Quality of services LoRaWAN satellite communication

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Article Info

Article history:

Received Mar 26, 2025
Revised Nov 18, 2025
Accepted Nov 23, 2025

Keywords:

Data transmission
IoT
Long-range
LoRaWAN
Satellite based

ABSTRACT

This research discusses research that focuses on the capabilities of satellite-based LoRa, for satellite positions orbiting in low earth orbit (LEO). The expectation of low power wide area network (LPWAN) satellite can find the quality of transmitting data using LoRaWAN which is part of LPWAN and can provide quality of service (QoS) with high-quality real-time sensor data, low latency, long-range, low-power, no attenuation signal, no problem with obstacles in terrestrial areas, and other benefits that can be widely optimized. This article uses a comprehensive analysis of mathematical calculations as well as precise and accurate simulations for the actual development of satellite-based LPWAN. The satellite-based IoT is unlimited in terms of distance, to provide good services to all IoT users in the world. The comparison with terrestrial measurements is analyzed in detail, especially the signal attenuation factor that causes a lot of signal loss and data is not well received. Several methods are used to help reduce collision data, such as adaptive data rate (ADR) which can reduce collisions by 30%.

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1. INTRODUCTION

The development of technology, especially satellite communication, has begun to develop since Elon Musk continued to explore space by launching various rockets that carried satellites into low earth orbit (LEO Orbit). One of the things developed by Elon Musk besides Tesla is Starlink, which is a satellite-based super-fast internet service in LEO that can provide speeds of >100 Mbps. Satellite communication is also developed, especially in this article is LoRaWAN which belongs to the family of low power wide area network (LPWAN). long range wide area network (LoRaWAN) based on satellite is a low-power communication system [1]-[4], with a frequency of 920-923 MHz or at ultra high frequency, is a free ISM Band, used for the development of the internet of things (IoT) which is cheap and easy to develop infrastructure. LoRaWAN is a combination of LoRa module and internet server so that LoRa can finally be run on the server application and can be seen in real-time for its data.

LoRaWAN and low power wide area networks or devices are expected to continue to be developed in Indonesia, based on several factors, such as technical factors related to economic growth, which cause economic improvement with the role of IoT systems built in areas such as food, agriculture, fisheries, and aquaculture, which have a real impact on the economic sector, as well as from the perspective of law and regulation in Indonesia. LPWAN is regulated in accordance with the Decree of the Minister of Communication and Information Technology of the Republic of Indonesia concerning low power wide area networks, which should further strengthen the role of LoRaWAN in Indonesia for the downstreaming of research in Indonesia [5]. The hope of using LoRa is that eventually, wireless communication systems can reach as far as possible transmitting data for example >15 km, with satellite communication, it may be able to reach more than 100 km in mountainous areas and also swamps and forests that ensures obstacles can occur and data can be lost if using terrestrial communication. When looking at the LoRaWAN communication system [6]-[9], it can be divided into several techniques such as the data transmitting technique used, the communication technique on the satellite, transmission to the gateway, and data processing. The right way of working for LoRaWAN data transmission will comprehensively determine the analysis technique [10]-[13].

2. THEORY

2.1. LoRaWAN satellite communication

LoRaWAN satellite-based has developed in such a way and developed by Lacuna Space.

$$s(t) = A.\cos(2\pi f_c t + \pi k^2) \quad (1)$$

$$T_{Payload} = T_{Sym}.n_{sym} \quad (2)$$

$$T_{sym} = \frac{2^{SF}}{BW} \quad (3)$$

In terms of the ability and capacity of LoRaWAN networks, several parameters are often mentioned, including duty cycle, collision, and the number of devices (n). The greater the value of n, certain it is that there will be many collisions, which will be shown in this paper in the analysis and results section [14]-[21].

$$P_{rx} = P_{tx} + G_{tx} - L_{Path} + G_{rx} - L_{misc} \quad (4)$$

$$L_{path} = 20\log_{10}(d) + 20\log_{10}(f) + 32.45 \quad (5)$$

$$\Delta f = f.\frac{v}{c}.\cos(\theta) \quad (6)$$

$$PDR = \frac{Number\ of\ packets\ received}{Number\ of\ packets\ sent}\ x\ 100\% \quad (7)$$

$$PLR = \frac{Number\ of\ missing\ Packages}{Number\ of\ packages\ shipped}\ x\ 100\% = (1 - PDR) \quad (8)$$

$$RSSI = -174 + 10.\log_{10}(BW) + NF + SNR \quad (9)$$

$$SNR = 10\log_{10}\frac{P_{Signal}}{P_{Noise}}\ dB \quad (10)$$

$$RTT = T_{received} - T_{send} - T_{processing} \quad (11)$$

$$ToA = T_{preamble} + T_{payload} \quad (12)$$

2.2. Okumura-Hata model

$$L_{Path} = 69.55 + 26.16\log_{10}(f) - 13.82\log_{10}(h_b) - C_h + |44.9 - 6.55\log_{10}(h_b)|\log_{10}(d) \quad (13)$$

2.3. Longley-Rice model

$$L = L_0 + L_s + L_e \quad (14)$$

2.4. Link budget LoRa

$$P_{rx} = P_{tx} + G_{tx} - L_{Cable} + G_{rx} - L_{Path} - L_{Fading} \quad (15)$$

2.5. Fresnel zone

$$r = 17.32x\sqrt{\frac{d1\ x\ d2}{f\ x\ d}} \quad (16)$$

2.6. LoRa range estimation based on spreading factor (SF)

$$\mathrm{d_{max}} = d_{ref}x10^{\frac{SNR\_\min - SNR_{ref}}{20}} \quad (17)$$

2.7. Data collision on LoRa

$$P_{collision} = 1 - e^{-2N\tau} \quad (18)$$

$$\int_{\Omega} \mathcal{L}(D_{collision}).\nabla x(\frac{\partial w_{lora}}{\partial t}) = d\Omega = \sum_{i=1}^{n} \alpha_i \iint_{\sum i} B.A^T.\digamma(x)d\sum \quad (19)$$

$$\Phi(s) = \lambda\int_a^b K(s,t).\Phi(t).\Delta_{LoRa}(t)dt + f(s) \quad (20)$$

$$\int_{\Omega} \mathcal{L}(D_{collision}).\nabla x(\frac{\partial w_{lora}}{\partial t})\ d\Omega = \oint_{\partial\Omega} \sum_{i=1}^{n} \alpha_i\, e^{i\theta_i} \iint_{\sum i}(B.A^T).\digamma(x)d\sum x \prod_{j=1}^{m} H_j(\xi) \quad (21)$$

$$H_j(\xi) = \frac{1}{2\pi i}\oint_{\gamma_j} \frac{g_j(z)}{z-\xi}\,\mathrm{dz.exp}\,(\int_0^{\tau} \frac{\Lambda(s)}{s^2+\omega^2}ds) \quad (22)$$

$$\Phi(s) = \lambda\int_a^b K(s,t).\Phi(t).\Delta_{LoRa}(t)dt + f(s) + \int_c^d \iiint_V \nabla^2\, \psi(r,\theta,\phi).e^{-k\|r-r_0\|^2 dV.\tau\,(s,t)} \quad (23)$$

$$E\left[\int_O^T \int_{R^d} \sigma(X_t^{\theta}, y).\nabla_{\theta} W_{LoRa}.dW_t dy\right] = \lim_{N\to\infty} \sum_{k=1}^{N} \beta_k.D^{\alpha}[F_k(t)] \quad (24)$$

$$Z[J] = \int D[\phi]exp(i\int d^4x[\mathcal{L}_{LoRa}(\phi, \partial_\mu\phi) + J(x)\phi(x)]) \quad (25)$$

3. METHOD

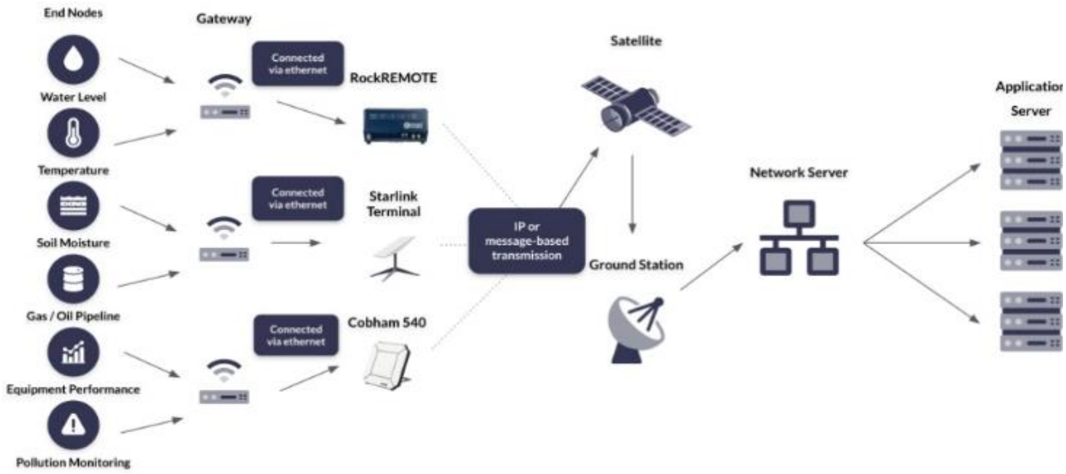
The next parameter is the signal-of-noise ratio (SNR) which can be related to the receive signal strength indicator where the SNR value will weaken from -7.5 dB at SF7 to -20 dB at SF12 [22]-[26]. This attenuation occurs because as the symbol duration increases, the receiver sensitivity increases, and Trade-off between range and SNR. Here is a graph of the increasing symbol duration depicted, and the LoRa Chrip shape at 125 kHz bandwidth and SF 7. The complete symbol duration on LoRa can be seen in Table 1 [27]-[31].

Table 1. Comparison of SF, BW, and symbol duration to the resulting bit-rate (bps)

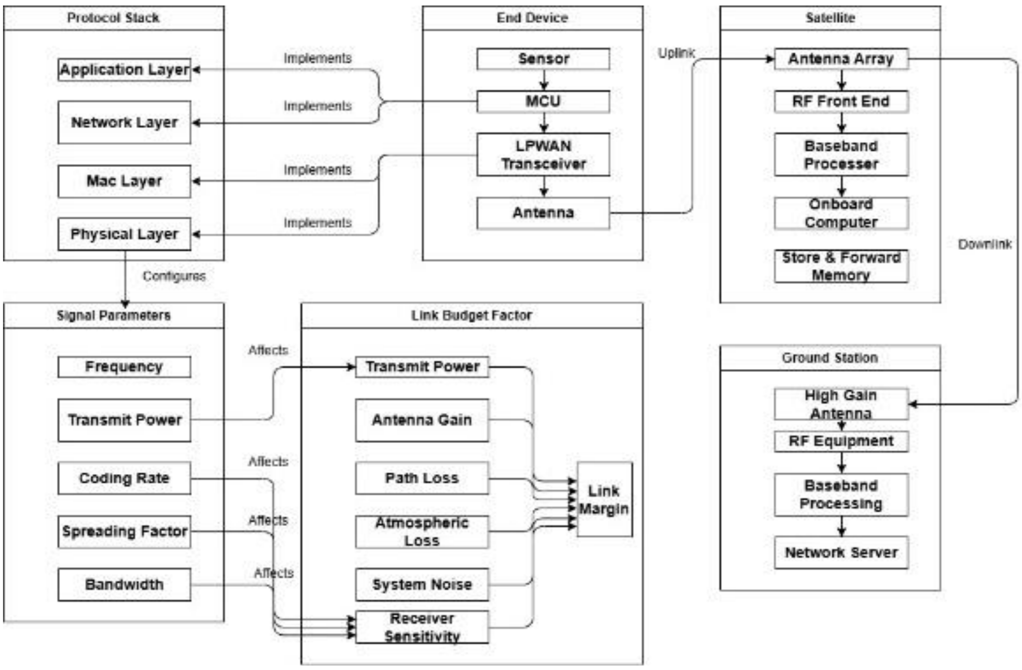
SF	BW (kHz)	Symbol duration (ms)	Bit rate (bps)
7	125	1.02	6835.94
7	250	0.51	13671.88
7	500	0.26	27343.75
8	125	2.05	3906.25
8	250	1.02	7812.5
8	500	0.51	15625
9	125	4.1	2197.27
9	250	2.05	4394.53
9	500	1.02	8789.06
10	125	8.19	1220.7
10	250	4.1	2441.41
10	500	2.05	4882.81
11	125	16.38	671.39
11	250	8.19	1342.77
11	500	4.1	2685.55
12	125	32.77	366.21
12	250	16.38	732.42
12	500	8.19	1464.84

Table 1 shows the variation of SF, BW, and symbol duration (ms), against the resulting bit rate (bps), we can see that bandwidth plays a big role in the creation of a large bit rate, so it takes a large bandwidth to get a large bit-rate as well, and is certainly supported by the smallest SF of 7. Conversely, if the

SF is the largest, it will produce the smallest bit-rate of 366.21 [32]-[36] with this bit-rate it can be ascertained that the Tx-Rx range on LoRa communication is the longest [37]-[41]. The structure of the LoRaWAN satellite communication system is shown in Figure 1, which consists of two main parts. Figure 1(a) shows the architecture of LoRaWAN satellite communication, and Figure 1(b) shows the flowchart of LoRaWAN satellite communication.



(a)

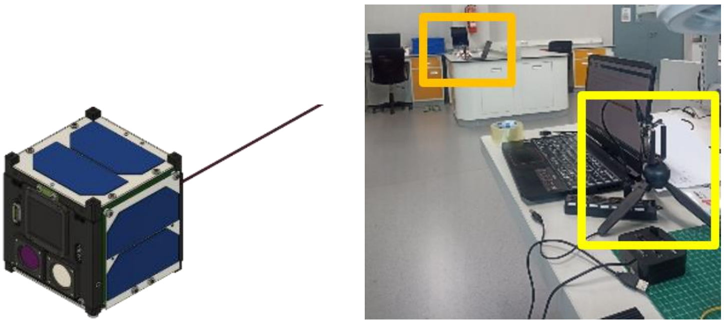


(b)

Figure 1. The structure of the LoRaWAN satellite communication system (a) LoRaWAN network satellite based (Source: Ground Control) and (b) flowchart of LoRaWAN satellite communication

4. RESULTS AND DISCUSSION

The overall experimental setup is shown in Figure 2, Figure 2(a) is an example of the SAT-1 Nano Satellite used as a data receiver from end-devices or ground stations on Earth, while Figure 2(b) is an example of LoRa module transmitter and receiver communication used for testing data transmission over short distances, which will then be continued in long-distance terrestrial communication and subsequently satellite communication. Meanwhile, Table 2 shows data on node differences with transmission, collisions, and collision rate data.



(a) (b)

Figure 2. Experimental setup (a) nano satellite SAT-1 [Source: nanosats.eu] and (b) end-nodes [Tx-Rx] LoRa testing at a certain distance, examples of communication affected by interferences

Table 2. Collision data based on different nodes

Nodes	Transmissions	Collisions	Collision rate
10	121.0	4.0	0.0328
50	639.3	97.0	0.1516
100	1265.7	374.3	0.2956

Moreover, Figure 3 illustrates the relationship between link margin, elevation angle, FSPL, and Doppler effect. The results indicate that SF7 exhibits the lowest link margin—approximately 120 dB at elevation angles below 20 degrees—while SF12 provides the highest, reaching around 130 dB at similar elevation angles. Under FSPL conditions, the signal attenuates with increasing distance, decreasing from approximately –50 dB at 100 km to about –140 dB at 600 km. Additionally, both the elevation angle and Doppler shift converge toward 0 when the elevation angle approaches 100 degrees. Meanwhile, Figure 4 specifically presents an SNR analysis showing that SNR decreases as the spreading factor increases. The time-on-air (ToA) also increases with higher spreading factors, while receiver sensitivity becomes more sensitive at higher SF values. For increased payload sizes, the ToA similarly increases. At different bandwidths—such as 125 kHz, 250 kHz, and 500 kHz—the chirp spacing of the LoRa modulation also differs, although higher bandwidths are less commonly used in standard LoRa operation. The spectrum becomes denser when higher frequencies and longer time durations are used, indicating higher intensity levels in dB.

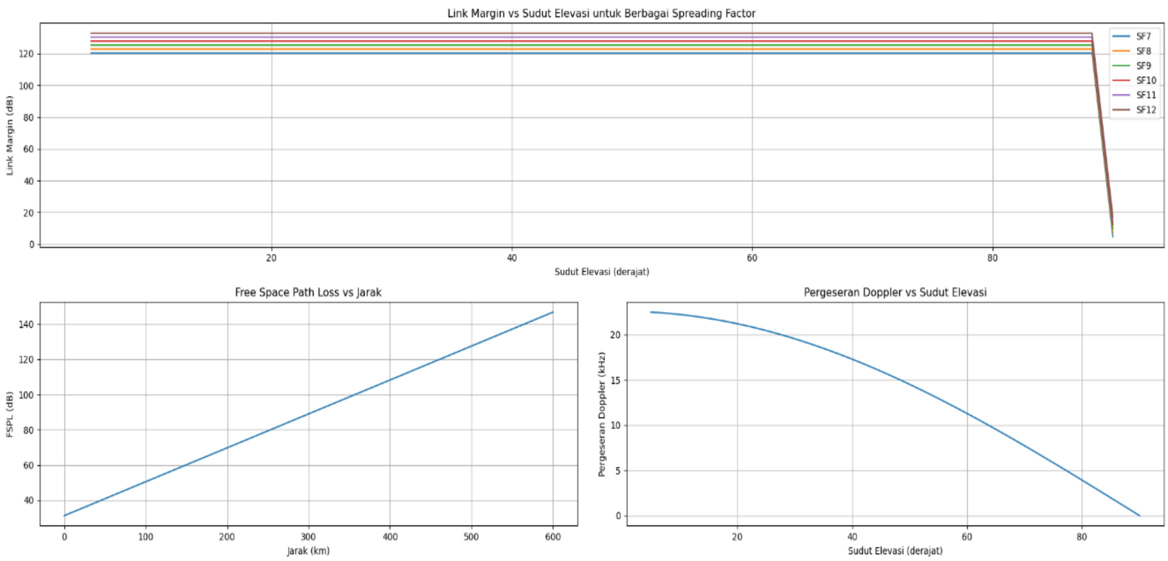


Figure 3. Link margin vs Elevation Angle, FSPL, and Doppler effect

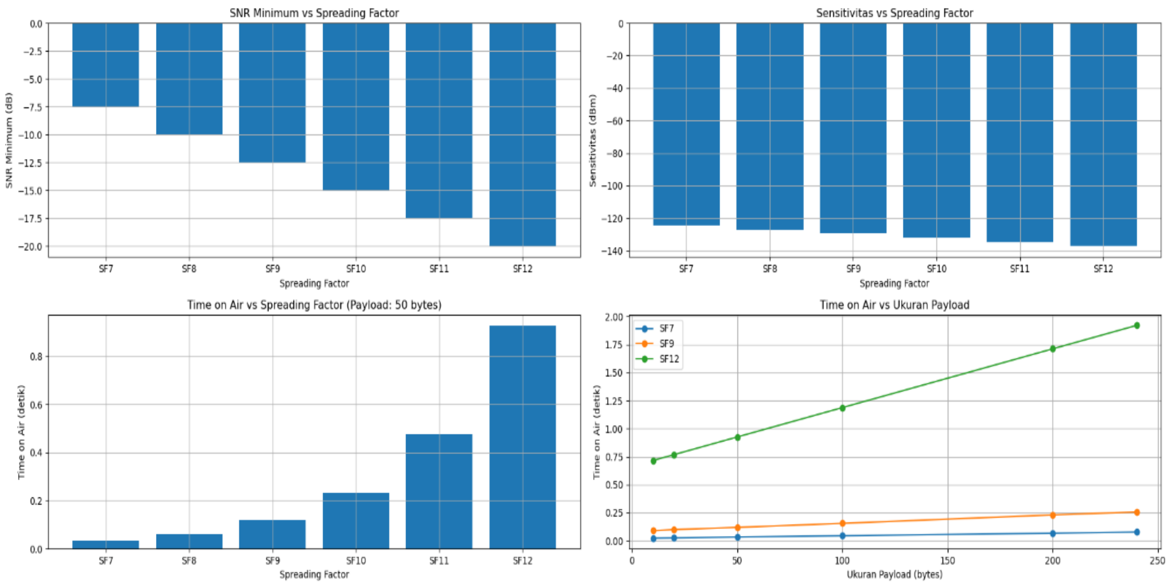


Figure 4. SNR minimum vs Spreading factor, sensitivity, and ToA

Furthermore, Figure 5 illustrates the LoRa chirp waveform for SF7 with a 125 kHz bandwidth, along with its corresponding spectrogram, which clearly shows the upward linear frequency sweep characteristic of LoRa's chirp spread spectrum modulation. This depiction also supports the analysis discussed earlier regarding bandwidth, frequency behavior, and signal intensity patterns in LoRa communication. In addition, Table 1 provides a clear comparison of the relationship between spreading factor (SF), bandwidth (BW), and symbol duration with the resulting bit rate (bps). It shows that higher spreading factors (e.g., SF12) produce lower bit rates, whereas lower spreading factors (e.g., SF7) yield shorter time-on-air (ToA). Furthermore, Figure 6 specifically shows the differences between SF7, SF9, and SF12 with the same bandwidth of 125 kHz, which is generally used by several LoRa modules, with different durations of 1.02 ms, 4.10 ms, and 32.77 ms. Meanwhile, Figure 7 shows the link margin and elevation angle of rainfall variation and water content in clouds, which will affect data transmission using LoRaWAN. the link margin vs elevation angle with rainfall variation (SF10), from the data it can be seen that the greater the rainfall in mm/h will cause the link margin (dB) to be smaller, otherwise, if there is no rain or 0 mm/h, the estimated link budget is at 120 dB.

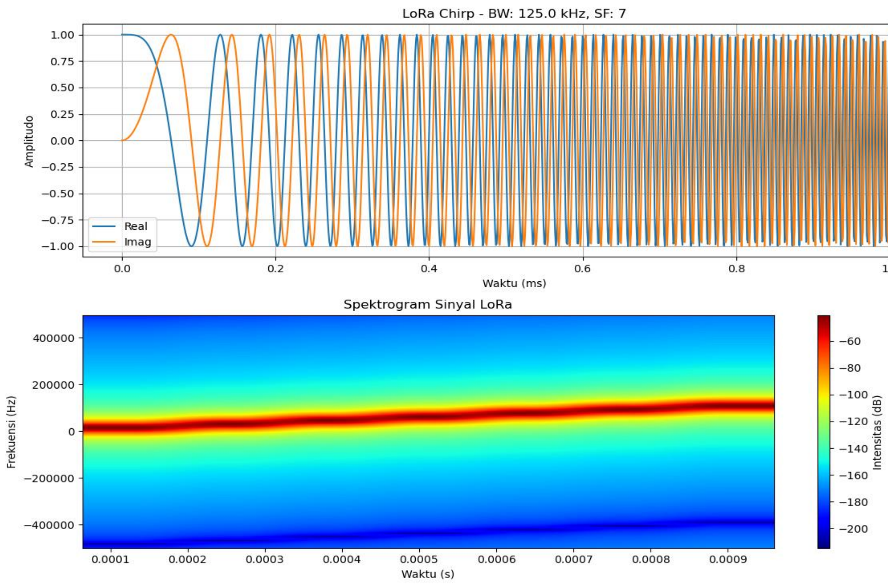


Figure 5. LoRa chirp with SF7, 125 kHz BW, and LoRa signal spectogram

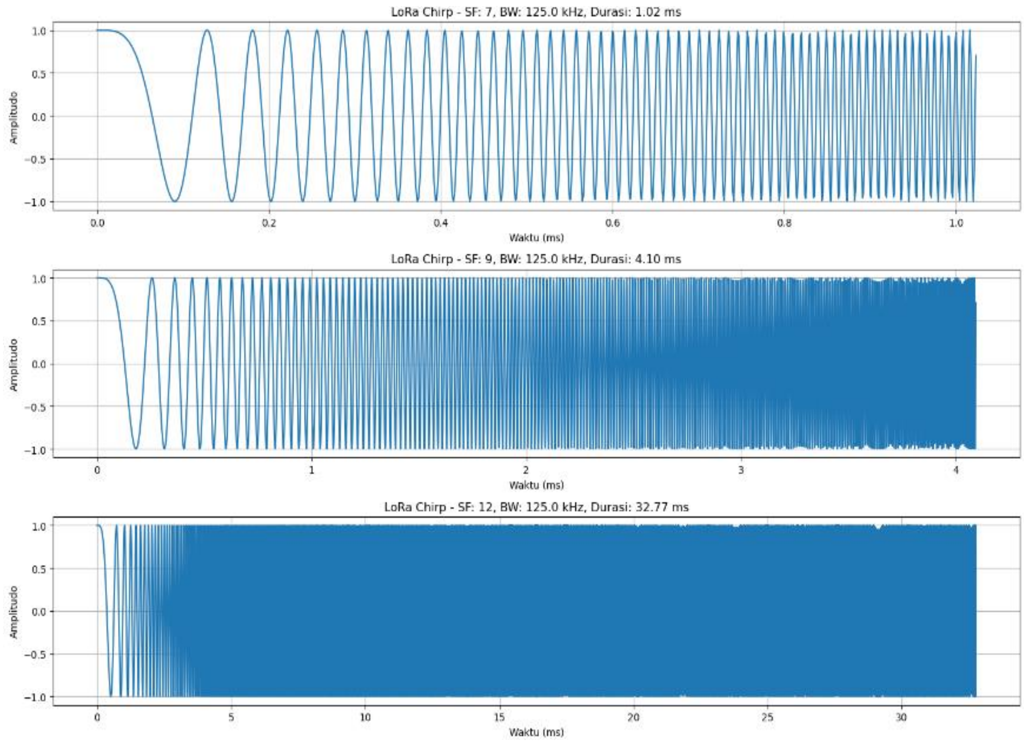


Figure 6. LoRa chirp with different SF, with 125 kHz BW and different durations

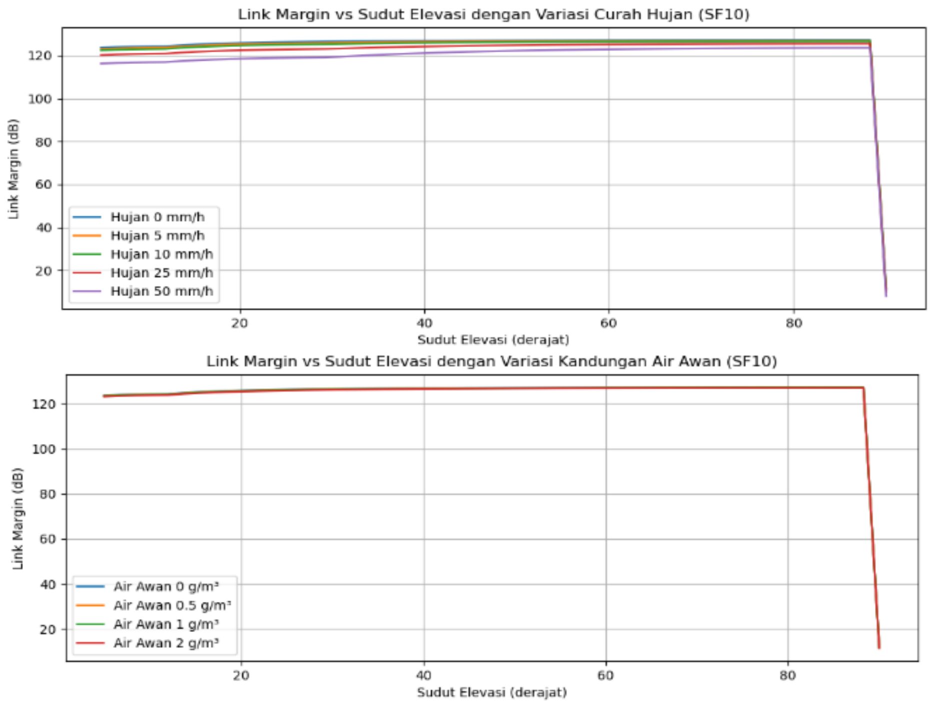


Figure 7. Link margin and elevation angle

Figure 8 shows various data, such as rain attenuation at an elevation angle of 20 degrees, cloud attenuation at an elevation angle of 20 degrees, atmospheric effects at an elevation angle of 20 degrees, and budget link components at an elevation angle of 20 degrees. Moreover, Figure 9 shows satellite distance data, SNR over time, received power over time, and packet transmission success rate. The overall analysis of collision behavior and success rate is shown in Figure 10, Figure 10(a) shows data on the number of collisions per time step and success rate over time with 10 nodes, while Figure 10(b) shows data on the number of collisions per time step and success rate over time with 100 nodes. From the data in Figures 10(a) and 10(b), with increasingly larger differences in nodes, collisions become more likely, so an improvement in the adaptive data rate (ADR) method is needed in this case.

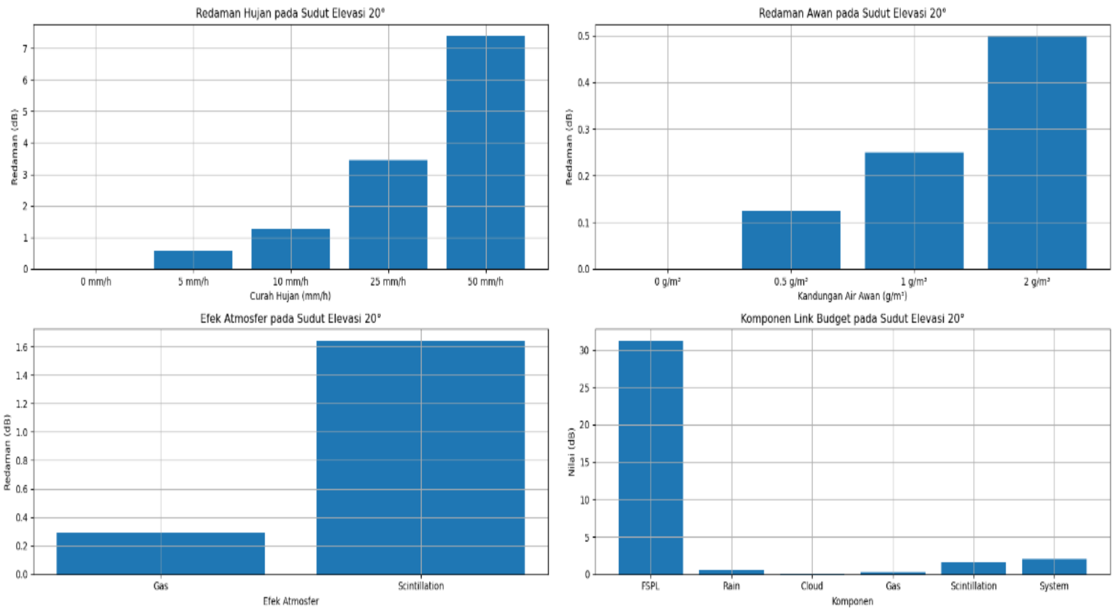


Figure 8. Rain attenuation, clouds, and atmospheric effects on link budget

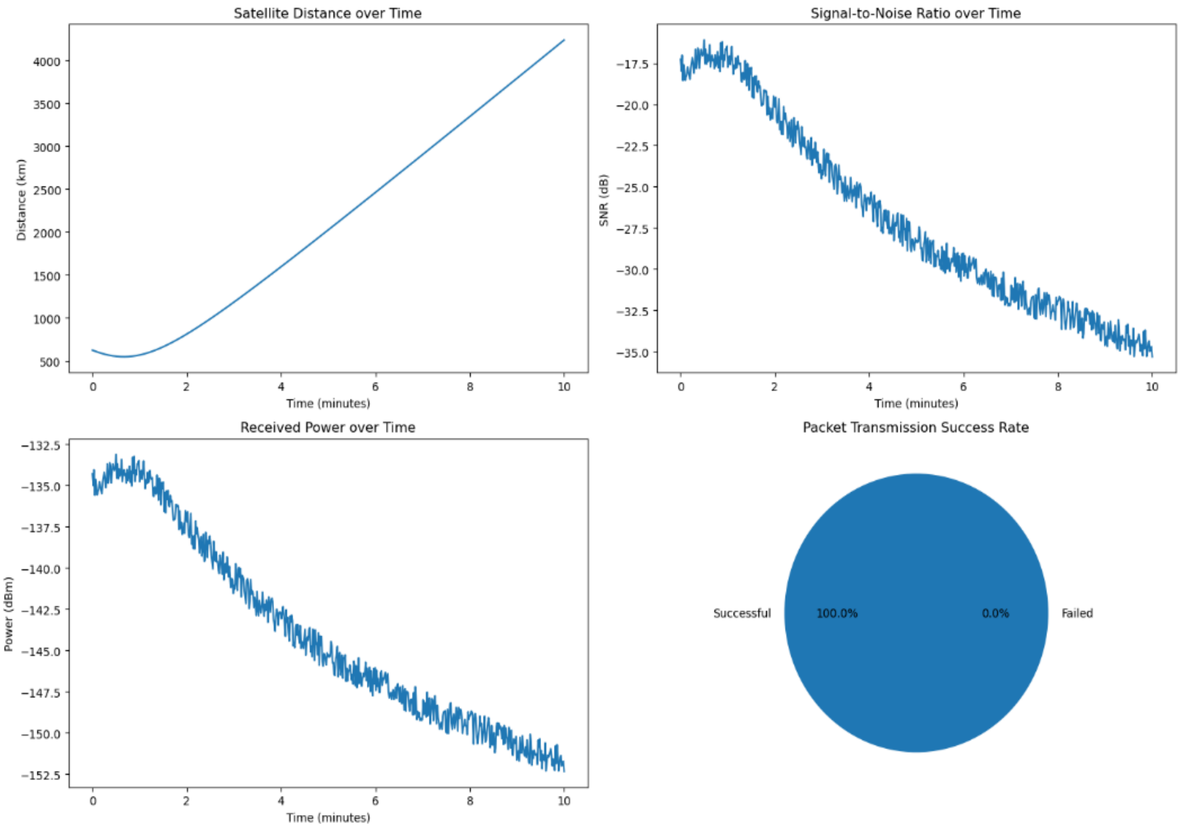
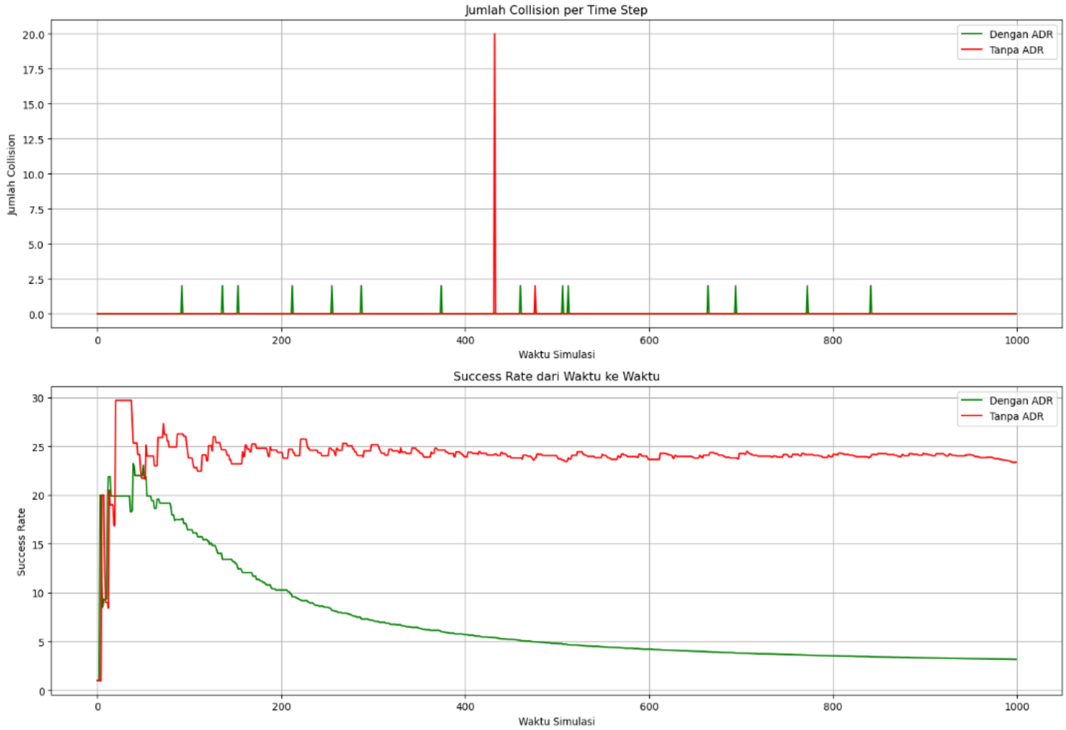
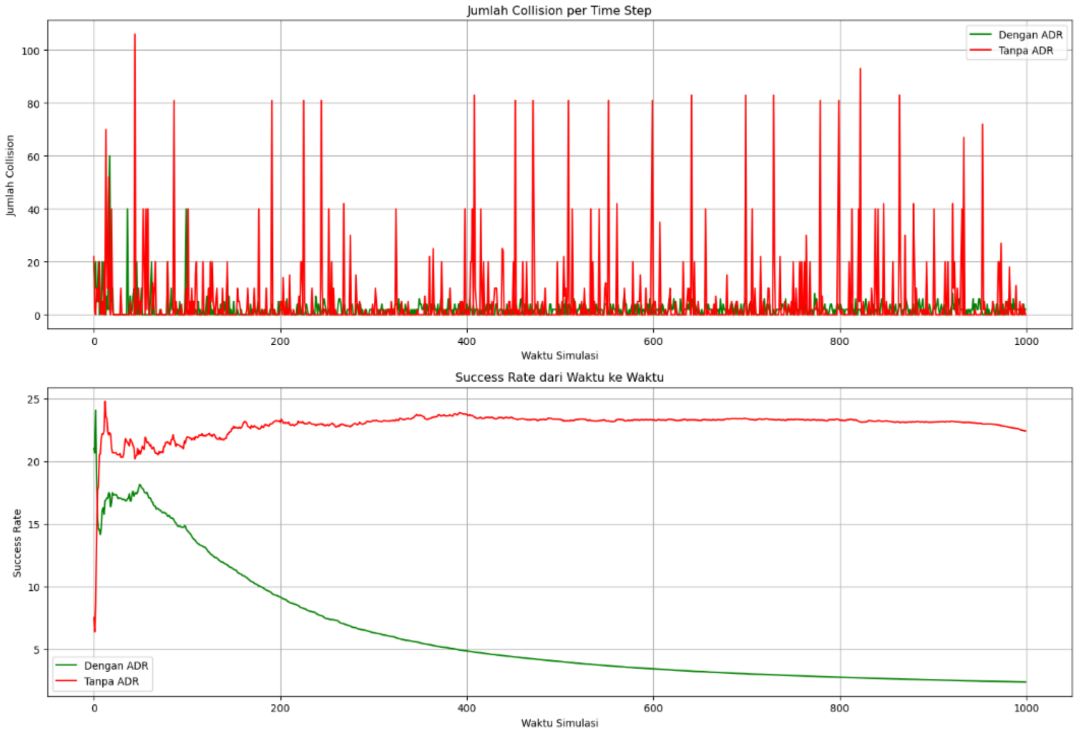


Figure 9. Satellite distance over time, receive power, SNR, and packet transmission success rate for LPWAN



(a)



(b)

Figure 10. The overall analysis of collision behavior and success rate (a) collision per time step with 10 nodes LoRa and (b) collision per time step with 100 nodes LoRa

5. CONCLUSION

In determining the quality of services (QoS) of LoRaWAN satellite communication, it is supported by various parameters including SF, bandwidth, CR, and other parameters. In the case of data collision reduction, several methods can minimize it, namely using ADR, protocol ALOHA, time synchronization, multiple channel access, frequency hopping, collision avoidance algorithm, scheduling transmission, beamforming, longer SFs, and gateway diversity, some of these methods are considered effective for minimizing data collisions to provide the right data as well as small packet loss. In LPWAN satellite communication is influenced by several factors even though it is in line-of-sight conditions but is still affected by the interference of rain and water content in clouds. Each parameter has a different coefficient value that if included in the simulation value will produce a percentage value of success that can be seen directly from the output graph. Where this percentage of success is influenced by the small amount of disturbance that exists, for example, there is no rain and cloud disturbance.

ACKNOWLEDGMENTS

Thanks to the entire team in several different agencies that helped in the smooth process of this writing or research, hopefully in the future it can be one of the references that is useful for many people, especially in the same discipline.

SUGGESTION

There is a need to build a real LPWAN Satellite based as done by Lacuna Space. And then this Satellite-based LPWAN can be used as optimally as possible to improve the performance of the IoT in the process of Transmitting data and Quality of Service on the Application Server or Internet Server.

FUNDING INFORMATION

The authors state no funding is involved.

AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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C : **C**onceptualization	I : **I**nvestigation	Vi : **Vi**sualization
M : **M**ethodology	R : **R**esources	Su : **Su**pervision
So : **So**ftware	D : **D**ata Curation	P : **P**roject administration
Va : **Va**lidation	O : Writing - **O**riginal Draft	Fu : **Fu**nding acquisition
Fo : **Fo**rmal analysis	E : Writing - Review & **E**diting	

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

- Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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