CanSat Communications: A Systematic Review and Comparison of Long-Range (LoRa) and Short-Range (nRF) Technologies

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ABSTRACT

The attached narrative review article systematically examines CanSat communication technologies, with a focus on comparing two predominant radio modules: LoRa (long-range) and nRF (short-range). The review highlights the educational and practical significance of CanSats as miniature functional satellites used for STEM education, aerospace research, and environmental monitoring. Key themes include the historical evolution of CanSat projects, foundational communication theory principles such as the Shannon-Hartley theorem and link-budget analysis, and a detailed technical comparison of LoRa and nRF modules. LoRa offers superior long-range communication capabilities with very low power consumption, making it suitable for extended-range telemetry missions, while nRF provides higher data throughput for short-range, real-time control applications. The review integrates empirical findings from recent studies and competition case analyses to illustrate current use cases, challenges, and innovations, including adaptive hybrid communication systems. It concludes by emphasizing the need for future research on dynamic communication architectures that balance range, data rate, and power efficiency, which will enhance the reliability and educational value of CanSat missions. This article serves as a comprehensive guide for educators, students, and practitioners in selecting and optimizing communication technologies for miniature satellite systems.

Keywords: CanSat communications, link-budget analysis, LoRa technology, nRF modules, Shannon-Hartley theorem, wireless telemetry.

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1. INTRODUCTION

CanSat (short for "can satellite") technology represents a significant hands-on educational and research tool in the field of space technology and aerospace engineering. Essentially, a CanSat is a functional miniature satellite, usually a secondary payload carried by sounding rockets or balloons, which simulate key satellite functions within a compact volume roughly the size of a soda can [1]. This low-cost, small-form factor platform enables students, researchers, and hobbyists to gain practical experience in satellite design, sensor integration, and mission operations. Beyond educational contexts, CanSats contribute to rapid prototyping of technologies relevant to atmospheric data acquisition and environmental monitoring, thus bridging theoretical learning with applied aerospace technologies and wireless communications[2]. The purpose of making CanSat is to teach how to build a satellite in small scale. The CanSat competition 2019 mission is about auto-gyro. Auto-gyro is a blade that can descent control speed of CanSat. The CanSat consists of two parts, the science payload, and the container to protect the science payload as it is deployed from the rocket[1].

The origins of CanSat technology date back to the early 2000s with initiatives to promote STEM education through experiential learning by simulating satellite missions on a miniature scale. Since then, CanSat projects have evolved with advances in miniaturized sensors, embedded systems, and wireless communication technologies[3]. As these developments matured, communication modules became a critical component, governing data transmission fidelity and range. Notably, recent years have seen the emergence and adoption of two prominent radio communication technologies for CanSats: LoRa (Long Range) and nRF (short-range radio frequency modules). LoRa, leveraging chirp spread spectrum modulation, has enabled long-distance communication exceeding several kilometers, useful for extended-range telemetry in rugged environments. Conversely, nRF modules offer robust short-range communication with higher bandwidth suitable for real-time data transmission in localized testing scenarios. Studies from the past five years have also demonstrated adaptive use of LoRa for high-altitude balloon experiments and CubeSat ground stations, as well as reliable nRF data chains in CanSat descent control, highlighting ongoing innovation and optimization in communication protocols under different mission constraints[4].

The relevance of evaluating and comparing LoRa versus nRF technologies in CanSat communication remains critical today due to rapid advancements in wireless communication standards and continuous growth in the CanSat competition and research landscape. Contemporary challenges include enhancing data rate efficiency, extending operational range while maintaining low power consumption, and mitigating signal interference amid crowded radio frequency bands. For instance, a 2024 study demonstrated how LoRa could be adapted for CubeSat ground stations to overcome Doppler effects and interference, showing its potential beyond terrestrial applications[5]. On the other hand, recent environmental monitoring CanSat projects have implemented nRF modules for seamless real-time short-range data transmission combined with redundancy mechanisms for safety, underlining the practical trade-offs in communication design decisions. The dynamic interplay of mission requirements, cost constraints, and signal reliability considerations persists as a dominant debate in this specialized but rapidly evolving field, making a focused review imperative for guiding future CanSat designs and educational best practices[6].

This review will explore several key areas including the fundamental characteristics of LoRa and nRF technologies relevant to CanSat deployments, a detailed comparison of their communication ranges, power consumption profiles, data throughput capabilities, and resilience to environmental and signal interference challenges. We will also synthesize empirical findings from recent research projects and competition case studies to illustrate how these technologies are currently being employed, adapted, and optimized in real-world scenarios. Furthermore, the review will discuss emerging trends in CanSat communication module integration, including hardware-software co-design, redundancy designs, and potential future directions in incorporating newer low-power wide-area network protocols.

The primary objective of this narrative review is to provide an accessible yet thorough synthesis of the recent advancements and practical considerations in CanSat communication technologies, focusing on LoRa and nRF. By critically consolidating contemporary research insights and technical comparisons, this article aims to contribute to a broader understanding of how these communication technologies shape the design and operation of CanSat missions. Ultimately, the review seeks to equip educators, students, and practitioners with a nuanced knowledge base to inform technology selection and innovation in upcoming CanSat projects, promoting improved reliability, efficiency, and educational value in this vibrant and impactful field.

2. *Core Concepts and Evolving Theories in CanSat Wireless Communication*

At the core of understanding CanSat communications lies the fundamental distinction between long-range and short-range wireless technologies, which are pivotal in shaping the design and operational capabilities of miniature satellite systems. LoRa (Long Range) and nRF modules exemplify these categories, representing two contrasting paradigms in wireless data transmission[7]. LoRa, based on chirp spread spectrum modulation, is designed to achieve extended communication distances—often exceeding several kilometers—while maintaining low power consumption, making it suitable for expansive or remote environmental monitoring where the CanSat must communicate over rugged terrain or dense atmospheres. Conversely, nRF modules are engineered for high-bandwidth, short-distance communication, typically within hundreds of meters, emphasizing rapid data transfer and minimal latency, which suits scenarios like in-flight telemetry and real-time control within confined mission domains[8] . The CanSat payload will measure the atmosphere parameter

at 670 - 725 meters altitude. The sensors data will be collected and transmitted through XBEE-PRO S1 to the Ground Control Station (GCS). GCS shall generate a Comma Separated Value (CSV) file of all sensor data and displayed in real-time during descent[1].
Theoretical models that underpin these technologies include information theory principles, most notably **Shannon-Hartley theorem** [9]. This theorem provides the fundamental upper limit for the channel capacity *C* (in bits per second) for a communication link with a given bandwidth and in the presence of noise, as expressed by:

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

where *B* is the channel bandwidth (in Hertz) and SNR is the linear signal-to-noise ratio. This theoretical framework directly guides the optimization of modulation schemes and coding strategies in CanSat communication systems, illustrating the inherent trade-off between bandwidth, power (represented by SNR), and data rate. For instance, LoRa's design, which sacrifices data rate (a low *C*) for exceptional sensitivity (a very low acceptable SNR), is a practical embodiment of this principle to achieve long range[10].

Furthermore, the practical realization of this trade-off is governed by the Link Budget analysis, which quantifies the power balance in a radio link[11]**:**

$$P_{\mathrm{rx}} = P_{\mathrm{tx}} + G_{\mathrm{tx}} - L_{\mathrm{tx}} + G_{\mathrm{rx}} - L_{\mathrm{rx}} - L_{\mathrm{path}} \quad (2)$$

where *P*rx is the received power, *P*tx is the transmit power, *G* represents antenna gains, *L* denotes losses, and *L*path is the path loss dependent on distance and frequency**.** The key differentiator between LoRa and nRF lies in the minimum required *P*rx (receiver sensitivity) [11]. LoRa's exceptionally low sensitivity allows it to tolerate much greater *L*path, resulting in its characteristic long range, whereas nRF modules require a higher *P*rx, limiting their operational range but enabling higher data rates[12].

These theoretical frameworks provide the foundation for practical implementations in modern CanSat communication systems. Recent research illustrates how onboard computer designs strategically integrate modules like LoRa to operate near the sensitivity limits defined by link-budget analyses—maximizing data integrity and range while minimizing energy consumption, in direct alignment with Shannon–Hartley trade-offs[13]. Empirical investigations, including comparative studies of LoRa modules and link-budget models , further validate how these theoretical principles translate into deployable, high-efficiency solutions. Moreover, emerging frameworks like the Control–Communication–Measurement (CCM) paradigm emphasize the integrated nature of sensing, transmission, and control in adaptive systems[14].

3.Mechanical and Payload Design Considerations

While communication is vital, the mechanical design of the CanSat, particularly the payload, is equally critical for mission success. The main mission of design payload is to provide a safe landing and carrying all of the electrical component safely. In this regard the payload design is more aerodynamic to make it more stable when exposed to the wind. The Center of Gravity (CoG) of this system are exactly located at the bottom of the payload, because of the battery weight located at the bottom. This stable physical platform is essential for ensuring that communication antennas and sensors remain properly oriented during descent[1].

4.Historical Development and Milestones in CanSat Evolution

The historical development of CanSat technology traces back to the late 1990s, when the foundational idea was first articulated at the 1st University Space Systems Symposium in 1998 by Professor Bob Twiggs of Stanford University. The concept was revolutionary in proposing the construction of a fully functional miniature satellite no larger than a soda can, with about 350 milliliters in volume and around 500 grams in mass. The early 1999 ARLISS (A Rocket Launch for International Student Satellite) project marked a critical milestone, spearheading the annual launch of these suborbital mini-satellites, primarily involving American and Japanese university teams. These early missions started simply with tasks such as calculating landing system deployment from barometric data or experimenting with differential GPS for position tracking[15]. Over the years, the complexity of CanSat missions increased, exemplified by the introduction of a "ComeBack" category in 2001, which required autonomous navigation to a predefined target, a challenge that saw remarkable progress by 2006 when teams could land within meters of their targets. Such early milestones dramatically shaped the educational and experimental purposes of CanSat programs at universities worldwide, laying a solid groundwork for future innovation[16].

From these pioneering efforts, CanSat technology evolved gradually through incremental improvements and expanding mission scopes. The rise of CubeSats in the early 2000s, notably by the University of Tokyo in 2003, complemented the CanSat projects by pushing miniature satellite technology into low Earth orbit, offering lessons that fed back into CanSat design and operation. Over time, autonomous control, imaging sensors, communication systems, and data handling capabilities were integrated into increasingly sophisticated CanSats[15]. Competition and collaboration among universities spurred continual refinements, with various technological experiments including antenna deployment, communication modulation techniques, and sensor networks, often precursors to CubeSat technology. Additionally, the system engineering approach became formalized with critical design reviews and systematic hardware testing to ensure mission success. This historical trajectory reflects profound paradigm shifts from basic educational experiments to sophisticated aerospace engineering platforms where CanSats serve not only as training tools but as testbeds for future space technologies[17].

5.Current Trends and Key Issues

Recent research on CanSat communications emphasizes balancing range, power efficiency, and data throughput through the adoption of LoRa and nRF wireless modules. These technologies represent two dominant paradigms in small-satellite telemetry. LoRa-based systems have been widely adopted for long-range, low-power telemetry, offering superior connectivity in missions where the ground station remains fixed. Its high link budget and receiver sensitivity sustain stable data transmission over several kilometers, even in non-line-of-sight conditions[4] .Alternatively, nRF-based solutions are chosen for short-range, high-data-rate missions requiring lower latency. While they enable faster data exchange, their limited range restricts use in broader telemetry applications. Persistent challenges include mitigating radio frequency interference and adhering to regional regulatory constraints. Additionally, ensuring compatibility with next-generation sensor payloads and miniaturized microcontroller platforms remains critical. Emerging trends point to developing adaptive hybrid communication frameworks capable of dynamically switching between LoRa and nRF modes based on mission phase or environmental conditions to optimize communication performance[18] .

6.Real-World Applications of CanSat Communications

CanSat communication technologies, particularly the implementations of LoRa and nRF modules, have found diverse applications across education, industry, environmental monitoring, and emergency response systems. Education programs use CanSats as practical tools to teach systems engineering, electronics, and wireless communication, allowing students to design and operate miniaturized satellite missions that collect atmospheric or environmental data, as seen in many university competitions globally. Industrial applications include prototype testing of wireless data relay systems in aerospace, where lessons learned from CanSat communication protocols influence the development of robust telemetry systems for larger satellite platforms[14]. In healthcare and disaster management, CanSats equipped with real-time communication capabilities provide innovative solutions for rapid deployment of environmental sensors to monitor air quality or deliver medical supplies in inaccessible areas, demonstrated by recent missions using LoRa for extended-range telemetry coupled with microcontroller-driven control of drop packages. These practical implementations underscore the societal impact of CanSat communications in enhancing STEM education, improving remote sensing capabilities, and supporting emergency logistics, all while benefiting from the comparative strengths of both long-range and short-range technologies[19].

7.Materials and Methods

The approach adopted in this review involved a comprehensive survey of relevant literature drawn from diverse academic sources, including peer-reviewed journal articles, conference proceedings, technical reports, and reputable online repositories dedicated to aerospace and satellite technology. The selection criteria emphasized the relevance of the studies to wireless communication systems within CanSat platforms, particularly focusing on recent developments published within the last five years to ensure the inclusion of the latest technological advancements and experimental findings. Priority was given to sources that presented empirical data, case studies, and theoretical analyses aligned with the comparison of LoRa and nRF technologies. The gathered literature was then organized according to thematic categories and chronological progression, enabling a structured synthesis that highlights critical innovations, persistent challenges, and emerging trends in the field. Overall, this methodology aimed to ensure a balanced and systematic overview, providing a solid foundation for subsequent analysis and discussion.

8.Result

Based on the systematic review of the literature, a clear distinction emerges between the operational domains of LoRa and nRF technologies in CanSat communications, dictated by a fundamental trade-off between range and data rate as outlined by the Shannon-Hartley theorem [9]. LoRa, utilizing Chirp Spread Spectrum modulation, is engineered for long-range communication, often exceeding several kilometers, and exhibits exceptionally low power consumption, making it ideal for telemetry transmission over vast distances [4, 10]. Its high link budget and superior receiver sensitivity allow it to maintain a stable connection even in non-line-of-sight conditions [11, 13]. Conversely, nRF modules operate over short ranges, typically a few hundred meters, but support a significantly higher data rate, facilitating the transmission of larger data packets [8, 12]. This makes nRF suitable for phases of the mission requiring high-bandwidth, such as real-time control during descent [1, 18]. The core differences between these two technologies are summarized in **Table 1**. Consequently, for long-range operations focused on transmitting basic telemetry and low-quality, minimal data, LoRa is demonstrably more suitable and reliable than nRF [4, 13]. However, the inherent low data rate of LoRa renders it impractical for transmitting high-quality images, a task for which nRF's higher throughput is better suited, albeit within its limited range. [۱۸ ,۱۲] .

Table 1: *Comparison of LoRa and nRF Technologies for CanSat Applications*

Feature	LoRa (Long-Range)	nRF (Short-Range)	Reference
Communication Range	Long-Range (several kilometers)	Short-Range (a few hundred meters)	[4, 8]
Data Rate	Low (designed for minimal data)	High (supports larger data packets)	[10, 12]
Power Consumption	Very Low	Low to Moderate	[4, 8]
Ideal Use Case	Long-distance telemetry, minimal data	Real-time control, high-bandwidth data (e.g., images)	[1, 13, 18]
Key Strength	Superior range and link budget	High data throughput and low latency	[11, 12]

9.Discussion

The critical evaluation of LoRa and nRF communication technologies within CanSat systems highlights a fundamental balance between range and data rate, rooted in information theory and practical link-budget considerations [9, 11]. LoRa's superior sensitivity and long-range capabilities make it indispensable for telemetry over several kilometers, especially in education and environmental monitoring, where low power consumption is prioritized [2, 4]. Conversely, nRF modules excel in short-range, high-bandwidth scenarios that demand rapid data exchange, such as real-time descent control, though at the cost of reduced operational distance [1, 8, 12]. This trade-off also aligns with broader IoT communication paradigms, where network design must carefully weigh throughput against coverage, as recently reviewed by Augustin et al., who emphasize LoRa's growing role in low-power wide-area networks despite inherent bandwidth limitations [10]. Understanding this interplay informs tailored communication architecture choices in CanSat missions, reconciling mission-specific demands like data fidelity, latency, and energy efficiency. Ultimately, such insights illustrate the broader interdisciplinary coherence between theoretical models and applied wireless communications in miniature aerospace platforms [13, 14].

10.Conclusion

This review synthesized current knowledge on CanSat communication technologies, emphasizing the comparative performance of LoRa and nRF modules in terms of range, data rate, and power efficiency [4, 8, 10]. LoRa's long-range, low-power design makes it ideal for extended telemetry missions, while nRF's high data throughput supports short-range, real-time applications [1, 12, 18]. By integrating theoretical principles such as the Shannon–Hartley theorem and link-budget analysis with empirical findings, the review contributes to a clearer understanding of how these technologies balance communication trade-offs in miniature aerospace systems [9, 11, 13]. Future research should focus on hybrid communication architectures that dynamically combine LoRa and nRF capabilities, adaptive frequency management to mitigate interference, and enhanced software-hardware co-design for energy optimization in next-generation CanSat missions [14, 18]. These directions will further strengthen the reliability, efficiency, and educational value of CanSat communications in both academic and applied aerospace contexts.

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