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A Hybrid Multi-Criteria and Factorial Analysis Framework for CIRFLINK CubeSats Communication Design

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Abstract

This research presents the design and optimization of a low-cost Inter-Satellite Link for the CIRFLINK project, a 1.5U CubeSat mission aimed at advancing smart farming and disaster monitoring in rural area. To address complex design trade-offs, this study introduces a novel integrated framework combining the Analytic Hierarchy Process for qualitative prioritization and 2^k factorial design for quantitative validation. The primary objective was to evaluate and optimize LoRa-based communication parameters for constrained satellite environments. Analytic Hierarchy Process results prioritized LoRa technology over optical and traditional RF subtypes due to its superior power efficiency and simplicity. Subsequently, 2^k factorial experiments and ANOVA revealed that distance and physical obstruction are the dominant factors affecting performance, while parameters like Spreading Factor and Bandwidth showed less immediate impact in the tested ranges. Experimental results using ESP32 and SX1278 modules demonstrated that the Signal-to-Noise Ratio and Received Signal Strength Indicator maintain reliable connectivity, with correlation analysis showing a strong negative relationship approximate -0.913b etween distance and signal quality. Field data confirmed that the system achieves stable communication with an average SNR in line-of-sight conditions. The novelty of this work lies in the systematic fusion of multi-criteria decision-making with statistical experimental design, providing a transparent engineering roadmap for small-satellite communication. This contribution offers a validated, cost-effective ISL solution that meets mission requirements with minimal complexity, serving as a scalable model for future educational and IoT-based CubeSat constellations.

Keywords: CubeSats Constellation, Analytic Hierarchy Process, Inter-Satellite Link, LoRa, APSCO Competition

1. Introduction

Over the past decade, there has been a notable growth in the popularity of small satellites, mainly CubeSats [1]. Satellite engineers are increasingly shifting away from bigger satellites due to the excessive costs associated with their development [2]. The traditional process of satellite development involves user requirements, system design, integration, testing and verification, which can be lengthy [3]. Consequently, the project may become outdated by the time they are launched, as technology develops rapidly. The development of small satellites is typically more cost effective and faster in the development process. Although there are concerns regarding the capabilities of small satellites if compared to bigger counterparts. As a result of the advancements in electronics and space technology have led to trends preferring smaller and lighter systems that can distribute performance comparable to that of larger devices [4]. Moreover, there have been significant advancements in key components, such as printed circuit board technology, powerful processors on FPGAs, the satellite subsystems availability of commercial-of-the-shelf as name COTS and other devices [5], [6]. Subsequently, small satellite capability is now comparable to the bigger satellite with great efficiency [7]. This alteration not only decreases time and budget constraints but also offers greater opportunities for young engineers, beginner satellite developers, and students to enhance their skills on real satellite development projects [8].

In the coming years, aging society and declining agricultural workforce will intensify the need for automation in managing farmlands and monitoring environmental conditions [9]. This challenge highlights the importance of adopting modern technologies to transform traditional agriculture into a smart farming model, which leverages data and advanced sensing tools for particular environmental assessment and data-driven decision-making [10]. The

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integration of such technologies aims to enhance efficiency while reducing labor dependency and providing early warnings of not normal weather or environmental changes. The CIRFLINK project addresses these national priorities by exploring the use of CubeSats satellites to strengthen smart farming and disaster monitoring capabilities. Through CubeSats-based Internet of Things (IoT) connectivity [11]., CIRFLINK pursues to extend communication coverage to remote areas.

The primary objective of CIRFLINK is to collect environmental data from ground-based IoT devices via a CubeSats operating in LEO, focusing on key parameters such as temperature, humidity, moiser, and other parameters. A secondary objective is to demonstrate the operational feasibility of an ISL between two CubeSats, which enhances data relay efficiency and ensures communication reliability within the constellation.

2. Literature Review

2.1. CubeSat technology

The market for nanosatellites and microsatellites is projected to grow substantially, as indicated by recent industry forecasts [12]. As illustrated in figure 1, the number of nanosatellite and microsatellite deployments is expected to accelerate significantly between 2023 and 2032 [12]. The increasing balance between hardware, software, and launch service revenues implies a growing ecosystem that integrates advanced technology of data processing abilities, hardware and competitive launch infrastructure. These are the key expected to insure the market growth through year 2032.

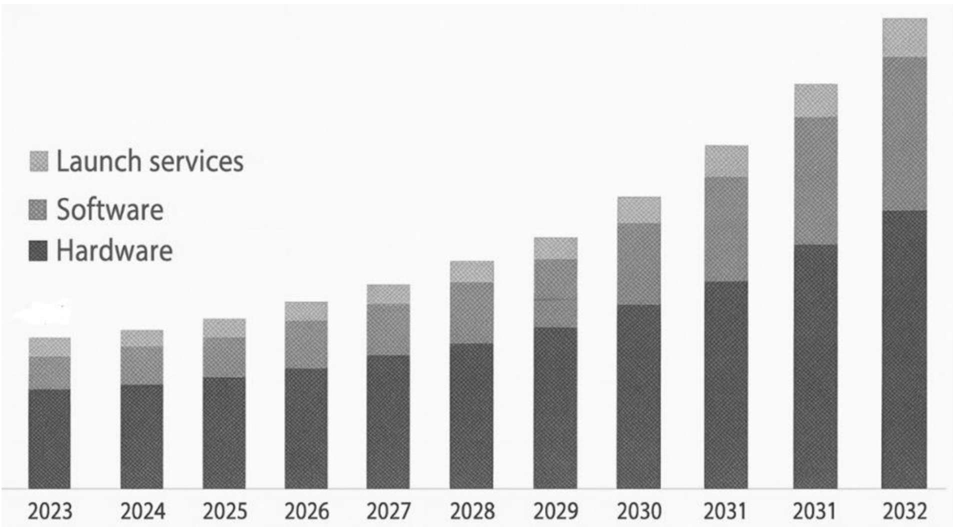

Figure 1. Nanosatellite and Microsatellite Market Analysis 2022-2023, USD Billion.

CubeSats have been in development for more than 25 years. The standard structure is 10 cm × 10 cm × 10 cm or 1U with a maximum mass of 1.3 kg. CubeSats are classify in microsatellites or nanosatellites as a result of their compact size. CubeSats are normally in a cubic form factor but can be configured into extended sizes, such as 1U, 1.5U, 2U, 3U, 6U, or 12U, to provide additional space for equipment and increase functionality [13]. These extensions allow CubeSats to integrated more devices to support the variety mission capabilities. Figure 2 Illustration of standardized CubeSats form factors ranging from 1U to 12U configurations. Each unit represents 1U, which can be stacked to achieve the desired satellite volume according to mission requirements [14].

The CubeSats standard are defined in the CubeSats Design Specification (CDR) document, which inform the general requirements for constructing CubeSats. There is the information of the mechanical, electrical, operational, and testing required for CubeSats development. Most of the CubeSats are deployed by the Poly-Picosatellite Orbital Deployer (P-POD), which functions as the interface between the CubeSats and the launch vehicle, allowing launch providers to organize CubeSats as secondary payloads [14].

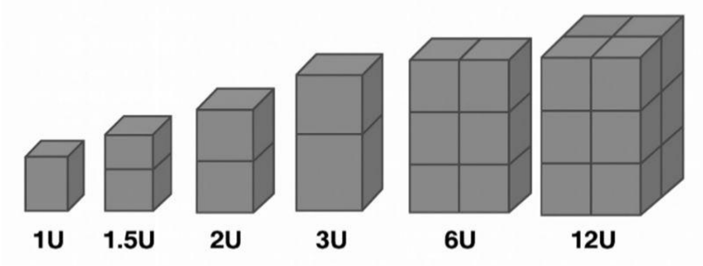

Figure 2. The CubeSats standard and extendable to larger sizes.

Initially, CubeSats were developed with the primary objective of providing university students with hands-on practical training in designing, building, testing, and operating real small satellites. Subsequently, CubeSats have evolved to support a wide range of applications. Nowadays, there are many CubeSats have been launched and operated in the difference missions. For instance, several early CubeSats missions were developed primarily as educational platforms, such as AAU CubeSat [15], and CubeSat XI-V [16] which provided hands-on experience for university students while demonstrating basic space technologies. CanX-1 and COMPASS-1 missions were designed as technology-demonstration projects to validate experimental systems in the space environment [17],[18],[19]. SwissCube-1 and QB50 missions were intended for the scientific research demonstration on space [4],[20]. PharmaSat mission was biological experimentation [21]. FLOCK-1 mission was for the remote sensing [22].

CubeSats technology have become an important platform for education and research in academic institutions and private companies. Nevertheless, CubeSats development projects conducted at universities remain highly challenging due to limited funding, strict time constraints, frequent student turnover upon graduation, and insufficient space-rated laboratory facilities. These limitations have significantly affected the overall development of CubeSats, influencing both the project schedule and the satellite's performance quality [13],[19].

The large satellite such as the Geo-stationary communication satellites have required massive budget and longer development times due to the design, manufacturing, integration and testing complexity. According to the 2022 International Telecommunication Union or ITU global connectivity report, approximately 37% of the world's population did not have internet access due to there are gaps between coverage area [23],[24]. In recent years, the concept of small satellite constellations has emerged as a promising alternative to traditional large satellites. These constellations consist of multiple small satellites operating cooperatively in Low Earth Orbit to achieve communication worldwide [25]. The study illustrates that these constellations can provide widespread Earth surface coverage and reduce latency [26]. However, mega-constellation system still requests many small satellites as reflect to the development budget. Advances in modern electronic technologies, which have become smaller and more efficient, have made small satellite constellations feasible with higher performance and lower cost.

Starlink, Telesat, and OneWeb represent the leading examples of Low Earth Orbit satellite networks [27], [28]. These extensive constellations of small satellites provide global service coverage, indicating the high potential and scalability of this technology. The continuing development and deployment of such systems indicate significant future advancements in Low Earth Orbit satellite communication infrastructure. Figure 3 shows the operating concept of a satellite-based store and forward system. This concept involves starting successful communication between a terrestrial station and the satellite for effective unlinking. Later, the data is stored in the satellite via this uplink. Finally, the stored data can be downloaded to another ground station for delivery or forwarding to its intended destination [29][30].

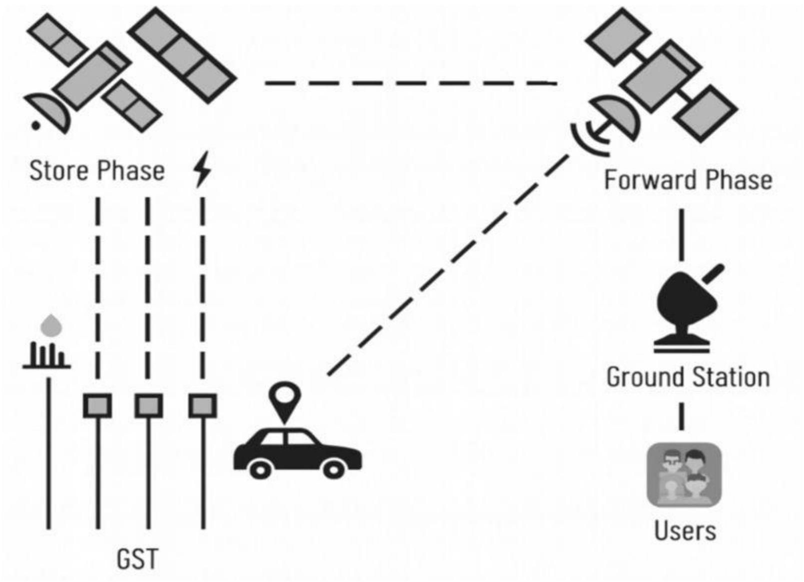

Figure 3. Conceptual illustration of the Store-and-Forward communication architecture in CubeSats systems.

Currently, digital technology plays a significant role in Thailand's agricultural industry, supported by the government's Thailand 4.0 initiative and the push towards smart farming. This movement includes the application of technology for real-time monitoring of agricultural production, environmental conditions, and weather through internet based smart systems. However, a significant challenge remains, as rural areas in Thailand still face limitations in internet accessibility, which restricts the effective adoption of smart agriculture technologies [31]. For smart farming and disaster monitoring to be effective, internet connectivity is essential for collecting, storing, and analyzing data. The absence of internet access in remote areas leaves farmers and residents without crucial information and alerts, limiting their ability to engage in smart farming or mitigate disaster impacts.

The communication system is one of the most critical and challenging aspects in satellite design, as it directly affects mission success and data reliability. For small satellites, this challenge becomes even more significant due to strict constraints on power, size, and antenna performance. Consequently, numerous studies have been conducted to explore various communication techniques suitable for small satellite constellations, with particular attention given to low-power technologies such as LoRa for space-based communication [32],[33]. LoRa modules can be used in the development of CubeSats receiver capable of functioning in isolated and limited resource environments [34]. Similarly, LoRa-based nanosatellite networks feasibility illustrated that the signal transmission remains stable under several environmental constraints. Additionally, LoRa's power efficiency is benefits in nanosatellite-based applications [34].

Although these works established LoRa's potential in space systems, they generally lacked a comprehensive design and evaluation framework that combines decision support tools and statistical analysis to optimize system performance under varying real-world conditions. To address this challenges, recent works explore integrating structured methodologies like the Analytic Hierarchy Process (AHP) to evaluate and prioritize communication parameters in constrained environments [35],[36]. AHP allows for systematic selection of key variables based on technical criteria, such as data rate, energy efficiency, and hardware compatibility [37]. Moreover, experimental designs like 2k factorial analysis assess the influence of factors such as spreading factor, bandwidth, and coding rate on transmission quality metrics, including Received Signal Strength Indicator (RSSI) and Signal-to-Noise Ratio (SNR) [38], [39]. Combined with statistical tools such as correlation analysis, this approach provides a complete framework for understanding system behavior in real world environments [40].

2.2. APSCO CubeSat Competition

APSCO was established in 2008 as an international entity designed at encouragement peaceful space activities for developmental progress across the area. Through shared resources in space science, technology and applications. APSCO supports member stages to leveraging space technology by encouraging multilateral collaboration on projects.

APSCO enhances the capacity of its member states, which include Bangladesh, China, Mongolia, Pakistan, Peru, Thailand, Iran and Turkey.

The APSCO CubeSats Competition (ACC), organized and funded by APSCO, establishes a collaborative framework for member states to enhance educational systems and actively involve university teams. The competition is designed to approximately 36 months from start to finish to develop Engineering Models (EM) of CubeSats. The mission concept allows flexibility within a 3U CubeSats format, enabling teams to propose configurations such as a 3-unit combination of 1U, 1U and 2U CubeSats or a 1.5U and 1.5U pairing. The ACC provides university students in member states with hands-on, practical experience in space engineering. Selected teams from each country advance through the phases of detailed design and EM development, where the EM must demonstrate adherence to the CubeSats Development Manual (CDM) and achieve validated performance standards based on comprehensive design evaluations. Therefore, Thammasat University by Faculty of Engineering attend the competition with the student team and pre-designing CubeSat mission with the name of CIRFLINK. Thammasat University team won the prices to be the representative of Thailand to attend the next phase of ACC project.

2.3. Statistical Validation using Correlation Analysis

Statistical validation is an essential step in evaluating the consistency and reliability of relationships among variables in engineering or system design studies. In this section, correlation analysis is used to verify whether the observed relationships between two quantitative parameters (e.g., signal strength vs. distance, power vs. temperature, or throughput vs. link margin) are statistically significant and directionally consistent with theoretical expectations [41],[42]. The Pearson Correlation Coefficient (r) is the most commonly used measure for linear correlation between two variables X and Y as in (1)

$$r = \frac{\sum_{i=1}^{n}(X_i - \bar{X})(Y_i - \bar{Y})}{\sqrt{\sum_{i=1}^{n}(X_i - \bar{X})^2 \ \sum_{i=1}^{n}(Y_i - \bar{Y})^2}} \tag{1}$$

Xi, Yi: observed values of the two variables; X¯,Y¯: mean values of X and Y; n: number of paired observations. The resulting value of r ranges between −1 and +1: r =+1: perfect positive correlation (both increase together); r =−1: perfect negative correlation (one increases, the other decreases); r = 0 : no linear correlation.

2.4. CIRFLINK CubeSats Project

2.4.1. Operation Scenario

The CIRFLINK operation scenario is illustrates in figure 4. The system comprises two 1.5U CubeSats, CIRFLINK-A and CIRFLINK-B together with ground-based IoT terminals and a ground station. The operation begins each IoT nodes deployed in smart-farming areas, rural regions, and maritime vessels transmit environmental data. Parameters include values such as humidity, temperature, time, location, and other parameters. The sensor data is directly transmitted to CIRFLINK-A through the uplink. The data are temporarily stored and relayed to CIRFLINK-B via the ISL. The constellation is designed to enable ISL, allowing bidirectional data transfer between the two spacecraft. CIRFLINK-B then forwards the collected data to the ground station through the downlink. The ground segment processes and uploads validated information to the server, where it becomes accessible to multiple stakeholders, including government agencies, farmers, students, and researchers for decision-making, analysis, and educational use.

The ISL between CIRFLINK-A and CIRFLINK-B allows for efficient data relay in orbit, ensuring continuous coverage and reducing latency in data delivery. This capability enhances the overall system performance by enabling store and forward operations even when a direct line of sight to a ground station is unavailable.

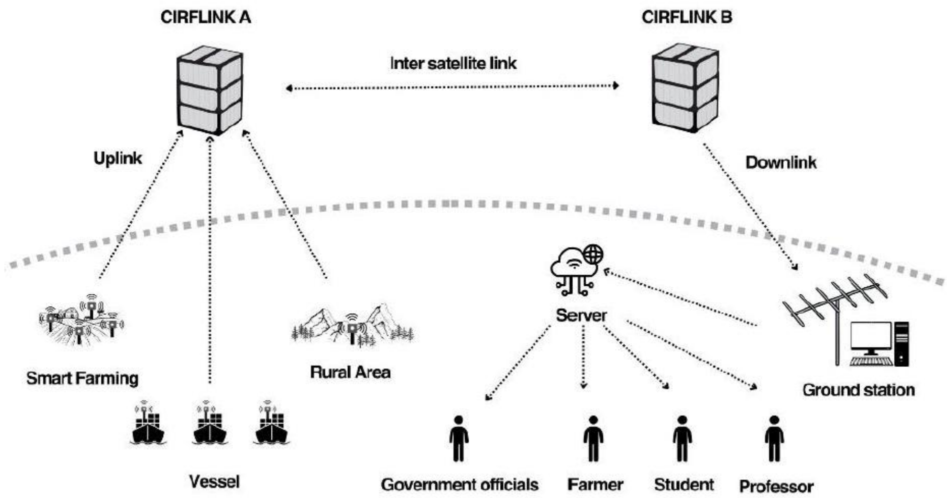

Figure 4. CIRFLINK Operational scenario.

The operation scenario section, two CIRFLINK CubeSats assuming deployed into Sun-Synchronous Orbits (SSO) at 600–800 km altitude with an orbital period of approximately 102 minutes, consistent with typical SSO mission parameters [43],[44]. Due to small differences in orbital elements such as semi-major axis, RAAN, and mean anomaly. CIRFLINK-A and CIRFLINK-B display relative along-track drift, generating cyclic variations in inter-satellite separation ranging between a few kilometers to several hundred kilometers over multiple orbits, which aligns with recognized formation-flying behavior in LEO CubeSat missions [45],[46]. The UHF-band inter-satellite link (400–403 MHz, 4.8–19.6 kbps) requirement therefore be scheduled around discrete visibility windows where the slant range remains within separational ranging and the angular separation, affecting link acquisition and pointing requirements as also characterized in LEO ISL constellation studies [47],[48]. These orbital-geometry constraints contact durations of typically recurring multiple times per day depending on CubeSats ISL performance [49],[50],[51]. Consequently, reliable ISL operations impose strict timing requirements on transceiver activation, power budgeting using to ensure data exchange is completed within each available window.

2.4.2. CIRFLINK Specification

The satellite adapts to the standardized CubeSats structural configuration with dimensions of 15cm × 10cm × 10cm, compatibility with conventional deployer systems. The mission architecture adopts a store and forward communication paradigm. Table 1 summarizes the essential physical and operational specifications of the CIRFLINK CubeSats. CIRFLINK-A and CIRFLINK-B constellation is designed to enable integrates six subsystems. First, Communication Subsystem, Utilizes LoRa-based radio modules (ESP32 + SX1278) for inter-satellite and ground communications, supporting low-power, long-range data exchange for IoT payloads. Ground-based IoT terminals transmit data within the Ultra High Frequency (UHF) band (400–403 MHz), achieving data rates in the range of 4.8–19.6 kbps. Second, Attitude Determination and Control Subsystem (ADCS), Employs sensors and magnetorquers to determine and maintain CubeSats orientation, ensuring stable communication links and payload alignment in Low Earth Orbit.Third, Power Subsystem generates and regulates electrical energy through solar panels and rechargeable batteries, optimized for the 1.5U CubeSat's limited surface area and energy demand. The power subsystem utilizes silicon based photovoltaic panels mounted on all four lateral faces, providing an average power output of approximately 1.2 W. Electrical energy is regulated and stored in a 6.4 Ah lithium-ion battery. Fourth, Structural Subsystem: Provides the mechanical integrity of the 1.5U CubeSats, integrating all subsystems within APSCO CubeSats standard constraints while ensuring vibration and launch survivability. Fifth, Thermal Subsystem, maintains onboard components within operational temperature limits using passive control techniques such as coatings, insulation, and structural heat dissipation. Sixth, On-Board Data Handling (OBDH) Subsystem, manages command execution and data storage via an onboard computer, enabling efficient communication between payload, subsystems, and the ground segment.

Table 1. Technical Specifications and Orbital Parameters of the CIRFLINK CubeSats

Item	Detail
Size	15 cm x 10 cm x 10 cm
Mission	Store and forward
Weight	1.25 Kg
Energy system	Solar panels on the surfaces of all four sides of the body
	1.2W (Average), Si Cells , Battery 6.4AH Lithium-Ion Battery
Communication	Frequency: UHF-band
Uplink/downlink	Frequency range (Tx-Rx): 400 – 403 MHz
Intersatellite link	Data rate: 4.8 - 19.6 kbps
End device Uplink	
Satellite Height	600 – 800 Km
Orbital Period	102 minutes
Type of orbit	Sun Synchronous Orbit

Orbital parameters are configured for a SSO at an altitude of 600–800 km, which consistent solar illumination and thus enhanced reliability in power generation. The orbital period, approximately 102 minutes, ensures frequent revisits and predictable communication windows with ground stations. Overall, the CIRFLINK CubeSats constellation demonstrates a cost effective, energy efficient, and educationally oriented design that merges experimental learning objectives with real world applications.

The success of ISL implementation in large satellites has generated growing interest in extending this technology to smaller platforms, particularly CubeSats. Due to their compact size and cost effectiveness, have been widely employed in various missions, including space exploration, environmental monitoring, and scientific experimentation. In recent years, ISL technology has been increasingly adopted in large constellation networks to enhance the efficiency of data exchange between satellites. Leading projects, such as SpaceX, Starlink and OneWeb, have demonstrated the effectiveness of ISL in enabling global internet services [52],[53]. ISL improves the overall reliability of satellite networks by providing redundancy through constellation communication pathways. However, the integration of ISL in CubeSats remains challenging due to constraints in size, weight, power consumption, and system complexity. As a result, practical applications of ISL in CubeSats are still limited.

3. Method

This study adopts a multi-phase methodology that combines qualitative multi-criteria decision analysis with quantitative experimental design and statistical validation to optimize the CIRFLINK ISL for two 1.5U CubeSats. The overall workflow, summarized in figure 5, consists of three main stages. In the first phase, AHP is employed as a qualitative decision-making tool to structure and prioritize communication-design choices under multiple, potentially conflicting criteria. AHP is first used to select the most appropriate ISL technology between Radio Frequency (RF) and optical links, considering criteria such as accuracy, sensitivity, durability, system complexity, cost, and speed. A hierarchical model is defined with the mission objective at the top level, evaluation criteria at the intermediate level, and technology alternatives at the bottom level.

In the second phase, a two-level full factorial design (2^k) is used to quantitatively evaluate how selected communication parameters influence signal performance. Based on the AHP results, four factors are considered in the initial screening experiment: Spreading Factor (SF), bandwidth (BW), Coding Rate (CR), and communication distance (D). Each factor is tested at two levels (low and high), yielding a 2^k design matrix. In the third phase, correlation analysis is used to validate the consistency and robustness of the observed relationships between distance, SNR, and RSSI under both obstructed and unobstructed conditions. Pearson correlation coefficients are computed for each pair of variables, together with corresponding p-values, to assess the strength and statistical significance of linear relationships. This statistical validation phase ensures that the effects identified in the factorial experiments are not only statistically significant but also physically interpretable and aligned with communication-theory expectations. When combined with the AHP-based qualitative prioritization and the 2^k factorial quantitative assessment, the correlation analysis completes a coherent methodology in which AHP defines and prioritizes design choices, while factorial experiments and correlation analysis provide quantitative evidence for the performance impact of those choices.

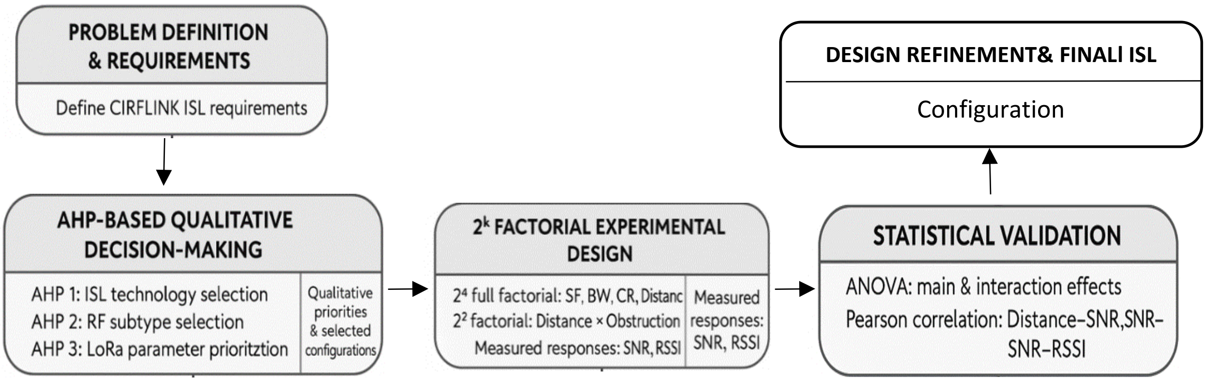

Figure 5. Multi-Criteria and Experimental Methodology Framework for CIRFLINK ISL Design.

4. Result and Discussion

4.1. Experiment Setup

CIRFLINK mission involves the design and development of two CubeSats. By leveraging modern CubeSats technologies in combination with IoT, the project aims to establish a new communication framework for small satellites. The communication subsystem of the CubeSats consists of three components: uplink, downlink, and ISL. The uplink is employed to transmit mission-specific sensor data from ground-based sources to the satellites, while the downlink facilitates the transmission of satellite-collected data to ground stations for subsequent utilization. The ISL enables direct communication between the two CubeSats. This feature is critical in scenarios where a satellite cannot complete the acquisition of a full data package before losing uplink contact. Through ISL, incomplete data segments can be relayed to the second CubeSat that remains within uplink range, ensuring mission informationcompleteness and continuity.

The choice of communication technology was led by the requirements of the mission and the available resources, and was based on criteria such as architecture simplicity, range distance, and power requirements. The AHP was utilized to select the best type of communication for the system and frame the system design criteria. To determine the most impactful parameters from spreading factor, bandwidth, and coding rate. A 2^k factorial design was performed. By reason of their price, low power consumption, and modularity. ESP32 modules were used in the prototype development. The system was tested indoors and outdoors at different distances and with obstacles. As part of the system performance evaluation, different qualitative parameters such as RSSI and SNR signal values were captured and processed using one sample t-tests, ANOVA, and correlation analysis. This research uses a multi-phase quantitative method to carefully select, improve, and validate the best inter-satellite communication system for 1.5U CubeSats CIRFLINK.

4.1.1. Inter-Satellite Link Communication Technology Selection Using AHP

In this session, AHP was employed to select the most suitable communication technology between RF and Optical for a 1.5U CubeSats ISL. Six criteria were established as demonstrated in figure 6 Accuracy, System Complexity, Cost, Durability, Sensitivity, and Speed. Pairwise comparisons were conducted to evaluate the importance of each criterion, and consistency was verified by calculating the consistency ratio, which was confirmed to be less than 0.01. Using the eigenvalue method, the relative weights of each criterion and the overall scores of both alternatives were computed.

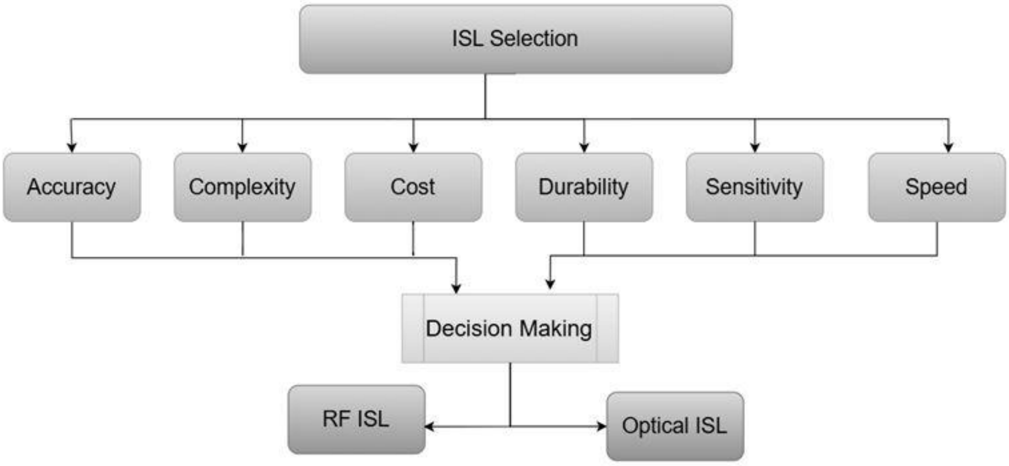

Figure 6. AHP hierarchy structure for communication technology selection.

Although the AHP provides a structured framework for qualitative decision-making, it has several inherent limitations [54]. The method relies on expert judgment, which introduces subjectivity into the pairwise comparisons. AHP is also sensitive to inconsistencies within the comparison matrices; therefore, evaluating the Consistency Ratio is essential to ensure logical coherence. Acknowledging these limitations enhances the transparency and credibility of the AHP-based decisions in this research.

4.1.2. Radio Frequency Subtype Selection using AHP

In this session, AHP was used to choose the best subtype of RF communication for CubeSats ISL. The options included VHF, UHF, S-Band, X-Band, Ku-Band, Ka-Band, and LoRa as demonstrated in figure 7. To guide this choice, three criteria were set: Data Rate, Power Consumption, and Range. A pairwise comparison matrix was created, and checked consistency by ensuring the Consistency Ratio was below 0.01. The Consistency Ratio was calculated to ensure the logical consistency of pairwise comparisons. According to [55], a Consistency Ratio value below 0.10 indicates acceptable consistency, while values above this threshold suggest that judgments may be inconsistent and require revision. In this study, all calculated Consistency Ratio values were below 0.01, indicating a very high level of decision consistency and methodological robustness. The eigenvalue method helped control the relative weights of the criteria and calculate the final scores for each RF subtype.

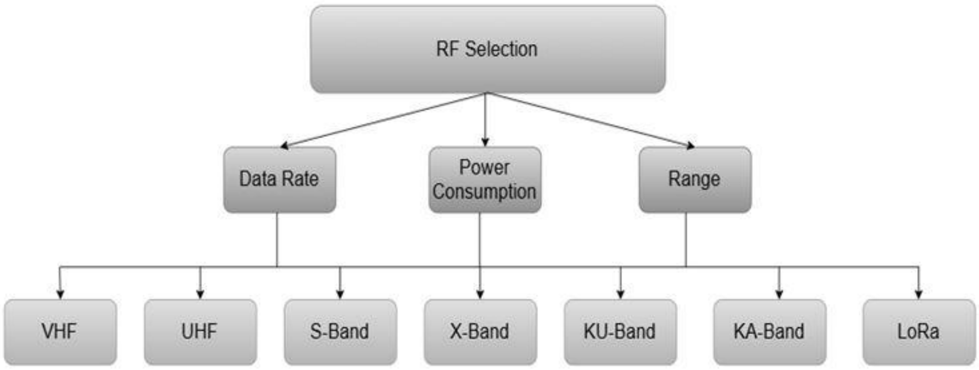

Figure 7. AHP hierarchy structure for communication technology selection.

4.1.3. Screening Factor using 2^k Factorial Design

To determine which transmission parameters significantly affect the signal performance of the selected LoRa communication system, A two-level full factorial design (2^k) was conducted. Four independent variables were examined: Spreading Factor, Bandwidth, Coding Rate, and Distance. Each variable was tested at two levels, low and high, following standard experimental design methods as demonstated in table 2. Output response was measured in terms of SNR and RSSI. The experiment was evaluated using Analysis of ANOVA and set a significance level of 0.01 as the threshold. Those parameters will be improved in the next phase using AHP.

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Table 2. Factors and Levels for 2k Factorial Design

Factor	Symbol	Factor Levels		Unit
		Low Level (-)	High Level (+)	
Spreading Factor (SF)	A	7	12	-
Bandwidth (BW)	B	125	500	kHz
Coding Rate (CR)	C	4/8	4/5	-
Distance (D)	D	0	300	m

4.1.4. Parameter Tuning using AHP (SF, BW, CR)

The analyses parameters SF, BW and CR show no statistically significant impact on the SNR and RSSI from the previous 2^k factorial design, their optimal settings remain crucial for overall LoRa system performance. For the AHP evaluation of each parameter. First, SF, there are six options (SF7 to SF12) were evaluated based on four criteria, Data Rate, Power Consumption, Range, and Reliability. Second, BW, three options were assessed (125 kHz, 250 kHz, and 500 kHz) using Data Rate, Power Consumption, and Range as criteria. Third, CR, there are four options (4/5, 4/6, 4/7, and 4/8) were compared based on Data Rate, Error Correction (Reliability), and Power Consumption.

4.1.5. System Experimentation using 2-Factor Factorial Design

A physical prototype of the communication system was tested using the chosen LoRa configuration. A two-factor design examined the effects of Distance and Physical Obstruction on signal quality, with each factor tested at two levels (low and high). SNR and RSSI were recorded in both obstructed and unobstructed settings. An analysis of variance was performed to evaluate each factor's impact.

4.2. Experimental Results

This study carefully verified all key statistical assumptions before performing the ANOVA and correlation analyses. The normality of the data distribution was assessed using Probability Plots, where all p-values exceeded 0.05, indicating that the data did not significantly deviate from a normal distribution.

4.2.1. Selection Inter-Satellite Link Communication Technology Analysis

AHP was employed to determine the most appropriate ISL technology for the CubeSats mission by comparing two alternatives: RF ISL and Optical ISL. Six evaluation criteria were defined Accuracy, Sensitivity, Durability, System Complexity, Cost, and Speed to capture both technical performance and practical implementation aspects.

Figure 8 summarizes the results of the AHP sensitivity analyses. Pairwise comparisons were carried out among these criteria, and the resulting consistency ratio = 0.01 verified that the judgment matrix was logically consistent and highly reliable. The computed weights for the criteria were as follows: Cost (0.376), System Complexity (0.242), Durability (0.149), Sensitivity (0.132), Accuracy (0.064), and Speed (0.037). These results indicate that cost and system simplicity are the most decisive factors for CubeSats-scale missions, whereas speed and accuracy have relatively lower significance due to the system's limited resources and short communication windows. The performance sensitivity chart shows that RF ISL achieve the highest overall score, primarily due to its lower cost and simpler system architecture. The dynamic and criterion sensitivity plots confirm that increasing the weighting of either cost or system complexity further strengthens the preference for RF ISL, while emphasizing speed slightly improves the ranking of Optical ISL. The comparison between the two alternatives clearly demonstrates that RF ISL better than Optical ISL in nearly all evaluation criteria except for transmission speed. The AHP results identify RF-based ISL as the most suitable solution for the CIRFLINK CubeSats mission.

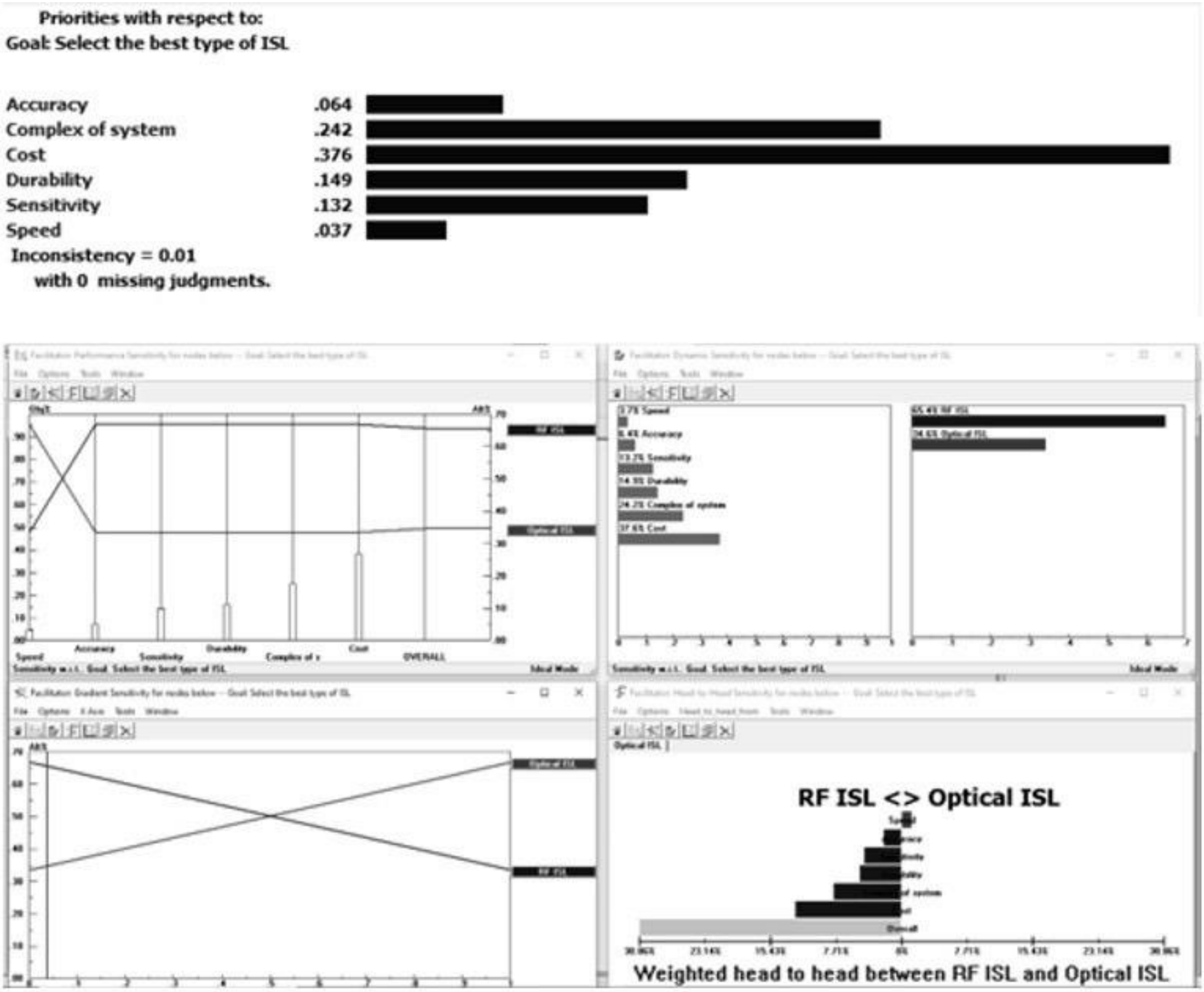

Figure 8. AHP Results for ISL Technology Selection

4.2.2. Selection of Radio Frequency Technology Type Analysis

The results of the pairwise comparison assigned the highest importance to range (0.540), followed by power consumption (0.297), and data rate (0.163). The consistency index of 0.00877 confirmed the reliability of the judgments. These weightings indicate that achieving long-distance communication is the primary priority for this mission, while energy efficiency is also significant, and data throughput is comparatively less critical.

The sensitivity analysis results illustrate in figure 9. The performance sensitivity chart shows that LoRa consistently provides superior scores in both range and power consumption, whereas UHF demonstrates advantages in data rate. The dynamic sensitivity analysis further reveals that when greater weight is assigned to range, LoRa emerges as the most favorable option, reinforcing its role as an appropriate solution for long-distance and low-power communication. The comparison between LoRa and UHF confirms the tradeoff. LoRa clearly is better than UHF in terms of range and energy efficiency. Taking into account the mission-specific priorities, the overall analysis indicates that LoRa is the most suitable RF communication technology for this CubeSats mission

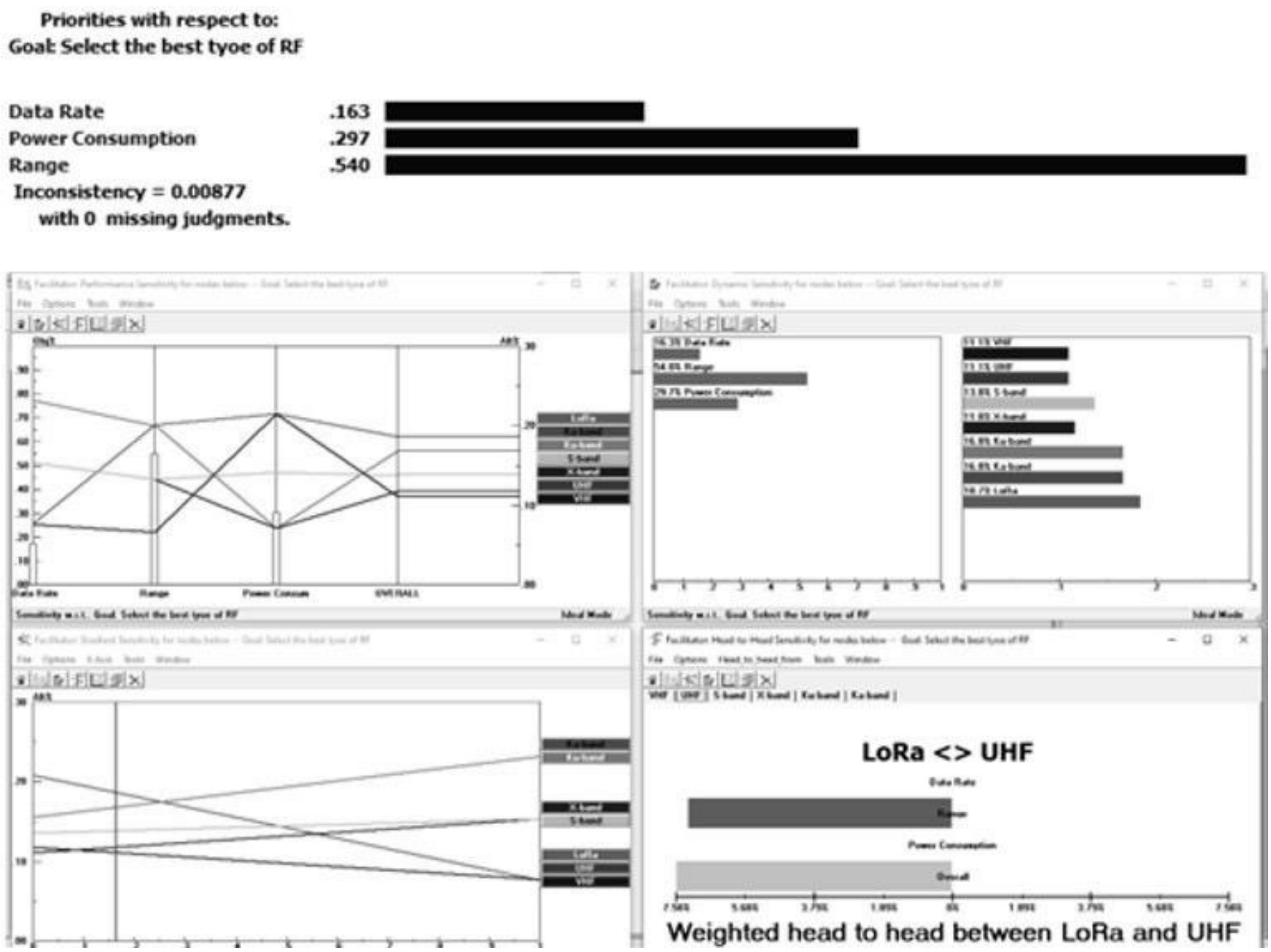

Figure 9. Results for RF Technology Type Selection.

4.2.3. Screening Factor using 2k Factorial Design Analysis

Figure 10 presents the Pareto chart of the standardized effects for the SNR with a significance level of α = 0.01. The chart ranks the main factors and interaction in terms of their relative influence on the response variable. The vertical dot reference line corresponds to the critical value of 2.92, which represents the minimum threshold for statistical significance at the chosen confidence level. Any factor or interaction term that exceeds this threshold can be considered to have a statistically significant effect on the response.

Among the examined factors, Distance (D) clearly demonstrates the largest standardized effect as the critical threshold. This indicates that the communication distance is the dominant factor influencing the SNR performance. Other main factors, such as Spreading Factor represent as (A), Bandwidth (B), and Coding Rate (C), as well as their interaction terms (e.g., CD, AD, AC), exhibit standardized effects below the reference line, and therefore are not statistically significant contributors at the α = 0.01 level.

The results suggest that distance is the most critical parameter in determining SNR performance, while the impact of the remaining parameters and their interactions is relatively minor. This finding aligns with theoretical expectations, as increasing communication distance typically leads to signal attenuation and reduced SNR. Consequently, optimizing or mitigating the effect of distance should be prioritized in system design and configuration to ensure reliable communication performance.

Figure 11 illustrates the Pareto chart of standardized effects for the received RSSI, analyzed at a significance level of α = 0.01. The red reference line corresponds to the critical standardized effect value of 2.92, which represents the threshold for statistical significance. The results clearly show that Distance (D) is the dominant factor influencing RSSI, with a standardized effect far exceeding the significance threshold. This indicates that the variation in RSSI is almost fully administered by the communication distance between the transmitter and receiver. In contrast, other parameters, Spreading Factor (A), Bandwidth (B), Coding Rate (C), and their interaction terms exhibit standardized effects below the threshold and hence do not have a statistically important influence on RSSI under the given experimental conditions. This outcome aligns with theoretical expectations, as RSSI is directly impacted by propagation losses that increase with distance. Factors such as modulation parameters (SF, BW, CR) may influence communication quality in terms of link robustness and data throughput, but their effect on raw received signal power remains negligible compared to distance.

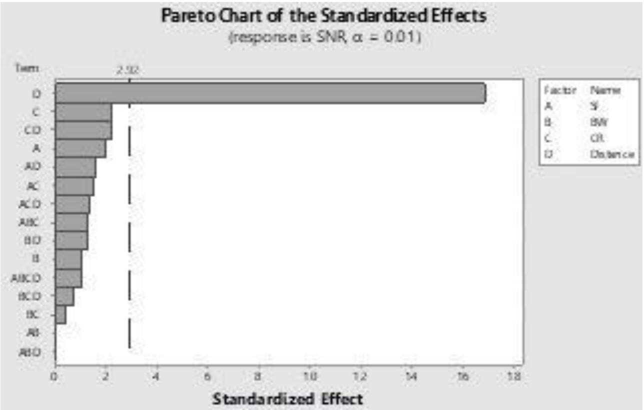

Figure 10. Pareto Charts of Standardized Effects for SNR

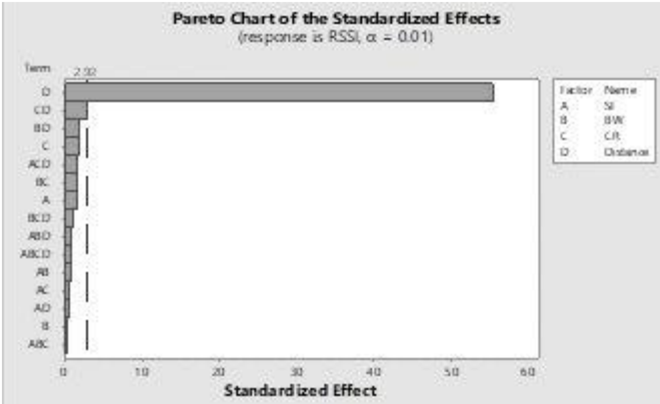

Figure 11. Pareto Charts of Standardized Effects for RSSI

4.2.4. Parameter Optimization for LoRa using AHP

Although the parameters Spreading Factor (SF), Bandwidth (BW), and Coding Rate (CR) were found statistically insignificant in the 2^k factorial design, they remain mandatory configuration parameters in the LoRa communication system. These variables fundamentally determine the communication range, data rate, and link reliability of the system. The design of experiment results indicates that, within the tested parameter ranges, variations in SF, BW, and CR did not produce statistically significant differences. However, from an engineering perspective, these parameters still possess system-level importance, as they directly influence the balance between performance and mission constraints such as energy consumption, channel collision, and inter-satellite communication efficiency.

Therefore, the inclusion of SF, BW, and CR in the subsequent AHP analysis aims to identify the optimal configuration at the system level. The AHP serves as a qualitative decision-making layer that complements the quantitative findings. The AHP was employed to identify the most suitable settings for each parameter based on multiple performance criteria. The outcomes of this multi criteria decision analysis are following.

Firstly SF selection, Six SF options (SF7–SF12) were evaluated using Range, Reliability, Power Consumption, and Data Rate as criteria. The analysis assigned the highest weight to Range (0.574), followed by Reliability (0.239), Power Consumption (0.131), and Data Rate (0.056), with a consistency ratio of 0.03. The results indicated that SF12 was the most suitable configuration, as it maximized range and reliability, which were supposed most critical for the mission objectives. Secondly, BW Selection, three BW options (125 kHz, 250 kHz, 500 kHz) were analyzed against Data Rate, Power Consumption, and Range. The criteria weights emphasized Range (0.637) and Power Consumption (0.258) over Data Rate, with a consistency ratio of 0.04. AHP analysis concluded that 125 kHz was the optimal selection, providing the best compromise between maximizing range and minimizing power consumption. Thirdly, CR Selection, four CR values (4/5, 4/6, 4/7, 4/8) were evaluated with Error Correction, Power Consumption, and Data Rate as criteria. The analysis gave the highest weight to Error Correction (0.582), followed by Power Consumption (0.309), and Data Rate (0.109). The consistency ratio was very low (0.00352), confirming robustness of the judgments. The AHP analysis identified CR 4/8 as the most appropriate option, emphasizing the importance of error correction capability and communication reliability in the ISL context.

Although the statistical analysis in this study did not show significant effects for SF, BW, and CR, these parameters remain fundamentally important from a communication-engineering perspective. Prior LoRa studies and theoretical link-budget models consistently demonstrate that spreading factor influences processing gain, bandwidth affects noise power and data rate, and coding rate contributes to error-correction capability and overall link robustness. Therefore, the practical relevance of these parameters is supported by established literature and physical communication principles, even if their effects were not detectable within the limited scale of the present experiment.

4.2.5. System Experimentation using 2k -Factor Factorial Design Analysis

Physical Obstruction on both SNR and RSSI, using the optimized LoRa configuration (SF12, 125 kHz, CR 4/8). The analysis revealed that both Distance and Physical Obstruction had a statistically significant impact on SNR and RSSI, with p-values of 0.000 for both factors, below the significance threshold of 0.05. This confirms that both factors apply strong and measurable effects on LoRa communication performance.

In addition, the interaction between Distance and Physical Obstruction was found to have a statistically significant influence on SNR ($p = 0.000$), whereas no significant effect was observed on RSSI ($p = 0.218$). This distinction suggests that while both factors degrade overall signal strength and quality, their combined effect specifically alters the SNR. Hence, it can be concluded that distance and obstruction independently affect both SNR and RSSI, but their interaction is particularly critical in determining SNR behavior, which directly relates to communication reliability and error performance.

4.2.6. Correlation result and Analysis

The correlation analysis presented in table 3 and table 4 provides important insights into the influence of distance and environmental conditions on LoRa communication performance. In both obstructed and unobstructed environments, distance exhibits a strong and statistically significant negative correlation with both SNR and RSSI, confirming that increasing transmission distance consistently degrades signal quality.

Table 3. Pearson Correlation Coefficients and P-values in Obstructed Environment.

The relationship between parameters	Distance (meters)	SNR (dB)	RSSI (dBm)
Distance (meters)	NA	-0.820	-0.857
	NA	(0.000)	(0.000)
SNR (dB)	-0.820	NA	0.517
	(0.000)	NA	(0.001)
RSSI (dBm)	-0.857	0.517	NA
	(0.000)	(0.001)	NA

However, the strength of the correlation between SNR and RSSI differs between the two conditions. In the obstructed environment (table 3*)*, the correlation between SNR and RSSI is moderate ($r = 0.517$*,* $p = 0.001$*)*, indicating that physical barriers introduce additional attenuation and multipath effects that weaken the reliability of RSSI as an indicator of signal quality. Conversely, in the unobstructed environment (table 4*)*, the correlation between SNR and RSSI is stronger ($r = 0.657$, $p = 0.001$*)*, reflecting the clearer propagation path and reduced interference under line-of-sight conditions.

Table 4. Pearson Correlation Coefficients and P-values in Unobstructed Environment.

The relationship between parameters	Distance (meters)	SNR (dB)	RSSI (dBm)
Distance (meters)	NA	-0.913	-0.878
	NA	(0.000)	(0.000)
SNR (dB)	-0.913	NA	0.657

	(0.000)	NA	(0.001)
RSSI (dBm)	-0.878	0.657	NA
	(0.000)	(0.001)	NA

The comparative analysis between obstructed and unobstructed environments provides critical insights for the CIRFLINK inter-satellite link (ISL) design. While distance remains the primary driver of signal degradation in both scenarios, the presence of physical obstructions significantly alters the correlation between signal metrics. In unobstructed line-of-sight conditions, a strong negative correlation exists between distance and signal quality ($r \approx -0.91$ for SNR). However, in obstructed environments, this relationship weakens, and the correlation between SNR and RSSI drops to a moderate level $r \approx 0.52$ to 0.55), indicating that RSSI alone is an insufficient standalone metric for predicting link stability under non-line-of-sight conditions. Consequently, integrating SNR-based evaluations alongside optimized LoRa parameters (SF12, BW 125 kHz, CR 4/8) is essential for ensuring robust communication reliability. These findings align with prior studies emphasizing the critical role of propagation environments in LoRa network performance.

Terrestrial obstructions, the LEO environment introduces Doppler shifts of approximately ±5-10 kHz due to high relative satellite velocities. Such frequency offsets can compromise symbol synchronization and increase packet errors, necessitating frequency pre-compensation or adaptive tracking techniques for practical LoRa-based ISL. Additionally, while the 2^k factorial design served as an efficient initial screening tool to identify primary performance factors, its two-level resolution limits the detection of non-linear or higher-order effects. Future research should employ response surface methodologies or additional factor levels to capture more complex system behaviors and strengthen the generalizability of the communication framework.

5. Conclusion

This study developed an integrated framework that combines decision-support and statistical validation techniques to optimize CubeSats communication system design. By integrating the Analytic Hierarchy Process with a 2^k factorial design, the research demonstrated how qualitative and quantitative analyses can jointly guide engineering decisions for low-cost nanosatellite communication. The hybrid framework effectively identified LoRa as the most suitable RF technology for inter-satellite communication, providing an optimal balance between range, energy efficiency, and implementation simplicity.

The findings revealed that transmission distance remains the dominant factor affecting link performance, while physical obstructions moderately degrade both SNR and RSSI. Despite their limited statistical significance within the tested range, parameters such as spreading factor, bandwidth, and coding rate maintain system-level importance in defining communication reliability. These results emphasize that CubeSats link optimization requires not only statistical evaluation but also engineering-based judgment to achieve robust and scalable designs.

In addition to validating a low-cost LoRa-based ISL prototype using ESP32 and SX1278 hardware, this work provides a methodology that is most applicable to 1.5U-class CubeSats employing low-power LoRa communication. The applicability of this framework to larger satellite platforms, high-rate communication systems, or non-LoRa protocols requires further investigation to ensure scalability under different mission profiles. Future work will focus on hardware-in-the-loop simulation and on-orbit validation to examine adaptive link control, real-time data scheduling, and inter-satellite coordination under orbital dynamics. Such advancements will strengthen the generalizability of the approach and support its extension toward multi-satellite constellations for academic and resource-constrained space missions.

6. Declarations

6.1. Author Contributions

Conceptualization: W.K. and R.C.; Methodology: W.K. and R.C.; Software: W.K.; Validation: W.K. and R.C.; Formal Analysis: W.K. and R.C.; Investigation: W.K.; Resources: R.C.; Data Curation: R.C.; Writing Original Draft Preparation: W.K. and R.C.; Writing Review and Editing: W.K. and R.C.; Visualization: W.K.; All authors have read and agreed to the published version of the manuscript.

6.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

6.3. Funding

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6.4. Institutional Review Board Statement

Not applicable.

6.5. Informed Consent Statement

Not applicable.

6.6. Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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