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# Experimental Implementation of Communication Network for Interoperable Building Microgrids Using LoRa Technology

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**Abstract**

To address the issues of utility grid outages and uncertain renewable energy, recent developments suggest integrating multiple community microgrids using advanced communication and networking technology, which are termed Interoperable Building Microgrids (IBMs). This integration enables more effective communication between suppliers and consumers, making these systems more adaptable and efficient. To establish the required communication in IBMs, various conventional technologies namely Wi-Fi, Zigbee, WiMax, and Cellular are available. However, these technologies cannot support long-range along with low power consumption. Alternatively, a Low-Power Wide-Area Network (LPWAN) is an advanced network designed for low-power devices over long distances for Internet of Things (IoT) applications. There are numerous LPWAN technologies available including Sigfox, LoRa (Long Range), NB-IoT (Narrowband IoT), LTE-M (Long-Term Evolution for Machines), and Weightless. Among these, the LoRa has the advantages such as working in scientific, industrial, and medical band (open band), long-range communication, low power consumption, standalone network building capacity, and can support a large number of devices simultaneously. So, its applicability for IBMs has to be thoroughly investigated. With this motivation, this paper presents an experimental implementation of a LoRa-based communication network. A case study is also presented to illustrate the proposed architecture, which was conducted in a real environment on a university campus. This allows to determine the suitability of LoRa communication technology for different smart grid wide area applications. The measured results illustrate that the proposed network can be successfully implemented for urban energy communities.

**Keywords:** communication network; Internet of Things (IoT); interoperability; LoRa; LoRaWAN; smart microgrid

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## 1. Introduction

A smart microgrid is a modern and advanced version of a localized power system known as a microgrid. This system consists of DERs and can function independently or in integrated mode with the utility grid. However, a smart microgrid leverages modern devices/technologies namely sensors, control systems, and communication networks to optimize its energy management and efficiency. By using real-time data and analytics, it can balance supply and demand and manage energy storage and distribution more efficiently, enabling advanced demand response and enhancing grid resiliency. Smart microgrids

also provide various important grid services that help balance the utility grid. Overall, these smart microgrids offer significant benefits, including improved energy efficiency, cost savings, increased reliability, and reduced carbon emissions [1,2].

Microgrids are known for their eco-friendliness, and decentralized nature, which can effectively lessen the burden on the conventional utility grid. Nevertheless, their power-generating capability can be uncertain due to varying environmental factors, leading to possible grid outages. To tackle this, multiple smart microgrids can be integrated and managed in a synchronized fashion (known as IBMs) at a particular location. This integration enables more effective communication between suppliers and consumers, making these systems more adaptable and efficient. By enabling microgrids to share energy resources and information, interoperability can contribute to lowering energy demand, strengthening the stability of the grid, and enhancing overall energy efficiency [3]. IBMs can enable advanced services such as distributed energy trading (marketplace), where microgrids can sell their excess energy to utility grid or other microgrids. This can cut energy costs and support the growth of renewable energy markets. Further, IBMs can improve grid resiliency and reliability by enabling the sharing of backup power during outages or emergencies. This ensures that critical infrastructure and important services remain operational, even in the advent of grid outages. Efficient communication enables seamless data exchange between IBMs [4].

LPWAN is a new wireless technology that extends the reach of IoT devices to vast distances while maintaining low power consumption. LPWAN technology is optimized for transmitting small quantities of data over long distances while using very little power, making it ideal for devices that are often in remote locations and are difficult to access for maintenance or battery replacement. LPWANs are designed to operate in diverse environments, including dense urban areas with numerous buildings and obstacles, as well as vast rural landscapes with limited infrastructure. Some examples of LPWAN technologies comprise LoRa, NB-IoT, and Sigfox. The comparison of these LPWAN technologies is shown in Table 1.

**Table 1.** Comparison of LoRa, Sigfox, and NB-IoT with respect to various features.

| Feature | LoRa | Sigfox | NB-IoT |
|---|---|---|---|
| Protocol | LoRaWAN | Proprietary | 3GPP Standard |
| Modulation | CSS | Ultra-Narrowband BPSK | QPSK |
| Radio Frequency (widely used bands) | 433 MHz, 868 MHz, 915 MHz (Unlicensed) | 862–876 MHz, 902–928 MHz (Unlicensed) | LTE Bands (Licensed) |
| Range | Up to 10 km | Up to 3–5 km | Few kilometers |
| Two-way communication | Yes | Limited downlink | Yes |
| Data Rate | 0.3 kbps–50 kbps | Up to 100 bps | Up to 250 kbps |
| Network Topology | Star, Peer-to-Peer, Mesh, Star-of-Stars | Star | Star |
| Network Installation | Enables independent network operation | By Service Provider | By Service Provider |

Unlike other LPWAN technologies, LoRa can transmit data over several kilometers without the need for repeaters, making it ideal for applications in remote areas. Additionally, LoRa devices have a low power consumption, enabling battery-powered devices to run for several years without any frequent replacements of battery. Furthermore, LoRa networks can assist a large number of devices simultaneously, making it a scalable so-

lution for large-scale deployments. These advantages make LoRa a highly promising technology for a variety of IoT applications, particularly those requiring long-range communication, low power consumption, and large-scale connectivity (ex: smart cities, smart grids, logistics, etc.) [5].

LoRaWAN is a wireless protocol specifically designed for IoT applications. It enables long-range communication between battery-operated devices (LoRa PHY) and a network gateway. The protocol operates in unlicensed frequency bands and allows bidirectional communication between sensors and gateways. The LoRa Alliance, a non-profit organization comprised of diverse members, developed and manages the LoRaWAN protocol, which is widely used and supported by many companies in the IoT ecosystem. The comprehensive overview of the advancements, challenges, and possible solutions for LoRa technology in various IoT applications is discussed below.

Edge computing is being used to boost the energy efficiency of smart metering systems. A deep learning-based compression-decompression model is used to reduce the size of energy multivariate time series, and an optimization problem is expressed to identify the optimal compressed energy time series [6]. The system also features an algorithm to determine the suitable SF for transferring the compressed time series. The characteristics viz., low-cost hardware, simple, open-source, transmitting short messages, and robustness of LoRa technology make it a viable option for efficient V2V and V2I communication in transportation systems. An experiment was carried out to evaluate the feasibility of using LoRa technology for vehicular communication by conducting field tests [7]. This experiment evaluates the reception ratio, signal strength, and signal-to-noise ratio with different scattering factors inherent to LoRa, as well as the effect of the Doppler effect on communication. The results of this study provide important insights into the potential of LoRa technology for vehicular communication. Furthermore, LoRaWAN has shown potential for collecting real-time data from underwater depths greater than one meter [8]. An experiment was conducted to decide the viability of using LoRa technology for such transmissions, considering the technical characteristics of the LoRa channel. Several field tests were conducted to evaluate the transmission performance using metrics such as RSSI and SNR under varying transmission parameters and increasing depths.

LoRa networks face challenges such as a higher probability of packet collisions due to random channel access. To address this, a new receiver has been proposed that can decode several IoT LoRa-like signals using SIC algorithms [9]. Mesh networking helps to address issues of signal attenuation over the distance and interference from trees, buildings, and other radio signal sources in LoRa technology. An experiment has been conducted in a university campus with a LoRa mesh networking system comprising nineteen LoRa mesh networking devices deployed over an 800 m × 600 m zone [10]. Experimental results demonstrate that the proposed LoRa mesh networking system achieves an average PDR of 88.49%, surpassing the star-network topology used by LoRa. This study provides an evaluation of LoRa mesh networking performance in real-world experiments and highlights its potential for large-scale IoT applications. In addition, a low-power and cost-effective approach utilizing both NB-IoT and LoRa communication technologies has been proposed to monitor information in IoT applications that require long-range transmission [11]. The approach offers benefits such as reducing operating costs, increasing transmission distance, and self-powered operation. The approach was tested and achieved a communication distance of up to 1.6 km in complex environments.

LoRa modulation has been shown to exhibit significant immunity to the doppler effect, as evidenced by results from laboratory testing and outdoor experiments [12]. This places LoRa technology as a very promising choice for satellite IoT applications, particularly for low Earth orbit satellite constellations like CubeSat nanosatellite constellations. LoRa

technology has been explored in the literature with a diverse range of applications, including but not limited to environmental radiation monitoring [13], smart waste management systems [14], temperature and humidity monitoring [15], gas and vibration monitoring [16], messaging systems [17], appliances control [18], manhole cover monitoring [19], landslide monitoring [20], smart buildings [21,22], water quality monitoring [23,24], data acquisition systems [25] and smart campus applications [26,27], showcasing its versatility and adaptability in various experimental settings. The current literature has explored LoRa technology for different applications. Unlike conventional broadband communication technologies, IBMs primarily exchange low-volume operational data such as energy consumption measurements, sensor readings, equipment status information, and fault notifications. These applications typically involve periodic reporting intervals ranging from a few seconds to several minutes and therefore do not require high data rates. Instead, the key communication requirements include reliable connectivity, sufficient coverage across geographically distributed buildings, low deployment and maintenance costs, energy-efficient operation, and support for privately managed network infrastructure. LoRa is potentially well suited to these requirements because it provides long-range communication capabilities, supports low-power communication, and is suitable for small packet transmissions. Furthermore, LoRa gateways can be deployed and managed locally, allowing organizations to maintain ownership and control of the communication infrastructure without relying on public cellular networks. These characteristics make LoRa a promising communication technology for monitoring and supervisory functions in interoperable building microgrid environments.

An IBM can be viewed as a coordinated network of multiple building-level microgrids that are capable of exchanging operational information and, where applicable, energy resources to improve overall system efficiency, resilience, and sustainability. Each microgrid typically consists of distributed energy resources, energy storage systems, local loads, and energy management functions. To enable effective coordination among geographically distributed microgrids, reliable communication infrastructure is required for the exchange of monitoring data, equipment status information, control commands, fault notifications, and energy-related measurements. Consequently, communication technologies play a critical role in supporting interoperability and information sharing within IBM environments. In this context, LoRa-based communication networks offer a promising solution due to their long-range coverage, low-power communication characteristics, and cost-effective deployment potential. The outline of this paper contributions are given below.

- LoRa technology-based network is proposed for establishing communication among various microgrids in the IBMs environment.
- The proposed communication network is experimentally implemented and evaluated using a three-location case study representing geographically distributed building microgrid entities.
- The proposed network is evaluated by assessing the RSSI and SNR metrics to determine suitability for IBM applications.
- From the experimental test results, it is found that LoRa can successfully establish communication among the investigated geographically distributed locations, demonstrating the feasibility of the proposed communication layer.

In this work, interoperability is considered primarily from the communication-layer perspective. The experimental prototype demonstrates LoRa/LoRaWAN-based communication among three geographically separated locations and a central gateway. It does not demonstrate energy exchange, heterogeneous-system integration, distributed energy management, or closed-loop microgrid control. Therefore, the proposed communication network is intended as an enabling layer for interoperable building microgrid applications rather than as a complete implementation of microgrid interoperability.

The organization of sections in the paper is given as follows. Section 2 outlines the layers of IBMs architecture. Section 3 presents the proposed communication network for IBMs. Section 4 describes the case study. Section 5 provides details on the prototype implementation. Section 6 describes the outcomes of the experiment and their analysis, followed by a concluding summary in Section 7.

## 2. Layers of IBMs Architecture

The interoperation of smart microgrids consists of three primary layers namely electrical, communication, and IT layers as shown in Figure 1. The electrical layer includes the hardware and software systems responsible for generating, distributing, and managing electrical energy. This layer comprises the IBMs physical components, including power generators, power converters, inverters, transformers, and other electrical devices. The electrical layer also includes protection and control systems that help ensure the IBMs reliability and stability [28]. The communication layer includes the networks and protocols used for communication between IBM components. This layer enables data exchange and control signals between devices and subsystems, facilitating coordination and collaboration. The communication layer includes both wired and wireless communication technologies. The IT layer includes the software, systems, and applications responsible for managing and optimizing the IBMs operation. This layer includes various control and monitoring systems. These systems practice machine learning algorithms and data analytics to optimize power consumption, storage, and generation. The IT layer also includes cybersecurity measures to protect the IBMs against cyber-attacks and other security threats. Together, these three layers form the backbone of IBMs, enabling them to operate efficiently and securely while providing reliable and sustainable energy to consumers.

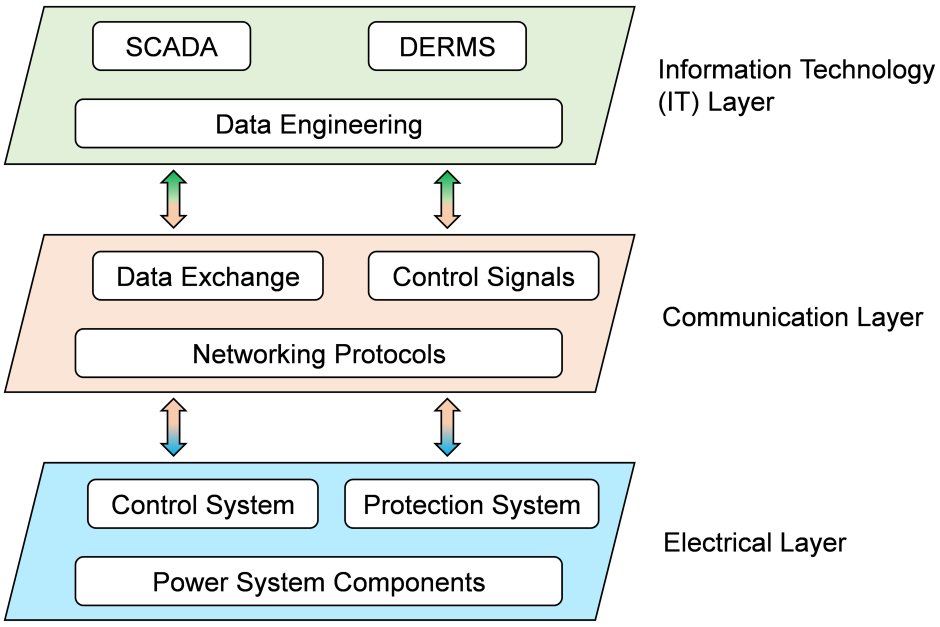



**Figure 1.** Layers present in IBMs architecture.

The communication layer is a critical component of IBMs because it allows different devices and systems within the grid to exchange operational information and support monitoring and control functions. IBMs require a high degree of coordination and control to manage the flow of electricity efficiently and effectively, and the communication layer enables this coordination and control. The importance of the communication layer is explained through the following.

- Remote monitoring and control: The communication layer allows utilities to remotely monitor and control devices, such as meters, switches, and sensors. This allows them to quickly identify and respond to issues such as equipment failures or power outages, which improves reliability and resilience.
- Operational data analysis: The communication layer enables IBMs to gather and analyze operational data for monitoring and system management.
- Demand response: The communication layer also enables utilities to organize demand response programs, which inspire consumers to decrease their energy usage during times of peak demand. By communicating with smart devices in homes and businesses, utilities can automatically adjust energy usage.
- Integration of renewable energy sources: The communication layer is essential for integrating renewable energy sources such as wind and solar power into the grid. These sources of energy are often intermittent, and the communication layer can help manage their variability and ensure that they are integrated into the grid reliably and efficiently.

## 3. Proposed Communication Network for IBMs

A proposed integrated architecture for IBMs is shown in Figure 2. As illustrated, each building has a LoRa end node that serves as the communication module for that building. Each building's electrical terminal equipped with sensors gathers relevant data and connects to the customized end node shown in Figure 3 using GPIOs. These terminals first connect to a local LoRa communication network (end node) within the building. Then the data read by the controller is sent to the CMCU using the LoRa radio present in the end node. The electrical terminals of the smart meters don't directly communicate with the utility grid. The CMCU uses captured values to calculate the power import/export needs for each microgrid based on the energy management strategy. The CMCU then controls the connected CBs through their LoRa end nodes to allow interconnectivity between microgrids and facilitate power transfer as directed by control commands from the CMCU. Further, CMCU will feature a master unit as well as a backup unit. The backup unit serves as a redundancy to guarantee data protection in the case of a failure of the primary unit [29].

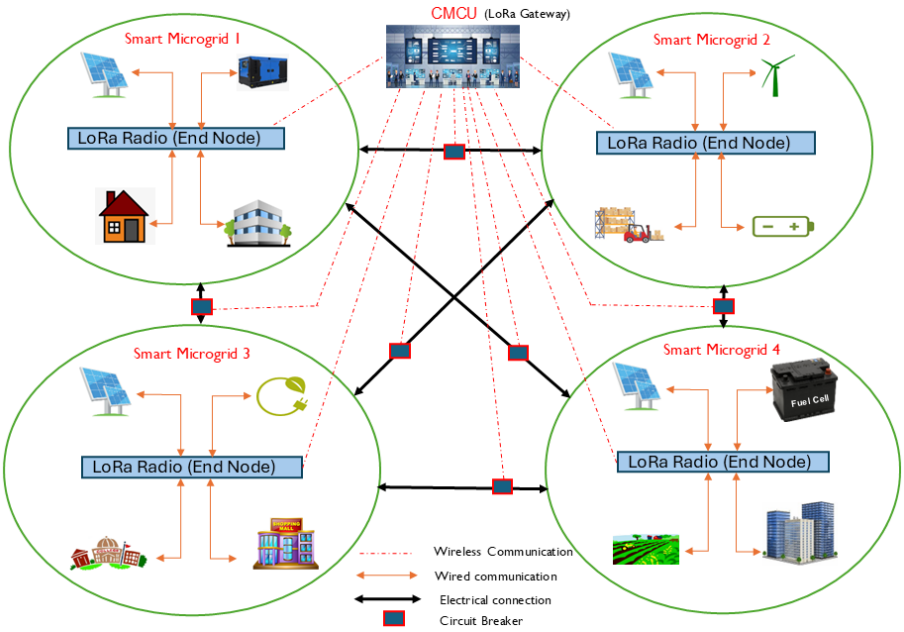



**Figure 2.** Proposed network architecture.

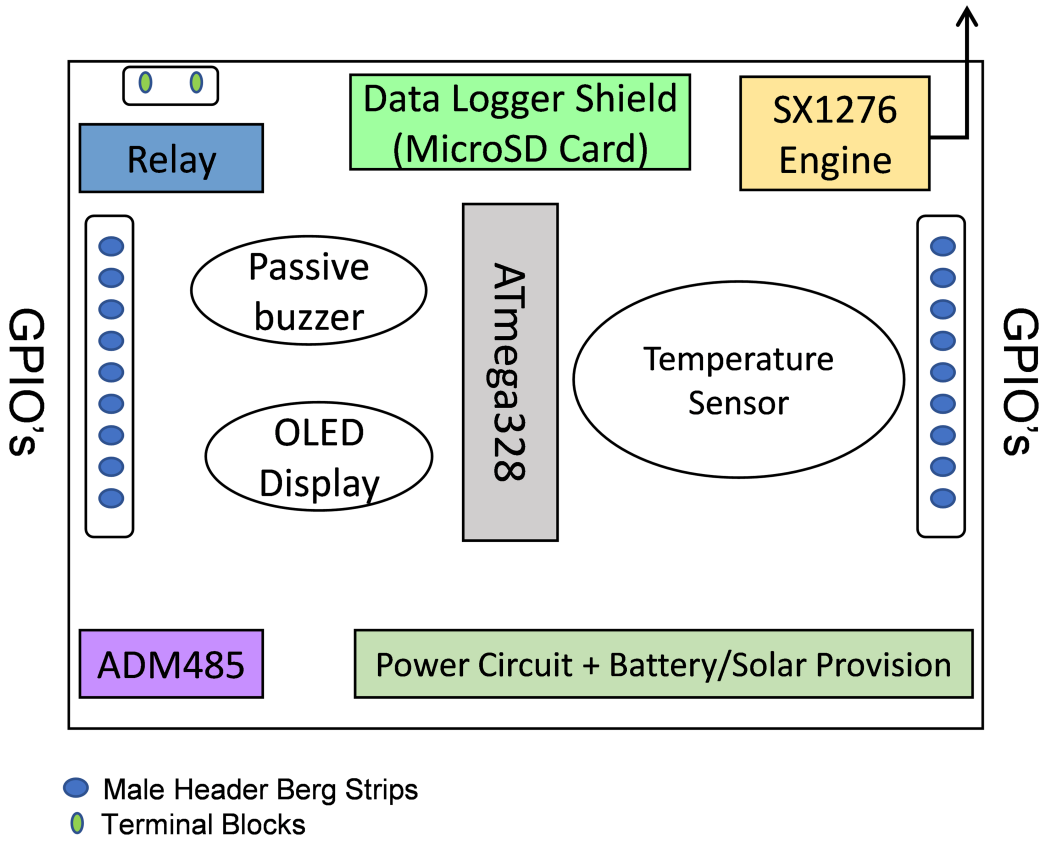



**Figure 3.** Customized end node.

## 4. Case Study

To execute the proposed architecture, a case study with three microgrids is considered. The details are given as follows. A summary of its specifications is given in Table 2 and the comprehensive view of the scenario is depicted in Figure 4. The gateway is placed in the AB1 block in the campus throughout the experiment.

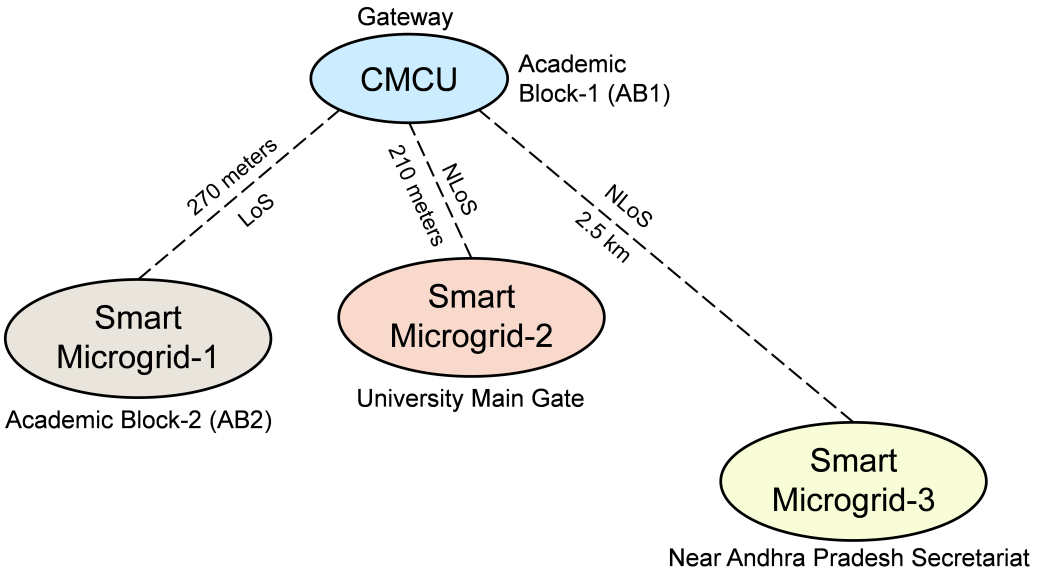



**Figure 4.** Case study implementation scenario.

**Table 2.** Details of Case Study Considered.

| Microgrid | Environment | End Node Location | Difference Between Gateway and End Node |
|---|---|---|---|
| SMG 1 | LoS | AB2 | 270 m |
| SMG 2 | NLoS | University main gate | 210 m |
| SMG 3 | NLoS | Near AP Secretariat | 2.5 Km |

- Smart Microgrid 1 (SMG 1): The end node is located at the AB2 block in the campus. In this case, the environment is of LoS type, and the distance between the end node and the gateway is 270 m.
- Smart Microgrid 2 (SMG 2): The end node is located at the main gate of the university campus. In this case, the environment is of NLoS type, and the distance between the end node and the gateway is 210 m.
- Smart Microgrid 3 (SMG 3): The end node is located near the Andhra Pradesh secretariat. In this case, the environment is of NLoS type, and the distance between the end node and the gateway is 2.5 km.

## 5. Prototype Implementation

This section includes four sub-sections, beginning with the propagation model, which determines how signals are transmitted and received within the system. Subsequently, the end node specifications and configurations define the features and settings of each node within the network. The gateway specifications and configuration are also important, as they provide the interface between the end nodes and the wider network infrastructure. Finally, test scenarios are developed to assess the effectiveness and functionality of the system.

### *5.1. End Node Specifications and Configuration*

To evaluate the functionality of the LoRa radio modules, the initial experiments were conducted in P2P mode. The radios used for the experiment are RYLR896 LoRa modules, which are manufactured by REYAX. The module and pinout are shown in Figure 5. The description of each pin is given in Table 3. The RYLR 896 is the breakout board that mainly consists of the RYLR 890, controller, pins, and antenna, where RYLR 890 is a Semtech SX1276 engine. The breakout board can be connected to other controllers/processors with the help of the UART protocol. The specifications of the RYLR 896 are given in Table 4.

**Table 3.** Pin Details of RYLR896.

| Pin | Description |
|---|---|
| VDD | Power Supply |
| NRST | Pull up/Pull down |
| RXD | UART Input |
| TXD | UART Output |
| GND | Ground |

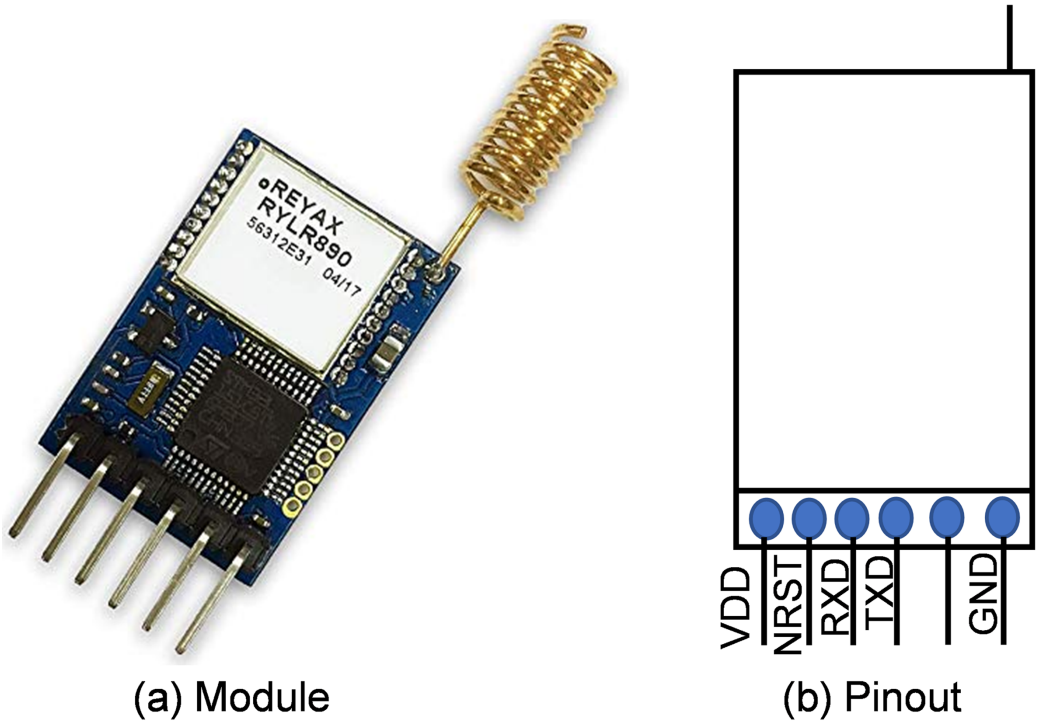



**Figure 5.** RYLR896 LoRa module.

**Table 4.** Specifications of RYLR896.

| Parameter | Typical Value |
|---|---|
| VDD | 3.3 v |
| RF Power output | 14 dBm |
| Frequency | 896/915 MHz |
| Baud rate | 115,000 |
| Operating temperature | 25 degrees centigrade |

As mentioned, the initial experiments were conducted in P2P mode to understand the radio functionality. Both the radios (Tx and Rx) are set with the help of FTDI USB to TTL serial converter. AT (attention) commands are used for configuring the radios. Table 5 lists the important AT commands used to configure the transmitter and receiver for establishing LoRa P2P communication, as summarized in Table 6. After using the mentioned commands, the data is received successfully. Figure 6 depicts the P2P environment setup.

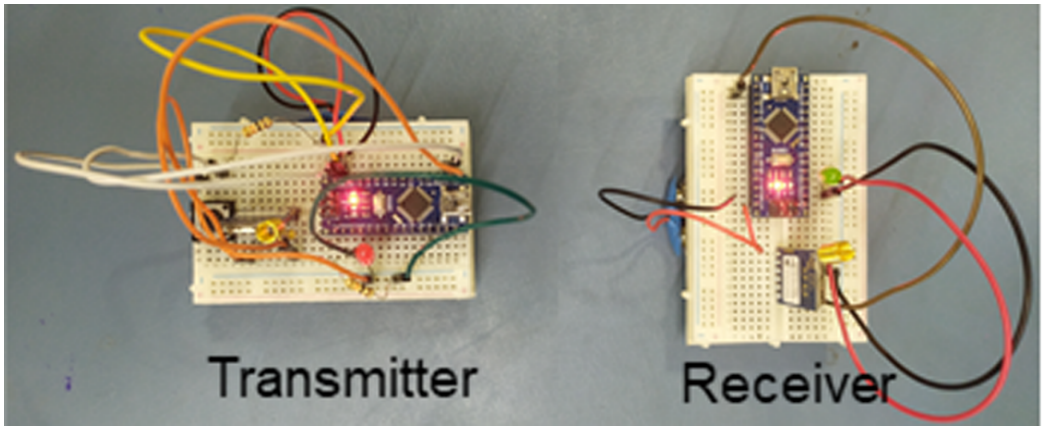



**Figure 6.** LoRa P2P communication deployment.

**Table 5.** Various AT Commands for Configuring the Radio.

| AT Command | Description/Details |
|---|---|
| AT+ADDRESS | To set the address of the device |
| AT+NETWORKID | To set the network id to the device. The devices within the same network only can communicate with each other |
| AT+BAND | To set the frequency band as per the country/user requirement |
| AT+PARAMETER | To set the RF parameters such as SF, Bandwidth, Coding rate, and Preamble |
| AT+SEND | To send the data |
| AT+IPR | To set the baud rate |
| AT+CRFOP | To set the RF power |

**Table 6.** Various AT Commands Used for Transmitter and Receiver.

| Transmitter | Receiver |
|---|---|
| AT+ADDRESS = 0 | AT+ADDRESS = 1 |
| AT+NETWORKID = 5 | AT+NETWORKID = 5 |
| AT+BAND = 865,062,500 | AT+BAND = 865,062,500 |
| AT+PARAMETER = 8,7,1,4 | AT+PARAMETER = 8,7,1,4 |

### *5.2. Gateway Specifications and Configuration*

To deploy a network with multiple LoRa end nodes using the LoRaWAN architecture, the gateway plays an important role. Dragino LPS8 (LoRa Pico Station 8 channels) is the gateway used for establishing the network. It converts LoRa packets to IP packets. The role of the data concentrator is to receive LoRa packets from the end nodes and demodulate them before forwarding them to the packet forwarder. The demodulated signal is then forwarded to the packet forwarder, which converts it to the TCP/UDP packet. The specifications of LPS8 are given in Table 7.

**Table 7.** Specifications of LPS8.

| Specification | Details |
|---|---|
| Interface | 802.11 b/g/n, RJ45 |
| Chips | SX1308, SX1257 |
| End Node Compatibility | Any LoRaWAN Compatible End node |
| Power Input | 5 V, 2 A |
| Max Output Power | 20 dBm |

The LPS8 can be configured via Wi-Fi. This is the factory default mode where the gateway is enabled as a Wi-Fi access point. Once the gateway is powered up, it generates a Wi-Fi network and can be connected to the laptop to complete the configuration process. The IP address is 10.130.1.1, and need to enter the credentials to log in to the gateway. After getting into the gateway page, the entire process of configuration can be done (such as entering Wi-Fi credentials, choosing a frequency plan, etc.,). Figure 7 shows the picture of the gateway in the laboratory during the initial configuration. The gateway is registered on the TTN platform to connect it to the LoRaWAN network. As shown in Figure 8, TTN provides network server/application server services for various versions of the LoRaWAN. Regional parameter documents (different for different versions) are well-drafted ones that are prepared by LoRa Alliance for the community. RP002-1.0.3 is the version of the document used for building the network for the experiments. After entering the details

such as Gateway ID, Gateway EUI, and Gateway name, etc., the gateway is successfully registered in the TTN, as shown in Figure 9.

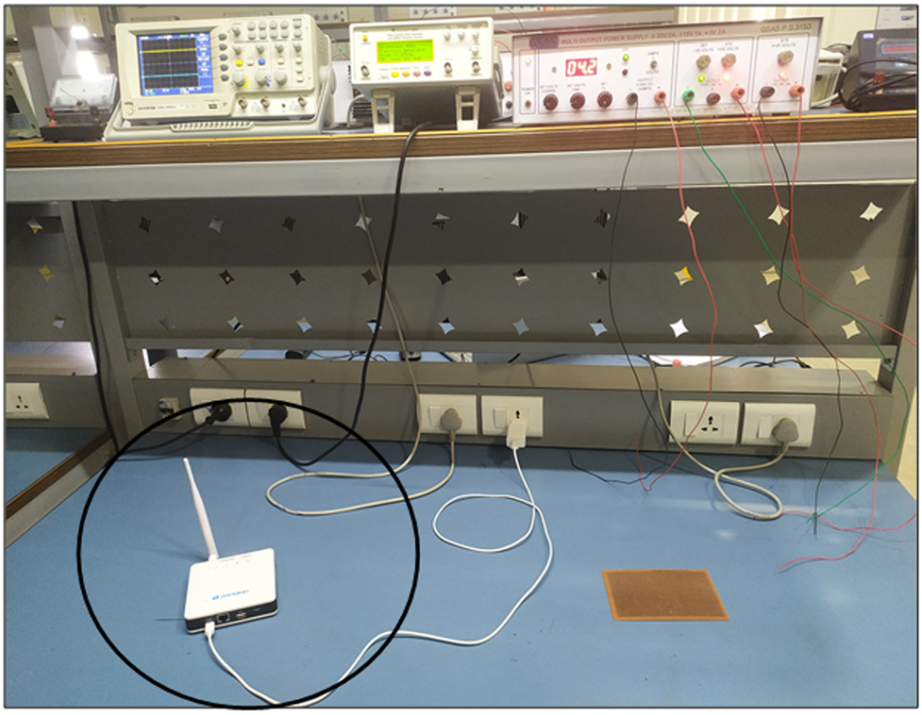


**Figure 7.** Gateway testing.

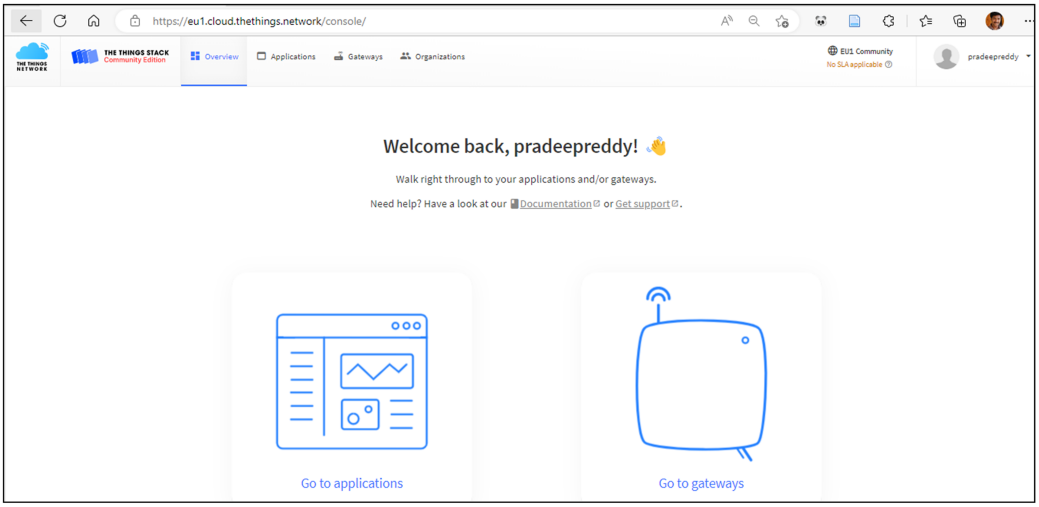



**Figure 8.** TTN console page.

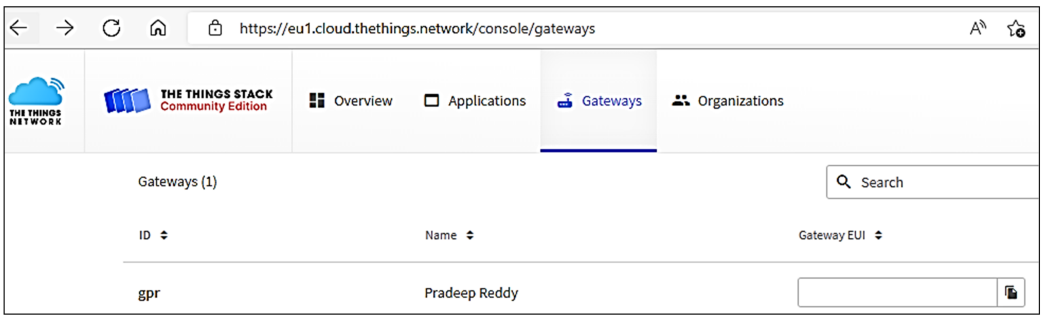



**Figure 9.** Gateway registration in TTN.

### 5.3. Test Scenarios

A new application is created in the TTN by entering details such as Application ID, name, etc. Then the end devices are registered (ABP mode) to the application by entering the details such as frequency channel, device address, app session key, network session key, etc. After uploading the code to the end devices, the data was received successfully in the application server. The data received in the TTN will be in hexadecimal format by default (encrypted message). This has to be decrypted (can be observed in TTN itself) to get in a human-readable format. To validate the performance of the network, performance metrics such as RSSI and SNR are considered. RSSI is the measure of the received radio signal power. It is measured in dBm, which is in negative values. If the value is closer to zero, it means it's a strong signal, and if it's moving away from zero (more in negative), means it's getting weak. SNR quantifies the strength of a signal relative to the interfering noise. A higher SNR implies a more robust signal and improved communication quality. However, the LoRa works below the noise floor, and the signal is decoded at very low SNR values. Five bytes of data were sent from the end nodes during all the experiments. The data was collected from three different smart microgrids. The maps indicating SMG 1 and SMG 2 are shown in Figure 10, whereas SMG 3 is shown in Figure 11. The test results of the experiment that are obtained with respect to the considered smart microgrids are given in Table 8.




**Figure 10.** Maps indicating SMG 1 and SMG 2.

The measurements reported in Table 8 were obtained from the RYLR896-based LoRa P2P field experiment. During this experiment, the RYLR896 modules were operated in P2P mode, and RSSI and SNR values reported by the receiving module were recorded for spreading factors SF7–SF12. The values were recorded directly from the radio module and should not be interpreted as standard raw transceiver values. The subsequent LoRaWAN/TTN experiment was conducted separately using the gateway-based communication architecture described in Section 5.2.

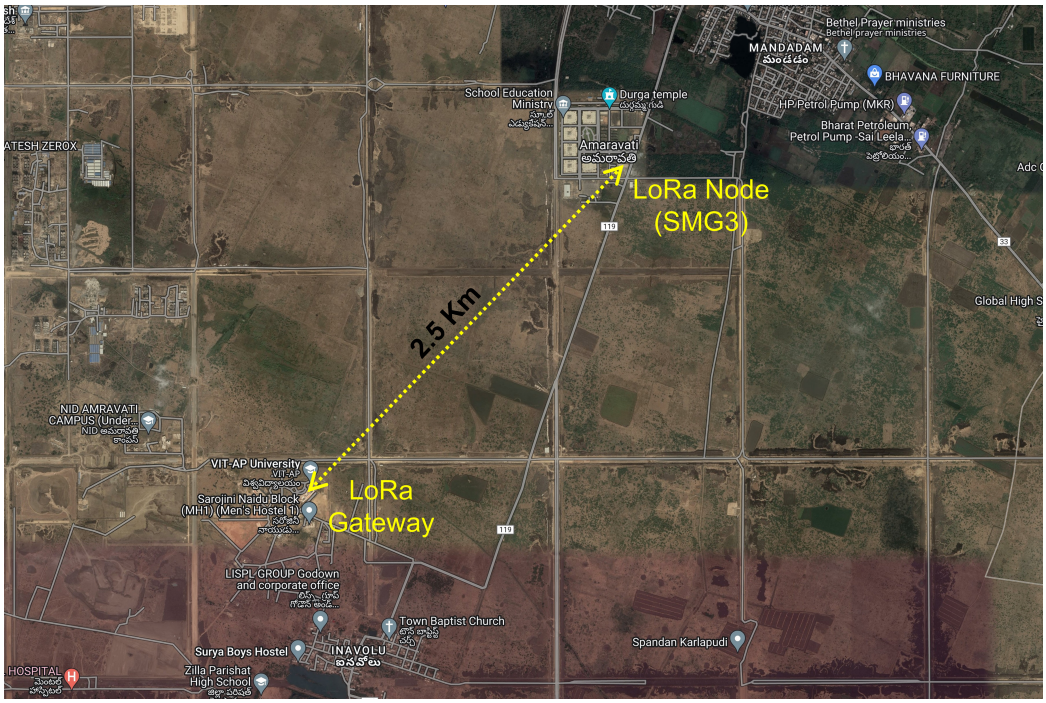



**Figure 11.** Maps indicating SMG 3.

**Table 8.** Test Results Computed for Various Smart Microgrids.

| Spreading Factor (SF) | For SMG1 | | For SMG2 | | For SMG3 | |
|---|---|---|---|---|---|---|
| | RSSI | SNR | RSSI | SNR | RSSI | SNR |
| 7 | −75 | 37 | −78 | 27 | −115 | −19 |
| 8 | −76 | 45 | −81 | 26 | −115 | −29 |
| 9 | −81 | 46 | −82 | 17 | −125 | −15 |
| 10 | −78 | 36 | −79 | 25 | −114 | −16 |
| 11 | −82 | 24 | −81 | 43 | −99 | −17 |
| 12 | −88 | 26 | −88 | 27 | −110 | −33 |

The RSSI and SNR values reported in Table 8 represent individual measurements obtained for the corresponding spreading-factor configurations rather than averages over repeated packet transmissions. The original field experiments were not instrumented to record the total number of packet transmission attempts, packet losses, measurement duration, or repeated RSSI/SNR samples for each configuration. In particular, the available measurements do not permit quantitative conclusions regarding packet delivery reliability or variability. Therefore, the reported values are presented as representative observations of the communication conditions rather than as statistically aggregated performance measures.

## 6. Results and Analysis

This section describes the experimental results by comparing the RSSI and SNR values for three SMGs. To have a better understanding of the signal reception at the CMCU in real environments for three SMGs, plots are generated and are shown in Figures 12 and 13. As SF has a vital role in LoRa network performance, so, all the tests were performed for different SFs. Further, Figure 14 represents the plot between the measures RSSI and SNR.

By looking at the obtained results in Figure 12, it is understood that the RSSI values received for SMG 1 are more (less value in negative) than the SMG 2, though the distance between the end node and CMCU for SMG 2 is less. For SMG 3, the values are much less, as the distance between the end node and the CMCU is 2.5 km away. From Figure 13, it

is understood that the SNR values received for SMG 1 are high when compared to SMG 2. For SMG 3, the values are negative, which means that the received signal is lesser than SMG 1 and SMG 2.

The results presented in Table 8 provide evidence of successful message reception at the three investigated smart microgrid locations under the tested deployment conditions. The LoS environment represented by SMG1 exhibited stronger RSSI and SNR values compared with the NLoS deployments. Although SMG3, located approximately 2.5 km from the CMCU, exhibited weaker RSSI and negative SNR values, message reception was observed during the field experiment. This observation provides evidence of LoRa-based connectivity under the investigated conditions; however, repeated measurements would be required to assess the consistency and reliability of this behavior.

The P2P communication experiments demonstrated successful LoRa connectivity across all evaluated deployment scenarios. The strongest communication performance was observed under LoS conditions, while NLoS deployments exhibited lower RSSI and SNR values due to increased propagation losses and environmental obstructions. A gradual reduction in signal quality was also observed with increasing communication distance. Successful message reception was observed across the tested locations, providing evidence of LoRa-based connectivity under the investigated deployment conditions. However, because packet delivery statistics and repeated measurements were not recorded, these observations do not establish communication reliability. These findings confirm the feasibility of employing LoRa technology for low-data-rate monitoring and supervisory applications within interoperable building microgrid environments.

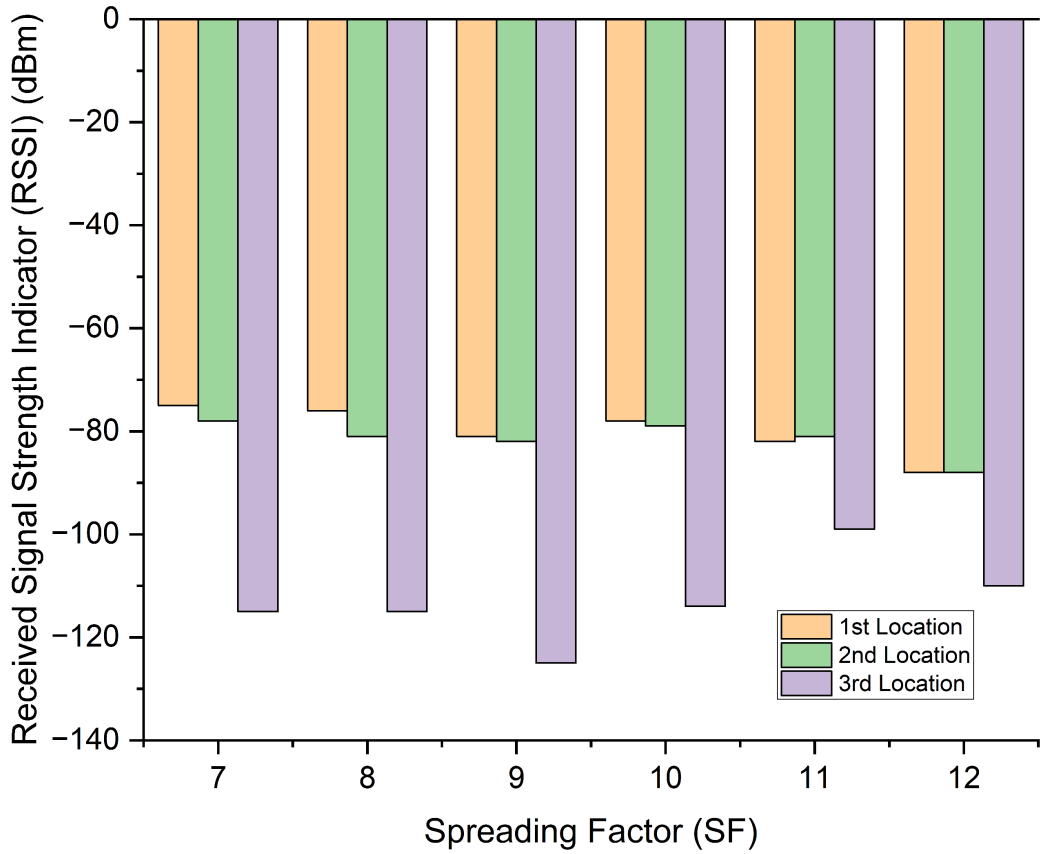



**Figure 12.** RSSI values for different SMGs.

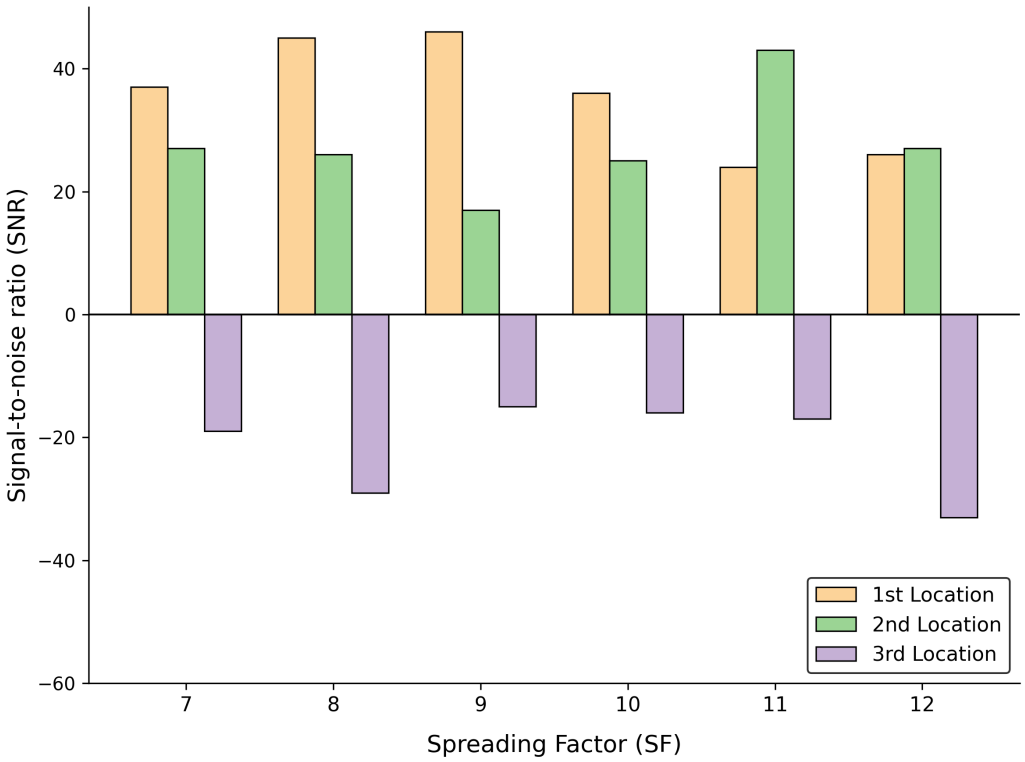



**Figure 13.** SNR values for different SMGs.

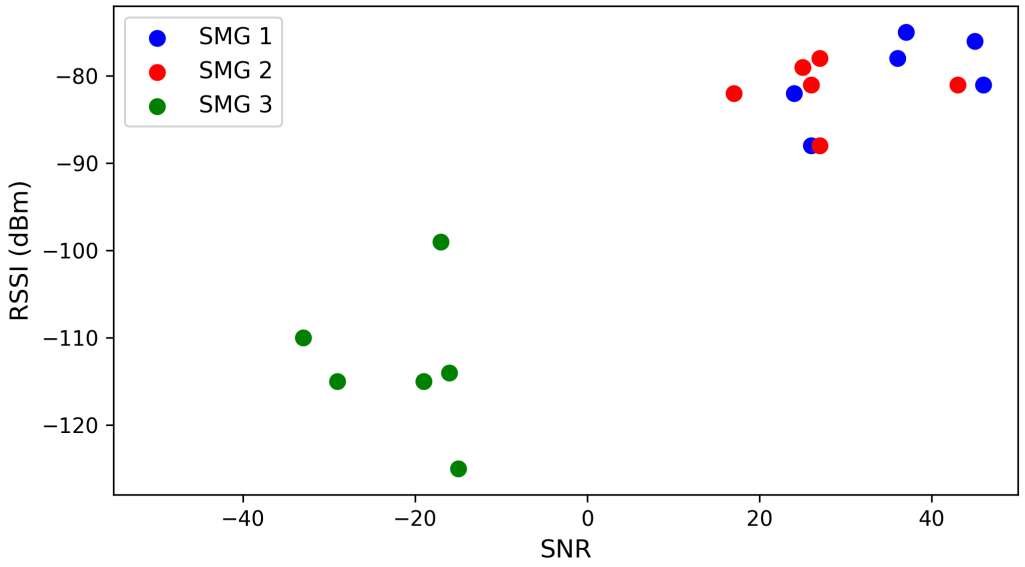



**Figure 14.** SNR versus RSSI for different SMGs.

## 7. Conclusions

This paper presents the experimental implementation of a communication network using LoRa technology for establishing communication among Interoperable Building Microgrids (IBMs). This is verified by considering a three-microgrid-based case study. The salient observations of this study are summarized as follows.

- From the LoRa P2P experiments and the three-location case study, successful signal reception was observed under the investigated deployment conditions.
- The proposed network is evaluated by assessing the RSSI and the SNR metrics.
- Figure 12 shows that the RSSI indicator for SMG1 is better than for SMG2. For example, at SF = 7, SMG1's RSSI is −75 while SMG2's is −78. Even though the distance between the end node and the CMCU is shorter in SMG2, the RSSI values received by SMG1 are better.
- Figure 13 shows that SMG1 has higher SNR values than SMG2, even though SMG2 is closer to the CMCU. For example, at SF = 7, SMG1 has an SNR of 37, while SMG2 has an SNR of 27.
- The experimental observations indicate the potential applicability of LoRa for long-range communication in smart-grid monitoring applications under the investigated deployment conditions. Successful message reception was observed across the three evaluated locations, including the 2.5 km NLoS case.

Thus, the experimental results demonstrate the feasibility of LoRa-based communication for information exchange among geographically distributed microgrid entities under the investigated deployment conditions.

### *7.1. Implications of the Findings*

The main idea behind the proposed research was to investigate the feasibility and effectiveness of utilizing LoRa-based communication networks for IBMs that align with the objectives of Sustainable Development Goal 7 (SDG-7) - Affordable and Clean Energy. Specifically, IBMs using LoRa can be implemented in remote areas where extending the traditional grid might be impractical. This helps to achieve SDG target 7.1 (universal access to electricity). Additionally, the proposed architecture can facilitate the effective management of distributed renewable energy sources such as solar or wind within IBMs, helps in achieving SDG target 7.2 (increased share of renewable energy). Furthermore, enhanced communication between energy suppliers and consumers in IBMs can encourage smarter energy usage and grid optimization, contributing to the realization of SDG target 7.3 (improved energy efficiency).

Thus, the experimental results provide evidence of LoRa-based connectivity for information exchange among geographically distributed microgrid entities under the investigated deployment conditions. The conducted experiments further indicate that both the propagation environment (LoS/NLoS) and the communication distance significantly influence the RSSI and SNR values, thereby affecting the overall network performance. The observed communication performance is suitable for representative IBM applications involving periodic transmission of low-volume operational data, such as smart metering, distributed energy resource monitoring, environmental sensing, and fault notification. However, the present study does not establish application-specific communication performance thresholds, as its primary objective was to validate the feasibility of the communication layer under real-world deployment conditions. The study validates the feasibility of the proposed communication infrastructure for future IBM implementations; Complete IBM operational validation would require further investigation of energy exchange, heterogeneous-system integration, energy management, distributed control, cybersecurity, and application-specific performance requirements.

### 7.2. Future Works

While the experimental results provide evidence of LoRa-based connectivity across geographically distributed microgrid locations, further investigation is required to evaluate network scalability, long-term communication reliability, packet delivery ratio, packet loss, repeated transmission performance, end-to-end latency, jitter, power consumption, and robustness under varying environmental conditions. Future experiments should involve repeated packet transmissions over defined measurement periods and report appropriate statistical measures, such as mean, standard deviation, and confidence intervals, where applicable.

### 7.3. Limitations

The proposed framework has certain limitations that need to be considered prior to its implementation.

- The experimental evaluation was conducted using representative measurements at three deployment locations and six spreading-factor configurations (SF7–SF12). For each location and spreading-factor configuration, an individual RSSI and SNR observation was recorded. However, the original field experiments did not record packet-level transmission statistics such as the total number of packets transmitted, packet delivery ratio, packet loss, measurement duration, repeated transmissions, end-to-end delay, or repeated RSSI and SNR samples for each configuration. Consequently, the available measurements do not permit quantitative evaluation of communication reliability, latency, jitter, or statistical variability. The RSSI and SNR values reported in Table 8 should therefore be interpreted as representative observations of the investigated communication conditions rather than statistically aggregated performance metrics.
- Limited Bandwidth: For advanced smart grid applications such as environmental status monitoring, real-time electricity usage monitoring, and real-time photovoltaic power control, LoRa's limited bandwidth can pose a challenge. When dealing with large data volumes, techniques such as data compression and optimization are necessary to reduce the amount of data to be transmitted while maintaining accuracy and reliability. Additionally, edge computing and data processing techniques may also be required to further reduce the amount of data.

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## Abbreviations

**Nomenclature**

| Symbol | Description | Unit |
|---|---|---|
| FSPL | Free Space Path Loss | decibel (dB) |
| $d$ | Distance between the end node and the gateway | meters |
| $c$ | Speed of light $(3 \times 10^8$ m/s) | meter/sec |
| $f$ | Frequency | Hz |
| $\lambda (= c/f)$ | Wavelength | meters |
| r | Fresnel zone radius – the elliptical region of space that is present between the end node and the gateway | meters |
| $S$ | Receiver Sensitivity | decibel-milliwatts (dBm) |
| $BW$ | Bandwidth | Hz |
| $SNR$ | Signal-to-noise ratio | dB |
| $NF$ | Noise figure | dB |
| RSSI | Received Signal Strength Indicator | dBm |

**Abbreviations**

| | |
|---|---|
| CBs | Circuit breakers |
| CMCU | Central monitoring and control unit |
| CSS | Chirp spreading spectrum |
| DER | Distributed energy resources |
| FSPL | Free-space path loss |
| IBMs | Interoperable building microgrids |
| IoT | Internet of things |
| LPWAN | Low-power wide-area network |
| LTE-M | Long-term evolution for machines |
| LoRa | Long range |
| LoRaWAN | Long range wide area network |
| LoS | Line-of-sight |
| MAC | Media access control |
| NB-IoT | Narrowband IoT |
| NLoS | Non-line-of-sight |
| P2P | Peer-to-peer |
| PDR | Packet delivery ratio |
| PLC | Power line communication |
| RSSI | Received signal strength indicator |
| SF | Spreading factor |
| SIC | Successive interference cancellation |
| SNR | Signal-to-noise ratio |
| V2I | Vehicular-to-infrastructure |
| V2V | Vehicular-to-vehicular |

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