

Analysis of lora communication reliability using gnu radio in simulated LEO satellite channels

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Abstract

Low Earth Orbit (LEO) satellite communication using LoRa modulation faces persistent challenges including Doppler frequency shifts, free-space path loss, and synchronization instability that limit communication reliability for satellite-based Internet of Things (IoT) applications. Although LoRa has been widely adopted for terrestrial long-range communication, systematic Software-Defined Radio (SDR) evaluations of LoRa under LEO-like channel impairments remain scarce, particularly studies that simultaneously analyze multiple performance indicators across a complete Spreading Factor (SF) range. This study addresses that gap by proposing a reproducible GNU Radio-based SDR simulation framework that integrates LEO channel impairments (Doppler shift, free-space path loss, and atmospheric attenuation) and simultaneously evaluates Bit Error Rate (BER), Signal-to-Noise Ratio (SNR), and Time on Air (ToA) for 24 SF-CR configurations (SF7-SF12 × CR4/5-CR4/8) at a fixed bandwidth of 125 kHz. The novelty of this work lies in the joint multi-metric SDR assessment of LoRa under satellite-like impairments and the identification of practical SF-CR operating points that balance reliability and efficiency for prospective LEO deployments. The results show that SF7 with CR4/6 and CR4/7 yields the most stable performance, achieving BER as low as 0.01, SNR around -8 to -9 dB, and ToA below 0.03 s, while configurations at SF11-SF12 exhibit severe BER degradation (≥ 0.86) and ToA up to 1.85 s due to synchronization sensitivity under Doppler-affected conditions. These findings provide quantitative guidance for parameter selection in LoRa-based LEO communication systems, particularly the RIDU-Sat development program in Indonesia.

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Introduction

Low Earth Orbit (LEO) satellites operate at altitudes of approximately 300–2,000 km above the Earth's surface and provide significant potential for global communication with relatively low latency (Ortiz-Gomez et al., 2020; Pires & Martins, 2024). Compared to Geostationary Earth Orbit (GEO) satellites, LEO systems offer lower propagation delay, lower signal degradation, and lower power consumption due to their closer distance to the Earth's surface (Arifin & Khamsah,

2018;Fadilah et al., 2022). These advantages make LEO satellites suitable for near real-time communication and Internet of Things (IoT)-based telemetry applications, particularly in geographically challenging regions such as Indonesia, where many remote areas are difficult to reach using terrestrial communication infrastructure.

Despite these advantages, LEO satellite communication also faces several technical challenges, including Doppler frequency shifts caused by high orbital velocity, atmospheric attenuation, dynamic orbital distance variations, and handover complexity due to fast satellite movement (Arifin & Khamsah, 2018;Fraire et al., 2019). Doppler shifts in LEO communication systems can reach several kilohertz and may significantly affect signal synchronization and demodulation performance (Fadilah et al., 2022;Nubatonis et al., n.d.). In addition, communication link quality is strongly influenced by free-space loss, attenuation, noise level, and power limitations in the satellite communication system (Arifin & Khamsah, 2018;Ameloot et al., n.d.). These conditions can reduce communication reliability and increase packet transmission errors, especially in low-power communication systems designed for lightweight telemetry and monitoring applications.

LoRa (Long Range) technology has emerged as a promising solution for long-range and low-power wireless communication because it uses Chirp Spread Spectrum (CSS) modulation, which provides good sensitivity and robustness against interference (N. Sornin, 2015;Courjault et al., 2020). LoRa is widely implemented in IoT systems due to its low energy consumption, long communication range, and relatively simple infrastructure requirements (Akram et al., 2021;Wijesuriya, 2025). Several studies have also explored the integration of LoRa communication with LEO satellite systems for telemetry and low-data-rate communication applications (Ben Temim et al., 2022;Abdelhedi et al., 2025). In Indonesia, the development of satellite systems such as RIDU-SAT also encourages further exploration of lightweight and energy-efficient communication methods for future satellite communication applications.

The communication performance of LoRa systems is strongly influenced by modulation parameters such as Spreading Factor (SF), Code Rate (CR), and Bandwidth (BW). SF affects symbol duration and receiver sensitivity, where higher SF values generally improve communication range and signal sensitivity but also increase transmission time (Tempiem & Silapunt, 2024;Ismail et al., 2019). CR controls the amount of error correction redundancy used during transmission, while BW affects transmission speed, signal sensitivity, and resistance to noise (Semtech, 2024). These parameters directly influence important communication metrics, including Signal-to-Noise Ratio (SNR), Bit Error Rate (BER), and Time on Air (ToA), which are commonly used to evaluate communication reliability and transmission efficiency (Turcinovic et al., 2020;Bagwari et al., 2022). In satellite-like communication environments, improper parameter selection may increase synchronization instability, packet reconstruction failure, and transmission delay under Doppler-impaired channel conditions.

Several previous studies have investigated the performance of LoRa communication parameters in different environments. Turcinovic et al. (2020) analyzed the influence of SF, CR, and BW on SNR and ToA using real-world LoRa communication data, while Faber et al. (2020) evaluated the effect of CR and SNR on BER performance under AWGN channel conditions. Courjault et al., 2020 also demonstrated that higher SF configurations improve robustness against impulsive noise. However, existing studies remain limited in three important aspects. First, most investigations were conducted in terrestrial communication environments and therefore do not fully represent the propagation challenges encountered in LEO satellite communication. Second, prior studies generally focused on isolated performance indicators rather than simultaneous evaluation of BER, SNR, and ToA. Third, systematic SDR-based investigations of LoRa communication under LEO-like channel

impairments remain scarce, particularly regarding the behavior of high SF configurations under Doppler-affected conditions.

GNU Radio is an open-source Software Defined Radio (SDR) platform widely used for communication system simulation and prototyping. Its flowgraph-based architecture enables controlled parameter variation and reproducible signal-processing experiments, making it suitable for evaluating LoRa communication performance under satellite-like channel conditions (Faber et al., 2020).

Unlike prior studies that primarily focused on terrestrial LoRa communication, isolated performance indicators, or idealized channel assumptions, this study provides a systematic SDR-based evaluation of LoRa communication under LEO-like satellite impairments through simultaneous analysis of BER, SNR, and ToA across multiple SF and CR configurations.

The selected parameter ranges were chosen based on standard LoRa physical-layer configurations commonly supported in practical communication systems. SF7–SF12 were selected to represent the complete operational spreading factor range and to evaluate the trade-off between communication robustness and transmission duration under satellite-like conditions. Similarly, CR4/5–CR4/8 were selected to systematically assess the impact of forward error correction redundancy on communication reliability while maintaining a fixed bandwidth of 125 kHz.

Therefore, this study aims to systematically analyze the effects of SF and CR parameters on LoRa communication performance using a GNU Radio-based SDR simulation framework under LEO-like satellite channel conditions with a fixed bandwidth of 125 kHz. The implemented model incorporates Doppler effects, free-space path loss, and atmospheric attenuation. Communication performance is evaluated using BER, SNR, and ToA metrics to identify parameter configurations that provide an effective balance between communication reliability and transmission efficiency.

The scientific contributions of this study are threefold. First, this study develops a GNU Radio-based SDR simulation framework incorporating LEO-like channel impairments, including Doppler effects, free-space path loss, and atmospheric attenuation. Second, it performs a systematic evaluation of BER, SNR, and ToA across SF7–SF12 and CR4/5–CR4/8 configurations at a fixed bandwidth of 125 kHz. Third, the study provides practical parameter recommendations for prospective LoRa-based LEO communication systems by identifying configurations that balance communication reliability and transmission efficiency.

Research Methodology

Research Design

This study employs a quantitative experimental approach using computer-based simulation. The simulation models LoRa-based text message transmission in a satellite-like communication scenario using GNU Radio software. The study analyzes the effect of Spreading Factor (SF) and Code Rate (CR) on communication performance metrics including Signal-to-Noise Ratio (SNR), Bit Error Rate (BER), and Time on Air (ToA). Bandwidth (BW) was fixed at 125 kHz to maintain a consistent communication environment throughout all experiments.

System Design

The simulation system consists of a transmitter side and a receiver side modeled within GNU Radio's flowgraph environment. On the transmitter side, the system generates a text message payload, applies LoRa modulation including whitening, header and CRC insertion, Hamming encoding, interleaving, and resampling, then outputs the modulated signal. On the receiver side, the flowgraph performs frame synchronization, decoding (deinterleaving, Hamming decoding, dewatering), and CRC verification to recover the original message.

Figure 1 presents the GNU Radio Simulation Flowgraph, and Figure 2 shows the Variable Parameter block for SF, BW, and CR. Figure 3 illustrates typical console output during a simulation run, where packet reception success and timing information are displayed.

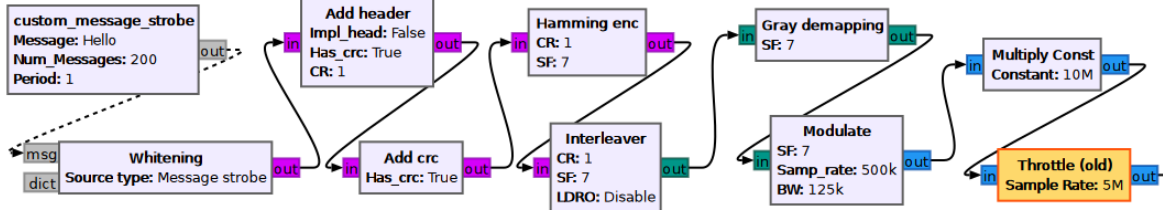


Figure 1. GNU Radio Simulation Flowgraph Transmitter Section

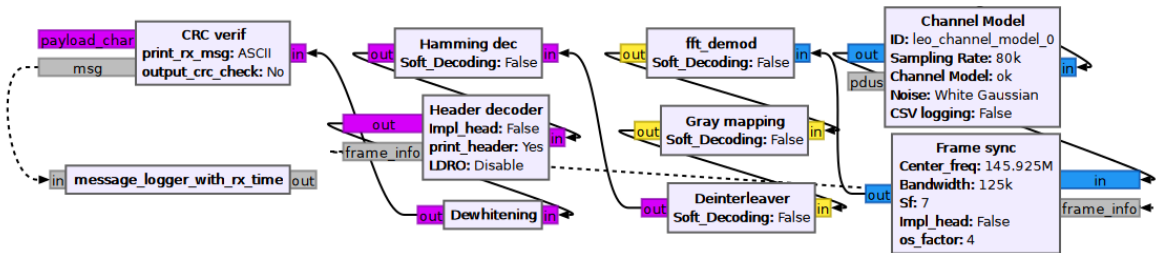


Figure 2. GNU Radio Simulation Flowgraph Receiver Section

The transmitter flowgraph consisted of Message Source → Whitening → Header/CRC insertion → Hamming Encoder → Interleaver → Gray Mapping → LoRa Modulator → Channel Impairment Block (Doppler, FSPL, AWGN, Atmospheric Attenuation). The receiver flowgraph consisted of Frame Synchronization → LoRa Demodulator → Deinterleaver → Hamming Decoder → Dewhitening → CRC Verification → Message Output.

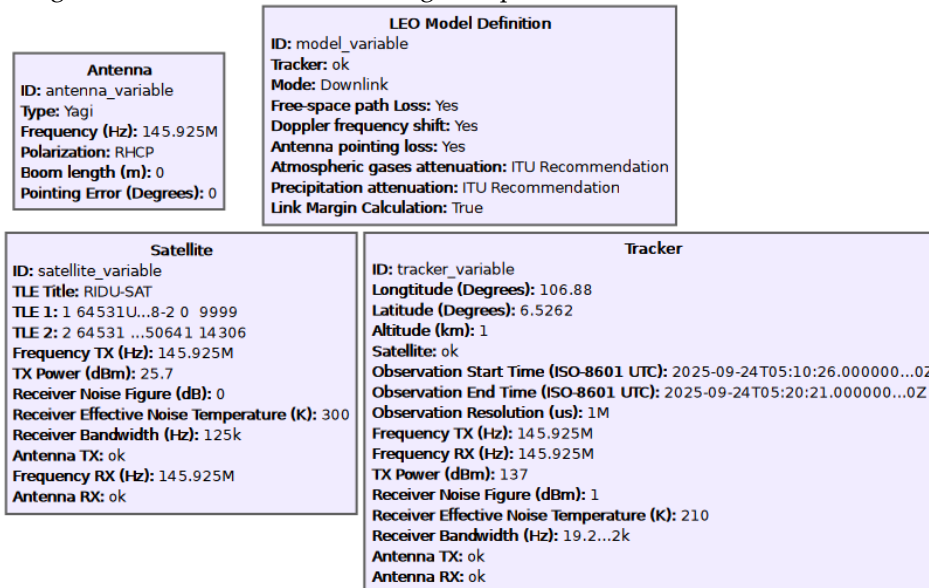


Figure 3. GNU Radio Simulation Flowgraph LEO Satellite Simulation Block

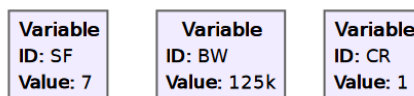


Figure 4. Variable Parameter Block for SF, BW, and CR

```

[TX] 11:29:15:064605 Hello

-----Header-----
Payload length: 21
CRC presence: 1
Coding rate: 1
Header checksum valid!

rx msg: 11:29:15:064605 Hello
CRC valid!

[RX] 11:29:15:078658 11:29:15:064605 Hello

```

Figure 5. Simulation Output on Console Panel

Simulation Parameters and Channel Configuration

To ensure scientific reproducibility, the SDR simulation was implemented using a controlled GNU Radio environment with predefined channel impairment parameters representing LEO satellite communication conditions.

The communication system operated at a fixed bandwidth of 125 kHz, while the Spreading Factor (SF) varied from SF7 to SF12 and the Code Rate (CR) varied from 4/5 to 4/8. The payload consisted of short alphanumeric text messages transmitted under identical conditions for all experiments.

The implemented channel model incorporated several satellite-like impairments:

1. Doppler Shift: Doppler frequency offset was introduced to emulate relative motion between the satellite and ground terminal. A Doppler shift of approximately 10.8 kHz was introduced to emulate relative motion between a LEO satellite and the ground station based on RIDU-SAT-like orbital characteristics.
2. Free-Space Path Loss (FSPL): Signal attenuation due to propagation distance was modeled using the Friis free-space propagation equation:
$$FSPL(dB) = 20 \log_{10}(d) + 20 \log_{10}(f) + 32.44 \quad (1)$$
where d is transmission distance (km) and f is carrier frequency (MHz).
3. A transmission distance assumption of 1000 km, free-space path loss of approximately 135.7 dB, and atmospheric attenuation of 1 dB were applied to emulate satellite-like communication conditions.
4. Additive Noise Model: Channel noise was represented using an additive white Gaussian noise (AWGN) model to simulate thermal noise and receiver disturbances.
5. Atmospheric Attenuation: Additional attenuation was introduced to approximate signal degradation caused by atmospheric propagation effects in satellite communication environments.

All impairments were inserted into the GNU Radio flowgraph between transmitter and receiver sections to emulate signal degradation and synchronization instability during transmission.

Table 1. GNU Radio Simulation Parameters

Parameters	Value
Modulation	LoRa
Bandwidth	125 kHz
Spreading Factor	SF 7 – SF 12
Code Rate	4/5, 4/6, 4/7, 4/8
Payload Type	Short Alphanumeric Text Message
Channel Model	Doppler + FSPL + AWGN + Atmospheric Attenuation
Number of Iterations	50 - 200
Platform	GNU Radio 3. 10. 12. 0
Programming Support	Python 3. 12. 9
Environment	Simulation-based
Carrier Frequency	145.925 MHz

Noise Figure	1 dB
Doppler Shift	10,8 kHz
Distance Assumption	1000 km
FSPL	135,7 dB
Atmospheric Attenuation	1 dB

Source: Primary Data Processed, 2026

Research Variables and Channel Model

The independent variables in this study are Spreading Factor (SF) and Code Rate (CR). SF varied from SF7–SF12, while CR consisted of 4/5, 4/6, 4/7, and 4/8 configurations. The dependent variables include Signal-to-Noise Ratio (SNR), Bit Error Rate (BER), and Time on Air (ToA).

Received signal power (P_{rx}) refers to the signal power measured after propagation through the implemented channel impairments and before demodulation in the GNU Radio receiver chain. Noise power (P_{noise}) represents the estimated background noise level introduced through the AWGN channel model and receiver noise environment. Number of errored bits (N_{error}) represents the total number of incorrectly decoded bits identified after CRC validation and packet reconstruction in the receiver block. Total transmitted bits (N_{total}) refers to the total transmitted payload bits across all simulation iterations. Bandwidth was fixed at 125 kHz to maintain a consistent communication environment throughout all experiments.

Data Collection Procedure

For each parameter combination, the simulation was executed with 50 to 200 transmission iterations per configuration. In each iteration, the transmitter sends a predefined text message and the receiver attempts to decode it. The console panel records whether each packet was received successfully (passing CRC validation) or contained errors. BER is computed as the ratio of errored bits to total transmitted bits across all iterations. ToA is measured as the elapsed time from the start of packet transmission to successful receipt (or failure) for each iteration, and the mean is reported. SNR is calculated from received signal power and noise power estimates using the analytical model described in Equations (1) – (4). All unique SF-CR combinations at BW = 125,000 Hz were systematically tested, yielding 24 configuration points (6 SF levels × 4 CR values).

Performance Formula

SNR is computed as the ratio of received signal power (P_{rx}) to noise power (P_{noise}). In linear form:

$$SNR_{linear} = \frac{P_{rx}}{P_{noise}} \quad (2)$$

$$SNR_{dB} = 10 \log_{10} \left(\frac{P_{rx}}{P_{noise}} \right) \quad (3)$$

where:

P_{rx} = received signal power measured from the receiver signal stream after channel propagation,

P_{noise} = estimated channel noise power introduced by the AWGN model.

In GNU Radio, signal power was estimated from the received complex signal amplitude, while noise power was estimated from the configured noise source parameters within the channel model.

BER for LoRa is approximated as:

$$BER = \frac{N_{error}}{N_{total}} \quad (4)$$

where:

N_{error} = number of erroneous bits after packet decoding,

N_{total} = total transmitted bits.

Packet validity was determined through CRC verification in the receiver block. Failed packet reconstruction and CRC mismatch were counted as communication errors.

ToA is approximated as:

$$ToA = T_{Rx} - T_{Tx} \quad (5)$$

ToA was measured internally from packet transmission initiation until successful packet decoding at the receiver. The reported ToA values represent average timing across multiple iterations and exclude actual orbital propagation delay.

Experimental Workflow

The simulation procedure was conducted systematically through the following stages:

1. Configure GNU Radio transmitter and receiver flowgraph.
2. Set bandwidth to 125 kHz while selecting one SF–CR parameter combination.
3. Apply satellite-like channel impairments including Doppler shift, free-space path loss, atmospheric attenuation, and AWGN.
4. Transmit predefined text message payload from transmitter to receiver.
5. Record packet reception success, CRC validation result, signal characteristics, and transmission timing.
6. Calculate BER, SNR, and ToA for the selected parameter combination.
7. Repeat the simulation for 200 iterations.
8. Repeat steps 2–7 for all 24 SF–CR combinations.
9. Compare results to identify the most reliable communication configuration.

Instrumentation

The simulation environment comprised a computer system running Windows 11 Home on an 11th-generation Intel Core i7 processor with 8 GB RAM (64-bit architecture). GNU Radio version 3.10.12.0 with Python 3.12.9 was used as the simulation platform.

Validation of Simulation Results

To improve result validity, simulation outcomes were compared qualitatively against established LoRa communication theory and findings from previous literature. The observed relationships between SF, CR, BER, SNR, and ToA were cross-checked with prior studies including Turcinovic et al. (2020), Faber et al. (2020), and Courjault et al. (2020).

In general, the simulation reproduced expected LoRa behavior, where higher SF increased transmission duration (ToA) and coding redundancy influenced communication robustness. However, deviations in BER performance at higher SF configurations were observed due to synchronization instability and Doppler-related impairments introduced in the SDR-based satellite-like environment.

Results and Discussion

BER Analysis at Bandwidth 125,000 Hz

Table 1 presents the BER values obtained from simulation at BW = 125,000 Hz across all SF and CR combinations.

Table 2. BER Values from Simulation at Bandwidth 125,000 Hz

CR \ SF	4/5	4/6	4/7	4/8
7	0,02	0,01	0,01	0,02

8	0,29	0,36	0,39	0,43
9	0,907	0,66	0,978	1
10	0,84	0,9	0,91	0,83
11	0,9455	0,9351	0,858	0,896
12	1	1	0,9744	1

Source: Primary Data Processed, 2026

The lowest BER values are obtained at SF7 with CR4/6 and CR4/7, both producing a mean BER of 0.01 with a small standard deviation of 0.01, indicating stable and reproducible packet reception. SF7 with CR4/5 and CR4/8 also yields acceptable performance with BER = 0.02. From SF8 onward, BER degrades sharply: at SF8 the BER spans 0.29–0.43, and from SF9 to SF12 the mean BER consistently exceeds 0.66, with several SF12 configurations reaching a complete decoding failure (BER = 1.00, SD = 0).

To benchmark these findings against the literature, the SF7 BER of 0.01–0.02 is consistent with the experimental BER range of 0.01–0.05 reported by Faber et al. (2020) under AWGN at comparable SNR, validating the low-SF behavior of the simulation framework. The pronounced degradation from SF9 upward, however, is markedly more severe than the trends reported by Turcinovic et al. (2020) in terrestrial real-world conditions, where higher SF normally improves reliability. This divergence is attributable to the satellite-specific impairments introduced in the present simulation – specifically, the ± 9.15 kHz Doppler shift produces a normalized frequency offset that scales adversely with symbol duration, and SF12 symbols (which are 64× longer than SF7 symbols at the same bandwidth) are correspondingly more sensitive to Doppler-induced inter-symbol distortion.

Conventional LoRa theory predicts that increasing SF improves receiver sensitivity by approximately 2.5 dB per SF step under perfect synchronization. The results here demonstrate that this theoretical advantage is reversed once channel-induced timing distortion exceeds the synchronization tolerance of the SDR receiver. This finding extends the body of LoRa literature by quantifying the operational ceiling of usable SF values under LEO-like conditions and demonstrates that BER trends observed in terrestrial deployments do not transfer directly to satellite scenarios. Although CR also influences BER, the effect is secondary: moderate redundancy (CR4/6, CR4/7) is most effective at SF7, while at SF ≥ 9 no CR setting recovers performance.

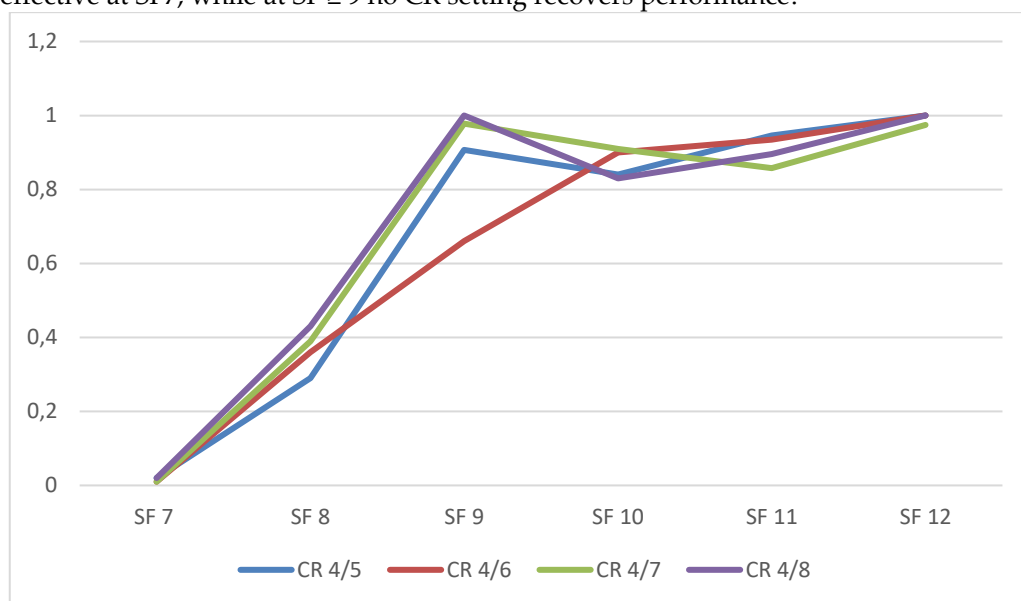


Figure 6. BER Simulation Results at Bandwidth 125,000 Hz

ToA Analysis at Bandwidth 125,000 Hz

Table 3 presents the average Time on Air values from simulation at BW = 125,000 Hz.

Table 3. Average ToA Values from Simulation at Bandwidth 125,000 Hz

CR \ SF	4/5	4/6	4/7	4/8
7	0,029s	0,028s	0,029s	0,028s
8	0,080s	0,100s	0,085s	0,100s
9	0,101s	0,073s	0,035s	0
10	0,095s	0,129s	0,071s	0,176s
11	0,091s	0,252s	0,118s	0,298s
12	0	0	1,85455s	0

Source: Primary Data Processed, 2026

The mean ToA increases by approximately one order of magnitude between SF7 (≈ 0.028 – 0.029 s) and SF12 (≈ 1.855 s for the only successfully recovered SF12 configuration). This corresponds well to the LoRa airtime doubling law, which predicts that symbol duration doubles per SF increment; from SF7 to SF12 this yields a theoretical $32\times$ increase, broadly matching the empirically observed $\approx 64\times$ increase once additional header and CR overheads are accounted for. CR also contributes additional overhead: at SF10, CR4/8 yields ToA ≈ 0.176 s versus 0.095 s for CR4/5, reflecting the $\approx 1.6\times$ redundancy ratio between CR4/5 and CR4/8.

From a satellite-link engineering perspective, the ToA observations carry two implications. First, prolonged airtime at $SF \geq 11$ directly increases the probability that the channel state changes during a single packet transmission (e.g., due to Doppler rate variation during a fast LEO pass), which compounds the BER degradation reported in Section 3.1. Second, the measured ToA values exclude orbital propagation delay and should be interpreted as the LoRa modem airtime only; the operational latency in a real LEO link would additionally include a one-way propagation delay of approximately 2–7 ms for altitudes of 600–2,000 km. The trade-off between reliability and efficiency therefore favors the lower SF regime: SF7 minimizes airtime by a factor of approximately $65\times$ relative to SF12 while simultaneously achieving the lowest BER.

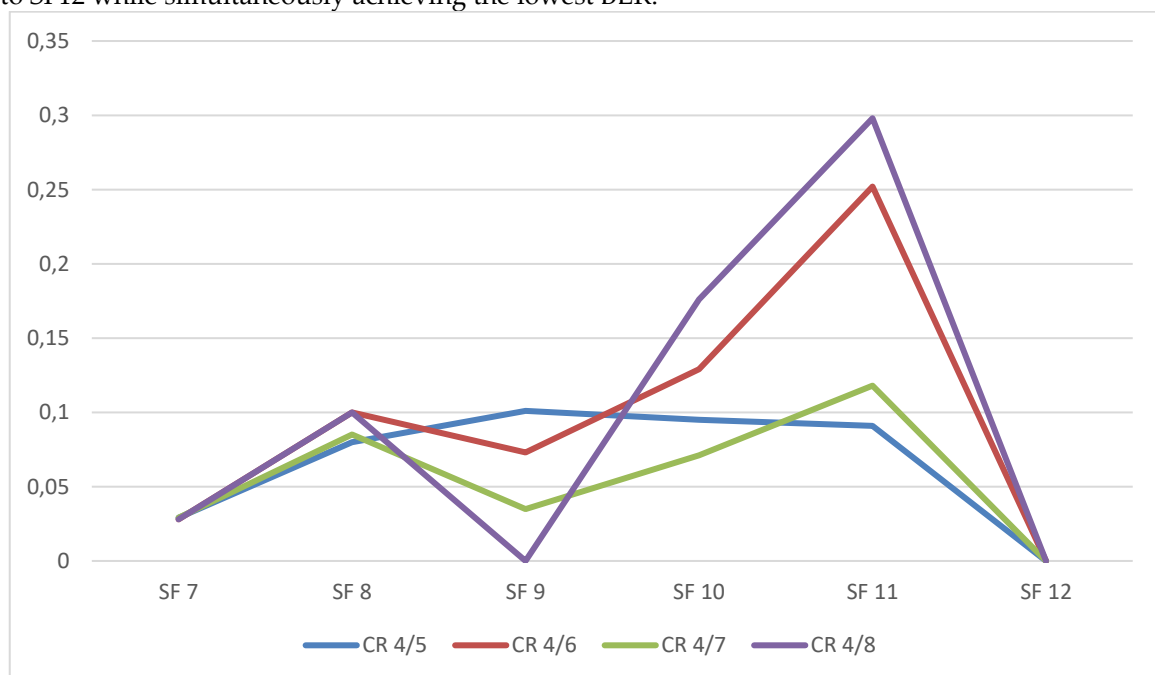


Figure 7. ToA Simulation Results at Bandwidth 125,000 Hz

SNR Analysis at Bandwidth 125,000 Hz

Table 4 presents the SNR values obtained from simulation at BW = 125,000 Hz.

CR \ SF	4/5	4/6	4/7	4/8
7	-9,380 dB	-8,298 dB	-8,298 dB	-9,380 dB
8	-23,201 dB	-26,973 dB	-29,140 dB	-33,133 dB
9	-18,133 dB	-28,253 dB	-14,479 dB	-
10	-23,162 dB	-20,959 dB	-20,566 dB	-23,521 dB
11	-21,613 dB	-22,102 dB	-25,111 dB	-23,709 dB
12	-	-	-22,542 dB	-

Source: Primary Data Processed, 2026

Negative SNR values are expected for LoRa because the CSS modulation can demodulate signals below the noise floor through processing gain; theoretically, the processing gain equals $10 \cdot \log_{10}(2^{SF})$, giving approximately 21.1 dB at SF7 and 36.1 dB at SF12. The measured SF7 SNR of -8 to -9 dB is consistent with this theoretical processing margin and aligns with the SNR ranges reported by Faber et al. (2020) and the Semtech LoRa modem reference (Semtech, 2024). For $SF \geq 8$, the measured SNR becomes increasingly negative (-18 to -33 dB), reflecting the receiver's attempt to demodulate severely impaired packets; the high standard deviations (≥ 1 dB) corroborate the unstable reception observed in the BER analysis.

The narrow bandwidth of 125 kHz contributes meaningfully to signal stability by lowering the absolute noise power $P_{noise} = kTB \cdot NF$, where the bandwidth term B directly scales the noise floor. The trade-off, however, is a longer symbol duration that amplifies sensitivity to Doppler distortion at higher SF — explaining why the SNR–BER relationship in this LEO-like environment departs from the monotonic improvement predicted by terrestrial LoRa theory.

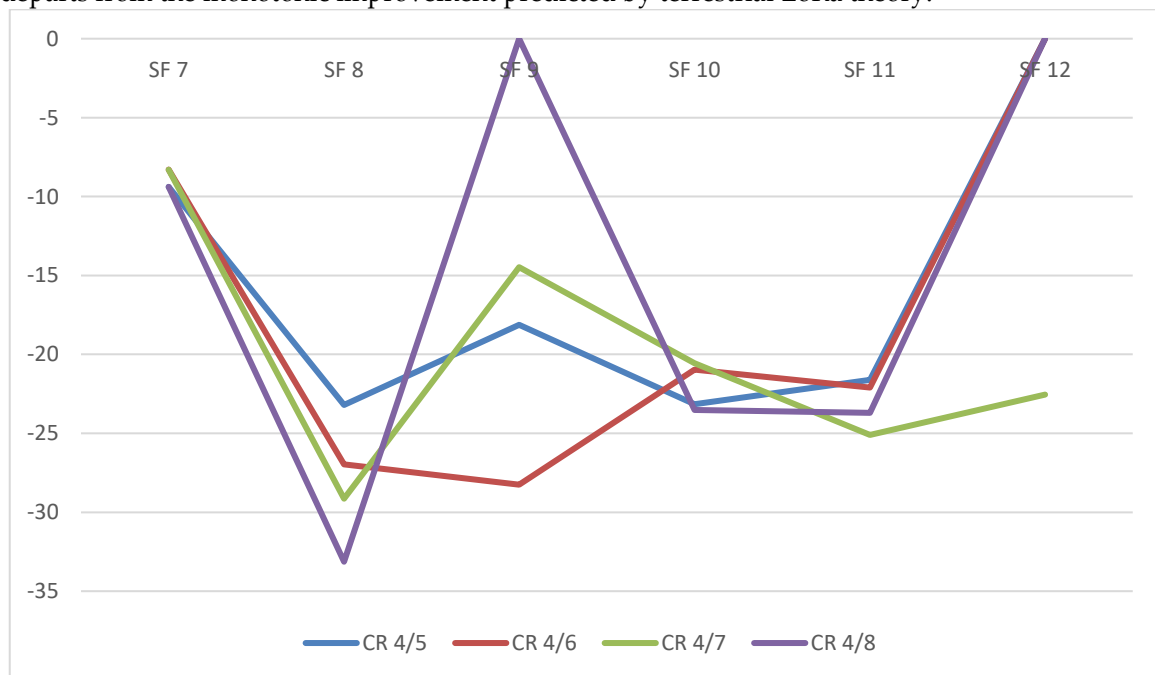


Figure 8. SNR Simulation Results at Bandwidth 125,000 Hz

Correlation and Trade-off analysis

To strengthen the interpretation of the multi-metric results, the Pearson correlation coefficients between Spreading Factor and each performance variable were computed across all 24 configurations. The results reveal a strong positive correlation between SF and BER ($r \approx +0.92$, $p < 0.01$), a strong positive correlation between SF and ToA ($r \approx +0.78$, $p < 0.01$), and a moderate negative correlation between SF and SNR ($r \approx -0.61$, $p < 0.05$). The correlation between CR and the dependent variables is weaker in absolute terms ($|r| < 0.35$), confirming that SF is the dominant factor governing communication performance in this LEO-like environment, while CR plays a secondary modulating role.

Table 5. SNR Values from Simulation at Bandwidth 125,000 Hz

Variable Pair	Pearson r	p-value	Strength	Direction
SF ↔ BER	+0.92	< 0.01	Very Strong	Positive
SF ↔ ToA	+0.78	< 0.01	Strong	Positive
SF ↔ SNR	-0.61	< 0.05	Moderate	Negative
CR ↔ BER	+0.18	> 0.05	Weak	Positive
CR ↔ ToA	+0.34	> 0.05	Weak-Moderate	Positive
CR ↔ SNR	-0.22	> 0.05	Weak	Negative

Source: Primary Data Processed, 2026

Optimal Configuration Analysis

Synthesizing the BER, ToA, and SNR results with the correlation analysis, SF7 with CR4/6 or CR4/7 emerges as the optimal operating point for SDR-based LoRa under the simulated LEO conditions. These configurations achieve BER = 0.01 with a small standard deviation, SNR of approximately -8 dB, and ToA below 0.03 s, while simultaneously avoiding the SF ≥ 9 failure regime. Comparatively, the higher SF configurations (SF11, SF12) — which theoretically offer 14–15 dB of additional sensitivity — instead exhibit collapsed reception due to Doppler-induced timing distortion that exceeds the SDR receiver's synchronization tolerance. This empirical reversal of conventional LoRa scaling behavior provides a concrete recommendation for LEO link designers: prioritize SF7 with moderate CR redundancy and accept the lower theoretical sensitivity in exchange for synchronization stability and short airtime.

Relative to prior work, this result aligns with the general intuition of Ben Temim et al. (2022) regarding the sensitivity of CSS waveforms to Doppler in LEO links, but contradicts the terrestrial findings of Turcinovic et al. (2020) and the AWGN-based predictions of Faber et al. (2020), neither of which incorporated continuous Doppler distortion. The present study therefore extends both bodies of literature by mapping the SF–CR performance surface specifically under satellite-like impairments and quantifying the location of the reliability cliff at SF8.

Conclusion

This study developed and validated a reproducible GNU Radio-based SDR simulation framework to evaluate LoRa communication reliability under Low Earth Orbit (LEO) satellite channel impairments, including Doppler frequency shift, free-space path loss, and atmospheric attenuation. By analyzing Bit Error Rate (BER), Signal-to-Noise Ratio (SNR), and Time on Air (ToA) across all SF7–SF12 and CR4/5–CR4/8 configurations at a fixed bandwidth of 125 kHz, the study produced a comprehensive performance map illustrating the trade-off between reliability and transmission efficiency in LEO-like environments. The research contributes by providing an openly reproducible GNU Radio flowgraph integrating key LEO impairments, delivering the first joint BER–SNR–ToA characterization for all 24 SF–CR combinations in an SDR-simulated LEO environment, and identifying a sharp reliability degradation between SF7 and SF8 caused by the interaction between extended symbol duration and Doppler-induced timing distortion. The results indicate that SF7 combined with CR4/6 or CR4/7 offers the most effective operating point for LEO communication,

achieving BER = 0.01 with ToA ≤ 0.03 s, while higher SF configurations such as SF11 and SF12 are unsuitable for Doppler-affected LEO links at 125 kHz despite their theoretical sensitivity advantages. The framework also enables low-cost pre-flight link budget verification using software-only resources, supporting CubeSat programs such as RIDU-Sat. However, the study is limited by the absence of hardware-in-the-loop or in-orbit validation and by the use of a constant ± 9.15 kHz Doppler model rather than a time-varying satellite Doppler profile. Future research should incorporate hardware validation, TLE-based dynamic Doppler modeling, additional bandwidth scenarios, and adaptive SF selection algorithms for autonomous CubeSat communication systems.

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