations of the provisions within this Law.

11. Articles 56-59

    These articles outline the criminal penalties for serious offenses and the seizure of telecommunications equipment used for criminal acts.

2.6.2 PDP Law of 2022

1. Article 2 Paragraph (1)

   This article affirms that the Personal Data Protection Law applies to any individual or entity that processes personal data, including foreign companies operating in Indonesia, such as Starlink.

2. Article 4

   This article outlines the fundamental principles of personal data processing, such as fairness, transparency, clear purpose, and data security.

3. Article 6

   This article establishes the obligation for data controllers to obtain explicit consent from data subjects before processing their personal data.

4. Articles 7 and 8

   These articles define the rights of data subjects, including the right to know, access, correct, and delete their personal data.

5. Article 15 Paragraph (2)

   This article details the exceptions for data processing in the interest of national defense and security, which is important in the context of data sovereignty.

6. Article 20

   This article specifies the obligation for data controllers and processors to maintain the confidentiality and security of personal data.

7. Articles 65 and 66

   These articles set forth the criminal sanctions and the right to sue for violations of personal data protection.

2.6.3 Government Regulation Number 46 of 2021 concerning Post, Telecommunications, and Broadcasting

1. Article 10

   This article regulates the scope of telecommunications provision, including the provision of fixed networks and mobile networks (comprising satellite and cellular networks).

2. Article 11

   This article governs the types of telecommunications network provision, such as fixed local networks, long-distance connections, terrestrial mobile networks, cellular mobile networks, and satellite mobile networks.

3. Article 14

   This article establishes the obligations for network development and service provision that must be fulfilled by every telecommunications provider.

4. Articles 55-57

   These articles regulate the transfer of radio frequency spectrum usage rights, including principles of healthy business competition, evaluation of the transfer, and approval from the Minister of Communication and Informatics.

5. Article 59

   This article outlines the administrative sanctionsfor violations in telecommunications provision.

2.6.4 Minister of Communication and Digital Regulation No. 3 of 2025 concerning the Use of Radio Frequency Spectrum for Satellite Services and Satellite Orbits

1. Article 1

   Defines key terms such as Telecommunications, Telecommunications Provision, Telecommunications Provider, Broadcasting, and various types of telecommunications providers, including those utilizing satellites.

2. Article 2

Stipulates that internet access service providers utilizing satellites are obligated to collaborate with telecommunications network operators possessing a Space Radio Spectrum Permit (Izin Spektrum Radio Angkasa - ISR Angkasa). This regulation ensures oversight and integration with the national network.

3. Article 4

   Elucidates the categories of Space Radio Spectrum Permits that may be issued, including those for foreign satellites (such as Starlink), which are required to possess Satellite Landing Rights (Hak Labuh Satelit) to operate within Indonesian territory.

4. Article 6

   Regulates the procedure for applying for a Space Radio Spectrum Permit, which must be accompanied by requisite documentation, including: a copy of the telecommunications or broadcasting operating license, proof of Business Identification Number (Nomor Induk Berusaha - NIB), a copy of the Satellite Landing Rights if utilizing a foreign satellite, an agreement for satellite capacity usage if not employing a proprietary satellite, and network configuration data and earth station specifications (location, frequency, transmission power, antenna, etc.).

5. Article 16

   Governs the registration of earth stations, including user terminals, which must include data on quantity, location, frequency, bandwidth, and device type. This provision is crucial for the oversight of Starlink user devices.

6. Articles 25 and 26

   Regulate the validity period of the Space Radio Spectrum Permit and Satellite Landing Rights, encompassing provisions for renewal and evaluation of the permit holder's performance and compliance.

7. Article 41

   Governs the payment of the Right of Use Fee (Biaya Hak Penggunaan - BHP) for Radio Frequency Spectrum pertaining to satellites, which must be paid by both foreign and domestic satellite operators in accordance with applicable tariffs.

2.6.5 ITU Regulation

1. ITU-T Recommendation E.800

   ITU-T Recommendation E.800 is an official document from the International Telecommunication Union (ITU) that defines terms related to Quality of Service (QoS) in telecommunications.

2. ITU-D QoS Regulation Manual

   The ITU-D Quality of Service Regulation Manual (2017) is a comprehensive guide designed for telecommunications regulators to regulate, monitor, and enforce Quality of Service (QoS) standards for telecommunication services.

CHAPTER 3
RESEARCH METHODOLOGY

3.1 Research Framework

This chapter will be described the stages of research to describe the process to be carried out. Research framework that will be used in this research. The research framework can be represented in Figure 3.1 and Figure 3.2.

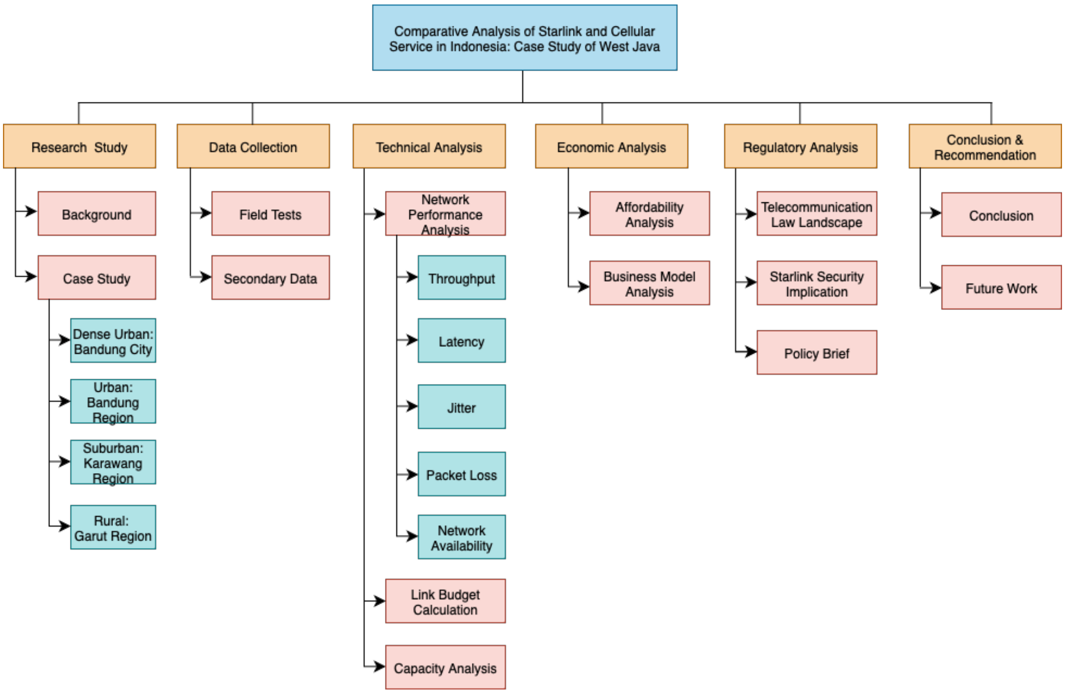

Fig. 3.1 Research Framework

The research framework consists of five main stages that are interconnected. The first stage is the Research Study, which serves as the foundation for building conceptual understanding and formulating the research problem. This stage outlines the background of the study and applies a case study approach in four representative areas of West Java Province: dense urban (Bandung City), urban (Bandung Regency), suburban (Karawang Regency), and rural (Garut Regency). These locations were selected based on differences in population density and geographic characteristics to reflect real-world conditions of Starlink and cellular network performance.

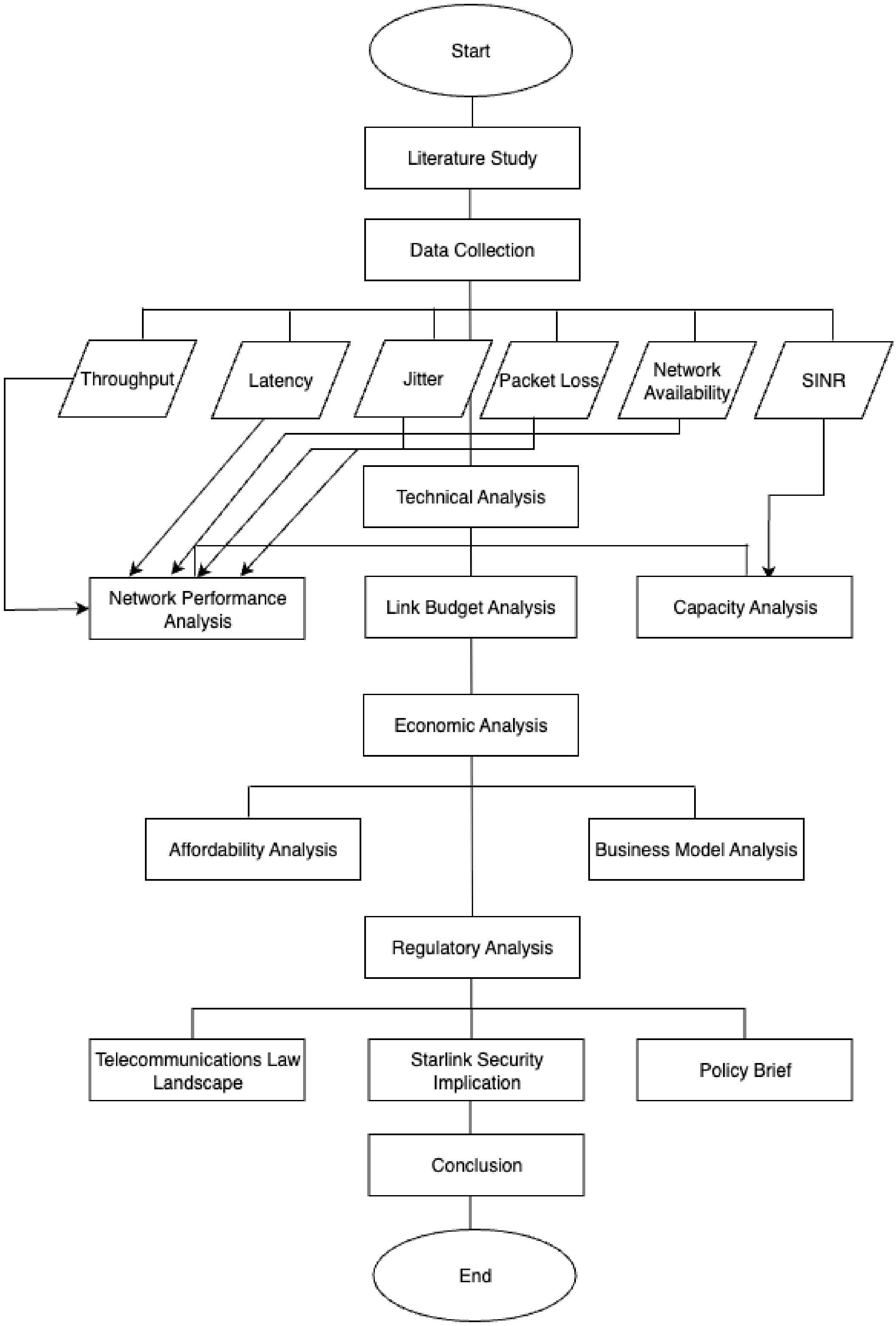

Fig. 3.2 Research Flowchart

The next stage is Data Collection, which involves gathering data through two main methods: field tests and secondary data. Field tests were conducted directly in each area to collect technical network performance data, such as throughput, latency, and jitter. Meanwhile, secondary data were obtained from official sources, including academic publications, economic, regulatory documents, and technical reports that support the overall analysis.

Following data collection, the Technical Analysis stage focuses on evaluating the network performance through network performance analysis and network capacity assessments. This analysis measures five key QoS indicators: throughput, latency, jitter, packet loss, and network availability. In addition, link budget and capacity analysis is conducted to understand the extent to which the network can handle traffic demand, based on technical parameters such as bandwidth and signal quality (SNR/SINR).

The Economic Analysis stage consists of affordability analysis and business model analysis. The affordability analysis aims to assess the financial accessibility of Starlink and cellular services by comparing service costs with the average income levels in different regions. This helps determine whether users from various socioeconomic backgrounds can reasonably afford the services. Meanwhile, the business model analysis focuses on identifying the key stakeholders involve, such as service providers, regulator, and end-users—and evaluates the value proposition from both user and corporate perspectives. For users, the analysis considers improvements in accessibility and service reliability. From the corporate perspective, it explores potential benefits such as market expansion opportunities and operational efficiency, particularly in areas that are difficult to reach with conventional infrastructure.

The Regulatory Analysis stage explores the policy and regulatory aspects relevant to the implementation and coexistence of Starlink services in Indonesia. This includes reviewing national telecommunication regulations, identifying potential security implications, and formulating policy recommendations in the form of a policy brief addressed to relevant stakeholders.

The Conclusion stage summarizes the key findings of the study and offers directions for future research or implementation strategies. This section includes the main conclusions drawn from both the technical and regulatory analyses, as well as suggestions for further work to enhance the integration of satellite and cellular technologies.

3.2 Research Location

Field testing is conducted in four distinct regions to evaluate network performance under varying geographic and demographic conditions. Table 3.1 presents the population, area size, and population density of each case study location.

- Dense Urban

  A highly populated city where 5G infrastructure is expected to perform optimally, though issues such as network congestion and interference must be considered. For this case study, we have selected Bandung City, a dense urban area with a population of approximately 2.59 million and a population density of 15,426 people per km².

- Urban

  Areas with moderate to high population density where both Starlink and 5G networks may coexist to complement each other. These areas may face challenges related to coverage consistency and spectrum efficiency. Bandung Regency was selected to represent the urban area, with a total population of around 3.77 million and a density of 2,177 people per km².

- Suburban

  Less densely populated regions where satellite connectivity, such as Starlink, can provide support to terrestrial networks like 5G. While coverage might be more stable than in urban zones, network capacity and environmental factors may influence performance. Karawang Regency was chosen as the suburban location, with a population of 2.61 million and a density of 1,364 people per km².

- Rural

  Sparsely populated areas where terrestrial infrastructure such as 5G may be limited, making satellite-based solutions more advantageous. These areas often face challenges in broadband access due to their geographic spread and infrastructure gaps. Garut Regency represents the rural category, with a population of approximately 2.79 million and a density of 911 people per km².

Table 3.1 Research Location

Category	Region	Population	Area Size (km^2)	Density ($people/km^2$)
Dense Urban	Bandung City	2,591,763	168	15,426
Urban	Bandung Regency	3,773,104	1,734	2,177
Suburban	Karawang Regency	2,612,065	1,914	1,364
Rural	Garut Regency	2,790,000	3,065	911

3.3 Technical Analysis

The technical analysis focuses on evaluating the performance and operational characteristics of Starlink and 5G networks in diverse geographic contexts. This section investigates key performance indicators, including network throughput, latency, jitter, packet loss, capacity, and coverage. These metrics are essential for understanding the behavior, strengths, and limitations of each technology when deployed under different demographic and environmental conditions.

3.3.1 Network Performance Analysis

Field tests are conducted to measure network performance parameters such as throughput, latency, jitter, and packet loss. This study uses nPerf, a robust and reliable network performance testing tool, to measure the core parameters of throughput, latency, jitter, and packet loss. nPerf chosen for its ability to provide detailed insights into network performance under real-world conditions, along with its feature of offering a 5G coverage map. This coverage map is especially valuable for visualizing the availability and quality of 5G signals across different regions, enabling more accurate performance analysis, particularly in areas with varying 5G infrastructure. For the 5G network tests, this study uses a smartphone device equipped with a 5G-capable SIM card, ensuring compatibility with the 5G network being tested. For the Starlink tests, this study utilizes a laptop connected to Starlink's Wi-Fi network to measure performance and reliability. The tests took place in outdoor/open spaces to minimize interference and physical obstructions that could affect signal reception. For Starlink, the non obstructed helps optimize satellite signal acquisition by reducing potential blockages from buildings, trees, or other structures. Similarly, the outdoor setting allows the 5G device to connect to the best available signal, especially in areas with complex infrastructure. Figure 3.3 shows the Starlink kit, Figure 3.2a is Starlink antenna and 3.2b is Wi-Fi router. The Starlink antenna establishes a direct connection to the satellite network in low Earth orbit, providing internet access, while the Wi-Fi router distributes the connection to local devices. The router has an impressive coverage range of up to 297 m^2 (3,200 ft^2), allowing it to provide connectivity over a significant area.

(a) (b)

Fig. 3.3 Starlink kit, (a) antenna, (b) router

- nPerf

  Nperf is a tool used to test and assess the performance of internet connections, often employed for evaluating mobile networks and broadband connections. It offers real-time measurements of various performance indicators to help users understand their network's speed, stability, and reliability [40]. Nperf is widely used by individual users, mobile network providers, and researchers to measure and compare the performance of their internet connections across various types of networks, including 5G, LTE, Wi-Fi, or satellite services like Starlink. Nperf evaluates important aspects such as:

  1. Download Speed: The rate at which data is received from the internet.
  2. Upload Speed: The rate at which data is sent from the device to the internet.
  3. Latency: The delay in data transmission between the device and the server (measured in milliseconds).
  4. Jitter: The variation in latency, which can impact network consistency.
  5. Packet Loss: The proportion of data packets lost during transmission, which can affect the network's quality.

3.3.2 Link Budget Analysis

Link budget analysis is used to evaluate the feasibility of wireless communication between the satellite and the ground receiver. The following parameters are grouped into five categories: transmitter characteristics, link geometry, propagation losses, receiver parameters, and resulting performance metrics.

1. Transmitter Parameters

   This section includes the characteristics of the transmitting system, which in this case is the satellite. The Effective Isotropic Radiated Power (EIRP) is determined by combining the transmit power and the antenna gain.

Table 3.2 Transmitter Parameters

Parameter	**Value**	**Unit**
Frequency	12	GHz
Bandwidth	0.24	GHz
Modulation Scheme	64-QAM	–
Spectral Efficiency (η_a)	60	%
Transmit Antenna Diameter	2	m
Transmit Antenna Gain	36	dB
Transmit Power	30	dBm
EIRP	35	dBW

   Starlink operates using a nominal channel bandwidth of 250 MHz. However, not all of this bandwidth is usable for data transmission. A 10 MHz guard band is typically allocated between adjacent channels to prevent interference and ensure signal integrity. Therefore, an effective bandwidth of 240 MHz was used.

2. Link Geometry

   This section defines the geometric relationship between the satellite and the receiver. The elevation angle affects the slant range and atmospheric loss. The satellite is assumed to operate at an altitude of 550 km, typical for LEO satellites.

Table 3.3 Link Geometry Parameters

Parameter	**Value**	**Unit**
Satellite Altitude	550	km
Elevation Angle	40	degrees

3. Propagation Loss

   Propagation losses include free-space path loss (FSPL), which depends on distance and frequency, and atmospheric loss caused by absorption, rain fade, and other environmental effects.

Table 3.4 Propagation Loss Parameters

Parameter	Value	Unit
Free Space Path Loss (FSPL)	169	dB
Atmospheric Loss	1	dB

4. Receiver Parameters

   This section lists the characteristics of the receiving terminal (ground user). The antenna gain and system noise temperature significantly affect the signal quality at the receiver.

Table 3.5 Receiver Parameters

Parameter	Value	Unit
Receive Antenna Diameter	0.7	m
Receive Antenna Gain	38	dBi
System Noise Temperature	290	K

5. Slant Range

   To compute the slant range, which is defined as the shortest line-of-sight distance through space between the satellite and the user terminal, the geographic positions of both endpoints are required. Table 3.6 shows the geographic coordinates (latitude and longitude) of user terminals across the four test regions.

Table 3.6 Geographic Coordinates of User Terminal Locations

Region	Latitude (°)	Longitude (°)
Dense Urban	-6.90	107.61
Urban	-6.97	107.63
Suburban	-6.27	107.37
Rural	-7.34	107.78

The position of the Starlink satellite is determined by its sub-satellite point (latitude and longitude) and its orbital altitude. These parameters are used together with the user terminal coordinates to compute the slant range using Equation (2.11). The complete satellite parameters are provided in Table 3.7.

In order to analyze the link condition for each region, the slant range between the satellite and user terminal was calculated based on geographic coordinates and a fixed elevation angle of 40°. Since Starlink satellites operate in low Earth orbit and move dynamically, the slant range varies by region. This

Table 3.7 Starlink Satellite Position Parameters

Parameter	Value	Unit
Satellite Altitude	550	km
Sub-Satellite Latitude	1.98	Degree
Sub-Satellite Longitude	107.66	Degree

distance reflects the actual inclined path the signal travels through the atmosphere, which directly affects propagation losses.

A geometric model was applied to compute the slant range by incorporating the satellite's altitude and user location. The resulting slant range values for each region are shown in Table 3.8.

Table 3.8 Slant Range in Each Region

Categories	Slant Range (km)
Dense Urban	1167
Urban	1174
Suburban	1103
Rural	1212

3.3.3 Capacity Analysis

The capacity analysis aims to estimate the maximum data throughput and traffic load that Starlink and 5G networks can accommodate under varying environmental and operational conditions. The analysis utilizes the Shannon–Hartley Theorem, which provides a theoretical upper bound on channel capacity based on bandwidth and signal-to-noise ratio (SNR).

3.4 Economic Analysis

3.4.1 Affordability Analysis

The affordability analysis in this study is conducted from the user's perspective, focusing on the financial burden that internet services impose on end-users. Affordability is measured by calculating the ratio between the total cost of ownership (TCO) which includes device cost and service subscription, and the annual minimum wage (UMR) in each region. This approach reflects the economic capacity of individuals or households to access and sustain the use of internet services over time.

The affordability threshold is based on ITU targets [41], which consider a service affordable if it does not exceed 2% of monthly income, or equivalently 24% of annual income.

1. Data Consumption Assumption

   In this study, the cost of internet services is analyzed based on a standardized assumption of data consumption. According to some reports on national usage patterns, the average daily mobile internet usage in Indonesia is approximately 500 MB per day. This value is used to represent a typical user's consumption behavior in both rural and urban contexts.

   Based on this figure, the assumed monthly data usage is:

$$500 \text{ MB/day} \times 30 \text{ days} = 15 \text{ GB/month} \tag{3.1}$$

   This assumption is applied uniformly across all services to assess affordability and total cost of ownership in a comparable manner.

2. Total Cost of Ownership

   The Total Cost of Ownership (TCO) includes both hardware cost and subscription service fees over a specified period. Table 3.9 presents the detailed cost breakdown for each service over one and three years.

Table 3.9 Total Cost of Ownership (TCO) for Each Service

Service	Hardware Cost	Service Cost	Total Cost 1-Year	Total Cost 3-Year
Starlink Standard Plan	IDR 4,680,000	IDR 750,000	IDR 13,680,000	IDR 31,680,000
4G/5G (HW Cost=0)	IDR -	IDR 75,000	IDR 900,000	IDR 2,700,000
4G	IDR 1,500,000	IDR 75,000	IDR 2,400,000	IDR 4,200,000
5G	IDR 2,500,000	IDR 75,000	IDR 3,400,000	IDR 5,200,000
Orbit Modem	IDR 600,000	IDR 80,000	IDR 1,560,000	IDR 3,480,000

3. Minimum Wage Income

   By using regional minimum wage as a proxy for income, this analysis captures the realistic financial constraints faced by users, particularly in rural and low-income areas. Minimum Wage for each regions can be seen in Table 3.10.

Table 3.10 Minimum Wage Income

Categories	Monthly	Annual	3-Year
Dense Urban	IDR 4,482,914	IDR 53,794,969	IDR 161,384,907
Urban	IDR 3,757,285	IDR 45,087,418	IDR 135,262,255
Suburban	IDR 5,599,593	IDR 67,195,119	IDR 201,585,356
Rural	IDR 2,328,555	IDR 27,942,665	IDR 83,827,995

3.4.2 Business Model Analysis

The business model analysis is carried out to understand how satellite-based internet services, such as Starlink, operate within the broader telecommunications ecosystem. This analysis examines the structural and functional components of the service delivery process from two perspectives: the end user and the corporation. Key aspects include the identification of business processes, responsible actors, beneficiaries, supporting technologies, and the regulatory or operational mandate that governs each scenario.

3.5 Regulatory Analysis

This section analyzes the legal and institutional frameworks that govern the deployment and operation of Starlink and 5G networks in Indonesia. The analysis encompasses a review of key national telecommunications laws, policies aimed at bridging the digital divide, and the regulatory related to data sovereignty and national security.

CHAPTER 4
RESULTS AND DISCUSSION

4.1 Network Performance Analysis

A total of 4,626 raw data samples were collected from Starlink and cellular networks (4G/5G) via extensive field surveys. The data was gathered in four different environments, dense urban, urban, suburban, and rural, to capture a wide spectrum of network performance across various deployment scenarios and population densities. The examined Quality of Service (QoS) parameters encompass download and upload throughput, latency, jitter, packet loss, and network availability. Data were collected hourly from 09:00 to 20:00 to capture network features during both off-peak and peak times.

4.1.1 Download Throughput

Download throughput measures how quickly users can receive data from the internet. This parameter is essential for activities such as streaming, downloading, and web browsing. In this study, download throughput performance is compared between cellular networks (4G/5G) and Starlink satellite in four regional categories.

4.1.1.1 Summary Statistics

Table 4.1 Download Throughput Statistics

Category	Tech	Mean (Mbps)	Min (Mbps)	Max (Mbps)	STD
Dense Urban	5G	115.40	28.80	210.00	31.15
Urban	5G	139.20	31.40	287.00	52.72
Suburban	4G	62.00	9.00	223.00	34.00
Rural	4G	118.05	2.81	359.00	95.84
Dense Urban	Starlink	135.92	100.60	153.70	14.64
Urban	Starlink	102.70	4.35	149.20	32.44
Suburban	Starlink	120.50	4.18	161.70	26.97
Rural	Starlink	131.95	25.50	154.70	20.84

a. Dense Urban

In Dense Urban settings, Starlink demonstrates a marginally superior mean download throughput of 135.92 Mbps compared to 5G, which records 115.40

Mbps. Crucially, Starlink exhibits notably higher consistency in these high-density areas, characterized by a minimum throughput of 100.60 Mbps and a relatively low standard deviation of 14.64. This suggests a more stable and predictable user experience with Starlink within dense urban landscapes.

b. Urban

In Urban environments, 5G emerges as the leading technology in terms of average download speed, achieving the highest mean throughput across all observed categories at 139.19 Mbps. Starlink, while maintaining a respectable mean of 102.66 Mbps, does not attain the peak average observed for 5G in this context. However, it is pertinent to note that 5G in urban areas displays a higher standard deviation (52.72) than Starlink (32.44), indicating greater variability in its performance despite its superior mean.

c. Suburban

For Suburban regions, Starlink significantly outperforms 4G, registering a mean download throughput of 120.52 Mbps, in stark contrast to 4G's 62.00 Mbps. Furthermore, Starlink's performance in suburban areas is characterized by enhanced consistency, as evidenced by a lower standard deviation of 26.97 compared to 4G's 34.00, implying a more uniform connectivity experience for users in these transitional zones.

d. Rural

In Rural areas, both Starlink (131.95 Mbps) and 4G (118.05 Mbps) demonstrate relatively robust mean download throughputs. Nevertheless, a critical divergence is observed in their respective consistencies. Starlink provides a substantially higher minimum throughput of 25.50 Mbps and a markedly lower standard deviation of 20.84. In contrast, 4G in rural settings exhibits an exceptionally low minimum throughput of 2.81 Mbps and the highest standard deviation within the dataset (95.84). This disparity underscores that while 4G may occasionally achieve high instantaneous speeds in rural areas, its overall performance is highly inconsistent and unreliable, positioning Starlink as a more dependable solution for stable internet connectivity in geographically dispersed regions.

4.1.1.2 Time Series Graph

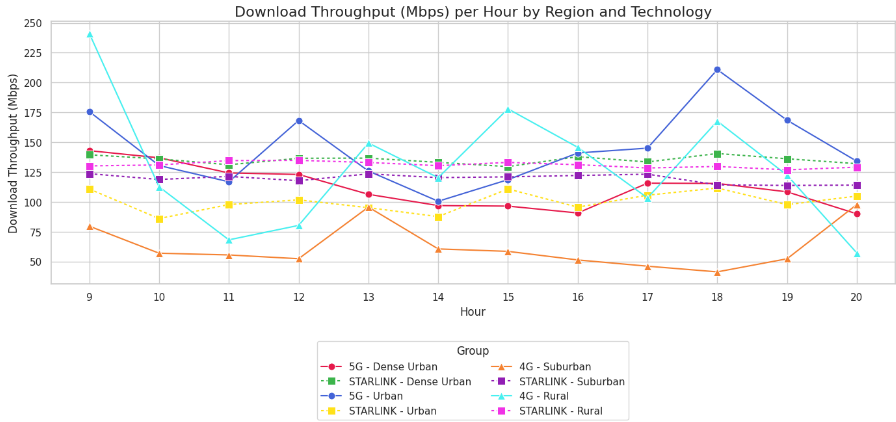

Fig. 4.1 Download Throughput Time Series

a. Dense Urban

In Dense Urban areas, both technologies exhibit strong performance. 5G displays relatively stable throughput, generally ranging from 125 to 145 Mbps, with a slight dip around 14:00 and peaks observed at 13:00 and 19:00. Starlink, conversely, demonstrates exceptionally consistent throughput in this dense urban context, largely maintaining speeds between 125 and 145 Mbps throughout the observed period. This higher stability in Starlink's hourly profile suggests a more uniform user experience in densely populated areas.

b. Urban

In Urban environments, 5G shows more significant fluctuations in throughput. It begins with a robust 175 Mbps at 9:00, experiences a brief decline, and then reaches its highest peak at over 210 Mbps around 18:00. This indicates very strong performance during evening peak hours. Starlink in urban areas, while averaging lower throughput than 5G, provides a more consistent performance, mostly staying between 100-110 Mbps. This highlights a trade-off between 5G's peak speeds and Starlink's stability in urban settings.

c. Suburban

In Suburban regions, a clear performance disparity is evident. 4G consistently records the lowest throughputs, often below 80 Mbps, with noticeable declines between 10:00-12:00 and 17:00-18:00. In stark contrast, Starlink in suburban areas shows significantly higher and more stable download throughputs, generally maintaining speeds between 115-130 Mbps throughout the day. This pronounced difference positions Starlink as a distinctly superior option for suburban connectivity, excelling in both speed and consistency.

d. Rural

In Rural areas, the performance patterns diverge sharply. 4G exhibits extreme volatility, starting at over 230 Mbps at 9:00, then dropping drastically to around 70 Mbps by 11:00, recovering to over 170 Mbps at 15:00, and declining again towards 50-60 Mbps by 20:00. This highly erratic behavior indicates significant inconsistency in rural 4G service. Conversely, Starlink in rural areas demonstrates robust and highly consistent performance, mostly staying between 120-135 Mbps. Despite minor fluctuations, Starlink maintains a far more stable throughput than 4G across all hours in rural settings, establishing it as a considerably more reliable solution for internet access in remote locations.

4.1.1.3 Distribution Graph

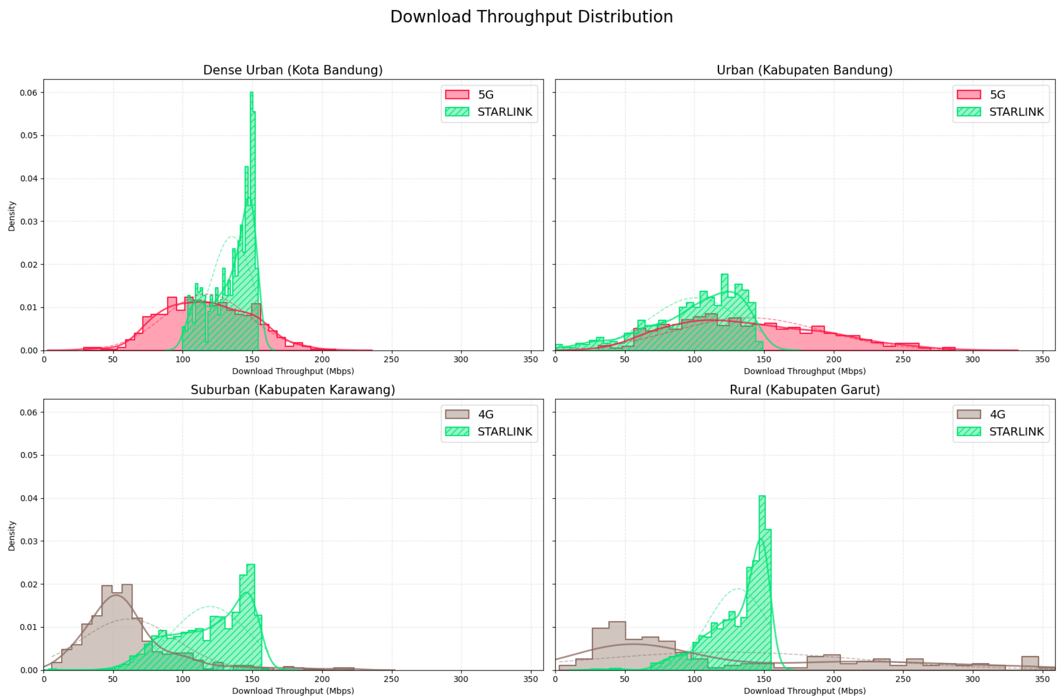

Fig. 4.2 Download Throughput PDF Distribution

a. Dense Urban

In Dense Urban areas (Kota Bandung), the distribution of download throughput reveals distinct characteristics for each technology. 5G exhibits a distribution that peaks around 100-120 Mbps, with a noticeable positive skew, indicating a tail extending towards higher throughput values, though with lower frequency. Conversely, Starlink in the same environment demonstrates a more concentrated and less skewed distribution, with a prominent peak around 140-150 Mbps. This suggests that Starlink offers a more consistent and predictable user experience, clustering tightly around a higher typical download speed compared to 5G, which shows greater variability.

b. Urban

In Urban areas (Kabupaten Bandung), the throughput distributions continue to differentiate the technologies. 5G presents a broader and less dense distribution, peaking around 120-140 Mbps, but crucially, it displays a substantial rightward tail, extending to very high throughputs exceeding 300 Mbps. This indicates that while its central tendency might be slightly lower than some Starlink instances, 5G possesses the capability for exceptionally high speeds, albeit less frequently. Starlink's distribution in urban settings is more tightly clustered with a higher peak density around 100-120 Mbps, signifying greater consistency in its performance, albeit without the extreme high-end throughputs observed with 5G.

c. Suburban

For Suburban regions (Kabupaten Karawang), the contrast between technologies is stark. The 4G throughput distribution is notably broad and relatively flat, indicating substantial variability in performance, with its peak density occurring around 50-70 Mbps. This wide spread implies a less consistent user experience, encompassing both very low and moderately high throughputs without a strong central tendency. In sharp contrast, Starlink in suburban areas shows a highly concentrated distribution with a distinct peak between 120-150 Mbps. This narrow clustering signifies significantly less variability and a much higher probability of users experiencing speeds consistently around this central value, highlighting Starlink's superior reliability.

d. Rural

In Rural areas (Kabupaten Garut), the throughput distributions underscore extreme differences. The 4G distribution is exceptionally wide and scattered, lacking a discernible dominant peak and exhibiting very low density across the entire range of observed speeds. This pattern unequivocally demonstrates highly inconsistent performance for 4G in rural settings, where users may experience anything from very poor to occasionally moderate throughputs with no predictable average. Conversely, Starlink's distribution in rural areas is highly concentrated with a prominent peak around 130-150 Mbps. This tight clustering signifies remarkably less variability and a substantially higher likelihood of users achieving consistent download speeds around its mean.

4.1.1.4 Conclusion

The comparative analysis of download throughput between Starlink and cellular networks (4G and 5G) across four regional classifications, which include dense urban, urban, suburban, and rural areas, reveals distinct performance patterns and contextual strengths for each technology. In dense urban areas, although both 5G and Starlink deliver high average throughput, Starlink demonstrates superior stability, as shown by its higher minimum throughput and lower standard deviation. In urban settings, 5G records the highest mean throughput among all areas, occasionally surpassing 200 Mbps, but it also exhibits greater performance variability. Meanwhile, Starlink maintains more consistent speeds with less fluctuation. In suburban regions, Starlink significantly outperforms 4G in both speed and reliability, consistently delivering higher average throughput and greater stability throughout the day. This contrast becomes even more pronounced in rural areas, where 4G shows the most inconsistent performance, marked by severe fluctuations and the highest standard deviation observed in the dataset. In comparison, Starlink provides steady throughput levels, typically ranging between 130 and 150 Mbps, offering a more dependable internet experience. These findings indicate that Starlink is more suitable for regions with limited terrestrial infrastructure, particularly in suburban and rural areas, while 5G remains the preferred solution in urban environments where its technological advantages can be fully optimized.

4.1.2 Upload Throughput

Upload throughput represents the rate at which users can transfer data from their devices to the internet, essential for services like cloud backups, video conferencing, and content uploads. This study evaluates performance using three visualizations: Table 4.2, which displays statistical summaries (mean, minimum, maximum, and standard deviation), Fig. 4.3, a time series graph illustrating hourly trends, and Fig. 4.4, the upload throughput probability distribution functions (PDFs) across various regions and technologies.

4.1.2.1 Summary Statistics

Table 4.2 Upload Throughput Statistics

Category	Tech	Mean (Mbps)	Min (Mbps)	Max (Mbps)	STD
Dense Urban	5G	61.77	5.40	104.00	16.99
Urban	5G	36.16	7.42	54.70	9.17
Suburban	4G	19.00	0.16	63.00	14.00
Rural	4G	36.02	1.88	75.90	21.96
Dense Urban	Starlink	31.77	0.12	73.06	14.81
Urban	Starlink	27.57	0.71	78.73	13.90
Suburban	Starlink	32.50	1.05	79.41	15.21
Rural	Starlink	37.71	0.01	74.53	15.28

a. Dense Urban

In Dense Urban areas, 5G demonstrates a significant advantage in mean upload throughput, registering 61.77 Mbps, which is nearly double that of Starlink's 31.77 Mbps. This superior performance extends to maximum speeds, with 5G achieving 104.00 Mbps compared to Starlink's 73.06 Mbps. While Starlink shows a marginally lower standard deviation, suggesting slightly more consistency, 5G's much higher minimum speed of 5.40 Mbps against Starlink's 0.12 Mbps indicates a more robust and reliable baseline for upload capabilities in these highly populated environments.

b. Urban

In Urban areas, 5G maintains its lead over Starlink in mean upload throughput, recording 36.16 Mbps versus Starlink's 27.57 Mbps. Furthermore, 5G exhibits superior consistency, as indicated by a lower standard deviation of 9.17 compared to Starlink's 13.90, suggesting more predictable upload speeds. Although both technologies show comparable maximum speeds, 5G's significantly higher minimum upload speed of 7.42 Mbps, in contrast to Starlink's 0.71 Mbps, points to a more reliable minimum performance for 5G in urban settings.

c. Suburban

For Suburban regions, Starlink distinctly outperforms 4G in terms of mean upload throughput, achieving 32.50 Mbps compared to 4G's 19.00 Mbps. Starlink also registers a higher maximum upload speed of 79.41 Mbps against 4G's 63.00 Mbps. While their standard deviations are somewhat similar, a critical distinction lies in the minimum upload speed: 4G records 0.00 Mbps, indicating instances of complete lack of upload connectivity, a significant drawback compared to Starlink's 1.05 Mbps minimum, which, though low, still represents some level of service.

d. Rural

In Rural areas, both Starlink and 4G show comparable mean upload throughputs, at 37.71 Mbps and 36.02 Mbps respectively. However, 4G exhibits a higher standard deviation of 21.96 compared to Starlink's 15.28, suggesting greater variability and less consistent upload performance for 4G in these less connected regions. Both technologies present very low minimum upload speeds, highlighting potential challenges for reliable uploads in rural environments, with 4G's minimum at 1.88 Mbps and Starlink's at 0.01 Mbps. Maximum speeds for both are also quite similar.

4.1.2.2 Time Series Graph

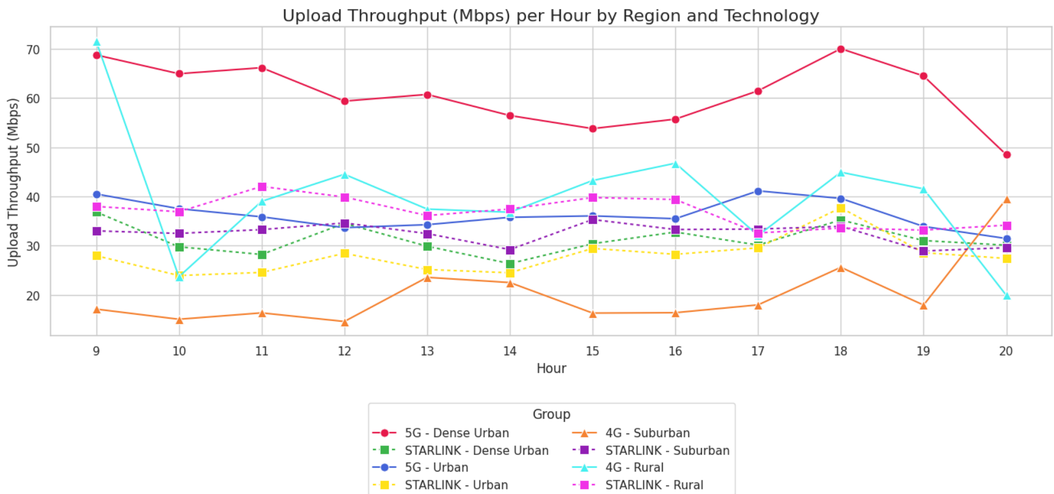

Fig. 4.3 Upload Throughput Time Series

a. Dense Urban

In Dense Urban areas, 5G consistently maintains the highest upload throughput, generally ranging from 55 Mbps to over 70 Mbps. It shows a peak around 9:00 (69 Mbps), a slight dip in the midday (around 59 Mbps at 12:00), and then steadily rises to its highest point of over 70 Mbps around 18:00 before a decline towards 20:00. Starlink in dense urban settings, while lower, exhibits a more stable performance, mostly hovering between 25-35 Mbps with minor fluctuations, suggesting a consistent, albeit lower, upload speed throughout the day.

b. Urban

   For Urban environments, 5G again leads in upload throughput, typically staying above 30 Mbps and reaching around 40 Mbps at certain hours (9:00, 17:00-18:00). Its performance is relatively stable without drastic drops. Starlink in urban areas shows consistently lower upload speeds, generally between 25-30 Mbps, with a slight dip around 20:00. While Starlink provides a steady baseline, 5G consistently offers higher upload speeds for urban users.

c. Suburban

   In Suburban regions, Starlink generally provides superior upload throughput compared to 4G. Starlink's performance is relatively stable, ranging from 30-40 Mbps for most of the day, with slight increases in the late afternoon. Conversely, 4G in suburban areas consistently exhibits the lowest upload speeds among all categories, mostly staying below 20 Mbps and showing minimal fluctuations throughout the day. This indicates that Starlink is a significantly better option for upload needs in suburban contexts.

d. In Rural areas, both 4G and Starlink show interesting dynamics. 4G in rural areas begins very high, exceeding 70 Mbps at 9:00, but then experiences a dramatic drop to around 20 Mbps by 20:00, with a notable recovery in the mid-afternoon. This volatility suggests highly inconsistent upload performance. Starlink in rural areas, on the other hand, provides a much more stable and consistent upload throughput, mostly staying within the 30-40 Mbps range throughout the day. Although 4G can achieve higher peaks, Starlink offers far greater reliability and a more predictable upload experience for rural users.

4.1.2.3 Distribution Graph

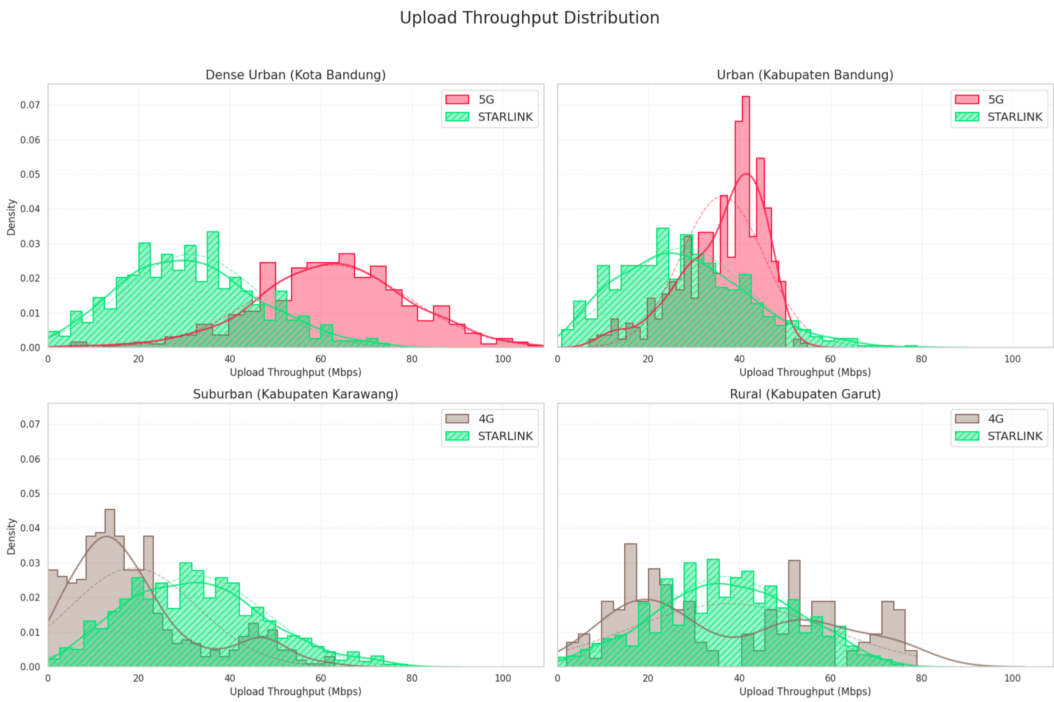

Fig. 4.4 Upload Throughput PDF Distribution

a. Dense Urban

In Dense Urban areas (Kota Bandung), the upload throughput distributions for 5G and Starlink present distinct characteristics. 5G's distribution is broader and more centered around 50-60 Mbps, indicating a range of upload speeds, with a slight positive skew suggesting a tendency towards higher values. Conversely, Starlink's distribution in this environment is more narrowly concentrated, peaking at a lower range of 20-30 Mbps. The higher density at Starlink's peak suggests greater consistency in delivering speeds within that narrower band, although at a lower average compared to 5G, which shows greater variability but also access to higher upload speeds.

b. Urban

In Urban areas (Kabupaten Bandung), the 5G upload throughput distribution is characterized by a high concentration with a sharp peak around 40-50 Mbps. This indicates that a significant majority of 5G users in urban settings experience upload speeds consistently within this optimal range, demonstrating high predictability. Starlink's distribution, while also showing a central tendency, is broader and less densely peaked, residing around 30-40 Mbps.

This suggests that Starlink in urban areas exhibits more variability in its upload performance compared to the highly consistent 5G.

c. Suburban

For Suburban regions (Kabupaten Karawang), the contrast between 4G and Starlink's upload throughput distributions is striking. The 4G distribution is notably skewed towards very low speeds, peaking sharply around 10-20 Mbps, and extending with a long tail towards higher values. This implies that while some higher uploads are possible, the vast majority of 4G connections in suburban areas suffer from very low upload speeds. In contrast, Starlink's distribution is more symmetrical and centered at a significantly higher throughput, typically peaking around 30-40 Mbps. Its narrower spread indicates much greater consistency and a more favorable typical upload experience for suburban users compared to 4G.

d. Rural

In Rural areas (Kabupaten Garut), the upload throughput distributions highlight severe differences in reliability. The 4G distribution is exceptionally broad and flat, spanning a wide range of speeds from near zero to over 80 Mbps with no strong central tendency. This wide dispersion underscores extreme inconsistency and unpredictability in 4G upload performance in rural settings. Starlink, conversely, presents a more defined and concentrated distribution, peaking around 30-50 Mbps. While still exhibiting some variability, Starlink's distribution is significantly tighter than 4G's, indicating a far more predictable and typically higher upload experience for rural users.

4.1.2.4 Conclusion

The analysis of upload throughput across four geographic classifications also reveals distinct patterns in the performance and consistency of Starlink and cellular networks. In dense urban areas, 5G significantly outperforms Starlink in average, minimum, and maximum upload speeds, making it the more reliable option in high-density settings. This trend continues in urban environments, where 5G again leads in mean throughput and shows less variability compared to Starlink. However, in suburban areas, Starlink emerges as the superior performer, offering higher average upload speeds and greater reliability than 4G, which is hampered by low minimum speeds and broader distribution. In rural regions, both 4G and Starlink deliver similar average upload throughputs, but Starlink demonstrates greater consistency, as evidenced by its narrower standard deviation and tighter distribution. While 4G can achieve occasional high peaks, its overall variability is high, resulting in an unpredictable user experience. Starlink, on the other hand, provides a more stable and dependable upload performance across the day, particularly in underserved and infrastructure-limited areas. These findings suggest that 5G is best suited for densely populated urban settings where infrastructure is robust, whereas Starlink offers more consistent and reliable upload connectivity in suburban and rural areas where traditional cellular networks tend to underperform.

4.1.3 Latency

Latency, measured in milliseconds (ms), represents the time delay between sending and receiving data across a network. It is a critical performance metric, particularly for applications requiring real-time responsiveness such as video conferencing, voice-over-IP, online gaming, and remote surgery. Beyond its average value, latency is also assessed based on its variability and distribution, as fluctuations can disrupt user experience.

4.1.3.1 Summary Statistics

Table 4.3 Latency Statistics

Category	Tech	Mean (ms)	Min (ms)	Max (ms)	STD
Dense Urban	5G	17.96	0.00	38.00	3.74
Urban	5G	26.02	18.00	37.00	3.10
Suburban	4G	28.00	0.00	66.00	7.00
Rural	4G	30.03	19.00	50.00	7.93
Dense Urban	Starlink	30.23	1.25	64.00	6.41
Urban	Starlink	31.33	20.67	77.00	6.24
Suburban	Starlink	32.10	20.00	93.50	9.46
Rural	Starlink	31.02	0.50	68.50	6.26

a. Dense Urban

In Dense Urban environments, 5G demonstrates exceptionally low latency, with a mean of just 17.96 ms. This is significantly lower than Starlink's mean latency of 30.23 ms. Furthermore, 5G exhibits superior consistency, as indicated by a very low standard deviation of 3.74 ms and a narrow maximum latency of 38.00 ms (noting the 0.00 ms minimum might be an anomaly). Starlink, while still providing relatively low latency, shows a higher standard deviation of 6.41 ms and a wider maximum range up to 64.00 ms, indicating greater variability in its performance compared to 5G in dense urban settings.

b. Urban

In Urban areas, 5G continues to maintain its lead in latency performance, recording a mean of 26.02 ms. It also boasts excellent consistency, with the lowest standard deviation across all categories at 3.10 ms and a narrow range of 18.00 ms to 37.00 ms. Starlink in urban areas has a higher mean latency of 31.33 ms and a greater standard deviation of 6.24 ms, with a wider range extending up to 77.00 ms. This indicates that 5G consistently provides a more responsive connection in urban environments than Starlink.

c. Suburban

For Suburban regions, 4G generally shows lower latency compared to Starlink. 4G records a mean latency of 28.00 ms, which is lower than Starlink's 32.10 ms. While 4G's 0.00 ms minimum might be an outlier, its maximum latency of 66.00 ms and standard deviation of 7.00 ms suggest a reasonable level of consistency. Starlink in suburban areas exhibits the highest variability among all categories, with a standard deviation of 9.46 ms and a maximum latency reaching 93.50 ms, implying less predictable latency performance for users.

d. Rural

In Rural areas, both 4G and Starlink present comparable mean latencies, with 4G at 30.03 ms and Starlink at 31.02 ms. However, Starlink demonstrates slightly better consistency, having a lower standard deviation of 6.26 ms compared to 4G's 7.93 ms. 4G maintains a higher minimum latency of 19.00 ms, suggesting a more consistent baseline compared to Starlink's 0.50 ms minimum (which might be an anomalous reading). Overall, both technologies offer relatively similar average latency in rural areas, though Starlink might be slightly more consistent in its range.

4.1.3.2 Time Series Graph

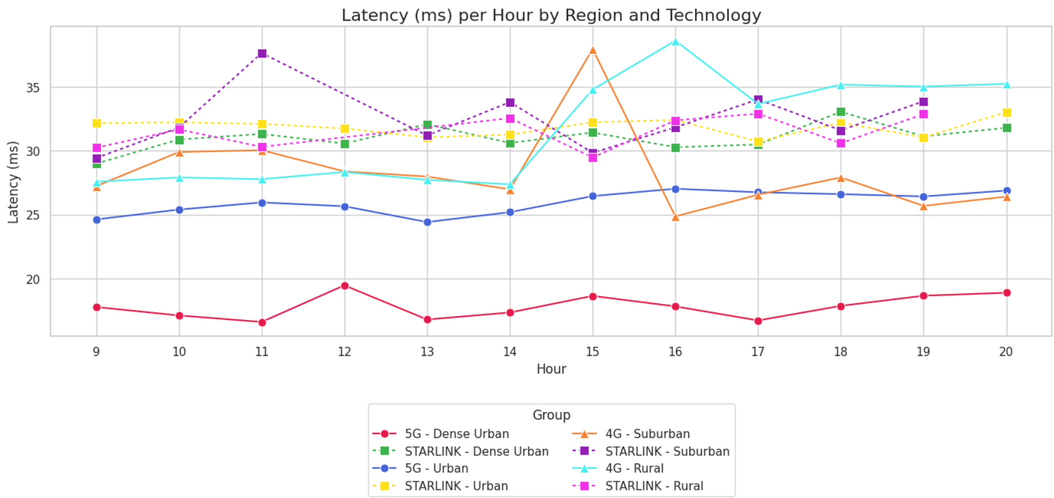

Fig. 4.5 Latency Time Series

a. Dense Urban

In Dense Urban environments, 5G consistently demonstrates the lowest latency across all categories, typically remaining below 20 ms. Its performance is remarkably stable throughout the day, showing only minor fluctuations, such as a slight dip around 11:00. In contrast, Starlink in dense urban settings consistently exhibits higher latency values, generally ranging between 30-33 ms. While Starlink's latency remains relatively stable, it is consistently above that of 5G. This indicates that 5G provides a significantly more responsive connection in densely populated areas.

b. Urban

In Urban areas, 5G continues to deliver low latency, generally staying within the 24-27 ms range. Its performance is highly consistent throughout the observed hours, with minimal variations. Starlink in urban environments consistently shows higher latency than 5G, typically between 31-33 ms. Similar to dense urban, Starlink's urban latency is relatively stable but remains above 5G. Therefore, 5G offers superior and more consistent responsiveness for urban users.

c. Suburban

For Suburban regions, 4G generally exhibits lower latency compared to Starlink. 4G's latency fluctuates, starting around 27 ms, dipping to approximately 24 ms during midday, and then rising again towards 27 ms by late afternoon.

Conversely, Starlink in suburban areas displays some of the highest latencies observed across all categories, notably peaking above 37 ms around 11:00. Its performance is also quite variable, ranging from about 30 ms to nearly 38 ms. This suggests that 4G generally provides a more favorable and less variable latency experience in suburban environments.

d. Rural

In Rural areas, the latency performance presents a contrast between consistency and extreme values. 4G in rural areas shows the most significant fluctuations among all categories, beginning around 27 ms, spiking dramatically to over 38 ms around 15:00, and then varying considerably. This high volatility indicates unpredictable responsiveness. Starlink in rural settings, however, maintains a much more stable latency profile, mostly staying within the 30-34 ms range throughout the day. While 4G can achieve lower latency at certain sporadic points, Starlink offers a significantly more consistent and predictable latency experience for rural users.

4.1.3.3 Distribution Graph

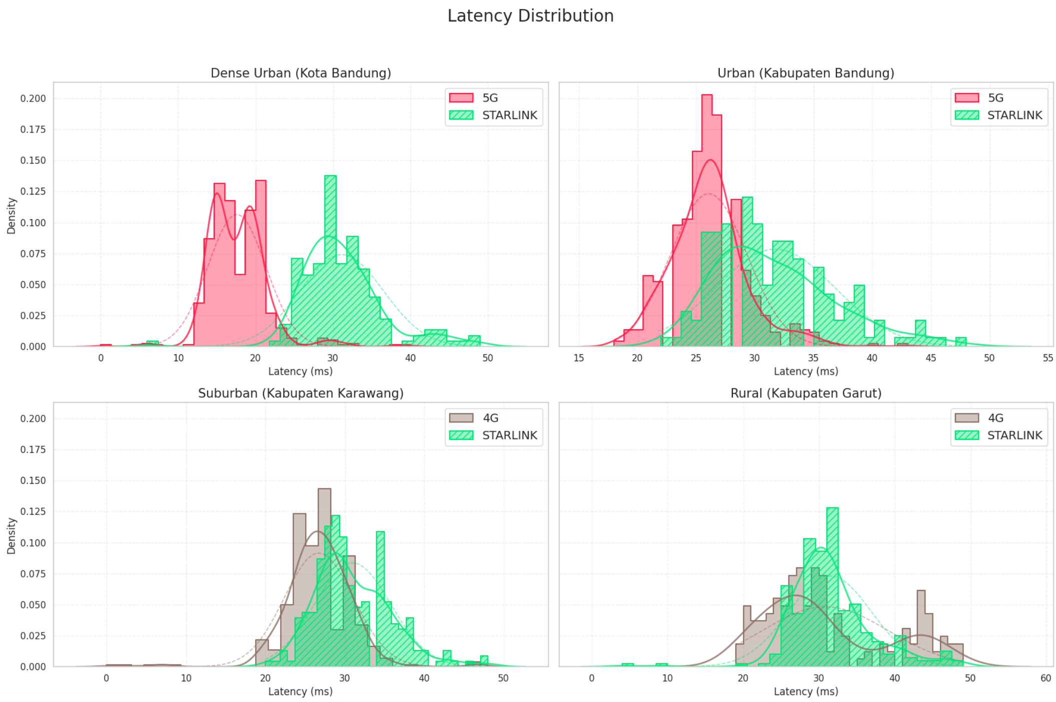

Fig. 4.6 Latency PDF Distribution

a. Dense Urban

In Dense Urban areas (Kota Bandung), the latency distributions starkly differentiate 5G and Starlink. 5G exhibits an exceptionally concentrated distribution, with a sharp, high peak centered around 15-20 ms. This indicates that 5G consistently delivers remarkably low latency values. Conversely, Starlink's distribution in this context is broader and peaks at a higher range, typically around 25-30 ms. While still providing generally good latency, Starlink's wider spread suggests greater variability compared to the highly consistent and low-latency performance of 5G in dense urban settings.

b. Urban

In Urban areas (Kabupaten Bandung), 5G continues to demonstrate superior latency performance. Its distribution is characterized by a very high-density peak around 25-30 ms, signifying an extremely consistent delivery of low latency. The narrowness of this distribution further underscores its reliability. Starlink's distribution in urban areas is comparatively wider and less concentrated, with its peak residing around 30-35 ms. This broader spread, coupled with a tail extending towards higher latency values (up to 50 ms), indicates greater variability and generally higher latency compared to 5G in the urban environment.

c. Suburban

For Suburban regions (Kabupaten Karawang), the latency distributions suggest that 4G generally offers a more favorable experience. 4G's distribution is relatively narrow and sharply peaked around 20-25 ms, implying consistent and low latency performance. In contrast, Starlink's distribution in suburban areas is broader and peaks at a slightly higher range of 25-30 ms, also exhibiting a more pronounced tail towards higher latencies. This indicates that Starlink's latency in suburban settings is not only higher on average but also more variable than that provided by 4G.

d. Rural

In Rural areas (Kabupaten Garut), the latency distributions reveal different patterns of consistency. 4G's distribution is notably broader and less concentrated, with its peak occurring around 20-30 ms, but importantly, it shows a significant spread extending towards higher latencies up to 50 ms. This wide dispersion suggests considerable variability and less predictable latency performance for 4G in rural contexts. Starlink, conversely, presents a more concentrated distribution with a prominent peak around 25-35 ms. Although it still exhibits some spread, Starlink's distribution is tighter than 4G's, indicating a more consistent and predictable latency profile for users in rural areas.

4.1.3.4 Conclusion

The latency analysis across dense urban, urban, suburban, and rural regions highlights the superior responsiveness of 5G in populated environments, while also revealing Starlink's potential in offering consistent performance in remote areas. In dense urban and urban regions, 5G consistently achieves the lowest mean latency, coupled with the most concentrated distributions and lowest standard deviations, confirming its suitability for real-time applications such as video conferencing or online gaming. Starlink, although delivering relatively stable latency, generally exhibits higher average values and greater variability in these areas. In suburban settings, 4G outperforms Starlink in both mean latency and consistency, while Starlink displays the highest variability, making it less reliable for latency-sensitive applications. In rural regions, mean latency between 4G and Starlink is similar, but Starlink demonstrates slightly better consistency with a tighter latency distribution, suggesting a more predictable user experience. Although 4G occasionally achieves lower latency in rural areas, its volatility across time makes it less dependable. Overall, 5G is best positioned for low-latency requirements in urban contexts, while Starlink offers a steadier alternative in rural and underserved regions where terrestrial network infrastructure is less robust.

4.1.4 Jitter

Jitter, measured in milliseconds (ms), reflects the variability in packet delay across a network. In practice, it plays a critical role in maintaining the quality of real-time applications such as voice over IP (VoIP), video conferencing, and interactive cloud services. Unlike latency, which focuses on end-to-end delay, jitter captures inconsistency, and is best assessed through mean values, standard deviation, and distributional characteristics.

Table 4.4 presents a summary of jitter statistics, including Mean, Minimum, Maximum, and Standard Deviation (STD), categorized by geographical region and technology.

4.1.4.1 Summary Statistics

a. Dense Urban

In Dense Urban areas, 5G demonstrates significantly superior jitter performance compared to Starlink. 5G records a mean jitter of 17.35 ms, which is notably lower than Starlink's 24.80 ms. Crucially, 5G also exhibits much greater consistency, with a standard deviation of just 9.11 ms, dramatically lower than Starlink's 19.06 ms. This indicates that 5G provides a far more stable and predictable connection in densely populated environments, essential for real-time applications, while Starlink, despite having a relatively low mean, shows considerably more variability.

b. Urban

In Urban environments, an interesting shift occurs in performance. Starlink surprisingly shows a slightly lower mean jitter of 28.46 ms compared to 5G's 31.44 ms. However, 5G maintains better consistency, as evidenced by a lower standard deviation of 16.22 ms against Starlink's 20.08 ms. Both technologies show high maximum jitter values, reaching close to 100 ms, suggesting that even in urban settings, significant spikes in jitter can occur regardless of the technology. Nevertheless, 5G's tighter standard deviation implies more reliable jitter performance overall in urban areas despite a slightly higher average.

c. Suburban

For Suburban regions, 4G generally provides a more stable jitter profile than Starlink. 4G records a mean jitter of 27.00 ms, which is marginally lower than Starlink's 27.24 ms. The key differentiator lies in consistency: 4G's standard deviation of 16.00 ms is considerably lower than Starlink's 20.97 ms, which is the highest standard deviation among all categories. This indicates that while their average jitter might be similar, 4G offers a more predictable and stable connection for users in suburban areas, whereas Starlink's jitter tends

Table 4.4 Jitter Statistics

Category	Tech	Mean (ms)	Min (ms)	Max (Mbps)	STD
Dense Urban	5G	17.35	0.00	91.00	9.11
Urban	5G	31.44	5.00	100.00	16.20
Suburban	4G	27.00	4.00	99.00	16.00
Rural	4G	23.43	3.00	97.00	13.96
Dense Urban	Starlink	24.80	0.58	98.33	19.06
Urban	Starlink	28.46	1.03	98.80	20.10
Suburban	Starlink	27.24	1.73	97.80	21.00
Rural	Starlink	23.72	0.00	98.67	19.47

to fluctuate more widely.

d. Rural

In Rural areas, both 4G and Starlink exhibit very similar mean jitter values, with 4G at 23.43 ms and Starlink at 23.72 ms. However, 4G demonstrates superior consistency, with a standard deviation of 13.96 ms, which is lower than Starlink's 19.47 ms. This suggests that despite comparable average jitter, 4G provides a more stable connection in rural settings, with less variability in the timing of data packets. Both technologies show very high maximum jitter values, indicating that even in these less dense areas, significant interruptions to real-time data flow can occur at times.

4.1.4.2 Time Series Graph

This time-series graph illustrates the hourly variations in jitter (ms) across different regions and technologies, providing a dynamic perspective on connection stability throughout the day.

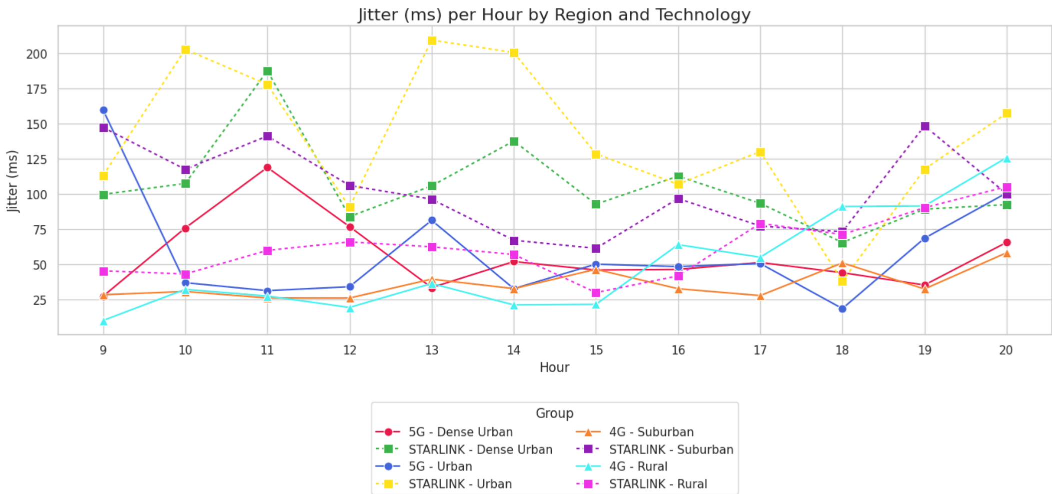

Fig. 4.7 Jitter Time Series

a. Dense Urban

In Dense Urban areas, both 5G and Starlink exhibit considerable fluctuations in jitter. 5G starts with relatively low jitter around 30 ms in the morning but experiences a significant spike to over 120 ms between 11:00 and 12:00, before stabilizing at lower levels later in the day. Starlink in dense urban settings generally shows higher jitter values, beginning around 100 ms, peaking above 180 ms around 11:00, and then fluctuating between 75-140 ms. This indicates that both technologies can experience periods of high instability in jitter performance in dense urban environments, though 5G shows periods of lower jitter.

b. Urban

In Urban environments, both technologies again demonstrate high variability in jitter. 5G's jitter starts relatively high, around 160 ms, but then drops significantly to its lowest point near 20 ms around 18:00 before rising again. This suggests a highly volatile profile. Starlink consistently displays the highest jitter values across all categories for most hours, frequently exceeding 100 ms and reaching peaks of over 200 ms around 13:00. This indicates extremely poor and highly variable jitter performance for Starlink in urban areas compared to 5G, which, while variable, achieves much lower minimums.

c. Suburban

For Suburban regions, 4G generally provides significantly more stable and lower jitter compared to Starlink. 4G's jitter consistently remains below 50 ms and exhibits remarkable stability throughout the day, with only minor fluctuations and a slight peak around 13:00. In sharp contrast, Starlink in suburban areas shows notably higher and highly volatile jitter, with dramatic peaks approaching 150 ms around 11:00 and 19:00. This pronounced difference indicates that 4G offers a much more reliable connection for applications sensitive to jitter in suburban contexts.

d. Rural

In Rural areas, a similar pattern of stability emerges, favoring 4G. 4G's jitter is generally low and stable, mostly staying below 40 ms, mirroring its consistent performance in suburban areas. Starlink, however, displays highly variable jitter in rural settings, ranging from approximately 45 ms to over 100 ms, with significant and frequent fluctuations. Therefore, while both technologies are present in rural areas, 4G provides a substantially more consistent and lower jitter experience, which is crucial for real-time communication and gaming.

4.1.4.3 Distribution Graph

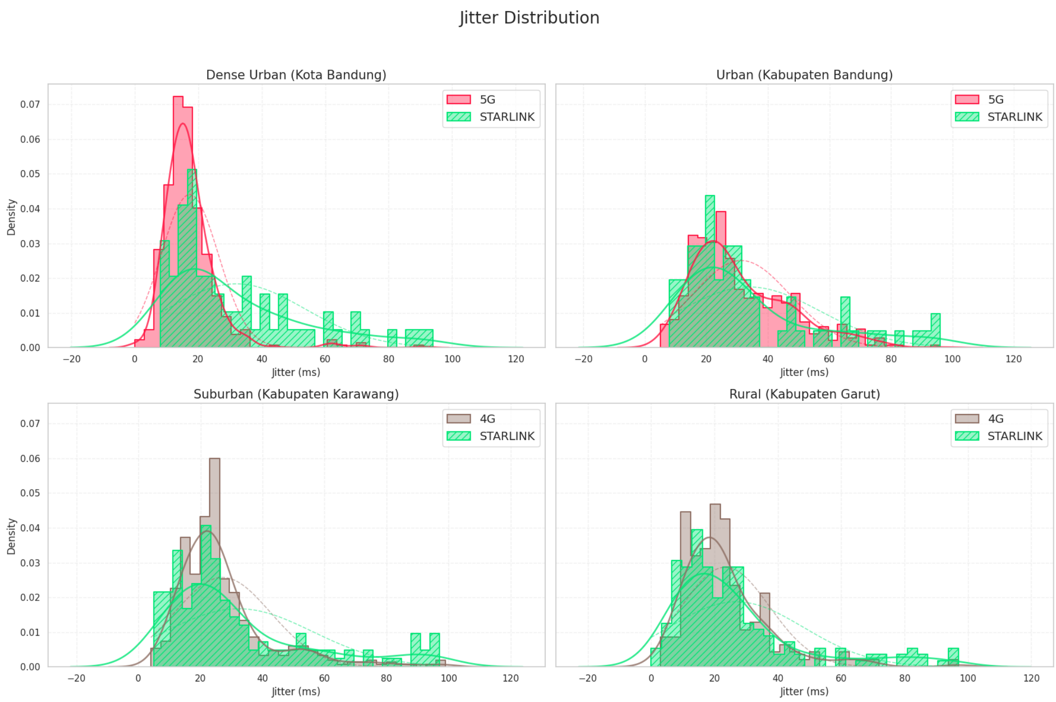

Fig. 4.8 Jitter PDF Distribution

a. Dense Urban

In Dense Urban areas (Kota Bandung), the jitter distribution highlights significant differences between the two technologies. 5G exhibits a highly concentrated distribution with a sharp, tall peak at very low jitter values, predominantly between 0-10 ms. This indicates exceptional stability and consistency for 5G connections. In contrast, Starlink's distribution is notably broader and less sharply peaked, with its main concentration around 10-20 ms. Critically, Starlink's distribution also features a more pronounced and extended tail reaching towards 100 ms, signifying a higher frequency of significant jitter spikes compared to 5G, which is much more confined to low values.

b. Urban

In Urban areas (Kabupaten Bandung), the jitter distributions continue to differentiate the technologies. 5G's distribution is characterized by a high density and a sharp peak around 10-20 ms, denoting a strong propensity for consistent low jitter. While it also shows a tail extending to higher values, its overall spread is narrower than Starlink's. Starlink's distribution in urban areas is broader and flatter, with its peak around 20-30 ms, and a much more elongated tail reaching significantly towards 100 ms. This indicates that Starlink, while capable of low jitter, experiences much greater variability and a higher likelihood of encountering substantial jitter spikes compared to 5G.

c. Suburban

For Suburban regions (Kabupaten Karawang), the jitter distribution demonstrates a clear advantage for 4G. 4G's distribution is highly concentrated with a very sharp peak at extremely low jitter values, predominantly within the 0-10 ms range. This signifies outstanding consistency and minimal jitter for 4G connections in suburban areas. Conversely, Starlink's distribution is considerably wider and less peaked, centered around 10-20 ms, and features a long tail extending to 100 ms. This broadness indicates higher average jitter and significantly greater variability in Starlink's performance, making 4G the more stable option in this context.

d. Rural

In Rural areas (Kabupaten Garut), the jitter distributions again show distinct patterns of stability. 4G's distribution is relatively concentrated at low jitter values, peaking around 10-20 ms. While not as sharp as in suburban areas, it generally indicates a more consistent performance than Starlink. Starlink's distribution is broader and flatter, primarily concentrated around 20-30 ms, and also displays a visible tail extending towards 100 ms. This broader spread suggests greater variability and a higher prevalence of jitter spikes compared to 4G, implying that 4G generally provides a more consistently stable connection for rural users.

4.1.4.4 Conclusion

The analysis of jitter across all regions reveals that terrestrial networks, particularly 5G and 4G, consistently outperform Starlink in terms of stability and predictability. In dense urban environments, 5G delivers the lowest average jitter and the narrowest distribution, indicating exceptional consistency vital for real-time services. Although Starlink performs adequately in terms of mean jitter, it exhibits significantly greater variability, reducing its reliability. In urban areas, Starlink occasionally achieves slightly lower average jitter than 5G, yet the broader spread and higher standard deviation reflect less predictable service quality. Suburban and rural regions show a clear advantage for 4G over Starlink, with 4G maintaining low average jitter and tighter distributions, signaling stable performance across time. Starlink's jitter in these areas is not only higher on average but also subject to frequent and severe fluctuations, as reflected in its time series and distribution graphs. These inconsistencies pose challenges for applications sensitive to delay variation. Overall, while Starlink offers acceptable jitter levels on average, terrestrial networks, particularly 5G in urban settings and 4G in suburban and rural areas, provide far more stable and reliable jitter performance, making them better suited for latency-sensitive applications such as voice and video communications.

4.1.5 Packet Loss

Packet loss, measured as a percentage (%), refers to the proportion of data packets that do not successfully reach their destination during transmission. This metric is essential in evaluating the reliability and quality of network services, especially for real-time applications such as video conferencing, voice over IP, and interactive streaming. Even small percentages of packet loss can result in noticeable disruptions, making this parameter a key indicator of user experience.

4.1.5.1 Summary Statistics

Table 4.5 Packet Loss Statistics

Category	Tech	Mean	Min	Max	STD
Dense Urban	5G	0.65	0.00	4.20	0.53
Urban	5G	0.41	0.00	8.10	0.60
Suburban	4G	0.15	0.00	3.00	0.00
Rural	4G	0.26	0.00	4.05	0.42
Dense Urban	Starlink	1.33	0.01	7.52	1.34
Urban	Starlink	2.15	0.00	9.48	2.09
Suburban	Starlink	2.00	0.01	9.73	1.68
Rural	Starlink	1.16	0.01	8.72	1.28

a. Dense Urban

In Dense Urban areas, 5G demonstrates superior packet loss performance compared to Starlink. 5G records a mean packet loss of 0.65%, which is notably lower than Starlink's 1.33%. Furthermore, 5G exhibits significantly greater consistency, evidenced by a standard deviation of 0.53, much lower than Starlink's 1.34. This indicates that 5G provides a more reliable connection in dense urban environments, with fewer instances of lost data packets and more predictable performance, while Starlink shows higher average loss and more variability

b. Urban

In Urban areas, 5G maintains its exceptional reliability in terms of packet loss. It records a remarkably low mean packet loss of 0.41%, which is the lowest among all categories where 5G is present. In stark contrast, Starlink in urban areas registers the highest mean packet loss among all categories at 2.15%. 5G also displays superior consistency with a standard deviation of 0.60, significantly better than Starlink's 2.09. This highlights that 5G offers a much more dependable and stable connection for urban users, with Starlink experiencing considerably higher and more variable packet loss.

c. Suburban

For Suburban regions, 4G exhibits outstanding reliability, achieving an exceptional mean packet loss of 0.00%. This perfect score is further reinforced by a standard deviation of 0.00, indicating virtually no packet loss whatsoever. Conversely, Starlink in suburban areas shows significantly higher mean packet loss at 2.00%. Notably, Starlink also has a minimum packet loss of 1.00% in this category, suggesting that some level of packet loss is almost always present for Starlink connections, a stark difference from 4G's flawless performance.

d. Rural

In Rural areas, 4G continues to demonstrate very strong reliability, with a mean packet loss of 0.26%. This is substantially lower than Starlink's mean packet loss of 1.16% in the same environment. 4G also maintains better consistency, with a standard deviation of 0.42 compared to Starlink's 1.28. Similar to suburban areas, Starlink records a minimum packet loss of 1.00% in rural regions, implying a persistent baseline of packet loss. These statistics collectively suggest that 4G offers a more reliable connection with fewer lost packets compared to Starlink in rural settings.

4.1.5.2 Time Series Graph

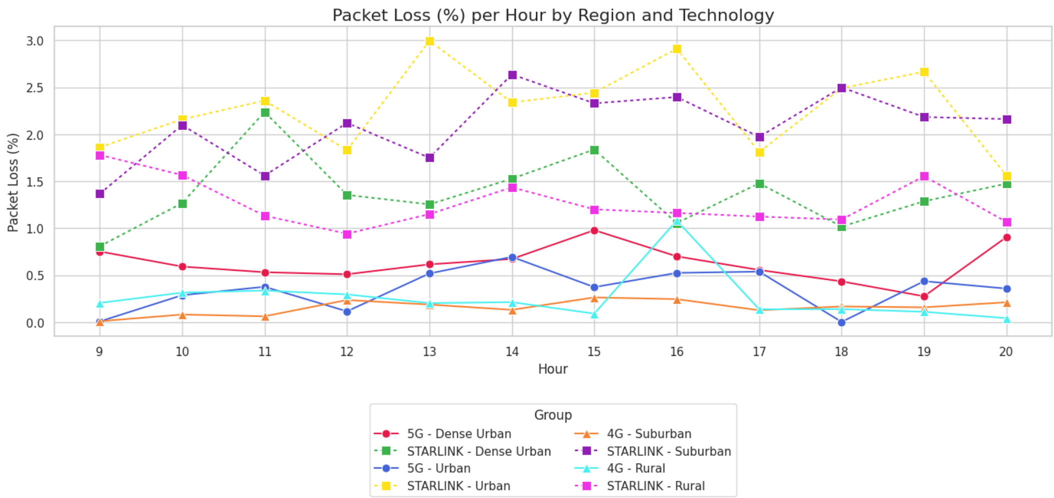

Fig. 4.9 Packet Loss Time Series

a. Dense Urban

In Dense Urban areas, 5G demonstrates consistently low packet loss, generally remaining below 1%. Its performance is relatively stable, fluctuating minimally, with a slight dip around midday and a brief peak near 1.0% in the afternoon. In contrast, Starlink in dense urban settings exhibits higher packet loss, starting around 0.8% and spiking to 2.2% around 11:00, before fluctuating between 1% and 2% for most of the day. This indicates that 5G provides a more reliable and consistent connection with fewer lost packets in densely populated areas compared to Starlink.

b. Urban

Urban environments, 5G shows exceptionally low packet loss, often staying below 0.5% and even dropping to near 0% around 18:00. This represents outstanding reliability. Conversely, Starlink in urban areas consistently records the highest packet loss among all categories, frequently exceeding 2% and reaching a peak of 3% around 13:00. Its performance is highly variable and consistently poorer than 5G. This stark difference highlights 5G's superior reliability and lower data loss in urban contexts.

c. Suburban

For Suburban regions, 4G exhibits remarkably low and stable packet loss, consistently remaining near 0% for most of the observed hours, with only minor, negligible fluctuations. This signifies exceptional reliability for 4G connections in suburban areas. In sharp contrast, Starlink displays significantly higher packet loss, starting around 1.8% and peaking at 2.5% in the late evening. Starlink's packet loss is consistently and substantially greater than 4G's, indicating that 4G is a vastly more reliable option for data transmission in suburban environments.

d. Rural

In Rural areas, 4G continues to show very low packet loss, generally staying below 0.5% and often around 0.1-0.2%. While there is a minor spike to 1% around 16:00, its overall reliability remains very high. Starlink, however, consistently demonstrates higher packet loss than 4G, typically ranging between 1% and 1.5%. Although its packet loss rate is relatively stable for Starlink, it is consistently at a higher level than 4G. This indicates that 4G provides a more reliable connection with fewer lost packets compared to Starlink in rural settings.

4.1.5.3 Distribution Graph

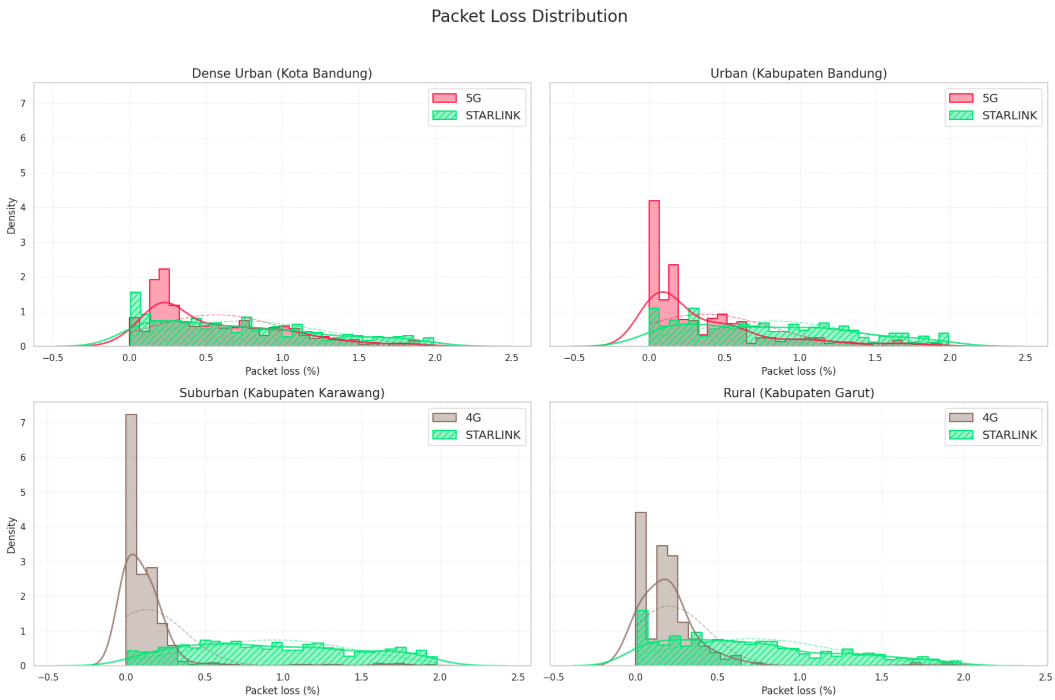

Fig. 4.10 Packet Loss PDF Distribution

a. Dense Urban

In Dense Urban areas (Kota Bandung), the packet loss distributions highlight significant differences. 5G exhibits a highly concentrated distribution with a sharp, tall peak positioned very close to 0% packet loss. This indicates that the vast majority of 5G connections in this environment experience negligible to no packet loss, signifying high reliability. Conversely, Starlink's distribution is notably broader and flatter, with its peak shifted slightly higher, around 0.5-1% packet loss. Furthermore, Starlink's distribution displays a more extended tail towards higher packet loss percentages, suggesting a greater frequency of moderate packet loss events.

b. Urban

In Urban areas (Kabupaten Bandung), the 5G packet loss distribution is characterized by an extremely sharp and tall peak at precisely 0% packet loss. This signifies an exceptional level of reliability, with nearly all 5G connections in urban settings experiencing perfect packet delivery. In stark contrast, Starlink's distribution is substantially broader and flatter, with a lower peak located around 1-1.5% packet loss. This wider spread, combined with a significant tail extending up to 2.5%, indicates considerably higher average packet loss and significantly greater variability in connection reliability for Starlink in urban environments.

c. Suburban

For Suburban regions (Kabupaten Karawang), 4G demonstrates overwhelmingly superior packet loss performance. Its distribution is characterized by an extremely sharp and tall peak at 0% packet loss, indicating virtually flawless reliability with almost no packet loss observed. The distribution is almost entirely confined to this zero-loss mark. Conversely, Starlink's distribution in suburban areas is much broader and flatter, with its peak around 1-1.5% packet loss. This wider and higher distribution, along with a notable tail, clearly indicates higher average packet loss and less consistent reliability compared to the near-perfect performance of 4G.

d. Rural

Rural areas (Kabupaten Garut), 4G continues to show excellent packet loss performance. Its distribution exhibits a very sharp peak at 0% packet loss, with the majority of its density concentrated at very low values. This signifies high reliability in data transmission. Starlink's distribution, however, is broader and flatter, with its peak occurring around 1% packet loss, and it features a longer tail extending towards higher packet loss percentages. This suggests that Starlink in rural areas experiences higher average packet loss and greater variability in packet delivery compared to 4G, which maintains more consistent and lower loss rates.

4.1.5.4 Conclusion

The packet loss analysis across all regions consistently shows that terrestrial cellular networks, particularly 5G in urbanized areas and 4G in suburban and rural settings, outperform Starlink in terms of reliability and stability. In dense urban and urban regions, 5G maintains impressively low packet loss percentages, often close to zero, with highly concentrated distributions indicating minimal disruptions during data transmission. Starlink, by contrast, exhibits significantly higher packet loss in these same environments, along with broader distribution curves and more frequent spikes, suggesting less reliable performance. The gap widens further in suburban and rural areas, where 4G demonstrates near-perfect reliability, recording virtually zero packet loss throughout the day and in its statistical distribution. Starlink's packet loss in these areas not only averages much higher but also shows persistent minimum losses and wider fluctuations, indicating that packet loss is an ongoing issue for its service. Although Starlink's performance remains within an acceptable range for general usage, the data strongly suggests that 5G and 4G provide more consistent and dependable packet delivery, which is especially crucial for real-time and interactive applications. Therefore, terrestrial networks offer superior performance in minimizing packet loss and ensuring seamless user experiences across all types of geographical environments.

4.1.6 Network Availability

Network availability analysis was also conducted for the dense urban and rural areas, which exhibit the most distinct characteristics. Network availability was calculated by dividing the total non-outage time by the total data collection duration. Based on the measurement results in Figure 4.11, there are significant differences in network availability between Starlink and 5G in dense urban and rural areas. Table 4.6 provides the detailed hourly availability data to support the visual trends.

In dense urban environments, the 5G network demonstrates significant instability and fluctuations in availability. A notable instance occurred at 11:00 AM, where availability sharply declined to 42.86%, a performance dip also evident in Figure 1. This erratic behavior suggests potential challenges such as high network congestion, increased interference, or other technical constraints inherent to heavily populated areas. Such instability raises concerns regarding the consistent delivery of services

Table 4.6 Network Availability

Time Hourly	Rural		Dense Urban	
	4G	Starlink	5G	Starlink
9	100.00%	97.14%	100.00%	93.78%
10	100.00%	99.98%	71.43%	91.24%
11	100.00%	100.00%	42.86%	91.75%
12	100.00%	100.00%	100.00%	93.97%
13	100.00%	100.00%	80.00%	91.36%
14	100.00%	100.00%	100.00%	88.86%
15	100.00%	100.00%	92.31%	87.94%
16	100.00%	100.00%	100.00%	91.94%
17	100.00%	100.00%	100.00%	94.17%
18	100.00%	100.00%	100.00%	91.75%
19	100.00%	100.00%	50.00%	89.56%
20	100.00%	100.00%	60.00%	91.31%

in peak usage periods or under demanding conditions. A crucial factor contributing to this instability is that the 5G infrastructure in these areas is still operating in Non-Standalone (NSA) mode. This means 5G relies on existing 4G LTE core networks for essential functions like control signaling, leading to potential bottlenecks and increased latency, which can negatively impact availability, especially during peak load times. The dependence on the underlying 4G infrastructure means that any limitations or congestion within the 4G network can directly affect the perceived performance of the 5G network.

Conversely, Starlink in dense urban areas exhibits greater stability, consistently maintaining network availability above 90%. For instance, at 11:00 AM, when 5G experienced its most significant drop, Starlink maintained an availability of 91.75%. While Starlink's urban availability is marginally lower than its performance in rural settings, its consistent reliability contrasts sharply with the volatile nature of 5G in the same densely populated context.

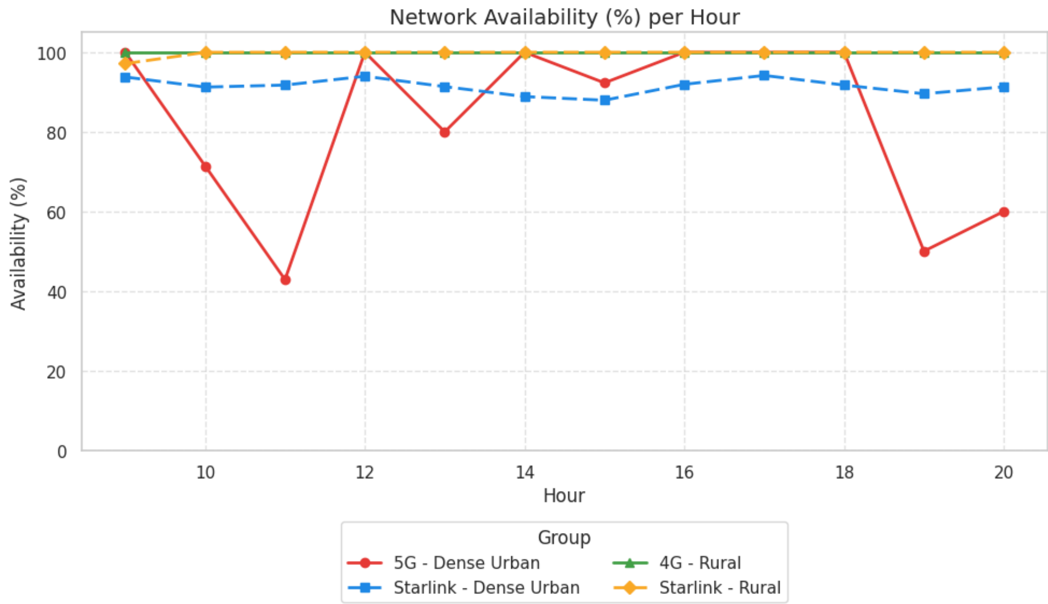

Fig. 4.11 Network Availability Time Series

In rural areas, Starlink demonstrates exceptional reliability, with network availability consistently approaching 100% throughout the observation period. As depicted in Figure 1, Starlink's availability line for rural areas remains consistently high, substantiated by hourly data in Table 1 showing values such as 99.98% at 10:00 AM and 100.00% from 11:00 AM to 8:00 PM. This high and stable performance underscores Starlink's suitability for deployment in regions characterized by limited or non-existent terrestrial infrastructure.

The 4G network in rural areas also displays robust and stable performance, consistently achieving 100% availability. This consistent high performance for 4G in rural settings notably outperforms 5G in dense urban areas, highlighting the effectiveness of established 4G infrastructure in less congested environments

4.2 Link Budget Analysis

The link budget analysis was conducted to evaluate the technical feasibility of the Starlink communication link. Based on the parameters defined in Chapter 3, the key results of the link budget calculation include the received power, system noise power, and the resulting signal-to-noise ratio (SNR). A summary of the results is presented in Table 4.7.

The calculation shows that the received signal power is -98 dBW, which is above the typical sensitivity threshold of Starlink user terminals. The system noise power is -120 dBW, resulting in an SNR of 22 dB.

Table 4.7 Starlink Link Budget Results

Parameter	Value	Unit
Received Power (P_{rx})	-98	dBW
System Noise Power (N)	-120	dBW
Signal-to-Noise Ratio (SNR)	22	dB

This SNR value is sufficient to support high-order modulation schemes such as 64-QAM, which generally require a minimum SNR between 18 and 20 dB. Therefore, the Starlink communication link is considered feasible and capable of delivering stable performance under normal atmospheric conditions, which serves as a baseline reference.

4.2.1 SNR Calculation

Using the slant range values provided in Table 3.8, the received power (P_{rx}) at the user terminal was calculated. The differences in P_{rx} across regions are primarily influenced by the variation in propagation distance and associated path losses.

Subsequently, the Signal-to-Noise Ratio (SNR) was determined by subtracting the system noise power, which is assumed constant at -120 dBW across all regions. The resulting SNR values are summarized in Table 4.8.

Table 4.8 SNR Calculation by Region

Categories	Noise (dBW)	Received Power (dBW)	SNR (dB)
Dense Urban	-120	-103.30	16.87
Urban		-103.35	16.82
Suburban		-102.81	17.36
Rural		-103.63	16.54

Despite the relatively narrow range, the SNR values exhibit meaningful variation among the four locations. The Suburban region achieves the highest SNR (17.36 dB), indicating the most favorable signal reception conditions, likely due to a combination of shorter slant range and minimal environmental obstructions. In contrast, the Rural region records the lowest SNR (16.54 dB), which can be attributed to the longest slant range and potentially higher atmospheric attenuation.

The Dense Urban and Urban regions yield intermediate SNR values of 16.87 dB and 16.82 dB, respectively. These are slightly lower than Suburban, possibly due to increased building-induced losses despite their proximity to the satellite.

All regions maintain SNR levels above 16 dB, which is considered adequate for supporting higher-order modulation schemes such as 64-QAM in satellite communication systems. These findings suggest that Starlink provides a consistent and robust link margin across diverse environments, with minor degradation primarily driven by topography and propagation distance.

4.3 Capacity Analysis

Capacity analysis is conducted to estimate the maximum achievable throughput for both the Starlink low Earth orbit (LEO) satellite system and terrestrial cellular networks. The analysis uses the Shannon capacity theorem, which provides a theoretical upper bound of data capacity based on bandwidth and signal-to-noise ratio (SNR). This section is divided into two parts: the first discusses capacity estimation for the Starlink system, and the second covers capacity analysis of cellular technologies based on field measurements.

4.3.1 Starlink Capacity Analysis

Starlink capacity was estimated using region-specific SNR values derived from the link budget analysis in the previous section. While Starlink systems typically do not provide open access to detailed radio parameters in the field, this study calculates SNR values based on received power and noise power levels. These SNR values are then used to estimate theoretical maximum capacity using a fixed bandwidth of 240 MHz across all areas. Table 4.9 presents the estimated Starlink capacity across four region types.

Table 4.9 Starlink Capacity Estimation

Region	Frequency Band (GHz)	Bandwidth (MHz)	SNR (dB)	Capacity (Mbps)
Dense Urban	10.7–12.7	240	16.87	1,352.29
Urban			16.82	1,348.24
Suburban			17.36	1,390.61
Rural			16.54	1,326.64

The Suburban region demonstrates the highest capacity (1,390.61 Mbps), followed by Dense Urban, Urban, and Rural regions. Although the variation is relatively modest, it reflects differences in slant range and signal quality across locations. These findings indicate that Starlink can consistently provide high-capacity broadband in diverse geographic conditions. The lower capacity in Rural areas is likely due to longer slant ranges and slightly reduced received power, which lead to lower SNR values.

Overall, the analysis shows that the Starlink system delivers comparable performance across regions, with all areas maintaining SNR above 16 dB. This supports the system's robustness in providing high-throughput connectivity even in remote or challenging environments.

4.3.2 Cellular Capacity Analysis

For cellular networks, capacity was calculated using field-measured Signal-to-Interference-plus-Noise Ratio (SINR) values. SINR is a practical and realistic indicator of link quality in terrestrial mobile systems, accounting for both background noise and inter-cell interference.

Table 4.10 shows the SINR values collected during field measurements in different regions, alongside the estimated channel capacity using corresponding bandwidth and frequency allocations.

Table 4.10 Cellular Network Capacity Estimation

Region	Technology	Frequency Band (GHz)	Bandwidth (MHz)	SINR (dB)	Capacity (Mbps)
Dense Urban	5G NSA	2.3	100	21.18	704.68
Urban	5G NSA	2.3	100	35	1 162.72
Suburban	4G	2.3	20	45.6	302.96
Rural	4G	1.8	20	27	179.44

As shown, Urban areas show the highest capacity (1,162.72 Mbps) due to strong SINR and wide bandwidth. In Dense Urban areas, capacity drops to 704.68 Mbps, despite using the same 5G configuration, likely due to greater interference and congestion. Suburban and Rural regions use legacy 4G technology and narrower bandwidths, resulting in lower overall capacity. However, the Suburban area benefits from excellent SINR (45.6 dB), leading to a respectable capacity of 302.96 Mbps, while the Rural region shows the lowest performance at 179.44 Mbps.

These findings suggest that while cellular networks offer high capacity in urbanized zones, performance in remote regions is more limited and dependent on interference, technology generation, and available spectrum.

4.4 Economic Analysis

This section is divided into two main components, affordability analysis and business model analysis. Affordability analysis focuses on measuring the financial burden of each service relative to the income levels of users in different areas. This provides insight into the accessibility of the service, especially in rural or economically disadvantaged regions. Meanwhile, the business model analysis examines how service providers generate revenue, recover investment costs, and ensure long-term viability, particularly in diverse geographical and demographic settings.

4.4.1 Affordability Analysis

Affordability analysis was conducted to identify the ratio between the total service cost (including device and subscription fees) and the annual minimum wage in each region. The objective of this analysis is to evaluate the affordability of various types of internet services.

According to the Policy Brief on the Affordability of ICT Services (2023), basic internet services in low- and middle-income countries are considered affordable if the monthly cost does not exceed 2% of the average monthly per capita income. Therefore, in this study, the affordability threshold is set at 2% of monthly income, which is equivalent to 24% of annual income. The services compared include Starlink (Standard Plan), cellular services (4G and 5G), and Orbit Modem. In addition, a scenario involving cellular users who already own a device is included to reflect actual user conditions in the field.

Figure 4.12 presents the annual affordability ratios of different services, while Figure 4.13 shows the affordability ratios over a three-year period, corresponding to the estimated average lifespan of user devices.

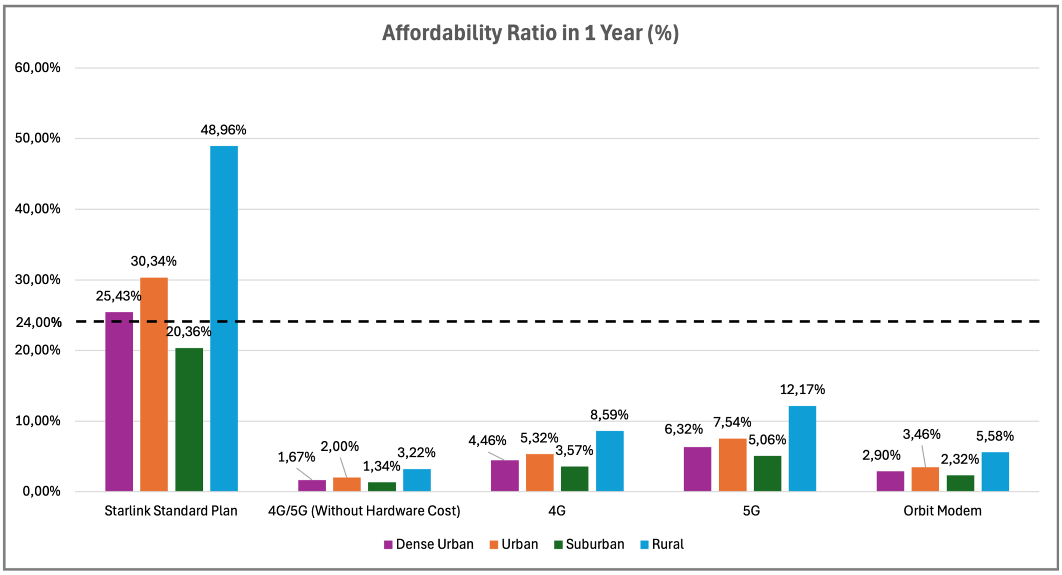

Fig. 4.12 Affordability Ratio in 1-Year(%)

The results show that the Starlink service (Standard Plan) has the highest affordability ratio across all regions. In rural areas, the ratio reaches 48.96% in the first year, far exceeding the 24% threshold, and remains high at 37.79% over a three-year horizon. These values indicate that Starlink is significantly unaffordable, especially in regions with lower income levels.

In contrast, cellular services (4G/5G) without hardware cost show the lowest affordability ratios, all of which are well below the 24% threshold, making them the most affordable option, particularly for users who already own a device. For 4G services with hardware cost, the affordability ratio ranges from 3.57% to 8.59% in the first year, decreasing to 2.08% to 5.01% over three years—still highly affordable.

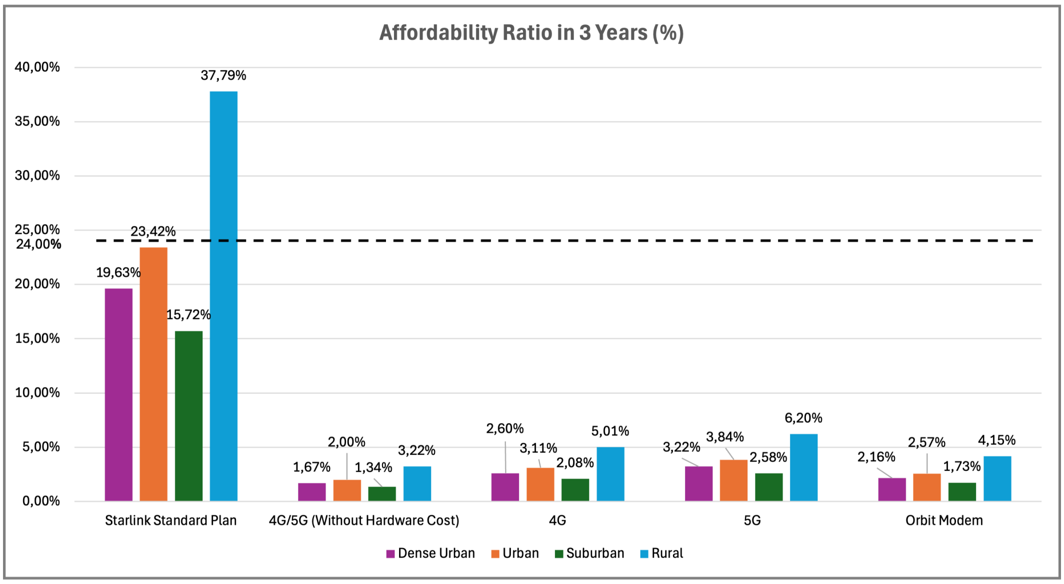

Fig. 4.13 Affordability Ratio in 3-Year(%)

5G services with hardware cost have slightly higher affordability ratios, ranging from 5.06% to 12.17% in the first year and 2.58% to 6.20% over three years. This suggests that although 5G offers better technical performance, the total cost is still manageable and well within the acceptable range. Meanwhile, Orbit Modem shows affordability ratios between 5.18% and 12.45% in the first year and 1.73% to 4.15% over three years, bringing it closer to the affordability threshold, particularly in Suburban areas.

Overall, these findings highlight that hardware cost is a major factor affecting affordability. When hardware costs are distributed across a longer usage period, most services become more economically viable and remain well below the 24% annual affordability threshold. As a result, expanding internet access in rural areas should be supported through device subsidies or flexible ownership models, especially for high cost services like Starlink.

4.4.2 Business Model Analysis

This section, analyze the business models of two contrasting broadband service delivery approaches, Starlink as a low Earth orbit (LEO) satellite-based system and national cellular operators using terrestrial 4G/5G networks. The analysis is structured around three main perspectives: user, regulator, and national. Figures 4.15 and 4.14 illustrate the structural differences between the Starlink and cellular network business models. In the Starlink model, end-users register directly with SpaceX and receive broadband access via the Starlink user terminal (dish and modem), which connects to a constellation of low Earth orbit (LEO) satellites. These satellites relay data to ground infrastructure gateway and Network Operation Center (NOC)—located in Indonesia and operated by Telkomsat, the official domestic partner. Telkomsat plays two critical roles: (1) holding the landing rights that legally permit Starlink to operate in Indonesia, and (2) acting as a backbone provider by building the physical ground stations needed for interconnection with the global internet. Oversight is provided by Komdigi, the Indonesian telecommunications regulator. In contrast, the cellular model relies on localized ecosystem actors—users purchase SIM cards from domestic ISPs and access the internet through BTS and core networks operated by licensed cellular providers. The entire network is subject to national infrastructure, policy, and economic frameworks.

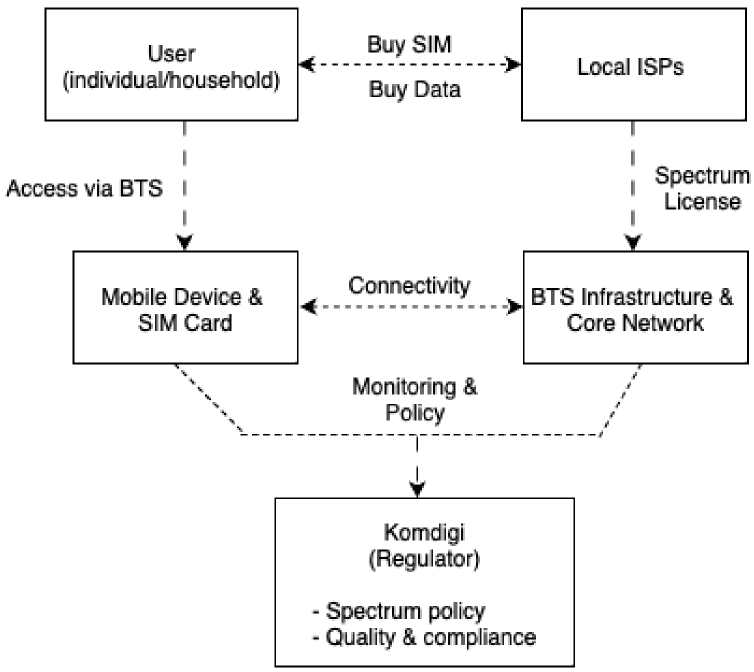

Fig. 4.14 Cellular Network Business Diagram

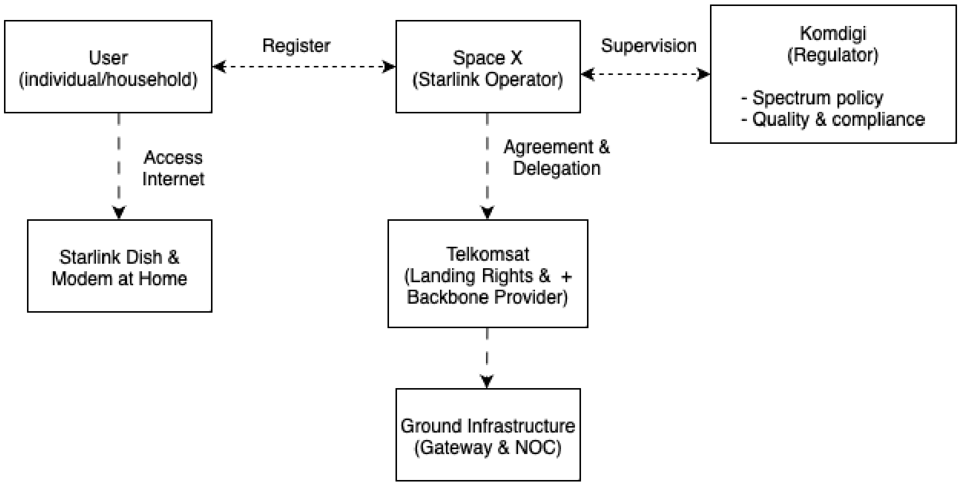

Fig. 4.15 Starlink Business Diagram

4.4.2.1 User Perspective

From the user's standpoint, the Starlink model offers a transformative connectivity option, particularly in rural and underserved regions where terrestrial infrastructure such as BTS and fiber optics is limited or non-existent. Users benefit from direct-to-home satellite internet that delivers relatively high throughput and low latency without reliance on local networks. This enables access to essential online services, such as e-learning, telehealth, and digital public services, resulting in improved quality of life and increased social mobility.

The intangible benefit of Starlink lies in its autonomous and decentralized access model, allowing users to connect independently from local service providers. In contrast, the cellular model provides lower upfront costs, flexible data plans, and integrated communication services (voice, SMS, and internet), making it attractive in urban and suburban markets. Cellular networks also offer strong interoperability with domestic digital systems, such as mobile banking, government apps, and transportation platforms, reinforced by national-level legal protections.

4.4.2.2 Regulator Perspective

From a regulatory perspective, Starlink presents both an opportunity and a governance challenge. On one hand, it aligns with national objectives for digital inclusion by expanding connectivity in remote areas. On the other hand, its globally centralized operational model limits the regulator's direct control over network infrastructure, data flows, and economic obligations. To mitigate this, Komdigi requires Starlink to operate via Telkomsat, which holds the landing rights and builds the necessary domestic gateway infrastructure. This arrangement enables regulatory oversight of traffic routing, lawful interception, service quality, and alignment with national policies.

In contrast, the cellular model offers high regulatory visibility and enforceability. Operators are licensed to use specific spectrum bands, must comply with quality of service (qos) standards, and are subject to consumer protection and data governance laws. This enables the regulator to enforce strategic priorities such as emergency alerts, lawful data access, and digital service integration.

4.4.2.3 National Perspective

From the national perspective, the two models differ significantly in their tangible economic contributions and strategic value. Starlink's model minimizes local infrastructure investment by operating through a centralized satellite system with minimal domestic presence. While this allows for rapid deployment and coverage extension in frontier areas, the direct economic impact is limited: Starlink does not pay domestic spectrum license fees (BHP), has no universal service obligations (USO), and creates little employment or infrastructure development locally. Its contribution is primarily intangible, serving as a connectivity safety net for emergencies, border security, or unreachable areas.

In contrast, the cellular network model is deeply embedded within the national economy. Operators pay significant spectrum fees, invest in expansive infrastructure, and generate employment at multiple levels. They also participate in universal service programs, contributing directly to nationwide digital development goals. Strategically, the presence of locally governed and physically grounded networks ensures digital sovereignty, allowing the state to retain control over critical infrastructure, data routing, and alignment with national digital agendas such as e-government, digital identity, and cybersecurity frameworks.

4.5 Regulatory Analysis

The regulatory analysis explores how national and international regulations address the potential coexistence of cellular networks (particularly 5G) and Starlink, aiming to bridge the connectivity gap between dense urban and rural areas in Indonesia.

4.5.1 Telecommunications Law Landscape

Indonesia's telecommunications sector is governed by a multilayered regulatory framework encompassing statutory laws, government regulations, presidential decrees, and ministerial regulations. This framework seeks to ensure fair competition, efficient spectrum management, national sovereignty, and universal service provision. It applies to both terrestrial (cellular) and non-terrestrial (satellite-based) communication systems, although the treatment of emerging technologies such as low-earth orbit (LEO) satellite constellations remains in a transitional phase.

1. Law No. 36 of 1999 on Telecommunications

   Law Number 36 of 1999 is the main pillar in the framework of telecommunications regulation in Indonesia. Articles 2 and 3 fundamentally affirm that the provision of telecommunications must be based on the principles of benefit, justice, and equity, with the primary aim of supporting the welfare of the people and national unity. The findings of this research significantly indicate that Starlink has great potential in realizing these principles, especially in rural areas. In Garut Regency, Starlink achieves an average download throughput of 131.95 Mbps and network availability approaching 100% in rural locations, which clearly indicates its capability to bridge the digital divide in 3T areas (Frontier, Outermost, Least Developed) that are poorly served by terrestrial infrastructure. Additionally, Article 4, which mandates state control over telecommunications and its regulation by the government, serves as the foundation for strict control over foreign entities like Starlink to maintain data sovereignty and national security. Licensing regulated in Article 11 emphasizes simple, transparent, and non-discriminatory procedures, ensuring that all operators, including Starlink, comply with the same requirements. Article 10 is also relevant in this context, prohibiting monopolistic practices and unfair competition in the telecommunications sector, a crucial aspect amid Starlink's expansion into the retail segment.

2. Law No. 27 of 2022 concerning Personal Data Protection

   The presence of the Personal Data Protection Law (UU PDP) of 2022 is very vital considering that Starlink has expanded its services to the retail segment in Indonesia. Article 2 Paragraph (1) explicitly states that the PDP Law applies to any individual or entity that processes personal data, including foreign companies like Starlink operating in Indonesia. This places an obligation on Starlink to adhere to the principles of fair, transparent, and secure data processing, as outlined in Article 4 of the PDP Law. Furthermore, Article 15 Paragraph (2), which discusses exceptions for data processing in the interest of national defense and security, becomes very important in the context of data sovereignty and government oversight of Starlink's data traffic. The obligation to obtain explicit consent from data subjects (Article 6) and to maintain the confidentiality and security of personal data (Article 20) are crucial points that Starlink must adhere to in order to protect Indonesian consumers.

3. Government Regulation No. 46 of 2021 on Post, Telecommunications, and Broadcasting (Postelsiar)

   Government Regulation Number 46 of 2021 complements the Telecommunications Law with a more detailed framework, specifically accommodating satellite technology. Articles 10 and 11 clearly regulate the scope and types of telecommunications services, including mobile satellite networks, which directly categorize Starlink within this regulatory framework. Article 14 establishes the obligation for the development and provision of services, which can serve as a basis for Starlink's contribution to infrastructure expansion in underserved areas, in line with the findings of this research. In addition, this Government Regulation also stipulates the obligation to obtain a Radio Frequency Band License (IPFR) and pay the Spectrum Usage Rights Fee (BHP) in Articles 17, 18, and 21, which directly applies to Starlink's operations in Indonesia.

4. Minister of Communication and Digital Regulation No. 3 of 2025 concerning the Use of Radio Frequency Spectrum for Satellite Services and Satellite Orbits

   Article 2 mandates that internet access service providers utilizing satellites must collaborate with telecommunications network operators possessing a Space Radio Spectrum Permit (ISR Angkasa), ensuring oversight and integration with the national network. Article 4 explicitly requires foreign satellites like Starlink to possess Satellite Landing Rights (Hak Labuh Satelit) to operate within Indonesian territory, a vital prerequisite for safeguarding data sovereignty and national security as recommended in your thesis. Article 6 details the procedure for applying for an ISR Angkasa and required documents, including Satellite Landing Rights. Furthermore, Article 16 governs the registration of earth stations, including user terminals , which is critical for the oversight of Starlink user devices in the field, aligning with the government's need to monitor usage and potential interference. The obligation to pay the Right of Use Fee (BHP) for Radio Frequency Spectrum for satellites, both foreign and domestic, is also regulated in Article 41, ensuring financial contributions from Starlink's operations.

5. ITU Regulations

   Regulations from the International Telecommunication Union (ITU), specifically ITU-T Recommendation E.800 and the ITU-D QoS Regulation Manual (2017), provide an essential global framework. ITU-T Recommendation E.800 defines terms related to Quality of Service (QoS), which form the basis of the network performance analysis methodology in this research. The research results presenting QoS metrics such as throughput, latency, jitter, and packet loss (for example, 5G latency in densely populated urban areas averages 17.96 ms compared to Starlink's 30.23 ms; 5G shows packet loss of less than 1%, while Starlink's is higher) are measured and interpreted based on these standards, ensuring the validity and global comparability of the findings.

4.5.2 Starlink Security Implications

National regulations emphasize that all telecommunications operations must uphold state sovereignty and ensure national security. Law No. 36 of 1999 on Telecommunications (Article 7, paragraph 2) explicitly mandates that the implementation of telecommunications must consider national interests and security. Furthermore, Article 5 grants the government full authority to regulate, supervise, and control telecommunications, while Article 4 classifies the sector as strategic and under state control.

These provisions are reinforced by the Personal Data Protection (PDP) Law of 2022, which provides a legal foundation to protect data sovereignty and user privacy. Satellite service providers like Starlink are thus obligated to comply with national regulations, including maintaining the confidentiality of personal data, prohibiting unauthorized cross-border data transfers, and enabling lawful interception. Violations can result in administrative or criminal sanctions, including the revocation of operating licenses.

However, Starlink's global architecture raises new challenges for national enforcement. Its backbone relies on inter-satellite links (ISL), which may route user traffic through neighboring countries such as Malaysia (e.g., Kuala Lumpur or Penang) before reaching global internet exchanges. Without intervention, this model risks undermining Indonesia's sovereignty, as data may bypass local infrastructure entirely, making it difficult for the government to monitor or control.

To address these concerns, the Indonesian government through the Ministry of Communication and Informatics (Kominfo) — must enforce the localization of ground infrastructure as a prerequisite for service operation. The following components are crucial:

- **Local Gateway Stations:** Foreign satellite operators should terminate traffic within Indonesian territory before routing it abroad. Existing teleport facilities owned by Telkomsat in locations such as Cibinong or Banjarmasin could be utilized as earth gateway stations to anchor Starlink traffic within national borders.
- **National Operations Center (NOC):** A centralized facility jointly supervised by Kominfo and the Indonesian Armed Forces (TNI) should be established to manage satellite-terrestrial network integration, oversee traffic monitoring, and enforce lawful interception.
- **Compliance with Ministerial Regulation No. 3/2025:** This regulation requires foreign satellite providers to localize critical infrastructure in Indonesia as a condition for landing rights and operational licenses. This includes gateway placement, traffic visibility, and cooperation with national security frameworks.

Without these measures, foreign-operated satellite systems risk bypassing Indonesian jurisdiction, weakening cybersecurity posture, and eroding regulatory control. Therefore, ground infrastructure development must be viewed not only as a technical requirement but also as an extension of Indonesia's digital sovereignty strategy.

4.5.3 Policy Brief

1. Background:
   As an archipelagic nation with complex geographical challenges, Indonesia requires a hybrid approach to ensure comprehensive internet access coverage. Case studies in West Java demonstrate that combining 5G technology for urban areas with LEO satellites (e.g., Starlink) for 3T regions (Underdeveloped, Frontier, and Outermost) could serve as an optimal solution, provided it is governed under principles of digital resilience and national sovereignty.

2. Key Findings:

   - Performance:
     - 5G excels in dense urban areas (e.g., Bandung City) with average download speeds of 115.4 Mbps, upload speeds of 61.77 Mbps, and ultra-low latency (17.96 ms), making it ideal for high-demand applications.
     - Starlink delivers superior performance in rural and suburban regions, achieving average download speeds of 131.95 Mbps and near-100% availability, addressing connectivity gaps where terrestrial networks falter.
   - Reliability:
     - Starlink exhibits remarkable consistency in throughput and availability across all regions, including dense urban areas, with minimal variability (standard deviation of 14.64 Mbps for downloads).
     - 5G demonstrates higher performance volatility in urban settings during peak hours, while 4G in rural areas shows extreme inconsistency, with download speeds ranging from 2.81 Mbps to 359 Mbps.
   - Affordability:
     - Cellular services (4G/5G) are more affordable, with annual costs at 3.57%–12.17% of minimum wage, whereas Starlink's upfront hardware costs make it less accessible (48.96% of rural incomes).
   - Regulatory Gaps:
     - Current policies lack stringent enforcement mechanisms for data sovereignty, equitable competition, and local infrastructure obligations for foreign satellite providers.

3. Policy Recommendation:

   Hybrid Network Deployment Strategy (Sovereignty-Based Model)

   To ensure equitable and strategic development of national broadband infrastructure, a hybrid deployment model is proposed, balancing the strengths of terrestrial and satellite-based connectivity. The approach emphasizes not only technical efficiency but also digital sovereignty and inclusive access.

   a. Mandatory Network Segmentation

- Urban focus for 5G: Accelerate 5G deployment in urban centers and high-density regions to meet high-capacity and low-latency demands.
- Rural and 3T focus for Starlink: Mandate Starlink and similar LEO satellite services to focus on underserved rural and 3T (frontier, outermost, and least developed) regions. This can be facilitated through targeted subsidies, universal service obligations, or public-private partnership schemes.

b. Supervised Infrastructure Interconnection

- Require the establishment of a National Operations Center (NOC) in Indonesia to monitor and manage satellite and terrestrial network integration.
- Enforce interconnection standards between foreign satellite services and domestic ISPs to ensure interoperability and network resilience.
- Satellite Gateway Regulation: In accordance with Ministerial Regulation No. 3/2025, mandate all foreign satellite operators providing services in Indonesia to establish local satellite gateways on Indonesian territory. This ensures that data exchange remains under national jurisdiction and can be lawfully intercepted or audited when required.

c. Data Protection and National Security

- Local data centers: Mandate that all foreign connectivity providers, including satellite operators, establish in-country data centers by 2026 to comply with Indonesia's data sovereignty laws.
- Real-time traffic monitoring: Deploy a joint cyber monitoring team under the supervision of Kominfo and TNI (Indonesian Armed Forces) to inspect and monitor cross-border data traffic for national security threats.

d. Sustainable Funding Mechanisms

- Universal Service Fund (USF): Require all foreign network service providers to contribute 5% of their annual revenue toward a national infrastructure development fund, aimed at improving access in remote and underserved areas.

- Terminal Subsidies (BLT Digital): Introduce a Direct Benefit Transfer (DBT) program to subsidize terminal and device costs for 3T communities, ensuring affordability and adoption of satellite services.

4. Implementation Strategy:

   - Phase I (2025–2026): Pilot implementation in 10 selected 3T regencies with strict oversight and performance monitoring.
   - Phase II (2027–2030): Nationwide rollout with quarterly impact evaluations conducted by independent panels from government, academia, and civil society.

5. Conclusion:
   The 5G–satellite synergy must serve not merely as a technical solution, but as a strategic pillar of national development. With well-designed policy frameworks and sovereign enforcement mechanisms, Indonesia can effectively harness foreign technologies while preserving its digital independence and promoting inclusive connectivity for all regions.

CHAPTER 5
CONCLUSION

5.1 Conclusions

This study comparatively analyzes the performance of Starlink and cellular networks (4G and 5G) in four different regions of West Java, Indonesia, to address the digital divide. In terms of download throughput, 5G in the Urban area (Bandung Regency) reached the highest average of 139.19 Mbps, while Starlink showed very high consistency across all regions, especially in rural areas (average 131.95 Mbps) compared to inconsistent 4G (average 118.05 Mbps, min 2.81 Mbps, STD 95.84). For upload throughput, 5G dominated in the Dense Urban area (61.77 Mbps), but Starlink outperformed 4G in suburban areas (32.50 Mbps vs 19.00 Mbps). In terms of latency, 5G consistently delivers the lowest performance in dense urban areas (average 17.96 ms) and urban areas (average 26.02 ms), while Starlink has higher and more variable latency in these areas, although it is more consistent in rural areas compared to 4G. Jitter also shows 5G's superiority in dense urban areas (average 17.35 ms, STD 9.11 ms), and 4G in suburban and rural areas, which is more stable than Starlink, which shows higher variability. Cellular networks, both 5G and 4G, significantly outperform Starlink in terms of packet loss, often approaching 0%, while Starlink shows higher average packet loss across all categories (e.g., 2.1% in urban areas). Although 5G in dense urban areas exhibits availability fluctuations (dropping to 42.86%), Starlink generally maintains high network availability (above 90% in dense urban areas and approaching 100% in rural areas), similar to 4G in rural areas, which also achieves 100% availability. Starlink link budget analysis shows adequate SNR values (above 16 dB) across all regions, supporting high capacity (e.g., 1,390.61 Mbps in suburban areas). However, from an economic perspective, Starlink is significantly unaffordable, especially in rural areas (affordability ratio of 48.96% of annual minimum wage) due to high hardware costs, in contrast to much more affordable mobile services (below the 24% threshold). Therefore, this study concludes that the coexistence of Starlink and 5G will be most effective if 5G is used in dense urban environments requiring high bandwidth and low latency, while Starlink will be a more reliable solution in rural and remote areas where terrestrial infrastructure is limited, with strategic government policy support. This policy must include mandatory network segmentation, supervised infrastructure interconnection, data protection and national security, as well as sustainable funding mechanisms such as device subsidies.

5.2 Future Works

To enrich and complement the findings of this research, several areas could be explored in future studies. First, it is recommended to conduct a more in-depth Quality of Service (QoS) analysis focusing on specific end-to-end applications, such as cloud computing, multiplayer online gaming, or industrial IoT remote monitoring systems, to provide more detailed insights into the user experience for each technology. Second, the development of more sophisticated economic models is highly recommended, which should not only include various subsidy schemes and flexible ownership models for Starlink devices to consider financial sustainability for users in rural areas, but also incorporate a comprehensive Cost-Benefit Analysis (CBA). This CBA should quantitatively analyze the Capital Expenditure (CAPEX) and Operational Expenditure (OPEX) of Starlink and cellular network deployment across different regions, comparing initial infrastructure costs, ongoing operational expenses, and potential return on investment, including long-term socio-economic benefits. Third, expanding the case study to other 3T regions in Indonesia with more diverse geographical and demographic conditions would be invaluable for strengthening the external validity of the findings and identifying broader performance patterns. Fourth, further research on the cross-border cybersecurity and data sovereignty challenges posed by foreign satellite service providers is urgently needed, including in-depth analysis of network architecture and the development of detailed policy recommendations.

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