

Performance Evaluation of Modulation Schemes on HAPS 28 GHz Backhaul Link: Reliability Analysis and Spectral Efficiency Trade-off

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Abstract – Selecting modulation schemes for High-Altitude Platform Station (HAPS) backhaul links at 28 GHz is critical, as higher-order modulations improve spectral efficiency but degrade reliability under tropical conditions. This study evaluates the trade-off for QPSK and 16-QAM through link budget analysis, log-normal fading modeling with 2.5 dB tropospheric scintillation variance, and outage probability estimation via Q-function under three scenarios: clear-sky, rain attenuation, and worst-case (rain + turbulence). Results show that 16-QAM achieves fourfold spectral efficiency improvement (0.8 to 3.2 bps/Hz) but requires 8.2 dB additional Eb/No, degrading receive margin from 12.1 dB to 2.1 dB under rain, with availability dropping from >99.9999% to 80–90%. QPSK maintains a rain margin of 16.3 dB and availability exceeding 99.9999%. These findings confirm that static 16-QAM deployment is unsuitable for tropical environments. Adaptive Coding and Modulation (ACM) is recommended, with dynamic switching to QPSK when the estimated receive margin falls below 5 dB or when the operating Eb/No cannot be sustained above 12 dB for the target BER of 10^{-5} . This threshold-based approach enables reliable HAPS deployment in Indonesia.

Keywords: HAPS, Backhaul Link, Outage Probability, Rain Attenuation, Spectral Efficiency



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I. INTRODUCTION

One of the major challenges in broadband equalization across Indonesia is providing adequate infrastructure given the country's geographic conditions as an archipelago nation, particularly in disadvantaged, frontier, and outermost regions [1], [2], [3], [4]. This situation results in these regions experiencing prolonged communication access

difficulties, necessitating the development of wireless infrastructure solutions capable of addressing the needs in these regions. High-Altitude Platform Stations (HAPS) technology emerges as a complementary solution that can meet broadband demands in these regions, serving as a means to achieve equitable communication access [5], [6].

HAPS platforms operate at altitudes of 20 to 50 kilometers in the stratospheric layer, and are capable of providing extensive coverage with a radius of up to 234 kilometers at 25 kilometers altitude [7], [8], [9]. HAPS offers significant advantages including considerably lower latency compared to geostationary satellites, as well as improved cost efficiency compared to large-scale terrestrial network expansion [5], [6]. The 28 GHz frequency band, through the WRC-23 Final Act decision in 2023 [10] at the International Telecommunication Union (ITU) conference and further clarified in Radio Regulations Articles 2024 [11], allocates this frequency spectrum for HAPS backhaul or gateway links to ground stations. The performance of the HAPS-to-ground station link is heavily influenced by the characteristics of the atmospheric propagation path. The selection of modulation schemes becomes critically important given that this directly determines the trade-off between spectral efficiency, which encompasses data rate, and connection reliability [12]. Prior research conducted by [13] analyzed the link budget by comparing QPSK and 16-QAM modulation schemes for HAPS backhaul links at 28 GHz. Although the study highlighted superior data rate performance of 16-QAM, the conclusions regarding 16-QAM's superiority warrant further investigation. Specifically, given the substantial decline in receive margin from

26.3 dB to 12.1 dB under clear sky conditions, and from 16.3 dB to merely 2.1 dB under rain attenuation, this indicates that 16-QAM operates at a high-risk position, approaching the connection failure threshold.

The specific scientific contribution of the present work beyond [13] lies in the systematic incorporation of log-normal fading characterization and quantitative outage probability estimation using the Q-function under tropical rain and scintillation conditions. This provides explicit reliability metrics that were absent in the baseline link-budget-only analysis. The work further correlates residual margin values with service availability levels to support QoS-based modulation decisions for real-world HAPS deployment in underserved Indonesian regions. This situation indicates a critical research gap regarding the capability of 16-QAM modulation to meet the 99.9% service availability standard. Additionally, an in-depth study is required on application scenarios that can justify such reliability, as well as identifying the most suitable modulation strategy based on Quality of Service (QoS) requirements in underserved regions with potential for HAPS deployment. To date available literature lacks a systematic evaluation of this trade-off in the context of real-world HAPS implementation [14].

Most studies on HAPS systems tend to emphasize coverage optimization or interference analysis, resulting in modulation selection being treated as a secondary element [6]. While link budget calculation is indeed critical, it remains insufficient as the sole foundation for decision-making in practical field implementation [14]. In addition, atmospheric gas attenuation due to oxygen and water vapor at 28 GHz, which can contribute approximately 0.1 to 0.2 dB per km according to ITU-R P.676, and potential rain-induced depolarization effects are considered in the overall propagation assessment for tropical paths. This research addresses the identified gap by evaluating connection failure probability across atmospheric conditions and providing precise modulation selection guidance.

The primary objective of this research is to comprehensively evaluate the trade-off between spectral efficiency and reliability of QPSK and 16-QAM modulation schemes in HAPS deployment. This study systematically measures receive margin under various propagation conditions, ranging from clear-sky conditions to rain and turbulence scenarios (worst-case conditions). Furthermore, this research aims to estimate connection failure probability while providing QoS-based modulation selection recommendations for HAPS development strategy in Indonesia.

II. LITERATURE REVIEW

A. HAPS Technology and 28 GHz Band Allocation

HAPS platforms occupy a unique position situated between terrestrial communication systems and satellite networks. The key characteristic of HAPS

technology is its deployment location within the stratospheric layer, which offers substantial advantages including extensive area coverage and lower latency compared to geostationary satellites [15]. Additionally, the relatively static position of HAPS platforms has enabled opportunities for antenna optimization and the utilization of green energy through solar panels within the HAPS ecosystem [16].

The ITU has specifically allocated the 28 GHz frequency band for backhaul links interconnecting ground stations and HAPS platforms. Utilization of this millimeter-wave spectrum enables abundant bandwidth availability, supporting multi-Gbps data capacity [17].

B. Tropical Climate Characteristics in Indonesia

HAPS implementation in Indonesia faces unique challenges due to substantially higher rainfall intensity compared to subtropical regions. According to BMKG (Indonesian Meteorological Agency) data, regions such as Jakarta and Medan experience annual rainfall significantly exceeding the global average assumptions embedded in the standard ITU-R P.838 model [18], [19]. Seasonal variation between dry season and monsoon season causes significant fluctuations in rain attenuation, with coastal regions typically requiring stronger modulation margins compared to inland areas. Consequently, adaptive modulation strategy becomes crucial for optimizing capacity across Indonesia's diverse geographic regions, each characterized by distinct propagation conditions.

C. Modulation in Digital Communication Systems

Modulation is an essential process in communication systems that converts data streams into signal format for transmission over physical channels. The characteristics of digital modulation schemes, determined by the number of constellation points and symbol spacing, fundamentally affect the trade-off between achievable data rate and signal immunity to noise [12].

Table 1. Simulation Parameters for HAPS Backhaul Link at 28 GHz Frequency

Parameter	QPSK	16-QAM
Bits per Symbol	2	4
Minimum Eb/No for BER 10^{-5}	7.8 dB	16.0 dB
Symbol Error Probability	Lower	Higher

As shown in Table 1, the difference in minimum Eb/No between 16-QAM (16.0 dB) and QPSK (7.8 dB) amounts to 8.2 dB, representing the additional power penalty incurred when transitioning to higher-order modulation. QPSK modulation maintains stable signal amplitude, contributing to minimal instantaneous power fluctuation and enhanced system immunity to noise interference [20]. With moderate energy-per-bit to noise power spectral density (Eb/No)

requirements, QPSK becomes an ideal choice for communication channels with power constraints or susceptibility to interference [20].

Conversely, 16-QAM modulation, which utilizes a 4×4 square constellation, enables the encoding of four bits per symbol; however, this significantly narrows the decision regions. Although its spectral efficiency quadruples compared to QPSK, this scheme requires substantially higher power to maintain equivalent error rates. The increased sensitivity to noise and distortion renders 16-QAM vulnerable to performance degradation in fading channels or environments susceptible to interference [12].

D. Link Budget and Propagation Modeling

Link budget calculation fundamentally encompasses the addition of Equivalent Isotropic Radiated Power (EIRP) and receiver antenna gain, followed by subtraction of various attenuation factors, including free-space path loss (FSL), rain attenuation, and other atmospheric losses [14], as expressed in Eq. (1):

$$\text{Receive Margin (dB)} = \text{Received Power (dBm)} - \text{Receiver Sensitivity (dBm)} \quad (1)$$

System margin can be comprehensively expressed through Eq. (2):

$$\text{Margin} = \text{EIRP} + G_{rx} - L_{path} - M_{impl} - L_{rain} - L_{atm} + G_{diversity} \quad (2)$$

where $EIRP$ is the Equivalent Isotropic Radiated Power (EIRP), G_{rx} is the receiver antenna gain, L_{path} is the free-space path loss, M_{impl} is the implementation margin, L_{rain} is the rain attenuation, L_{atm} represents other atmospheric losses, and $G_{diversity}$ is the diversity gain.

As previously discussed, positive receive margin indicates the system can still operate reliably, whereas negative receive margin indicates the occurrence of outage [14]. The primary contributing factors can be explained as follows:

1. Free-Space Path Loss, which results in significantly greater propagation losses, estimated to be approximately 20 dB higher than the propagation losses associated with geostationary satellites operating in the 4–6 GHz band [9]. Consequently, high-gain antennas are required to compensate for the incurred losses.
2. Rain Attenuation, where rainfall, particularly in tropical regions such as Indonesia, causes exponential signal attenuation. This phenomenon is modeled in ITU-R P.838 [19], which estimates rain attenuation of approximately 10 dB to achieve a service availability level of 99.9% [18].

Atmospheric Turbulence, where stratospheric winds and temperature variations induce phase noise, scintillation, and fading phenomena, ultimately

exacerbating the effects of incurred losses, estimated to range from 2 to 5 dB [9].

E. Outage Probability and Service Availability

Inadequate link margin renders the system vulnerable to minor weather disturbances, which can cause significant signal degradation below the acceptable reception threshold. Such situations trigger outage or service interruption, ultimately violating the Service Level Agreement (SLA) and Quality of Service (QoS) parameters offered by HAPS services. This mathematical relationship [12] is expressed in Eq. (3):

$$P_{out} \approx Q\left(\frac{\text{margin}}{\sigma_{margin}}\right) \quad (3)$$

where Q represents the probability of the standard Gaussian distribution and σ denotes margin volatility induced by signal fading, which can reach 2–4 dB [18]. A link with a margin of 2.1 dB will experience 2–3 dB standard deviation margin volatility and encounter an outage probability exceeding 10%, resulting in reduced availability (SLA < 90%).

III. METHOD

A. System Model and Parameters

This research methodology extends the previous link budget analysis [13] by incorporating fading channel characterization and outage probability calculation. This research focuses on QPSK and 16-QAM as representative modulation schemes, as these two configurations were established in the baseline study [13] and represent the fundamental trade-off between reliability-oriented and capacity-oriented deployments in tropical HAPS environments. All numerical calculations, link budget evaluations, and BER curve simulations were performed using MATLAB R2023a.

Table 2. HAPS System Model Parameters*

Parameter	Value
Operating Frequency	28 GHz
Bandwidth	50 MHz
Platform Altitude	17 km
Ground Station Distance	10 km
Line of Sight (LOS) Distance	19.72 km
Elevation Angle	± 30°
Coverage Zone	Rural / Sub-Urban
Receiver Noise Figure	5 dB
Cable Loss	2 dB
Noise Temperature	300 K
Thermal Noise Density	−173.8 dBm/Hz
EIRP	61.6 dBm
Receiver Antenna Gain	32.6 dBi

*Parameters adopted from [13] to ensure consistency with the baseline study.

Identical baseline parameters are employed for both modulation schemes to ensure fair comparison, including 28 GHz operating frequency and 17 km platform altitude. The distance to the ground station is set at 10 km with an elevation angle of approximately 30°, representing service scenarios in rural as well as

sub-urban regions. The parameters and values employed in the system model are summarized in Table 2.

B. Link Budget Calculation Framework

Within the link budget calculation framework, the transmission path from transmitter to receiver encompasses several primary components, as detailed below:

1. At the transmitter (Tx) side, the employed parameters include carrier power of 30 dBm, antenna gain of 32.6 dBi, and feed loss of 1 dB [13]. The combination of these values yields Equivalent Isotropic Radiated Power (EIRP) of 61.6 dBm.
2. In the propagation domain, free-space path loss (FSL) at 28 GHz is calculated using the standard equation that accounts for distance in kilometers, namely $FSL = 20 \log_{10} \left(\frac{4\pi d}{\lambda} \right) = 147.3 \text{ dB}$ for $d = 19.72 \text{ km}$.
3. At the receiver (Rx) side, the essential parameters include antenna gain of 32.6 dBi, cable loss of 2 dB, and noise figure of 5 dB [13]. The minimum sensitivity is determined from the combination of these parameters, considering the data rate and modulation scheme employed.

Regarding margin, it is assumed there is no fading under clear-sky conditions. Meanwhile, rain attenuation follows the ITU-R P.838 model, with 10 dB required to achieve 99.9% availability in tropical regions [19].

C. Modulation-Specific Performance Thresholds

To calculate the probability of bit error (BER) for each modulation scheme in an AWGN channel, the calculation follows theoretical curves that have been mathematically derived. These expressions are presented in Eq. (4) and Eq. (5) as follows [20]:

For QPSK modulation scheme:

$$BER_{QPSK} \approx Q \left(\sqrt{\frac{2Eb}{No}} \right) \quad (4)$$

For 16-QAM modulation scheme:

$$BER_{16-QAM} \approx \frac{3}{4} Q \left(\sqrt{\frac{4Eb}{5No}} \right) \quad (5)$$

The Eb/No value is thus the primary basis for evaluating the sensitivity of each modulation scheme to noise, as well as for determining the receive margin required to ensure the system continues to operate at the desired performance level.

D. Atmospheric Propagation Scenarios

This research evaluates three primary propagation conditions as propagation scenarios [18]:

1. Clear-Sky, where there are no precipitation and turbulence is negligible. This condition represents

the baseline performance in the best-case scenario.

2. Rain Attenuation, where the ITU-R P.838 model accounts for a margin loss of 10 dB to maintain time availability of 99.9%.

Worst-case condition, which combines rain attenuation with an additional 3 dB for scintillation margin due to turbulence. This situation represents an extreme outage scenario in determining the final results.

E. Outage Probability Estimation

Based on receive margin statistics, this research estimates outage probability using two primary approaches [14]:

1. Deterministic worst-case approach, where outage is considered to occur if operating margin falls below 0 dB, and
2. Statistical fading model approach, which assumes margin distribution follows log-normal with standard deviation approximately 2–3 dB for tropospheric fading under specific conditions. From this, outage probability can be calculated more accurately using Q-function approximation.

By applying the Q-function approach to the statistical fading approach with log-normal distribution, where tropospheric scintillation variance is set at 2.5 dB, outage probability estimation can be obtained with higher accuracy.

For QPSK modulation scheme:

$$P_{out} \approx Q \left(\frac{16.3}{2.5} \right) = Q(6.52) \approx 3 \times 10^{-11} \quad (6)$$

For 16-QAM modulation scheme:

$$P_{out} \approx Q \left(\frac{2.1}{2.5} \right) = Q(0.84) \approx 0.20 \quad (7)$$

For the rain attenuation scenario, receive margin is recorded as 16.3 dB for QPSK modulation and 2.1 dB for 16-QAM modulation. This relationship has been calculated mathematically in Eq. (6) and Eq. (7) above.

IV. RESULTS AND DISCUSSION

A. Link Budget Analysis

In link budget analysis, the parameters employed play a critical determining role in producing accurate, precise, and reliable calculations [14]. The combination of EIRP, free-space path loss, and rain attenuation directly determines the residual margin available for each modulation scheme. These calculated margins form the basis for the subsequent outage probability estimates under clear-sky, rain, and worst-case conditions. Table 3 compares the link budget results of QPSK and 16-QAM under clear-sky and rain conditions. The higher-order 16-QAM scheme reaches four times the spectral efficiency of QPSK yet leaves

only 2.1 dB of receive margin under rain attenuation while QPSK retains 16.3 dB.

Table 3. Link Budget Calculation Results and Receive Margin across Various Propagation Conditions

Performance Metrics	QPSK	16-QAM
Modulation Parameters:		
Bits per Symbol	2	4
Code Rate	0.50	1.00
Data Rate	40 Mbit/s	160 Mbit/s
Spectral Efficiency	0.8 bps/Hz	3.2 bps/Hz
Receiver Sensitivity:		
Required Eb/No for BER 10^{-5}	7.8 dB	16.0 dB
Minimum Sensitivity	-165.8 dBm	-157.8 dBm
Receive Margin (Clear Sky)	26.3 dB	12.1 dB
Receive Margin (Rain Atten.)	16.3 dB	2.1 dB
Minimum Tx Power	3.7 dBm	17.9 dBm

B. Spectral Efficiency Analysis

In the analysis of spectral efficiency metric (bps/Hz), which measures data rate per unit bandwidth, the calculation is performed using Eq. (8) as follows [12]:

$$\text{Spectral Efficiency} = \frac{(\text{Data Rate})}{\text{Bandwidth}} \quad (8)$$

For a bandwidth of 50 MHz:

$$\text{QPSK} = \frac{40 \text{ Mbit/s}}{50 \text{ MHz}} = 0.8 \text{ bps/Hz}$$

$$16 \text{ QAM} = \frac{160 \text{ Mbit/s}}{50 \text{ MHz}} = 3.2 \text{ bps/Hz}$$

C. Link Reliability Evaluation

Receive margin reflects the excess signal power available above the minimum receiver detection threshold, and this value is critically related to the overall system robustness level [13].

Under ideal conditions, 16-QAM modulation can still operate satisfactorily; however, its margin level is sufficiently vulnerable to sudden weather disturbances. Conversely, QPSK modulation provides substantially greater power reserve, enabling it to withstand significant signal fading without causing service interruption. This behavior is illustrated in Figure 1, which depicts receive margin performance across various propagation conditions.

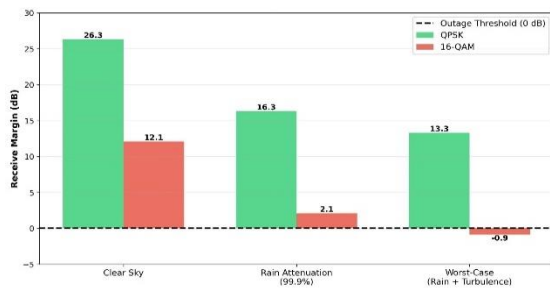


Figure 1. Comparison of Receive Margin: QPSK vs 16-QAM across Various Propagation Conditions

Based on the data presented in Figure 1, a deeper evaluation is conducted regarding the robustness of both modulation schemes across various propagation conditions:

1. Ideal Condition (Clear-Sky)

Under no-fading conditions, both modulations still operate above the required threshold. 16-QAM modulation exhibits a receive margin of 12.1 dB, which, in calculation terms, remains above the rain attenuation value of 10 dB. However, it provides only limited room for additional fluctuations. Conversely, QPSK modulation demonstrates significantly superior stability with a margin of 26.3 dB, providing substantial headroom to absorb various fading events without disrupting service continuity.

2. Rain Attenuation Condition

Referencing the 99.9% availability target in Indonesia's tropical climate, which is assumed to require a rain attenuation margin of 10 dB, a striking reliability difference becomes evident:

- QPSK scheme maintains a link margin of 16.3 dB. This margin reserve functions as a sufficiently strong safety factor to ensure connection stability even during heavy rainfall.
- 16-QAM scheme experiences drastic margin reduction, leaving only 2.1 dB. This value represents a critical operating point, where the system becomes highly vulnerable to even minor atmospheric disturbances and faces significant risk of service interruption.

3. Worst-Case Condition (Rain + Turbulence)

When rain attenuation is combined with 3 dB scintillation loss from atmospheric turbulence, a highly significant operational difference emerges:

- QPSK modulation remains robust and in a safe operating condition, with residual margin of 13.3 dB still maintaining connectivity above the failure threshold.
- 16-QAM modulation falls into negative values, as indicated in the graph of Figure 1, at -0.9 dB, which technically causes outage. This occurs because the received signal level has fallen below receiver sensitivity, triggering complete service interruption.

D. Outage Probability and Service Availability

By employing Q-function approximation on the log-normal fading model where σ of 2.5 dB represents tropospheric scintillation variance, the outage probability for QPSK can be estimated to reach 3×10^{-11} , which practically indicates negligible outage, whereas for 16-QAM it reaches 0.20 or 20%, as shown in Table 4.

The calculated outage probabilities highlight a clear reliability gap between the two schemes under rain. QPSK remains essentially immune to service interruption with an outage rate near zero. In contrast 16-QAM faces a 20 percent chance of link failure that translates into substantial daily downtime.

Table 4. Summary of Outage Probability and Operational Impact

Scenario	QPSK (Margin/ σ)	16-QAM (Margin/ σ)	Impact
Clear-Sky	$Q(26.3 / 2.5) =$ $Q(10.52) \approx$ 10^{-25}	$Q(12.1 / 2.5) =$ $Q(4.84) \approx 10^{-6}$	Negligible Difference
Rain Attenuation	$Q(16.3 / 2.5) =$ $Q(6.52) \approx$ 3×10^{-11}	$Q(2.1 / 2.5) =$ $Q(0.84) \approx 0.20$	16-QAM 20% Outage Rate
Worst-Case	$Q(13.3 / 2.5) =$ $Q(5.32) \approx 10^{-7}$	$Q(-0.9 / 2.5) =$ $Q(-0.36) \approx$ 0.64	16-QAM 64% Outage Rate

By translating outage probability values into availability metrics, a clearer and more realistic picture emerges regarding the operational performance of both modulation schemes when facing rain attenuation:

1. QPSK scheme demonstrates exceptionally high reliability, with service availability exceeding 99.9999% (equivalent to outage probability of 3×10^{-11} under rain attenuation conditions with $\sigma = 2.5$ dB), far exceeding the ITU 99.9% minimum requirement for backhaul links. In technical terms, this figure equates to extremely minimal downtime, specifically less than 0.1 seconds per year. This makes QPSK a highly suitable choice for mission-critical communication infrastructure.
2. Conversely, 16-QAM scheme can only achieve approximately 80% availability. Under adverse weather conditions, this translates to average downtime of approximately 3 hours per day. This will clearly significantly disrupt service continuity. To further illustrate the sensitivity of 16-QAM, additional calculations were performed for rain attenuation values of 5 dB, 10 dB, and 15 dB. At 5 dB rain attenuation the residual margin for 16-QAM remains approximately 7.1 dB, supporting availability near 99 percent under the same scintillation variance. At 15 dB the residual margin becomes negative, confirming that 16-QAM outage risk rises sharply once rain attenuation exceeds roughly 12 dB in the modeled tropical path.

E. Service Level Agreement (SLA) Compliance Evaluation

For industrial applications that establish service availability requirements of 99.9% with a maximum downtime limit of only 45 minutes per year [25], the selection of 16-QAM modulation on a permanent or static basis in field practice is deemed insufficient. The availability achieved by this scheme, particularly under adverse weather conditions, falls far short of the expected threshold.

To fulfill these requirements, the implementation of several mitigation strategies is necessary, as follows:

1. Forward Error Correction (FEC)
This technique is capable of reducing the effective E_b/N_0 requirement by up to 3–4 dB, thereby improving receiver sensitivity and providing additional margin to maintain connection stability [22].
2. Adaptive Coding and Modulation (ACM)
This mechanism enables real-time switching between QPSK and 16-QAM according to time-varying or dynamic channel conditions. By monitoring channel state information, the system can switch to more robust modulation when conditions degrade and revert to more efficient modulation when signal conditions stabilize [22]. Explicit switching thresholds derived from the margin analysis are recommended as follows. Switch from 16-QAM to QPSK when the estimated receive margin falls below 5 dB or when the operating E_b/N_0 drops below 12 dB relative to the 16-QAM requirement of 16.0 dB for BER 10^{-5} . Switch back to 16-QAM only when the margin recovers above 8 dB and remains stable for a defined observation window. These numerical thresholds transform the ACM recommendation from normative advice into an implementable rule set.
3. Spatial Diversity
The use of two or more antennas enables the implementation of signal diversity techniques to reduce fading margin variance [9]. This approach helps maintain reliable performance despite significant propagation fluctuations.

F. Bit Error Rate (BER) Comparison

Figure 2 presents MATLAB simulation results depicting the comparative curves of Bit Error Rate (BER) versus E_b/N_0 for QPSK modulation (shown with green line) and 16-QAM modulation (shown with purple line).

16-QAM modulation exhibits a much steeper increase in error rate in the low SNR range. This is attributable to the narrower decision regions within its signal constellation, rendering this scheme far more susceptible to noise interference compared to QPSK.

In an operational scenario where E_b/N_0 reaches 20 dB, QPSK modulation still maintains a headroom or power reserve of 12.2 dB (at $E_b/N_0 = 20$ dB: $20 - 7.8 = 12.2$ dB). This reserve provides excellent stability against various signal fluctuations that may occur. Conversely, 16-QAM modulation leaves only approximately 4.0 dB ($20 - 16.0 = 4.0$ dB) margin under the same conditions. This thin margin renders the system highly vulnerable to even minor signal deviations, thereby significantly increasing outage risk.

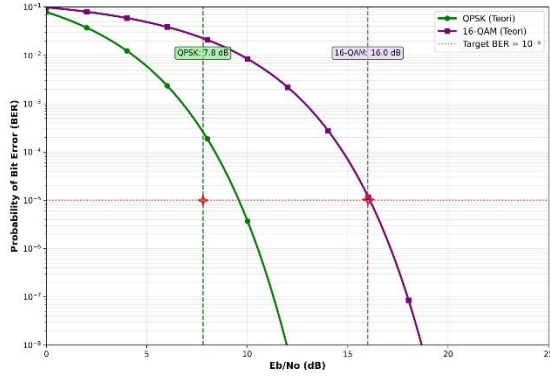


Figure 2. Bit Error Rate (BER) vs Eb/No Comparison: QPSK (Green Line) and 16-QAM (Purple Line)

Ultimately, although 16-QAM modulation is capable of delivering substantially higher data rates, its deployment demands far more stable and interference-free channel conditions to avoid service interruption.

G. Spectral Efficiency and Reliability Trade-off

The evaluation in this research also highlights the fundamental principle of Shannon-Hartley theory, which forms the foundation of information physics in digital communications. This theorem states that the maximum channel capacity C (in bits per second) is given in Eq. (9) as follows [12]:

$$C = B \cdot \log_2(1 + SNR) \quad (9)$$

where B is the bandwidth in Hz and SNR is the signal-to-noise ratio in linear form.

To quadruple the data capacity from 40 Mbit/s to 160 Mbit/s at the same bandwidth requires approximately 8 dB increase in SNR. However, margin fluctuations caused by fading, atmospheric turbulence, and rain attenuation will degrade effective SNR randomly and in ways that are difficult to predict.

Constellation expansion from QPSK to 16-QAM renders decision regions far narrower, reducing from $\pm 45^\circ$ to $\pm 22.5^\circ$ per quadrant [12]. Consequently, this scheme becomes far more vulnerable to phase noise and fading, thereby significantly increasing symbol error risk when channel conditions degrade [12].

H. Adaptive Modulation Strategy

The optimal strategy for operating HAPS backhauls links at 28 GHz frequency is to implement adaptive modulation based on Channel State Information (CSI). This system monitors channel conditions in real-time, where the ground station measures uplink SNR every 10 to 100 milliseconds to determine the most suitable modulation scheme at that moment [22].

With such an approach, the HAPS system can effectively balance between achieving high data capacity under clear weather conditions and maintaining consistent connection reliability when facing atmospheric attenuation or rain. This adaptive modulation approach is expected to ensure optimal

backhaul link performance in tropical environments such as Indonesia.

V. CONCLUSION

This research presents a comprehensive evaluation of the balance between spectral efficiency and reliability of QPSK and 16-QAM modulation on HAPS backhaul links at 28 GHz frequency. From the analysis conducted, the following conclusions can be drawn. The use of 16-QAM modulation yields a fourfold increase in data rate, from 40 Mbit/s to 160 Mbit/s. Furthermore, spectral efficiency increases fourfold compared to QPSK, from 0.8 bps/Hz to 3.2 bps/Hz. Constellation expansion in 16-QAM requires an additional 8.2 dB Eb/No to achieve equivalent error performance. Consequently, receive margin undergoes substantial degradation, from 26.3 dB in QPSK to 12.1 dB in 16-QAM under clear-sky conditions. This degradation becomes critical during rain attenuation, where 16-QAM margin is reduced to only 2.1 dB. Under clear-sky conditions, both modulation schemes achieve availability levels exceeding 99.99%. However, in rain attenuation scenarios, a striking difference emerges. QPSK modulation maintains service availability above 99.9999%, while 16-QAM availability drops to approximately 80–90%. Modulation scheme selection must be aligned with desired Quality of Service (QoS) requirements. For mission-critical backhaul services requiring high robustness, QPSK modulation is the more appropriate choice. Conversely, applications prioritizing high data capacity can leverage adaptive modulation mechanisms with smart-switching between QPSK and 16-QAM according to channel conditions. This study is limited by its reliance on theoretical link-budget models and statistical fading assumptions without real-time field measurement validation or hardware prototype testing. Future research directions include evaluation of higher-order modulations such as 64-QAM and 256-QAM combined with advanced forward error correction schemes including LDPC and Turbo codes, development of practical ACM algorithms tested under measured tropical channel traces, and experimental campaigns to refine scintillation and rain attenuation parameters specific to Indonesian HAPS deployment sites.

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