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STUDY OF NGSO VHTS SATELLITE SYSTEM FOR BROADBAND CONNECTIVITY IN INDONESIA

Rama Setya Anggara[1*], Heroe Wijanto[2], Budi Syihabuddin[3]
Center of Excellence for Intelligent Sensing–IoT, Telkom University, Bandung, Indonesia.
E-mail: ramasetyaa@student.telkomuniversity.ac.id

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Abstract

Indonesia's archipelagic geography, uneven population distribution, and limited terrestrial infrastructure present persistent challenges to achieving inclusive and sustainable broadband connectivity. These constraints contribute to the digital divide, limiting access to digital public services. This study examines a Ka-band Very High Throughput Satellite (VHTS) system implemented in a Non-Geostationary Satellite Orbit (NGSO) Low Earth Orbit (LEO) constellation specifically tailored for tropical regions. The work combines orbital modeling, Ka-band link budget analysis, multibeam capacity evaluation, and rain attenuation mitigation. A 400 km LEO altitude gives the best balance between coverage, latency, and performance, with round-trip delays of about 3.5–4 ms. Automatic Transmit Power Control (ATPC) and adaptive phased array beamforming maintain the link availability even in severe tropical rain, which reduces the signal by more than 12 dB. A staggered national deployment plan shows that NGSO-VHTS systems can be used for broadband access and future 5G/6G Non-Terrestrial Networks (NTNs) in Indonesia.

Keywords: VHTS, LEO, Ka-band, NTN.

INTRODUCTION

Satellite communications are still an important way to provide broadband access in places where building a terrestrial network is too expensive or too far away, like Indonesia, which is made up of many islands and has a population that is spread out unevenly [2], [8], [9]. In this context, digital connection is increasingly acknowledged as a crucial enabler of sustainable development, as it facilitates access to digital services, economic inclusion, and the reduction of regional connectivity inequities in geographically diverse and developing countries [7], [9]. Conventional Geostationary Earth Orbit (GEO) satellite systems provide extensive coverage. however, their inherent long propagation delay limits their suitability for latency sensitive broadband services [5], [8]. Recent improvements in Very High Throughput Satellite (VHTS) technology have greatly enhanced system capacity by permitting aggressive frequency reuse, multibeam topologies, and onboard digital payload processing. The resulting technology has made it possible to achieve throughput of multi terabits per second [3], [4]. Non-Geostationary Satellite Orbit (NGSO) Low Earth Orbit (LEO) constellations have also gotten a lot of attention because they have less latency and can be used in many places at once [5]. Combining VHTS payload ideas with LEO constellations has become a potential way to offer high capacity, low-latency broadband services [5], [8], [11]. especially in tropical areas like Indonesia, where the weather is sometimes adverse and the propagation conditions are complicated [4], [10]. Enhancing broadband accessibility in these locations further advances sustainable development objectives by diminishing dependence on substantial terrestrial infrastructure, which may impose environmental and ecological limitations in distant and insular regions [7], [9]. Therefore, this project is mostly about designing and testing a Ka-band NGSO-VHTS system that works best in Indonesia's tropical climate.

NGSO VHTS System Overview

Very High Throughput Satellite (VHTS) systems gain a lot of capacity by splitting the service area into several narrow spot beams and using frequency resources across beams that aren't next to each other. You can roughly figure out the entire throughput of the system in current multibeam topologies as:

$$C_{total} = \sum_{b=1}^{N_b} B_b \eta_b$$

Where N_b is the number of active beams, B_b denotes the allocated bandwidth of the b-th beam, and η_b represents the spectral efficiency achieved under the prevailing link conditions. This demonstrates the link's performance in terms of spectral efficiency. Recent studies on LEO and VHTS designs confirm that multibeam frequency reuse is the key enabler for terabit class capacity, particularly when combined with digital payload processing and flexible beamforming techniques [14], [6]. Powerful onboard digital computers and phased array antennas make it feasible to handle beam steering, beam shaping, and power distribution in real time in NGSO systems. This capability lets the satellite adjust how it sends out radiation in orbit based on where users are and how much interference there is. This functionality is extremely essential for LEO constellations that are relatively close together [15], [12]. The antenna's gain in a given direction of the beam

$$G(\theta, \phi) = G_0 \mid AF(\theta, \phi)|^2$$

The array factor $AF(\theta,\phi)$ is based on the amplitude and phase excitation of each antenna element. These electronically steerable beams make it easier to reuse space and cut down on co-channel interference between beams that are close to each other [15]. LEO satellites, which fly between 300 and 450 km above the Earth, lose much less free space route and propagation delay than GEO systems. The loss of free space path (FSPL) is:

$$FSPL = \left(\frac{4\pi d}{\lambda}\right)^2$$

The carrier's λ is its wavelength. Because LEO has a much shorter slant range, both FSPL and round-trip latency are much lower than in GEO systems. Because of this, NGSO VHTS systems are perfect for low-latency broadband and 5G/6G backhaul applications [14], [13]. But the constellation must be properly planned to ensure that NGSO VHTS systems are always available. The coverage continuity, revisit time, and handover frequency are all set by the satellites' orbital altitude, inclination, and spacing. The two key factors that impact how well a satellite can be seen from a specific position on the ground are the minimum elevation angle limit and the shape of the orbit, as illustrated in analytical NGSO visibility models [10]. For places like Indonesia that are close to the equator, low-inclination or near-equatorial orbits are especially useful because they focus satellite ground tracks over populated areas and reduce the number of satellites needed to provide continuous coverage compared to polar or high-inclination constellations [14], [12]. From a networking perspective, NGSO VHTS systems are employing inter satellite links (ISLs) more and more to aid with routing traffic more efficiently and rely less on gateways on the ground. Recent studies on routing and resource allocation indicate that LEO networks equipped with ISLs can significantly enhance end-to-end latency and throughput stability by diverting traffic off overly congested satellite-gateway links [1], [2], [12]. In next generation broadband satellite networks, when there are more satellites in a constellation, flexible payloads, adaptive beamforming, and smart routing mechanisms are needed to make the most of the capacity of NGSO VHTS systems.

METHOD

A deterministic link-level analytical methodology and time-varying geometric sampling along the satellite pass are used to evaluate the system's performance. This method makes it possible to systematically evaluate how orbital shape, atmospheric problems, and modulation thresholds affect physical-layer performance and throughput. The flowchart shows how the Ka-band NGSO VHTS system will be checked. Setting up and checking the system parameters, such as the connection arrangement, orbital shape, and uncertainty settings, is the initial step. Next, to make the operation more realistic, things like changes in orbit, pointing problems, atmospheric influences, and interference are added. Then they figure out how much signal loss there is and what the satellite and ground look like. Next, we find C/N and C/N+I for both clear skies and rain. We use the restrictions that have been set for modulation and coding to compare the C/N+I values that we obtain. The throughput and spectral efficiency for that level are found out when the thresholds are met. This stage is the last phase of the review of the performance.

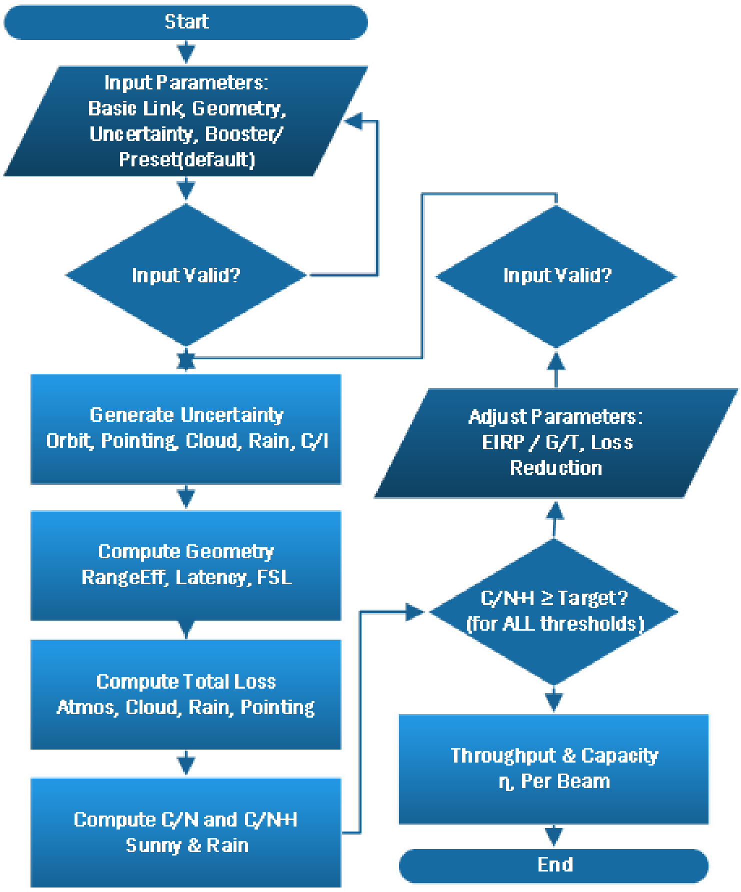

Figure 1. The Ka-band NGSO VHTS system

Making the Link Budget

There are different link budgets for the user downlink and the gateway uplink. The carrier-to-noise-plus-interference ratio (C/N+I) is determined by considering free-space path loss, antenna gains, system noise temperature, atmospheric gaseous absorption, rain attenuation, and co-channel interference [5], [6], [8]. The reference situation is clear skies, and rain fading is added as another attenuation factor that fits with how signals travel in the Ka-band in tropical areas [9]. The study omits power boosting, adaptive power regulation, and dynamic margin allocation to isolate the impacts of geometry and propagation, ensuring that fluctuations in C/N+I result exclusively from alterations in geometry and propagation.

Sampling and Orbital Geometry

We take samples of the satellite-to-terminal geometry at several places throughout the visible arc of each satellite pass. These samples are shown by separate indices that correspond to distinct elevation angles. This sampling technique captures the transition from geometry-limited situations at low elevation angles to propagation-limited conditions at high elevation angles, guaranteeing that link performance is tested over all operationally important geometries for NGSO LEO systems [5], [10].

Determining Spectral Efficiency

Using predetermined modulation and coding thresholds of 0 dB, 6 dB, 12 dB, and 15 dB, spectral efficiency is calculated based on instantaneous C/N+I values. Broadband satellite systems increasingly utilize these levels for modulation and coding methods [4], [6]. The connection is considered unavailable at that operational point if the instantaneous C/N+I is below a certain level. If it is above that level, the associated spectral efficiency is enabled. This threshold-based mapping shows the real-world limitations of modulation and coding in satellite communications.

Estimating Throughput

To find the throughput per beam, multiply the spectral efficiency by the bandwidth that was given to it. Because the bandwidth allocation is the same in all cases, changes in throughput are directly related to changes in connection quality and modulation efficiency. This concept establishes a distinct and comprehensible correlation between physical-layer performance and user-level capacity [4], [5].

RESULTS AND DISCUSSION

C/N+I Performance at the End User (Downlink)

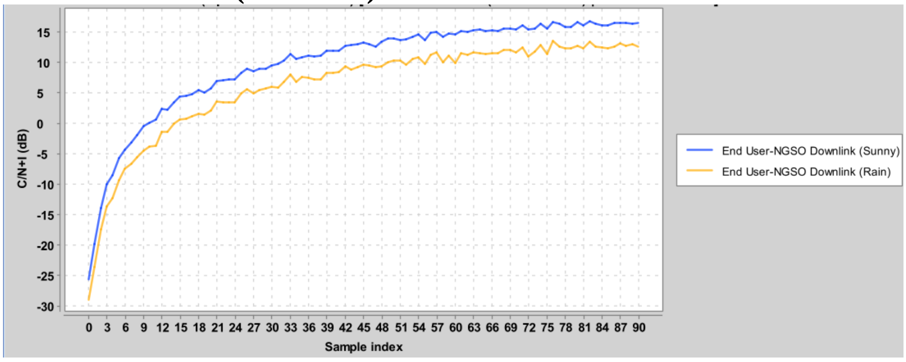

Figure 2. C/N+I Performance at the End User (Downlink)

Figure 2 shows how the carrier-to-noise-plus-interference ratio (C/N+I) at the end-user terminal for the NGSO downlink changes when the sky is clear and when it is raining. When the sample indices are low, which means the elevation angles are low and the connection geometry is bad, the C/N+I stays quite negative, going below −25 dB. This behavior is mostly caused by excessive free-space path loss, increased atmospheric absorption, and insufficient antenna gain at low elevation angles. The C/N+I rises quickly as the satellite moves along its visible arc, and it finally levels off at greater elevation angles. When the sky is clear, the downlink C/N+I levels off at about 15–17 dB. When it rains, however, the levels drop by about 3–4 dB. This gap shows how much Ka-band rain attenuation affects user links, especially when there is no adaptive power boosting or dynamic margin adjustment. The fact that both curves come together in a fairly smooth way shows that the system is mostly constrained by geometry at low elevations and by propagation at higher elevations. Understanding these dynamics is important for optimizing satellite communication systems. By implementing adaptive techniques, we can mitigate the adverse effects of rain and improve overall link performance.

C/N+I Performance at the Gateway Station (Uplink)

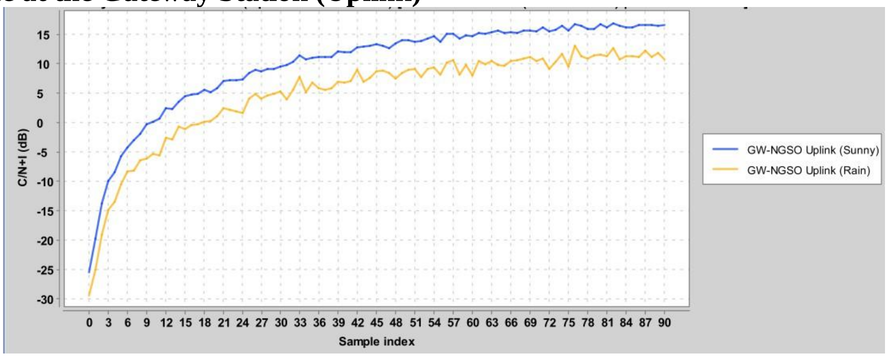

Figure 3. Spectral efficiency at the end-user terminal

Figure 3 shows the uplink C/N+I performance between the NGSO satellite and the gateway station. The uplink consistently has higher C/N+I values than the end-user downlink because it uses large-aperture gateway antennas, has a higher effective isotropic radiated power (EIRP), and has better G/T characteristics. When the sky is clear, the uplink C/N+I stays consistent at about 16–17 dB. When it rains, on the other hand, the C/N+I changes between 11 and 13 dB. The uplink shows slightly more variation when it rains, which is likely due to problems that only affect the uplink, like rain cell nonuniformity and uplink scintillation effects. Still, the positive C/N+I margin shown in most samples shows that the gateway link is still strong even without uplink power boosting. This data shows that high-performance gateway infrastructure is good for NGSO VHTS systems.

How Spectral Efficiency Changes When C/N Thresholds Are Set

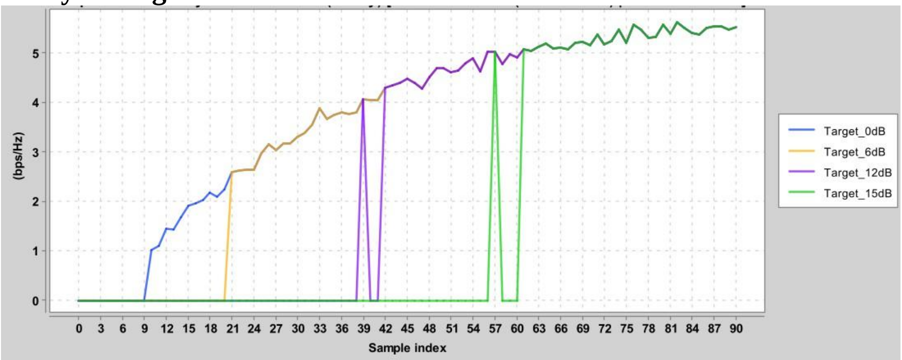

Figure 4. Spectral efficiency at the end-user terminal

Figure 4 shows the spectral efficiency at the end-user terminal as a function of the instantaneous C/N+I and the target thresholds of 0 dB, 6 dB, 12 dB, and 15 dB. Each curve only works when the C/N+I threshold is crossed, which is a sign of a threshold based modulation and coding selection technique. The 0 dB target lets links activate early at low elevation angles, but it doesn't do a satisfactory job of using the spectrum, usually below 2 bps/Hz, which is what extremely resilient modulation and coding schemes do. The spectral efficiency that can be achieved goes up dramatically when the target threshold goes up to 6 dB and 12 dB, reaching about 3.5–4 bps/Hz and 4.8–5.0 bps/Hz, respectively. The 15 dB goal can only be reached at high elevation angles, when the spectral efficiency levels out at about 5.4–5.6 bps/Hz. When the spectral efficiency drops to zero, it means that the instantaneous C/N+I is below the chosen threshold. This means that the connection is down or that the system is switching to lower modulation and coding schemes. This behavior shows how important adaptive modulation and coding (AMC) are for keeping service going when propagation and geometry change.

Analysis of throughput per beam

Assuming a fixed bandwidth allocation Fig. 4 shows how the spectral efficiency results turn into throughput per beam for the end-user NGSO downlink. The throughput curves are quite similar to the spectral efficiency trends, which shows that link-layer efficiency, not bandwidth variation, is what mostly controls throughput. When the target threshold is set to 15 dB, the throughput per beam becomes close to 1 Gbps when the link conditions are satisfactory. At the 12 dB target, throughput stays between 0.85 and 0.9 Gbps, while at the 6 dB target, it stays between 0.6 and 0.7 Gbps. The 0 dB objective allows for early connecting, but it has a much lower throughput, staying below 0.4 Gbps. These results indicate that the high per-beam capacity in NGSO VHTS systems is quite sensitive to the C/N+I margin that is available, especially when booster mechanisms are turned off. As a result, atmospheric fading and elevation-dependent geometry make link availability at higher throughput tiers less and less reliable.

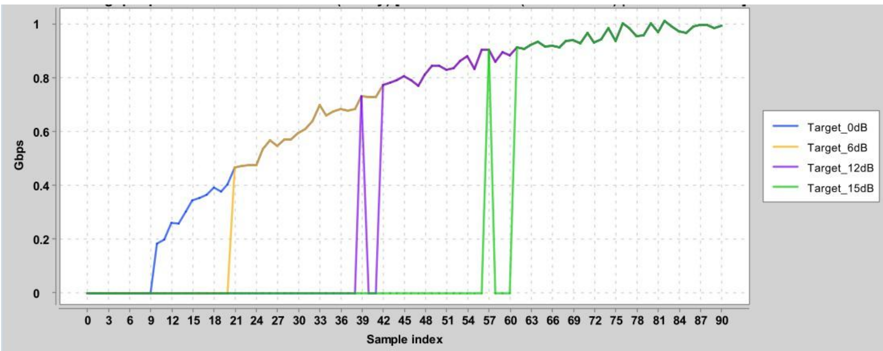

Figure 5. Throughput per beam

Talk About the System Level Overall

The results show that a booster-off NGSO VHTS system operating in the Ka-band may achieve excellent spectral efficiency and near-gigabit per-beam throughput when conditions are satisfactory for propagation. However, performance reduction due to rain fading is still a major problem, especially for high-order modulation techniques. The results show that to make links more resilient and services more available, we need to use adaptive approaches such as dynamic power control, adaptive coding and modulation, gateway site diversity, or multi-layer orbital topologies. Without these processes, the system's performance is very dependent on environmental changes, especially in tropical areas with heavy rainfall.

CONCLUSION

This study investigates how well a Ka-band NGSO VHTS system works at the link level while it is using fixed transmission conditions and no booster devices. The study indicates that when the orbital geometry is suitable and the sky is clear, it is possible to acquire very adequate spectral efficiency and nearly giga-bit per beam throughput. Rain, on the other hand, can make things work much worse, especially for higher- order modulation approaches. The results also reveal that uplinks from gateways are more stable than downlinks to end-users. This highlights how crucial it is for NGSO VHTS installations to have strong and dependable gateway infrastructure. Booster off installations are a nice way to start figuring out how much capacity is available. But in regions where it rains a lot, power management and dynamic modulation and coding are essential to maintain high service quality. This model will grow to include adaptive payload operation and multi-orbit constellation analysis in the future. This will help us learn more about the tradeoffs between capacity, resilience, and scalability in next-generation NGSO VHTS systems.

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