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Design and analysis of multibeam communication satellite links operated at Ka Band Frequency in Indonesia

Aulia Haque Qonita and Nurul Muhtadin

Satellite Technology Center, National Institute of Aeronautics and Space (LAPAN), Bogor, Indonesia

Email: aulia.haque@lapan.go.id

Abstract. In this paper, we design the link budget of communication satellite. This communication satellite is designed for Ka-Band Frequency for broadband communication in Non-Geostationary Orbit (NGSO) with altitude of 1200 km. The ability of this communication satellite depends on the strength of the signal and the amount of thermal noise. Ka-Band has wider bandwidth and higher data capacity but the drawback of this frequency is it is susceptible to rain attenuation in which Indonesia is an equatorial area that has high rainfall rate, so that the design of communication satellite in Ka-Band needs more consideration to determine satellite system parameter to keep the signal strength great. Indonesia is a wide archipelago country and satellite link design requires beam that can cover all Indonesia with great signal strength and multibeam antenna technology is one of solutions to overcome it. In this research, design and analysis of communication satellite is done using multibeam antenna. The main challenge of the design is to generate the link budget's result to meet determined parameter. Iterative calculation in design must be used to find an effective link margin and bit rate of this communication satellite. The main result of this research is multi beam satellite provide better performance than single beam satellite in Ka band frequency. The use of BPSK modulation in multi beam satellite shows better performance than other modulation types.

1. Introduction

In this decade, the demands of digital wireless communication technology with high data rate and reliability have increased significantly. Terrestrial systems are unable to satisfy these demands in all geographical areas and thus broadband access by satellite is a key service provision platform [1].

Indonesia is a tropical country with high rainfall so if the satellite working on high frequency the rain attenuation becomes an important issue in determining the signal strength. Appropriate frequency has to be considered to keep the link performance operate properly [2]. Moreover, Indonesia is a wide archipelago country, it is important to consider the beamwidth in order to obtain the proper signal strength [3].

One of the communication technology trends that is capable to address the demands in Indonesia is a non-geostationary orbit (NGSO) satellite technology using Ka-band frequency [4]. Ka-band has some advantages that are enable to provide applications with wider bandwidth, high data rate, smaller ground antenna, but this frequency is vulnerable to rain attenuation [5].

In the design of communication satellite, link budget is another important factor to be achieved for satellite missions and it will determine the success rate of a communication carried out. The link budget calculation aims to ensure that the received power level is greater than or equal to the transmitted power level. The calculation result is affected by the internal factor of the satellite and the external factor such as rain, free space, atmospheric loss, and antenna miss pointing loss [6].

In Indonesia, wireless communications using satellite are not optimally implemented [7]. If Indonesia does not catch up with the latest trend of satellite communication technology, Indonesia will fall further behind. Therefore, in this paper, the authors analyze the link budget performance of communication using satellite in Indonesia. The communication satellite is designed to support real-time communication services throughout Indonesia. The satellite will have low earth orbit or non-geostationary orbit with altitude around 1200 km and will operate in Ka-band frequency for broadband applications. The challenge is to design a satellite beamwidth that can cover whole regions of Indonesia with reliable signal strength for the user and can tolerate the attenuation due to rain/weather condition. Authors do the iteration for the link budget calculation to get a reliable link performance. Hopefully, this design of link budget calculation will become a pioneer of research and development of NGSO communication systems in Indonesia which can be proceeded to further research and development.

2. Link Budget Parameter

2.1. *Effective Isotropic Radiated Power* (EIRP)

Equivalent isotropically radiated power (EIRP) in a given direction is defined as the gain of a transmitting antenna multiplied by the net power accepted by the antenna from the connected transmitter. EIRP can be written as (equation 1):

$$\mathrm{EIRP} = P_T G_T (\mathrm{W}) \tag{1}$$

where P_T is the net power accepted by the antenna from the transmitter and G_T is the gain of the transmitting antenna [8].

2.2. *Free Space Loss (FSL)*

Free space path loss is proportional to the square of the distance between the transmitter and receiver, and also proportional to the square of the frequency of the radio signal. For satellite communication, this is the primary mode of signal loss. Even though no other source of attenuation or impairment is assumed, a transmitted signal attenuates over distance because the signal is spread over a larger and larger area (equation 2).

$$L_{FSPL} = \frac{P_t}{P_t} = \frac{(4\pi d)^2}{\lambda^2} = \frac{(4\pi f d)^2}{c^2} \tag{2}$$

where: λ is the signal wavelength (in metres), f is the signal frequency (in hertz), d is the distance from the transmitter (in metres), c is the speed of light in a vacuum.

2.3. *Atmospheric Loss*

Attenuation due to gas in the atmosphere depends on the frequency, the elevation angle, the altitude of the station, and the water vapor concentration. The attenuation is negligible at frequencies less than 10 GHz and does not exceed 3 dB at 22.4 GHz for mean atmospheric humidity and elevation angle greater than 10^{o} [9].

2.4. *Cloud Attenuation*

The specific attenuation due to a cloud can be determined from (equation 3):

$$\gamma c = \kappa c \, M \ (\mathrm{dB/km}) \tag{3}$$

where, γc is the specific attenuation of the cloud in dB/km, κc is the specific attenuation coefficient in (dB/km)/(g/m^3), and M is the liquid water density in g/m^3 [10].

2.5. *Rain Attenuation and Temperature*

Rainfall is a major cause of signal degradation for radio-communication systems operating at centimeter and millimeter wave bands, especially in the tropical region environment [11]. Determination of attenuation due to rainfall plays a significant role in the design of earth-satellite radio link at frequencies above 10 GHz [12]. Rain attenuation is occurred as a result of absorption of part or all of the signal's radiation power by the raindrop. This absorption is the consequence of scattering effect (diffraction and refraction) of the rain drop to the signal. Rain attenuation is prevalent at frequencies above 10 GHz and increases with frequency. This is because as frequency increases, the signal wavelength decreases and approaches the size of a rain drop and hence gives the rain drop more scattering and absorption capabilities to the signal. At a particular frequency, rain attenuation increases exponentially with increasing rain rate values because the higher the rainfall rate, the higher the rain drop size (rain drop diameter). Hence, it has more scattering effect on the signal, because as the rain drop size increases, it tends to approach the wavelength of the signal.

Rain will cause not only signal attenuation and depolarization; it will also cause increase in noise temperature, which, in turn, will increase the overall system noise temperature. The impact of the increased sky noise temperature can be high for low noise receiving system at Ku-Band. Increase of system noise level can lead to a reduction in Carrier to Noise ratio (in dB) in rain. The increase in antenna noise temperature due to rain T_n, may be estimated by (equation 4):

$$T_n = 280(1-\sigma)K = 280\left(1 - e^{-\frac{A}{4.34}}\right)(K) \quad (4)$$

where A is the rain attenuation (in dB) and the value 280 K is an effective temperature of the rain medium in Kelvin. Values between 273 and 290 K may be used, depending in whether the climate is cold or tropical [8].

2.6. Scan Loss
The scan loss is defined as the relative gain loss in decibels with respect to bore-sight scan of the antenna. Scan loss for a phased array antenna normally follows the relationship (equation 5):

$$-Scan\ Loss = (cosine\ \phi)^k \quad (5)$$

where ϕ is the scan angle of boresight and k is an empirical number between 1.2 and 1.5. A typical value to use for k is 1.3.[8]

2.7. Antenna Mispointing Loss
The most significant antenna losses are polarization mismatch and pointing inaccuracy. Polarization mismatch can be occurred due to improper use of antenna polarization, the satellite rotation, and Faraday rotation. Inaccuracy of antenna pointing can be divided on the inaccuracy due to satellite antenna pointing the fixed direction not necessarily in our antenna direction and due to ground station antenna mis-pointing. The second type of misalignment is the antenna pointing loss and it has usually quite small yielding less than 1(dB) [4].

2.8. Carrier to Noise Ratio (C/N)
The carrier-to-noise ratio (CNR) is an average power ratio of a signal C with a carrier to the noise N within the signal bandwidth. The C/N and CNR have the following relationships with E_b/n_0.

$$\frac{C}{N} = \frac{C\ \ T_b}{B\, n_0\ T_b} = \frac{R_b}{B}\,\frac{E_b}{n_0} \quad (6)$$

$$CNR = 10\log\left(\frac{C}{N}\right) = 10\log\left(\frac{E_b}{n_0}\right) + 10\log\left(\frac{R_b}{B}\right)\ (\text{dB}) \quad (7)$$

where T_b is data bit duration, $R_b = 1/T_b$ is bit rate, and n_o is noise density within in signal bandwidth [9].

2.9. Link Margin

Link availability is the percentage of time the overall availability of the service in which the system is able to provide service without interference and to meet the specified BER. On the other hand, link margin is a backup power provided in the communications link to overcome the fading. The equation to calculate the margin is given by the following equation (equation 8-10):

$$Margin = \frac{C}{N_{total}} - \frac{C}{N_{required}} \text{ (dB)} \tag{8}$$

where:

$$\frac{C}{N_{required}} = \frac{Eb}{N_{o\,required}} - 10\log\left(\frac{Tr}{B}\right) \text{ (dB)} \tag{9}$$

$$\frac{Eb}{N_{o\,required}} = \frac{Eb}{N_{o\,modem\,specification}} \tag{10}$$

T_r is data rate of transmission and B is occupied bandwidth in transmission [13].

3. System Design

In this study, the communication satellite design will be named as LAPAN-satcomm. The satellite is designed to be orbiting at an altitude of 1200 km so that the satellite will have an orbital period about 109 minutes and pass through Indonesia 13 times with 15-minute duration for each pass. One of the main payload carried by the satellite is the communication payload. The satellite will operate in Ka-band of 30 GHz for uplink and 20 GHz for downlink.

The total area of Indonesia is 18-39^o north latitude to 18-39^o south latitude, so the satellite antenna beamwidth minimum is 57^o to cover whole areas of Indonesia for single-beam and 42 ^{o} to cover Indonesia for a multi-beam with 7 spot beams. figure 1 and figure 2 shows the design of single beamwidth and multi beamwidth to cover Indonesia.

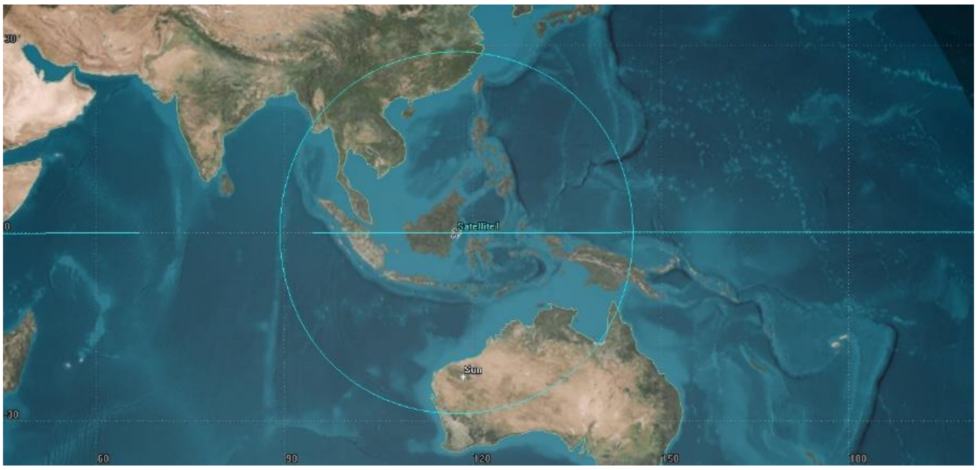

Figure 1. Coverage of 57° single-beamwidth antenna.

The satellite antenna that is used has 9.98 dBi gain for a single beam with a downlink frequency of 30 GHz and uplink frequency 20 GHz. For multi-beam satellite antenna, it is designed to have a gain of 9.98 dBi for the downlink frequency of 30 GHz and 12.48 dBi for the uplink frequency of 20 GHz. On the ground segment, 3.7 meters Alignsat Ka-Band antenna is used which has a gain of 58.4 dB. Full specifications of the gateway antenna can be seen in the datasheet [14]. The communications of the satellite are designed with 4 types of adaptive modulation (AM), which is BPSK, QPSK, 8PSK, and 16-QAM that will be compared.

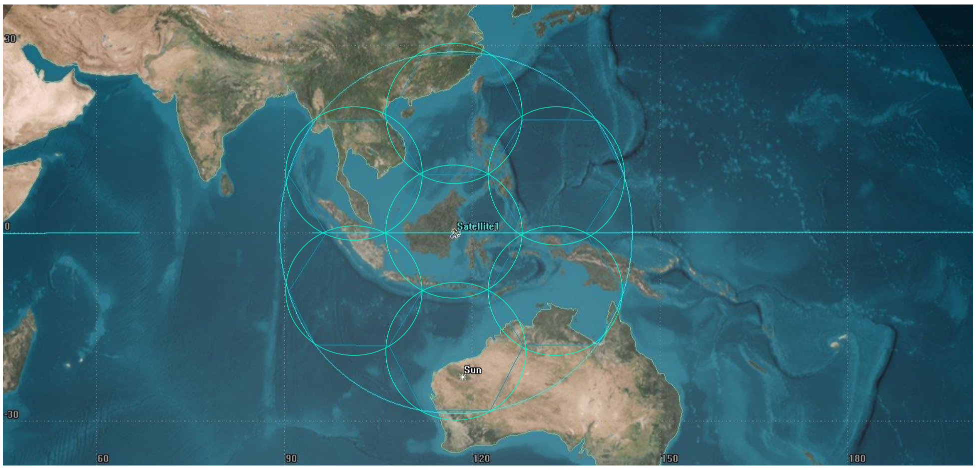

Figure 2. Coverage of 42^o multi-beamwidth for each spot beam antenna.

The gateway antenna is placed on the Observation Center for Space and Atmospheric LAPAN, Kototabang in West Sumatra with 100.32 east longitude, 0.23 south longitude, and a latitude of 900 meters above sea level. The place was chosen because it has an existing backbone network that is used for LAPAN-A2 and LAPAN-A3 satellite. In addition, Kototabang is chosen because it has a high rain attenuation.

In this link budget calculation, the transmitter power is 70 W. Some of the parameter values on a link budget calculation assumption are derived from satellite Telesat technical books [15], papers and books which are in the reference. Satellite transponder is assumed to provide occupied bandwidth 16 MHz.

This paper analyzes the link budget performance comparison between clear sky and rainfall condition, the link performance comparison between minimum and maximum elevation angle, the satellite link performance comparison between single-beam and multi-beam, and the performance comparison of multi-beam communication satellites using different modulation type and FEC rates. figure 3 and figure 4 show the position of gateway antenna on the current ground segment with minimum elevation. Table 1 shows the parameters used in the design of a communications satellite system.

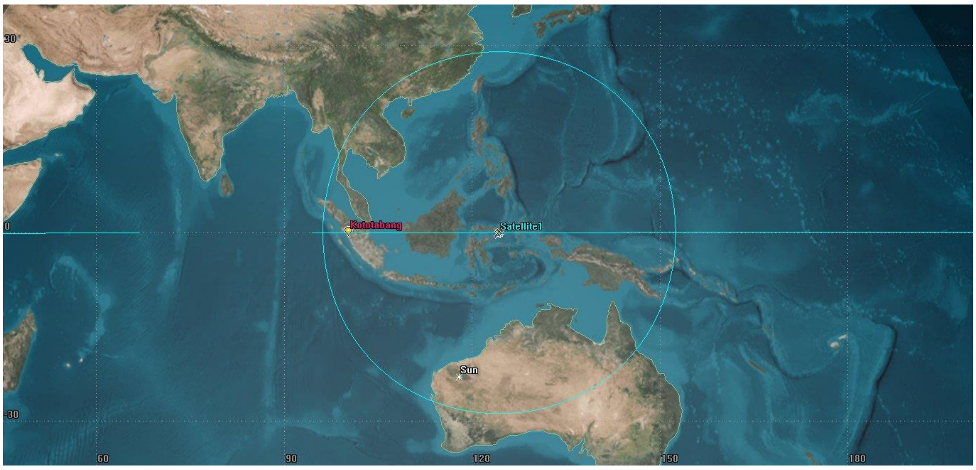

Figure 3. The position of the satellite antenna gateway to the single beam current minimum elevation of 10°.

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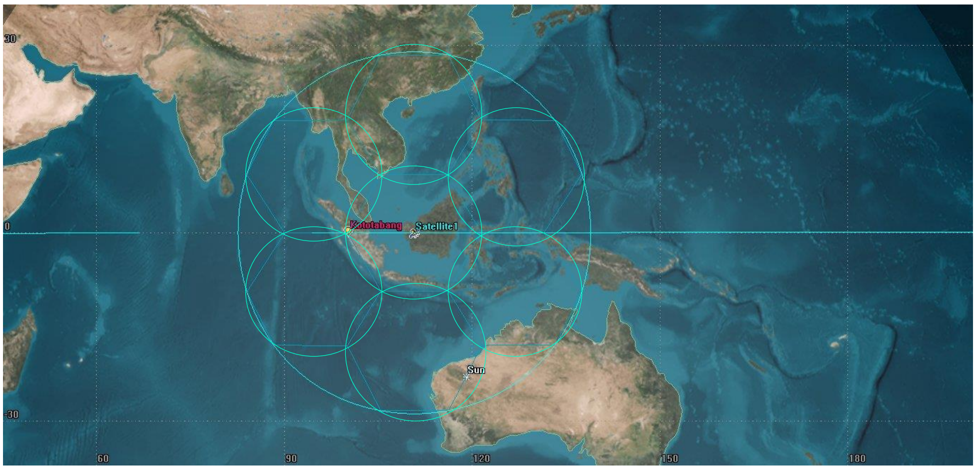

Figure 4. The position of the satellite gateway antenna multi-beam current minimum elevation 38°.

Tabel 1. Satellite System Specification.

Satellite Parameter		
Parameter	Value	Unit
Satellite Orbit	1200	Km
Frequency Uplink	30	GHz
Frequency Downlink	20	GHz
Occupied Bandwidth	16	MHz
Number of Beam (Multi Beam)	7	spot beam
Beamwidth (Single Beam)	57	deg
Beamwidth (per Spot Beam)	42	deg
Transmitter Power	70	W
Transmitter Power per Spot Beam	10	W
Noise Temperature	850	K
Single Beam Satellite Antenna Gain (Transmitter)	9.98	dBi
Single Beam Satellite Antenna Gain (Receiver)	9.98	dBi
Multi Beam Satellite Antenna Gain (Trasmitter)	12.48	dBi
Multi Beam Satellite Antenna Gain (Receiver)	9.98	dBi
Minimum Elevation (Single Beam)	10	deg
Minimum Elevation (Multi Beam)	38	deg
Maximum Elevation	88.79	deg
Modulation Scheme	BPSK, QPSK, 8PSK, 16-QAM	
Gateway Parameter (Alignsat 3,7m Ka Band)		
Parameter	Value	Unit
Transmitter Power	100	W
Cable Loss	1	dB
Gateway Transmitter Gain	58.4	dB
Gateway Receiver Gain	55.1	dB
Noise Temperature Gateway	121	K
Loss, Interference, and Other Parameters		
Parameter	Value	Unit
Cable Loss	1	dB
Atmospheric Loss	0.2; 0.3	dB
Cloud Attenuation	0.1413; 0.343	dB
Antenna Misspointing Loss	1	dB
Boltzmann Constant	-228.5991389	dB
Rain Attenuation (1%) f=30 GHz, $\theta = 88.79°$	8.13	dB

Parameter	Value	Unit
Rain Attenuation (1%) f=20 GHz, $\theta = 88.79°$	4.6	dB
Rain Attenuation (1%) f=30 GHz, $\theta = 10°$	11.9	dB
Rain Attenuation (1%) f=20 GHz, $\theta = 10°$	8	dB

4. Link Budget Calculation and Analysis

In the calculation of the link, we will calculate several parameters to determine the performance of the satellite communication system. There are several parameters to be calculated, namely C/No, C/N, Eb/No, and link margin that must be provided to overcome fading.

4.1. Clear Sky and Rainfall Link Budget Comparison

In this section, the link performance comparison between the maximum and minimum elevation angle has been done. In addition, the comparison of the link performance in the clear sky condition and rainfall is analyzed. This calculation is designed using a single-beam satellite antenna with BPSK Turbo Product Code modulation scheme, FEC Rate 21/44, and the data rate before the applied FEC is 8 Mbps. The Required Eb / No is 3.3 dB which is obtained from the modem specification. Data rate range for the modulation schemes is 64 - 30545 KHz.

Table 2. Clear Sky and Rainfall Link Budget Comparison.

Parameter	Clear Sky				Rainfall			
	On-Axis Beam		Edge Beam		On-Axis Beam		Edge Beam	
	Uplink	Downlink	Uplink	Downlink	Uplink	Downlink	Uplink	Downlink
Modulation	BPSK	BPSK	BPSK	BPSK	BPSK	BPSK	BPSK	BPSK
FEC Rate	21/44	21/44	21/44	21/44	21/44	21/44	21/44	21/44
Data Rate (Mbps)	8	8	8	8	8	8	8	8
Data Rate FEC (Mbps)	3.818	3.818	3.818	3.818	3.818	3.818	3.818	3.818
Required Eb/N0 (dB	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3
C/N Uplink (dB)	29.434	36.875	12.522	19.898	20.220	28.228	-0.562	7.153
Required C/N (dB)	-2.923	-2.923	-2.923	-2.923	-2.923	-2.923	-2.923	-2.923
Link Margin (dB)	32.357	39.798	15.445	22.821	23.142	31.151	2.360	10.075

From Table 2, we can see from the link budget calculation results link margin between clear sky and rainfall when the elevation angle is maximum and minimum. At the minimum elevation angle with clear sky condition, link margin drops around 16.912 dB for uplink and 16.977 dB for downlink compared to the maximum elevation angle. While in the rain condition, a drop in the link margin is around 20.782 for uplink and 21.076 for downlink. In rainfall condition at maximum elevation angle, a drop in the link margin compared to the clear sky condition is about 9.215 dB uplink and 8.647 downlinks. While at minimum elevation angle, a drop in the link margin compared to the clear sky condition is about 13.085 dB for uplink and 12.746 for downlink.

The decline in link margin from maximum elevation angle to minimum elevation angle and from clear sky condition and rainfall is a common thing. This phenomenon can be explained; when a ground station has a minimum elevation angle to the satellite, it means that the distance among them is maximum, so the loss signal that occurs when doing transmission at the minimum elevation angle will be more often than doing transmission at the maximum elevation angle. In the rain condition, a signal drop in the link margin compared with clear sky condition becomes proper due to an increase in rain attenuation and increase in system noise temperature. The enhancement in rain attenuation and system noise temperature gives a reduction of C/N parameter. [16]. In a single beam, the distance between a high elevation point (on-axis beam) to a low elevation point (edge beam) is greater than multibeam so that it is easier to analyse the level of margin drop. In the case of multibeam, there is still a decrease in margin drop but not as large as a single beam.

4.2. Single and Multibeam Link Budget Comparison

In this section, the link budget calculation is among the single beam and multibeam antenna applied on the satellite. The calculation is designed using the BPSK Turbo Product Code modulation scheme, FEC Rate 21/44, and the data rate before the applied FEC is 64 Mbps. The Required Eb / No is 3.3 dB which is obtained from the modem specification. Data rate range for the modulation schemes is 64 - 30545 KHz.

Table 3. Single beam and Multibeam Link Budget Comparison.

Parameter	Single-Beam				Multi-Beam			
	On-Axis Beam		Edge Beam		On-Axis Beam		Edge Beam	
	Uplink	Downlink	Uplink	Downlink	Uplink	Downlink	Uplink	Downlink
Modulasi FEC Rate	BPSK 21/44	BPSK 21/44	BPSK 21/44	BPSK 21/44	BPSK 21/44	BPSK 21/44	BPSK 21/44	BPSK 21/44
Data Rate (Mbps)	64	64	64	64	64	64	64	64
Data Rate FEC (Mbps)	30.545	30.545	30.545	30.545	30.545	30.545	30.545	30.545
Required Eb/N0 (dB	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3
C/N Uplink (dB)	29.434	26.773	12.522	9.861	29.434	30.924	23.447	24.937
Required C/N (dB)	6.108	6.108	6.108	6.108	6.108	6.108	6.108	6.108
Link Margin (dB)	23.326	20.665	6.414	3.753	23.326	24.816	17.339	18.829

Table 3 shows a link margin of the link budget calculation among the single beam and multibeam at the condition of maximum and minimum elevation angle. The link margin at maximum elevation angle is increased by 4.151 dB from a single beam to multibeam for downlink. While at the minimum elevation angle, the link margin is increased by 10.925 dB for uplink and 15.076 for downlink.

The increase of link margin in the single beam to multibeam is due to the gain enhancement on the satellite antenna; the beamwidth of the multibeam antenna is smaller than single beam so the directivity of antenna gain is greater than a single beam antenna. Moreover, the minimum elevation angle in the multibeam antenna is greater than a single beam antenna, so the maximum distance among the ground station and satellite in multibeam is smaller and also the scan loss is lower compared to a single beam antenna systems. The enhancement in gain and the minimum elevation angle for multibeam system gives a better result of C/N parameter.

The implementation of the BPSK modulation technique is to provide an “apple to apple” comparison for both single beam and multibeam. In addition, BPSK modulation can provide better link margin for each calculation has been done. The analysis of the modulation comparison used in this calculation can be seen in section 4.3.

4.3. Modulation use Comparison

The third calculation analyzes the link performance among different modulation schemes, such as BPSK, QPSK, 8-PSK, and 16-QAM in the clear sky condition. This calculation is done using a multi-beam satellite antenna with data rate 64 Mbps before the FEC is applied, where the data rate is the maximum value that is enabled by the modem specification. Required Eb/No for each modulation is shown in Table 4. These parameter values are obtained from modem specifications.

Table 4. Modulation Use Comparison in Link Budget.

Parameter	Modulation Schemes								
Modulation	BPSK TPC	BPSK TPC	QPSK TPC	QPSK TPC	QPSK TPC	8PSK TPC	8PSK TPC	16-QAM TPC	16-QAM TPC
FEC Rate	5/16	21/44	21/44	3/4	7/8	3/4	7/8	3/4	7/8
	Uplink								
Data Rate (Mbps)	64	64	64	64	64	64	64	64	64
Data Rate FEC (Mbps)	20	30.545	30.545	48	56	48	56	48	56
Required Eb/N0 (dB) (BER 10^{-6})	2.5	3.3	3.3	4.1	4.5	6.5	7.1	7.6	8.2
C/N Uplink (dB)	23.447	23.447	23.447	23.447	23.447	23.447	23.447	23.447	23.447
Required C/N (dB)	3.469	6.108	6.108	8.871	9.941	11.271	12.541	12.371	13.641
Link Margin (dB)	19.978	17.339	17.339	14.576	13.507	12.176	10.907	11.076	9.807
	Downlink								
Data Rate (Mbps)	64	64	64	64	64	64	64	64	64
Data Rate FEC (Mbps)	20	30.545	30.545	48	56	48	56	48	56
Required Eb/N0 (dB) (BER 10^{-6})	2.5	3.3	3.3	4.1	4.5	6.5	7.1	7.6	8.2
C/N Uplink (dB)	24.937	24.937	24.937	24.937	24.937	24.937	24.937	24.937	24.937
Required C/N (dB)	3.469	6.108	6.108	8.871	9.941	11.271	12.541	12.371	13.641
Link Margin (dB)	21.468	18.829	18.829	16.066	14.997	13.666	12.397	12.566	11.297

Table 4 shows that all modulation schemes in modem specification can be used in this satellite communication as indicated by the link margin for each modulation scheme tends to be high. The determination of the modulation scheme for designing communication satellite is very relative depending on the satellite requirement. For this design of communication satellite, the BPSK modulation scheme is the most optimal to be applied in the communication [17]. The calculation has been done with clear sky condition to show the optimum performance that can be achieved.

5. Conclusion

The authors result some conclusions in link budget calculation and analysis on this paper. First, Ka-band can be implemented and provide good performance in Indonesia while for uplink frequency 30 GHz and the downlink frequency 20 GHz, with determined satellite specification. Second, while in the worst condition (minimum elevation and rainfall), this satellite design is still feasible to be implemented in Indonesia with determined satellite specification. Third, from the calculation, the use of multi-beam antenna is more feasible to be implemented in Indonesia. Fourth, all the modulation types, such as

BPSK, QPSK, 8-PSK and 16- QAM, can be applied on this communication satellite. According to the results, the calculation shows good link performance. So, the main result from this research is multi beam satellite provide better performance than single beam satellite in Ka band frequency. The use of BPSK modulation in multi beam satellite shows better performance than other modulation types.

Although the use multi beam satellite provide good performance, but many aspects must be in consideration if we want to implement multi beam satellite, such as the antenna design, handover schemes, power requirement, etc. In future, that consideration can be learned to continue the research on this satellite communication and then we will know how feasible the multi beam satellite to be implemented in Indonesia. In subsequent work, the author will extend the study of this communication satellite which has not yet included, such as satellite constellation if we want to make 24/7 communication in Indonesia, user requirement, handover schemes, antenna design, etc.

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