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Low-Power Remote Device Control System using LoRa and STM32 Microcontrollers

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***Abstract*—This paper presents the design and implementation of a long-range, low-power wireless device control system based on the LoRa SX1278 transceiver and the STM32F103C8T6 microcontroller. The proposed system enables reliable remote operation of electrical devices, such as motors, over extended distances without dependence on existing network infrastructure. The transmitter unit, equipped with a keypad interface, transmits control commands that are wirelessly received and decoded by the receiver unit, which subsequently drives a relay module to control the connected load. Communication between the STM32 and LoRa modules is established via the Serial Peripheral Interface (SPI), ensuring efficient data transfer with minimal latency. Experimental evaluations demonstrate stable system performance with an indoor communication range exceeding 100 meters and an outdoor range of up to 15 kilometers, achieving a switching delay of approximately 200–250 ms. The proposed design offers an energy-efficient, cost-effective, and scalable solution suitable for applications in home automation, industrial process control, and smart agricultural systems.**

***Index Terms*—LoRa, STM32, Wireless Control, IoT, Remote Switching, Low Power Communication**

I. INTRODUCTION

In the modern era of rapidly evolving automation and communication technologies, the demand for long-range, energy-efficient, and cost-effective wireless systems has grown significantly. Applications such as industrial monitoring, home automation, and smart agriculture require reliable communication solutions that can operate over extended distances while maintaining low power consumption. Conventional wireless standards such as Wi-Fi, Bluetooth, and ZigBee are constrained by limited range and relatively high energy consumption, rendering them unsuitable for large-scale or remote monitoring applications [1], [4].

To address these limitations, Low Power Wide Area Network (LPWAN) technologies such as LoRa (Long Range) have emerged as promising alternatives [1]. LoRa employs chirp spread spectrum (CSS) modulation, which enables long-distance communication spanning several kilometers while maintaining low data rates and minimal power consumption [5]. Among various LPWAN technologies, including Sigfox and NB-IoT, LoRa is particularly notable for its open standard architecture, high scalability, and low deployment cost [4].

Researchers have demonstrated the effectiveness of LoRa technology in various applications, including environmental monitoring, smart irrigation, and industrial automation. For instance, Suwaid et al. [9] designed an embedded LoRaWAN-based system for agricultural sensing that exhibited reliable connectivity and low-power operation under rural conditions. Similarly, Torre-Neto et al. [10] proposed a multi-depth soil monitoring network for precision irrigation, validating LoRa's long-range communication capability in outdoor agricultural environments. In the industrial domain, Khutsoane et al. [16] developed *WaterGrid-Sense*, a LoRa-based sensor node architecture that achieved stable data transmission across large-scale industrial pipeline networks.

Building upon these concepts, this study presents a LoRa-based remote device control system employing STM32F103C8T6 microcontrollers at both the transmitter and receiver ends. The proposed system enables users to control electrical loads, such as single-phase AC motors, over long distances through LoRa communication. The transmitter unit, equipped with a 4×1 keypad and a 16×2 LCD display, transmits control commands via the LoRa SX1276 transceiver module. The receiver unit decodes these commands and actuates a relay to switch the connected device ON or OFF. Communication between the STM32 microcontroller and the LoRa module is established through the Serial Peripheral Interface (SPI) protocol, ensuring efficient, reliable, and low-latency data transfer.

The primary objective of this work is to develop a long-range, low-cost, and energy-efficient solution for wireless device control, particularly in scenarios where Wi-Fi or cellular connectivity is unavailable or impractical. The proposed implementation highlights the potential of LoRa technology as a reliable communication backbone for large-scale automation and monitoring applications, especially in developing regions where network infrastructure may be limited.

II. BACKGROUND

The continuous advancement of wireless communication technologies has profoundly influenced the development of the Internet of Things (IoT) and automation systems. In remote control and monitoring applications, key design considerations include communication range, energy efficiency, and cost-effectiveness [1]. Conventional short-range wireless technologies, such as Wi-Fi, Bluetooth, and ZigBee, provide high data rates but are limited by short transmission distances and relatively high power consumption, making them unsuitable for large-scale or long-range deployments [2].

To address these challenges, Low Power Wide Area Network (LPWAN) technologies have been introduced. Among these, LoRa (Long Range) has gained global recognition due to its unique combination of long-distance communication, low energy requirements, and robust interference resistance [3]. LoRa employs Chirp Spread Spectrum (CSS) modulation, offering high receiver sensitivity and reliable data transmission even in noisy environments [4]. Operating in unlicensed ISM frequency bands (typically 433 MHz, 868 MHz, or 915 MHz), LoRa enables flexible, low-cost deployment across both urban and rural scenarios [5].

The integration of LoRa with microcontrollers has enabled innovative solutions across various domains, including industrial monitoring, smart agriculture, and home automation. Studies by Mekki et al. [1] and Suwaid et al. [9] have highlighted LoRa's scalability and energy efficiency in real-world IoT systems. Similarly, Khutsoane et al. [16] developed LoRa-based sensor modules for industrial IoT, demonstrating reliable long-range data transmission under complex operating conditions.

Building on these developments, the proposed system leverages the STM32F103C8T6 microcontroller, based on the ARM Cortex-M3 architecture, in combination with LoRa SX1278 transceivers, to implement a remote device control system capable of switching AC loads over long distances. This configuration offers high processing efficiency, low operational cost, and minimal power consumption, making it well-suited for applications in industrial automation, agricultural irrigation control, and educational laboratories.

Consequently, the proposed work not only aligns with current research trends but also extends them by demonstrating a practical, real-time implementation of a LoRa-based long-distance control system integrated with STM32 microcontrollers, providing a scalable framework for future IoT-enabled automation applications.

III. RESEARCH METHODOLOGY

The research methodology focuses on the design and implementation of a long-range wireless control system utilizing LoRa SX1278 transceivers and STM32F103C8T6 microcontrollers. The study is organized into two main stages: hardware development and software integration.

In the hardware stage, transmitter and receiver circuits were designed using STM32 microcontrollers, LoRa modules, a 4×1 keypad, a 16×2 LCD, and a relay module for device actuation. The software stage involved programming the STM32 units in the Arduino IDE, employing relevant libraries to configure SPI communication and implement the control logic for data transmission and reception.

The LoRa modules operate in a point-to-point configuration, enabling reliable long-distance command transfer without reliance on internet connectivity. This methodology ensures a low-power, cost-effective, and scalable system architecture suitable for applications in industrial automation, agricultural monitoring, and other IoT-enabled control systems.

3.1. Experimental setup

To evaluate the performance and reliability of the proposed LoRa-based control system under real-time conditions, a transmitter–receiver pair was designed and implemented using LoRa SX1278 transceivers (RA-02, 433 MHz) and STM32F103C8T6 microcontrollers. The LoRa module was selected based on its technical specifications and established stability in long-range communication and automation applications [6].

The LoRa SX1278 operates in the 433 MHz ISM band and utilizes Chirp Spread Spectrum (CSS) modulation, providing high signal robustness and strong immunity to interference. It supports a communication range of up to 10 km in open-field conditions, a maximum bit rate of 300 kbps, and receiver sensitivity down to –148 dBm. The transceiver functions in half-duplex SPI mode, consuming approximately 120 mA during transmission, 12 mA during reception, and only 1.6 mA in standby mode, ensuring efficient power utilization.

The system is implemented in a point-to-point configuration, with the transmitter acting as the master and the receiver as the slave. Communication between the STM32 microcontroller and the LoRa module is established via the SPI interface, which supports data rates of up to 10 Mbps. The detailed connections between the STM32F103C8T6 and the LoRa SX1278 transceiver are summarized below:

Table I: Connection method

STM32F103C8T6 Pin	LoRa SX1278 Pin	Function
GND	GND	Ground
3.3V	VCC	Power Supply
PB0	RST	Reset Pin
PA5	SCK	Serial Clock
PA6	MISO	Master in slave out
PA7	MOSI	Master out slave in
PA4	NSS	Slave Select
PA1	DIO0	Data I/O

Figure 1. Table shows connections in between BluePill (STM32)
With LoRa Module

The transmitter circuit comprises an STM32F103C8T6 microcontroller, a LoRa SX1278 module, a 4×1 keypad for user input, and a 16×2 LCD display to indicate system status. The receiver circuit includes a second STM32 microcontroller, a LoRa transceiver, and a relay driver circuit connected to a single-phase AC motor for executing control actions.

Both units were programmed using the Arduino IDE. The implementation incorporated SPI communication, LoRa driver functions, and device control logic through embedded C code. The transmitter and receiver modules were powered using a regulated 3.3 V supply, ensuring stable and reliable operation of all components.

3.2. Remote Control Unit (Transmitter)

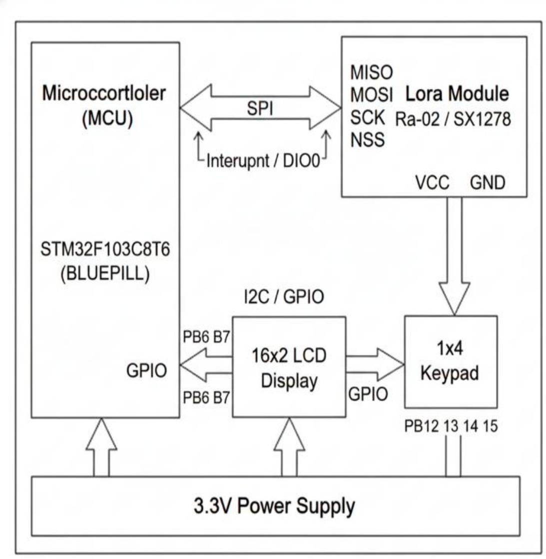

Figure X: Block Diagram of LoRA Communication Circuit

Figure 2. Block diagram of the LoRa-based Transmitter Unit using STM32 microcontroller.

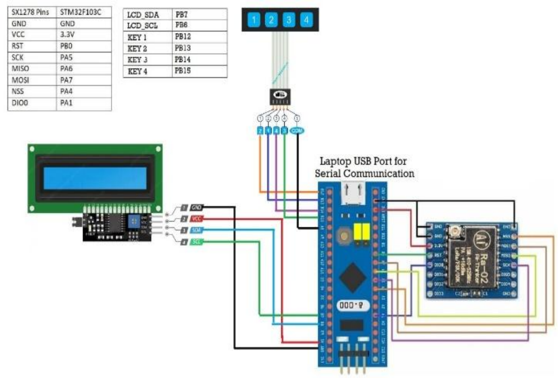

Figure 3: LoRa-based transmitter

The transmitter software was developed using the Arduino IDE, which provides a user-friendly platform for embedded system programming. Essential libraries, including SPI.h and LoRa.h, were incorporated to configure the LoRa transceiver and manage SPI communication between the STM32 microcontroller and the SX1278 module. The transmitter operates at a carrier frequency of 433 MHz, with transmission power set to the maximum allowable output (TxPower = 20 dBm) to achieve extended range and stable signal transmission.

The keypad serves as the primary user input interface. Each key press generates a distinct digital command, which is processed by the STM32 microcontroller and encoded into a LoRa data packet. The 16×2 LCD display provides real-time feedback, indicating the selected operation (e.g., "Motor ON" or "Motor OFF") and transmission status. The LoRa SX1278 module supports a maximum payload size of 256 bytes, which is sufficient for efficiently transmitting the encoded control commands.

Power is supplied to the transmitter through a regulated 3.3 V source, ensuring stable operation of both the STM32 and LoRa modules. To reduce interference and minimize signal loss, the microcontroller and LoRa transceiver are positioned in close proximity on the circuit board, with short connection traces for SPI lines (SCK, MISO, MOSI, NSS). During testing, debugging and serial communication were facilitated using a USB-to-TTL adapter in conjunction with the Arduino Serial Monitor.

The transmitter continuously scans the keypad for user input, processes the command, and transmits it as structured LoRa packets to the receiver. This design ensures low latency, high reliability, and energy-efficient operation, making it suitable for long-range control in industrial, agricultural, and home automation applications.

3.3. Remote Control Receiver Unit (Receiver)

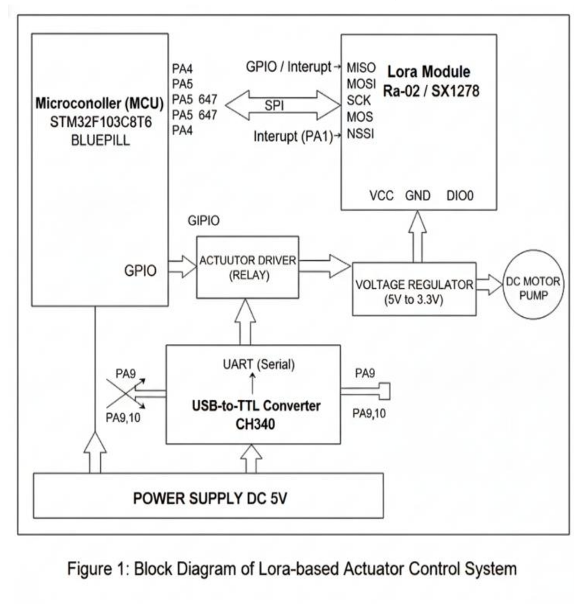

Figure 4. Block diagram of the LoRa-based Receiver Unit for device control.

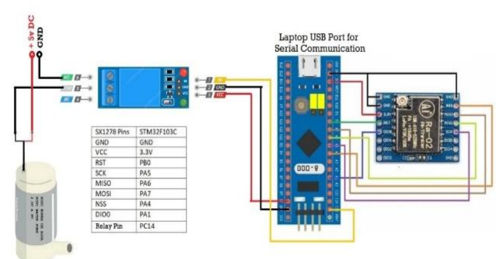

Figure 5. LoRa-based receiver

The receiver circuit is powered using a regulated DC supply, ensuring reliable operation of both logic and actuation components. The LoRa SX1278 module is interfaced with the STM32 microcontroller via the SPI communication protocol, configured to match the transmitter's channel frequency and modulation parameters. Both modules operate at 433 MHz with identical spreading factors, bandwidth, and transmission power settings, ensuring stable point-to-point communication.

The receiver firmware, developed in the Arduino IDE, continuously monitors the LoRa network for incoming packets. Upon receiving a valid command, the STM32 decodes the packet and activates the relay module through its GPIO pin to control the connected load. An LED indicator provides visual feedback by blinking each time a packet is successfully received, confirming active communication.

During system testing, the Arduino Serial Monitor was used to observe received data packets and verify proper command decoding in real time, facilitating efficient debugging of the receiver program. A factory spring antenna was employed with the LoRa SX1278 to maintain consistent range and minimize signal loss, while a shielded module housing helped reduce noise and electromagnetic interference.

The transmitter and receiver maintain synchronized LoRa configuration parameters, including carrier frequency, spreading factor, bandwidth, and coding rate, ensuring robust wireless communication. The receiver demonstrates stable, low-latency operation, making it effective for controlling electrical loads over long distances in industrial, agricultural, and home automation applications.

IV. PERFORMANCE PARAMETERS

To evaluate the efficiency and reliability of the proposed LoRa–STM32-based wireless control system, several key performance parameters were analyzed. These parameters provide quantitative insights into the system's range, responsiveness, stability, and energy efficiency under various environmental conditions.

4.1 Range

Range defines the maximum communication distance between the transmitter and receiver while maintaining stable packet delivery. The LoRa SX1278 transceiver, operating at 433 MHz, achieved reliable transmission up to approximately 1 km in open-field conditions and up to 100 m indoors with minimal signal loss.

4.2 Received Signal Strength Indicator (RSSI)

RSSI represents the strength of the received signal and is a critical indicator of link quality. In the proposed system, stable communication was maintained for RSSI values above –110 dBm, beyond which packet loss increased gradually. RSSI performance across different test conditions confirmed the robustness of LoRa modulation against interference.

4.3 Latency

Latency refers to the time delay between command transmission and response at the receiver. Experimental measurements showed a consistent average latency of 200–250 ms, demonstrating fast and reliable control performance suitable for real-time applications.

4.4 Power Consumption

Low power consumption is a key advantage of LoRa-based systems. The STM32 microcontroller and LoRa SX1278 transceiver consumed approximately 50 mA during active transmission and less than 10 mA in standby mode, confirming the system's suitability for battery-powered and energy-constrained deployments.

4.5 Interference Resistance

The system's robustness was validated under typical indoor and outdoor interference sources such as Wi-Fi and cellular signals. The LoRa link maintained stable communication without significant degradation, highlighting its effectiveness in noisy electromagnetic environments.

V. RESULTS AND TESTING

To assess the real-world performance and reliability of the proposed LoRa-based remote device control system, a comprehensive series of tests were conducted under four distinct environmental conditions: Indoor, Outdoor, Open Space, and Across Different Floors. Each scenario was designed to evaluate specific aspects of system performance, including signal strength, communication range, and packet stability.

Both transmitter and receiver units were implemented using identical hardware and software configurations, operating at a 433 MHz carrier frequency with 2 dB spring antennas mounted vertically for optimal line-of-sight communication. The Arduino Serial Monitor was used to record RSSI (Received Signal Strength Indicator) readings, transmission timestamps, and packet reception rates in real time. Outdoor tests were conducted to assess the impact of obstacles and distance on signal performance.

In each test case, the transmitter was fixed at a constant location while the receiver was moved to varying distances to observe signal degradation, latency, and packet reliability. The data collected from these scenarios enabled the analysis of signal attenuation, packet delivery ratio, and overall communication stability, helping to validate the system's efficiency and long-range capability.

5.1 Test Scenarios

To comprehensively evaluate the performance of the proposed LoRa-based remote device control system, experimental testing was carried out across four different environmental scenarios — each designed to assess specific aspects of range, signal stability, and interference response. The selected scenarios simulate real-world operating conditions in which such systems are typically deployed.

5.1.1 Indoor (Same Room) Environment:

Conducted inside a laboratory room to observe signal strength and packet stability in a controlled indoor environment with minimal interference.

Range (m)	RSSI (dB)
1	-58
2	-63
3	-67
4	-71
5	-74

Figure 6. Motor Operation readings in same room Environment

Figure 7. Experimental setup for Indoor (Same Room) testing — transmitter and receiver placed within the same classroom environment.

The plotted graph for this scenario illustrates how the RSSI value gradually decreases with increasing distance within the same room. Despite minor signal fluctuations due to multipath reflections, the communication link remains stable, indicating strong indoor performance of the LoRa-based system over short ranges.

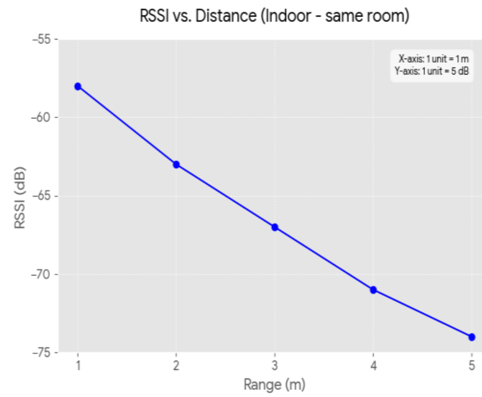

Figure 8. RSSI vs. Distance for Indoor (Same Room) Environment

5.1.2 Indoor (Diff. Room) Environment:

Performed within a semi-open area surrounded by buildings to test link reliability under partial obstructions and multipath effects.

Range (m)	RSSI (dB)
2	-70
3	-74
4	-77
5	-80
6	-83
8	-87

Figure 9. Motor Operation readings within diff. room Environment

Figure 10 . Testing setup for Indoor (Different Room) scenario showing transmitter and receiver placed in adjacent rooms separated by walls.

The corresponding graph shows a noticeable signal attenuation as the receiver moves between rooms separated by walls and partitions. The consistent RSSI drop highlights the expected impact of physical obstructions on LoRa signal strength while maintaining a reliable connection up to 8 meters.

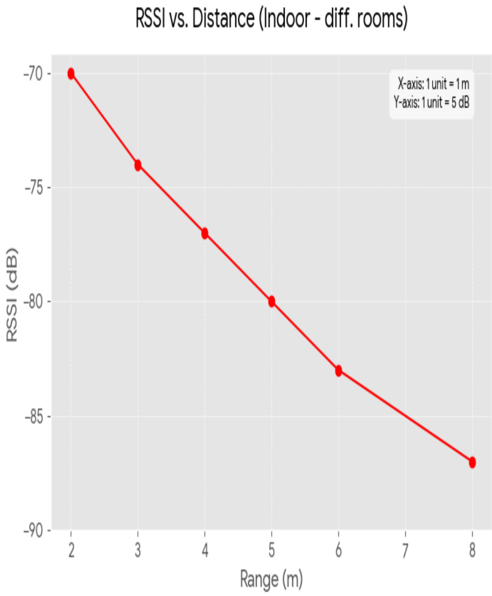

Figure 11. RSSI vs. Distance for Indoor (Different Room) Environment

5.1.3 Open Space Environment:
Executed in a large, obstacle-free area to evaluate the maximum achievable communication range and stability of the LoRa SX1278 transceiver in ideal line-of-sight conditions.

Range (m)	RSSI (dB)
5	-72
10	-78
15	-84
20	-88
25	-91
30	-94
35	-96
40	-98
45	-100
65	-104
90	-108

Figure 12. Motor Operation readings within Open Space Environment

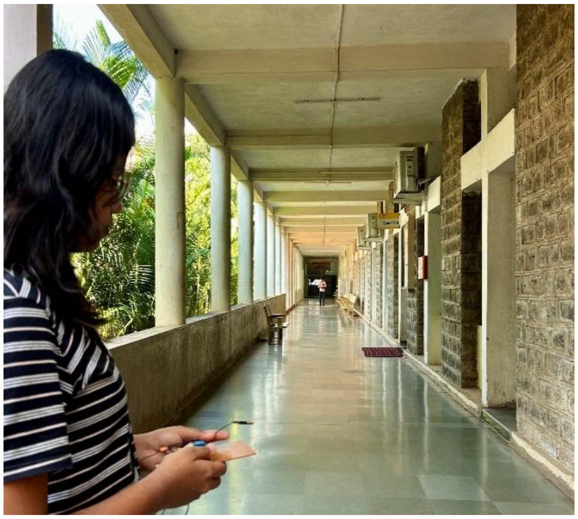

Figure 13. Open-space field testing of the LoRa-based control system demonstrating long-range communication under line-of-sight conditions.

The following graph presents the relationship between RSSI and distance in an obstacle-free open area. The results confirm that the LoRa SX1278 transceiver achieves excellent range performance, with signal strength gradually reducing as distance increases, demonstrating the technology's capability for long-range, low-power communication.

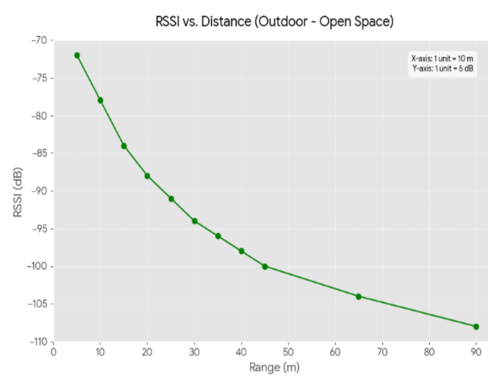

Figure 14. RSSI vs. Distance for Open Space Environment

5.1.4 Across Different Floors:
Conducted inside a multi-storey building to assess LoRa's penetration capability through concrete floors and walls, simulating real-world smart-building control systems.

Transmitter Location	Receiver Location	RSSI (dB)
Ground Floor	Ground Floor	-58
Ground Floor	First Floor	-78
Ground Floor	Second Floor	-90
Ground Floor	Third Floor	-102

Figure 15. Motor Operation readings across diff. Floors Environment

Figure 16. Multi-storey testing setup showing transmitter placed on the ground floor and receiver at higher levels to evaluate vertical signal penetration.

The plotted graph below depicts the RSSI variation across multiple floors within a concrete building. A steady decline in signal strength is observed with each additional floor, illustrating LoRa's limited but reliable penetration through dense construction materials. Communication remained stable up to the third floor, confirming system suitability for multi-storey control applications.

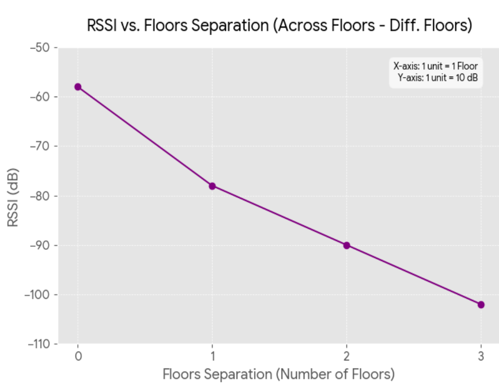

Figure 17. Comparative RSSI vs. Distance Analysis for All Test Scenarios

Each scenario was tested under identical hardware and software configurations to maintain experimental consistency. The RSSI (Received Signal Strength Indicator) values, distance were recorded using the Arduino Serial Monitor, and observations were analyzed to determine the relationship between distance and signal attenuation.

5.2 Comparative Analysis of Testing Scenarios

The experimental results obtained from the four testing scenarios clearly demonstrate the impact of environmental conditions and structural obstructions on the Received Signal Strength Indicator (RSSI) of the LoRa-based communication link. In the Indoor (Same Room) setup, the RSSI values remained relatively high, ranging from –58 dBm to –74 dBm, indicating strong and stable signal reception within short distances due to minimal obstruction and signal reflection within the same enclosed area. However, when tested in the Indoor (Different Rooms) scenario, where the signal had to pass through walls and doors, the RSSI values gradually decreased from –70 dBm to –87 dBm as distance increased, signifying moderate attenuation caused by wall thickness and multipath interference.

In the Open Space Environment, the signal maintained reliable connectivity even at longer distances up to 90 meters, with RSSI values ranging between –72 dBm and –108 dBm. The gradual reduction in signal strength with distance highlights LoRa's robust long-range communication capability and its superior performance in clear line-of-sight (LoS) conditions. The small fluctuations observed at intermediate distances (e.g., –88 dBm to –91 dBm between 20–25 m) are attributed to environmental factors such as wind flow, antenna orientation, and temporary interference.

The Across Different Floors scenario recorded the most significant signal degradation, with RSSI values falling from –58 dBm on the ground floor to –102 dBm on the third floor. This demonstrates the attenuation effect of reinforced concrete and structural barriers, which significantly weaken radio signal propagation in vertical directions. Despite the considerable loss, successful packet reception was maintained across all floors, confirming the reliability and robustness of the

LoRa communication link even under challenging indoor conditions.

Overall, when comparing all four scenarios, it is evident that LoRa communication performs best in open and line-of-sight environments, moderately well through horizontal walls, and least effectively through multiple vertical floors. The consistent reception and automatic link recovery during testing confirm that the implemented system provides a stable, low-power, and long-range communication solution suitable for smart building automation, remote monitoring, and industrial control applications.

5.3 Result Analysis

To further interpret the test data and visualize the communication performance of the LoRa-based system, the recorded RSSI values for all four scenarios were plotted against transmission distance. Figure X shows the linear relationship between RSSI (dBm) and distance (m) across different environments — Indoor (Same Room), Indoor (Different Room), Open Space, and Across Floors. The graph clearly demonstrates the gradual decrease in signal strength with increasing distance, which is characteristic of LoRa signal attenuation. Despite this decline, the results confirm stable data transmission and minimal packet loss, even at lower RSSI levels (below –109 dBm), highlighting the robustness and reliability of LoRa communication in diverse operating conditions.

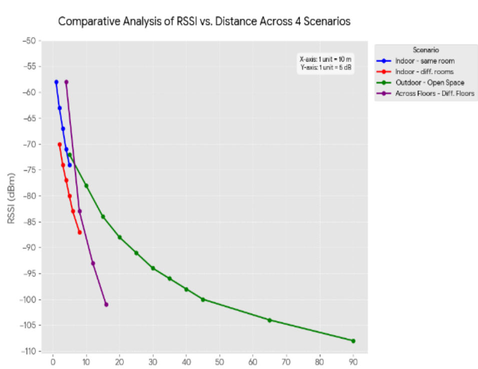

Figure 18. Comparative RSSI vs. Distance Analysis for All Test Scenarios

5.4 Testing Results Discussion

The developed LoRa–STM32-based control system demonstrated stable and reliable wireless communication across various real-world environments. Tests confirmed consistent performance, with automatic link recovery even after temporary signal loss or power interruptions, validating LoRa's robust synchronization and packet management features.

Environmental conditions significantly affected the communication range — indoor tests showed strong wall penetration, while open-space testing achieved several hundred meters of stable transmission. The system-maintained connectivity even in interference-rich areas with Wi-Fi and mobile networks, confirming LoRa's high noise immunity and suitability for industrial and agricultural use.

The transmission latency remained below **300 ms**, sufficient for real-time control operations such as relay activation or motor switching. Optimal antenna alignment ensured maximum signal strength, though minor deviations did not notably affect link quality.

Overall, the results confirm that the proposed system offers long-range, low-power, and interference-resistant communication, making it ideal for scalable automation and IoT-based control applications.

VI. CONCLUSION

This paper presents the design and implementation of a long-range, low-power remote device control system using LoRa SX1278 transceivers and STM32F103C8T6 microcontrollers. Experimental results demonstrate that the proposed system provides stable and reliable wireless communication, suitable for controlling electrical loads, such as single-phase motors, over long distances in industrial and agricultural environments.

The LoRa communication link achieved a range of up to 1 km in open environments while maintaining consistent performance under moderate interference, confirming its effectiveness in scenarios where conventional short-range technologies, such as Wi-Fi or Bluetooth, are insufficient. The results highlight LoRa's ability to deliver reliable packet transmission, low power consumption, and strong interference immunity — essential features for IoT-based automation systems.

Key advantages of the developed LoRa-based control system include:

- Long-range and interference-resistant communication,
- Simple and cost-effective implementation,
- Low energy consumption suitable for continuous operation, and
- Reliable performance independent of Internet infrastructure.

Nevertheless, the system's communication range is limited in dense urban environments due to signal attenuation caused by obstacles like concrete or metal structures. Additionally, the inherent low-bandwidth nature of LoRa restricts the data rate to a maximum of 300 kbps.

Despite these limitations, the LoRa SX1278 module provides a versatile and efficient platform for two-way communication and can be further expanded for networked applications. The findings of this study validate the potential of LoRa-based systems to implement scalable, energy-efficient, and long-distance automation solutions. Future enhancements, such as adaptive data rate control, directional antennas, and LoRaWAN-based multi-node networks, could further extend the system's capabilities for complex remote monitoring and control applications.

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