

LoRa-Based Ground Sensor Terminal for L-Band Satellite IoT Applications

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Abstract

This study addresses the increasing demand for Internet of Things (IoT) solutions in remote areas by developing a LoRa-based Ground Sensor Terminal (GST) designed for L-Band Satellite IoT Applications. The GST was evaluated through indoor, outdoor, and maximum range performance tests, achieving a maximum transmission distance of 450 m under current conditions using a 2 dBi antenna. The Received Signal Strength Indicator (RSSI) ranged from -46 dBm to -104 dBm, and the Signal-to-Noise Ratio (SNR) varied between -20.25 dB and 4 dB, depending on the testing environment and distance. These results demonstrate the impact of environmental factors on transmission quality. The study further verified the successful integration of the GST with L-Band satellites, achieving real-time data transmission with an optimized communication window between Acquisition of Signal (AOS) and Loss of Signal (LOS). By upgrading to a 5 dBi antenna, the system's range and reliability could be significantly enhanced. This research contributes to the advancement of IoT technologies for applications in remote monitoring, environmental management, and other critical areas, highlighting the GST's potential to provide reliable and scalable IoT solutions.

1. Introduction

Ground Sensor Terminals (GST) are communication devices used to send sensor data to satellites [1]. This project involves developing a GST with LoRa communication for node-to-gateway connections and L-band connectivity to Low-Earth-Orbit (LEO) IoT satellites. The terminal's primary function is to store and transmit sensor data to satellites using the L-band, which refers to the radio spectrum from 1 to 2 GHz. The L-band is favored in satellite

communications due to its excellent propagation characteristics. It is commonly utilized in satellite communications, navigation, and remote sensing systems [2]. Understanding these characteristics is crucial as we delve into the specific methodologies employed in our study.

Telecommunications, navigation, and remote sensing rely on L-band satellite systems for dependable connectivity and data transmission. LEO satellites are known for their effective propagation [3], stable connectivity [4], and efficient data transmission capabilities [5],[6]. These characteristics make them suitable for use in GSTs to ensure reliable sensor data transmission to satellites [7].

The satellite IoT study utilizes sensors to measure temperature, humidity, altitude, and air pressure. LoRa modules enable communication from sensor nodes to gateways, extending terrestrial monitoring capabilities up to 7 km [8]. However, field tests conducted at UiTM Shah Alam revealed a reduced transmission range of 450 m due to challenges in achieving clear line-of-sight (LOS) over 7 km and the use of a passive antenna with a 2 dBi gain. To improve performance, it is recommended to upgrade to a 5 dBi antenna and set the air data rate to 0.3 kbps [8].

The report details the development of the ground sensor terminal and its successful data transmission to satellites. It describes the use of open-source software to determine satellite directions, demonstrating effective data reception in lab environments. This research enhances real-time data transfer for space-based IoT applications by improving connectivity and data transmission efficiency.

1.1 Ground Sensor Terminal

Ground Sensor Terminal (GST) architecture typically refers to the design and components of a system used for collecting, processing, and transmitting data from ground sensors. This architecture includes the following components: Sensor Node and Gateway, both equipped with antennas for wireless transmission.

1.1.1 A Modular Design Approach

Ground sensor terminals are designed to be modular, scalable, and customizable. The terminal's modular design simplifies component replacement and upgrades, facilitating the integration of new technologies or capabilities. This adaptability ensures the ground sensor terminal remains current and effective as needs and technology evolve. Modularity also promotes standardization and interoperability, allowing the architecture to easily integrate components from multiple manufacturers due to standard module interfaces.

When designing a modular ground sensor terminal for customized L-band to VHF satellite communication interfaces, several considerations must be taken into account. Architectural modularity ensures that modules for satellite communication interfaces are interchangeable, with each module handling signal, frequency, and protocol conversion. The terminal must support L-band to VHF frequency ranges to utilize various satellite communication systems, offering flexibility to support multiple satellite networks and protocols. Standardizing module interfaces allows for easy integration and modification, enabling frequency band module switches without hardware changes. Incorporating Software-Defined Radio (SDR) technology allows adjustable communication settings, modulation schemes, and frequency bands, facilitating customization of the satellite communication interface using software [9], [10]. Scalability and upgradeability in the terminal's design accommodate advancements in satellite communication technology, ensuring adaptability to new technologies and requirements. Thorough testing and validation of the ground sensor terminal for reliability and performance across various frequency bands, including field experiments and compatibility testing with satellite communication systems, are essential.

These design considerations make the ground sensor terminal a flexible and adaptable solution for L-band to VHF satellite communication interfaces. The modular ground sensor terminal architecture, illustrated in Fig. 1, follows a system layout as shown in the block diagram [11]. The MCU can integrate sensors via I2C, analog, or digital pins, creating a versatile sensor interface. LoRa sensor nodes timestamp data with GPS or real-time clocks, and a Satellite Modem transmitter antenna sends data packets using UART. SD card memory stores the packets. The proposed method uses a simpler, energy-efficient EPS compared to typical sensor nodes, which includes a Li-Ion rechargeable battery, a battery charging circuit (BCR), and low-efficiency external solar panels

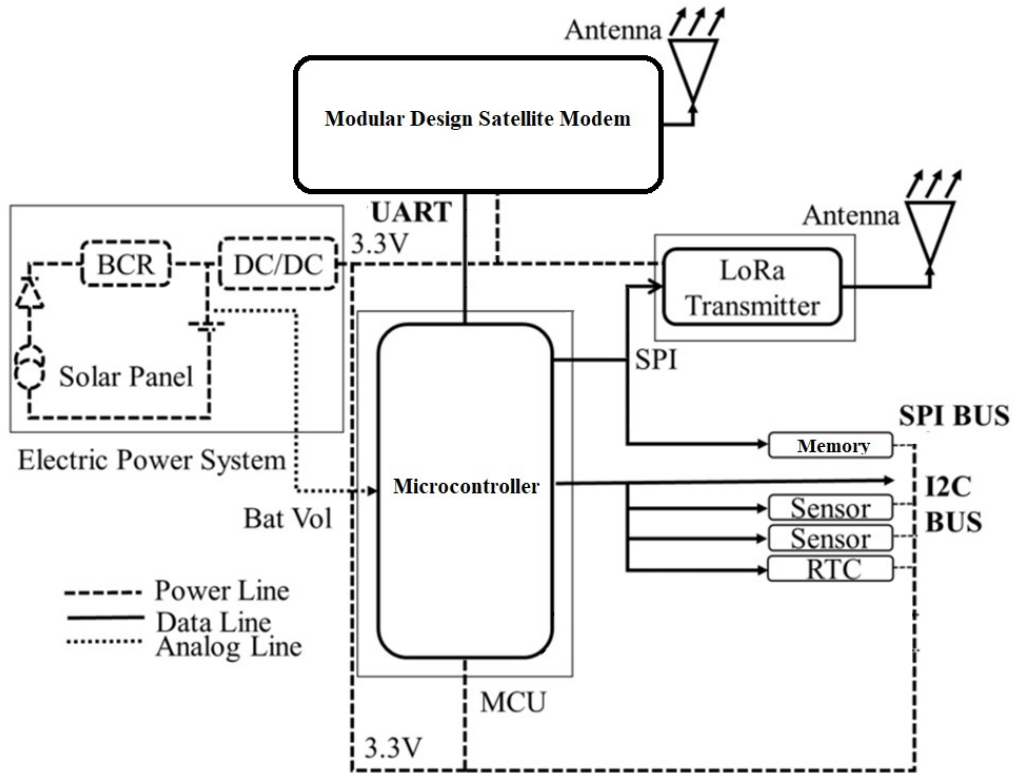


Fig. 1 A modular design approach for Ground Sensor Terminal architecture

1.1.2 System Architecture

The system architecture consists of interconnected components that collectively enable the functionality of the ground sensor terminal. These components include sensor nodes, LoRa communication modules, microcontrollers, power management systems, data storage, and satellite communication interfaces in the gateway. Each component plays a specific role in the data acquisition, processing, and transmission workflow of the terminal.

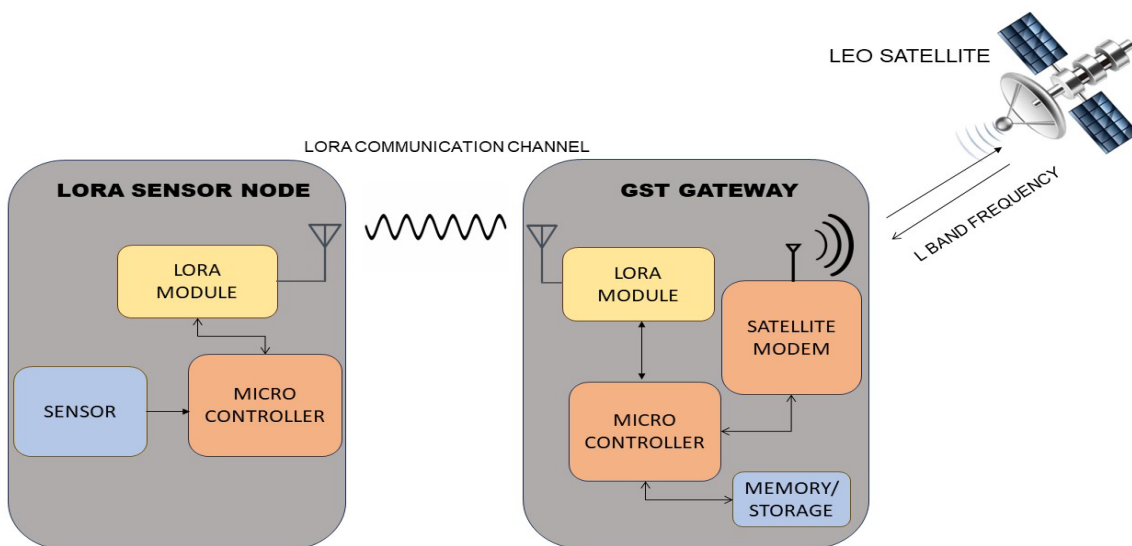


Fig. 2 Ground Sensor Terminal system architecture

Fig. 2 illustrates the communication between the LoRa sensor node, gateway, and satellite. The figure delineates the sequential steps and data transfer mechanisms within a LoRa-based Ground Sensor Terminal (GST)

system. It begins with the sensor collecting environmental data, which is then processed by the microcontroller. The processed data is transmitted via the LoRa module to the GST gateway, showcasing a bidirectional flow that facilitates both sending and receiving information. The gateway further processes this data through its own microcontroller, stores it, or forwards it via the satellite modem. Finally, the data is transmitted to a Low Earth Orbit (LEO) satellite on the L-band frequency, completing the upward flow of information.

1.1.3 Ground Sensor Terminal Gateway

Gateway serves as the bridge between Sensor Nodes and the satellite [1]. Satellite communication interfaces enable the integration of the ground sensor terminal with L Band Satellite networks, allowing bidirectional data exchange between the terminal and satellite ground stations [13]. These interfaces may include antennas, transceivers, and protocol converters that facilitate communication protocols compatible with L Band Satellite standards.

Overall, the ground sensor terminal (GST) architecture is designed to efficiently collect data from ground sensors, transmit it to a central location for processing and analysis, and provide insights that can be used for various applications. These applications include forest monitoring [14] ocean monitoring [15], earthquake monitoring [13], environmental monitoring [16], industrial automation [17], smart grid [18], and smart city initiatives [19].

1.1.4 LoRa Sensor Nodes

LoRa uses chirp pulses to encode data on radio waves using Chirp Spread Spectrum (CSS) technology. This modulation approach ensures signal reliability, interruption resistance, and long-distance coverage. Sensor nodes and gateways communicate using LoRa communication modules, which use modulation principles to enable long-range, low-power connectivity. These modules enable microcontroller-based packetization, modulation, and airborne data transmission. LoRa has a better range than WiFi, Bluetooth, and ZigBee for short data chunks at low bit rates [20-21].

LoRa sensor nodes, which are low-power microcontrollers equipped with data gathering and monitoring sensors, are essential components at the network periphery. These nodes can deliver data packets to gateways using LoRa transmitters, enabling long deployment periods without the need for maintenance [22-23]. In this study, sensor nodes with temperature sensors are used to measure temperature, humidity, pressure, and altitude in various situations. The sensor node's microcontroller executes programs to acquire sensor data in real time and send it directly to the LoRa module without intermediary data storage.

2. Methodology

The methodology section outlines the systematic approach used in developing and evaluating the LoRa-based Ground Sensor Terminal (GST) for L-band satellite IoT applications. The research framework is divided into four main phases: system design, prototype development, performance testing, and data analysis. In the system design phase, the architecture of the GST was conceptualized to include three main components: the sensor module, the LoRa communication module, and the L-band satellite module. The sensor module includes sensors for measuring temperature, humidity, altitude, and air pressure. The LoRa communication module handles data transmission from the sensor nodes to the gateway, while the L-band satellite module transmits the collected sensor data from the GST to the LEO satellites using the L-band frequency. Design considerations focused on ensuring low power consumption, long-range communication, and reliable data transmission.

The prototype development phase involved assembling and programming the GST according to the design specifications. Key steps in this phase included integrating sensors with the LoRa communication module and the L-band satellite modem, writing and deploying firmware to control the operation of the GST (including data collection, processing, and transmission), and conducting initial tests to ensure that all components functioned correctly and communicated with each other.

Performance testing was conducted to evaluate the GST's efficiency in various conditions. The testing process was divided into three scenarios: indoor testing, outdoor testing, and maximum range testing. Indoor testing evaluated the GST's performance in an environment with potential signal obstructions, while outdoor testing assessed its performance in an open field to determine its range and reliability without physical obstructions. Maximum range testing measured the maximum range of the LoRa communication link by gradually increasing the distance between the sensor nodes and the GST. During these tests, key performance metrics such as Received Signal Strength Indicator (RSSI), Signal-to-Noise Ratio (SNR), Acquisition of Signal (AOS), and Loss of Signal (LOS) were recorded and analyzed.

The data analysis phase involved processing the collected data to assess the GST's performance. The steps taken included gathering data on RSSI, SNR, latency, and energy consumption from the performance tests, using statistical methods to analyze the data and identify patterns and correlations, and comparing the results with the

expected performance metrics to identify areas for improvement. The analysis showed that the GST is capable of maintaining a reliable connection over long distances with low power consumption, making it suitable for remote IoT applications.

2.1 Received Signal Strength Indicator (RSSI)

RSSI is a measure of the power level that a receiver perceives from a transmitted signal. It is crucial in evaluating the performance of wireless communication systems such as LoRa. In this study, RSSI is used to assess the strength of the signals received by the Ground Sensor Terminal (GST) from the sensor nodes and the L-band satellite. A higher RSSI value typically indicates a stronger signal, which implies better communication reliability and lower chances of data loss.

For example, during our field tests, the RSSI values were recorded for various distances between the sensor nodes and the GST. These values were then analyzed to determine the effective range of the LoRa communication link.

2.2 Signal-to-Noise Ratio (SNR)

SNR is a measure of the signal strength relative to the background noise. It is an important parameter that affects the quality of the received signal. A higher SNR indicates a clearer signal with less interference from noise. In the context of this research, SNR was measured to evaluate the quality of the data transmission from the sensor nodes to the GST and from the GST to the satellite.

During our experiments, we observed that SNR values decreased as the distance between the sensor nodes and the GST increased, indicating a higher level of noise interference at greater distances. This information helped us to optimize the placement of the sensor nodes to ensure reliable communication.

This structured methodology, supported by a clear research framework and flowchart, ensures a logical progression of the study and helps in understanding the methods used to achieve the results.

2.3 Operation Workflow

Figure 3 depicts the operational workflow of the Ground Sensor Terminal (GST). Terminal (GST) involves several key steps. When both the Gateway and Sensor Node are powered on, the Gateway initiates the satellite modem's warming process. Next, the GST acquires GPS time from the satellite modem, using this temporal information as the filename for each sensor node data file created. Following the data acquisition phase, we detail the testing procedures implemented to evaluate the performance of the GST, specifically focusing on the LoRa communication range and reliability.

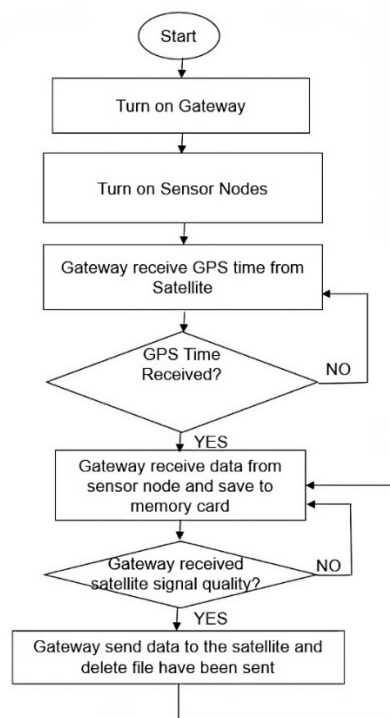


Fig. 3 Process flow of Ground Sensor Terminal (GST)

After obtaining the GPS time, the Gateway retrieves data from the sensor node, stores it in memory, and creates a file within the designated transmission folder intended for the satellite. The Gateway then assesses signal quality, proceeding with file transmission to the satellite if the signal quality exceeds a predefined threshold of 2. This procedure is repeated for each new sensor node data received after a successful transmission.

2.4 Testing Procedures

The diagram in Fig. 4 illustrates a communication setup involving a LoRa sensor node, a gateway, and a satellite connection, showing line-of-sight (LOS) pathways for data transmission in indoor and outdoor environments. In an indoor scenario, the LoRa sensor node communicates directly with the gateway in a line-of-sight manner, indicating minimal obstructions and a clear communication path. In contrast, the outdoor scenario introduces obstacles, such as buildings, which disrupt the direct line of sight between the LoRa sensor node and the gateway. The LoRa sensor node, located at a distance from the gateway, sends data along a direct LOS path to the gateway positioned on a building. The gateway serves as an intermediary, receiving data from the sensor node and forwarding it through a satellite link. This setup enables remote data collection and transmission over long distances, utilizing LoRa technology's low-power, wide-area capabilities to reach the gateway, which then leverages satellite connectivity for extended communication coverage. This transmission test analyzes LoRa performance and measures RSSI and SNR over three range circumstances. Initial signal levels are measured indoors with 100 m coverage. RSSI, SNR, and sensor data are incrementally monitored at 10 m intervals. After that, outdoor measurements are collected. Finally, the test determines the sensor node's and gateway's maximum data transmission and reception range. The LoRa module handbook states that a 5 dBi gain antenna may transmit up to 7 km in clear, open regions. Current configuration uses a 2 dBi gain antenna, therefore finding free regions is difficult. However, the study determines the maximum range possible with the current arrangement.

Optimizing satellite data transmission timing requires satellite path monitoring and pass prediction software. Satellite livemap, with its dynamic map interface showing real-time satellite visibility from selected places, is an important resource. Orbitron is cross-platform satellite monitoring program that provides real-time tracking, pass prediction, orbit visualization, and visibility warnings. Celestrak Two-Line Element (TLE) sets filter out non-operational and spare satellites, ensuring reception of active satellites, confirmed by satellite provider livemap website data for continuous satellite tracking. This helps estimate pass timings for best signal reception.

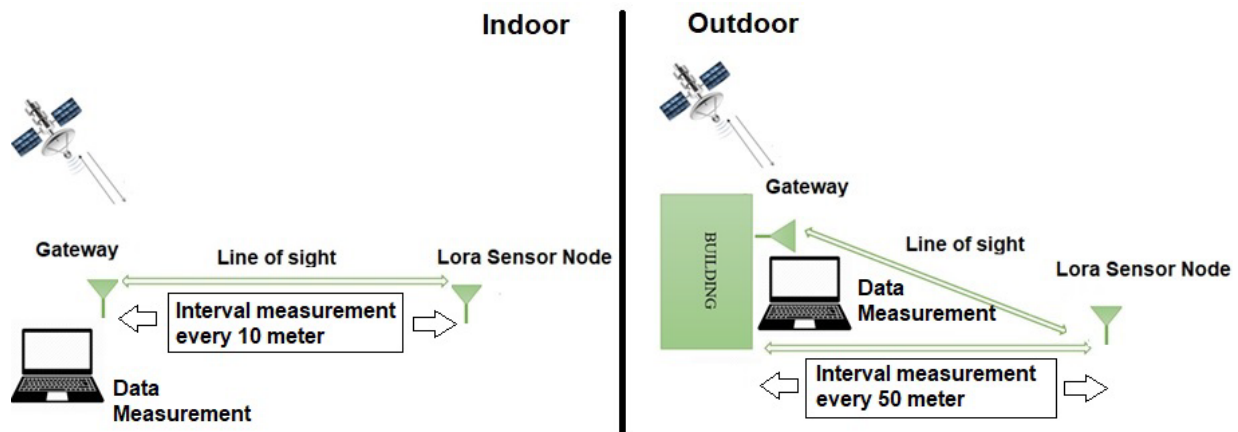


Fig. 4 Line-of-sight communication between LoRa sensor node and gateway with satellite connectivity for indoor and outdoor measurement

2.5 Acquisition of Signal (AOS)

AOS refers to the point in time when a satellite first establishes contact with the ground station and starts receiving signals. It is a critical event in satellite communications as it marks the beginning of the data transmission window. In our study, AOS was monitored to determine the timing and duration of the communication link between the GST and the L-band satellite.

By analyzing AOS data, we were able to synchronize the transmission schedules of the sensor nodes to ensure that data packets were sent during the satellite's visibility period, thereby maximizing the efficiency of the data transmission process.

2.6 Loss of Signal (LOS)

LOS refers to the point in time when the satellite communication link is lost, either due to the satellite moving out of range or other factors such as signal obstruction. Monitoring LOS is essential to understand the communication link's duration and to plan for retransmission of data if necessary.

In this research, LOS was recorded alongside AOS to calculate the total available communication window for each satellite pass. This information was used to optimize the scheduling of data transmissions from the GST to the satellite, ensuring that critical data could be sent before the communication link was lost.

3. Results and Discussion

This section explores three major results aimed at assessing the performance of the LoRa module both indoors and outdoors, as well as its capacity to transmit over maximum distances.

3.1 Result of Indoor vs Outdoor Transmission

The data presented in Fig. 5 illustrates a comparison between indoor and outdoor environmental factors across various ranges. Indoor measurements generally demonstrate lower values for RSSI (Received Signal Strength Indicator) and SNR (Signal-to-Noise Ratio) in comparison to outdoor readings across all ranges, suggesting potentially weaker signal strength and higher noise levels indoors. This section will further discuss these observations in relation to the maximum range tests and payload delivery performance, providing a comprehensive view of the GST's capabilities and limitations.

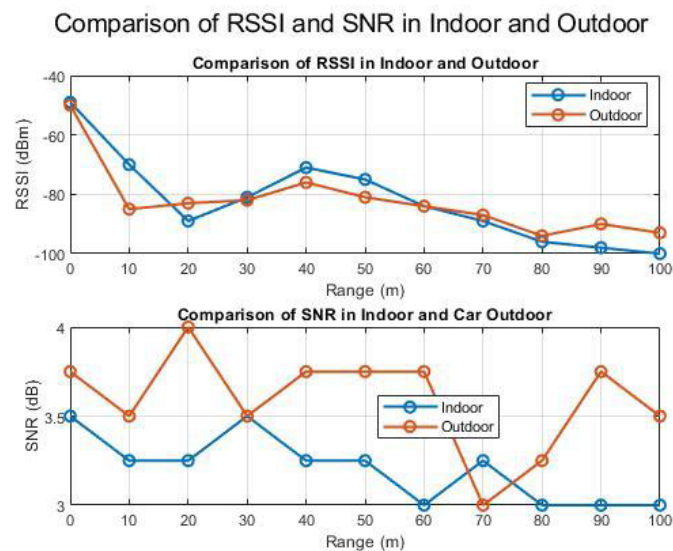


Fig. 5 LoRa experiment result of indoor vs outdoor environment

3.2 Lora Experiment Result of Maximum Range

The environmental parameters were measured at various ranges during the LoRa experiment and were recorded as shown in Fig. 6. Under the current configuration, data reception was achieved at distances of up to 450 m. The RSSI (Received Signal Strength Indicator) decreases as the range increases, indicating a weakening signal over distance, which can affect wireless communication reliability. SNR (Signal-to-Noise Ratio) fluctuates, sometimes negatively, suggesting variations in signal quality and potential interference.

To summarize the data from Fig. 6 a line graph effectively represents the relationship between the different variables across the specified ranges. The x-axis represents the range values, while the y-axis depicts the respective parameters such as RSSI and SNR. Each variable's trend over the range can be visually assessed through the graph, providing insights into any patterns, correlations, or anomalies present in the data.

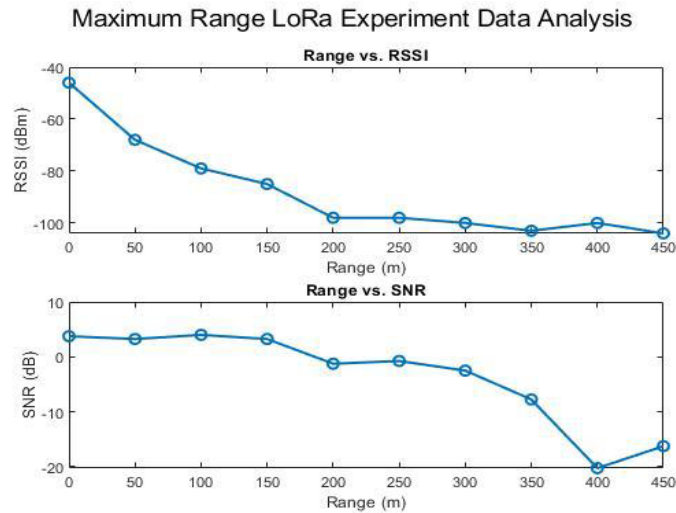


Fig. 6 LoRa experiment result of maximum range

3.3 Payload Dashboard Satellite Data Transmission

As shown in Table 1, satellite data transmission results were obtained from serial monitor and satellite provider dashboard. The dashboard received satellite data and identified the passing satellite. The analysis of payload delivery performance involves examining the transmission success rates, latency, and data integrity. During the peak signal phase between Acquisition of Signal (AOS) and Loss of Signal (LOS), the data transmission success rate was highest. This indicates that timing the data transmissions to coincide with these peak periods can significantly enhance the reliability and efficiency of the GST. Additionally, the placement of the gateway plays a critical role in transmission clarity, as obstructions can lead to signal degradation and data loss. The gateway is not on a rooftop or in the open sky, therefore transmission clarity depends on satellite characteristics. The table shows that only satellites facing indoors with a 270-degree azimuth could send signals. The gateway's placement limits prevented satellites at 90 degrees from transmitting, even if they were nearest. Transmissions occurred within the peak signal phase between Acquisition of Signal (AOS) and Loss of Signal (LOS), according to transmission timing data. The satellite provider dashboard displays sensor payload data and its visibility time. Notably, the satellite processes data in real time, improving dashboard data availability.

Table 1 Satellite data transmission results

	Time (+8)	Satellite	Azimuth (°)	Elevation (°)	Range (km)	Serial Monitor Time Transmit	Dashboard data Timestamp	
AOS	13:46:14		186.5	0	3315			
MAX	13:53:53	IRIDIUM	269.5	61	877	13:51:15	13:51:15	
ELEVATION	14:01:31		100	353.6	0			3301
LOS								
AOS	14:04:44		195.5	0	3317			
MAX	14:12:09	IRIDIUM	270.1	36.2	1209	14:10:43	14:10:42	
ELEVATION	14:19:33		125	345.1	0			3303
LOS								14:11:01
AOS	14:14:05		200.5	0	3316	14:18:46	14:18:46	
MAX	14:21:17	IRIDIUM	270.2	27.7	1434	14:20:21	14:20:21	
ELEVATION	14:28:28		136	340.2	0	3302	14:20:35	14:20:35

4. Conclusion

This paper shows the architecture of space-based IoT and how it can complement the connectivity by integrating LoRa technology with L Band Satellite communication. By synthesizing the findings from our indoor, outdoor, and

maximum range tests, we highlight the practical implications and future directions for deploying GSTs in remote and challenging environments. Through an exploration of system design, performance evaluation, and potential applications, the study underscores the transformative potential of ground sensor terminals in various sectors, including precision agriculture, environmental monitoring, disaster management, and wildlife conservation. By addressing challenges such as power efficiency, communication reliability, scalability, security, and interoperability, researchers and practitioners can unlock the full potential of satellite-based IoT networks, paving the way for greater efficiency, resilience, and innovation in interconnected systems.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

*The authors confirm contributions to the paper as follows: **study conception and design:** Mohd Farid Omar, Fatimah Zaharah Ali, Muhammad Syazwan Johari; **data collection:** Mohd Farid Omar, Zafirah Faiza, Muhammad Syazwan Johari; **analysis and interpretation of results:** Mohd Farid Omar, Mohamad Huzaimy Jusoh, Fatimah Zaharah Ali; **draft manuscript preparation:** Mohd Farid Omar, Fatimah Zaharah Ali, Muhammad Syazwan Johari; **manuscript review and intellectual content:** Fatimah Zaharah Ali, Mohamad Huzaimy Jusoh, Mardeni Roslee; **conceptualization, research methodology, and supervision:** Mohamad Huzaimy Jusoh, Fatimah Zaharah Ali; **reviewed the results and approved the final version of the manuscript:** Fatimah Zaharah Ali, Mohamad Huzaimy Jusoh, Mardeni Roslee.*

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