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A LoRa-Oriented Communication Approach for Reliable Data Transfer in Micro Smart Grid–Supported Groundwater Monitoring Stations

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***Abstract*— This paper presents the design and implementation of a low-power, long-range wireless communication system for groundwater monitoring, integrating LoRa-based Internet of Things (IoT) technology with a micro smart grid (MSG). The system operates in the 923.2 MHz ISM band and employs Chirp Spread Spectrum (CSS) modulation to enable reliable data transmission from remote monitoring stations to a centralized application server via a LoRa gateway. A Free-Space Path Loss (FSPL) model and link budget analysis were used to characterize the communication channel and were validated through Keysight ADS simulations and field experiments. Experimental results over a 2 km line-of-sight link achieved an average RSSI of –108 dBm and a packet delivery rate of 95%, demonstrating robust operation near the receiver sensitivity threshold. With a measured time-on-air of 452.6 ms per 30-byte packet, the proposed system minimizes active-duty cycle and energy consumption, supporting energy-efficient and timely transmission of groundwater monitoring data, including water level and micro smart grid electrical parameters. These characteristics make the system well suited for long-term autonomous deployment in energy-constrained, solar-powered groundwater monitoring applications.**

Keywords—LoRa IoT, Micro-smart grid, ground water monitoring stations.

I. INTRODUCTION

The proliferation of Internet of Things (IoT) technologies has necessitated the development of communication networks capable of supporting extensive device connectivity with minimal energy and cost requirements. Low Power Wide Area Network (LPWAN) technologies have emerged as a fundamental component in this landscape, with LoRa (Long Range) technology gaining particular prominence. LoRa offers a distinctive combination of long-range communication, low power consumption, and scalability, characteristics that are highly advantageous for large-scale, geographically dispersed IoT deployments [1], [2], [3]. Its ability to maintain connectivity across challenging environments, coupled with its cost-effectiveness and adaptability, has positioned LoRa as a key enabler for a wide range of IoT applications, including environmental monitoring, agriculture, industrial automation, and urban infrastructure management [4], [5], [6].

In the context of smart grid systems, the application of LoRa technology presents significant advantages for enhancing data transmission capabilities. Smart grids, which integrate advanced sensing, communication, and control technologies into traditional electrical networks, require robust, reliable, and scalable communication infrastructures to facilitate real-time data exchange between distributed assets [7], [8], [9]. LoRa's long communication range, strong penetration through physical obstacles, and minimal energy demands make it particularly suitable for supporting the dense and geographically widespread sensor networks essential to smart grid operations [10], [11], [12], [13], [14]. Moreover, the inherent low deployment and maintenance costs associated with LoRa networks contribute to economic efficiency, while its support for secure, low-bandwidth data transmission aligns well with the communication requirements of smart metering, grid monitoring, and demand-response applications [15], [16], [17], [18], [19]. Consequently, the integration of LoRa technology within smart grid frameworks not only enhances operational resilience and efficiency but also supports broader objectives related to energy sustainability and grid modernization [20], [21], [22].

Building upon these capabilities, this research focuses on the design of the data transmission system for micro smart grid devices, specifically linking solar cell power supplies with the electrical grid at groundwater quality monitoring stations. The study will address the design of the communication channel by analyzing path loss and link budget calculations between IoT nodes and IoT gateways. Experimental measurements of Received Signal Strength Indicator (RSSI) values will be conducted and compared with theoretical calculations, along with an evaluation of the system's packet delivery performance, to validate the reliability and efficiency of the proposed transmission system.

The communication system architecture, illustrated in Fig. 1, starts at the groundwater monitoring station, where voltage and current data from the solar power source and electrical grid are measured, packetized, and transmitted via a LoRa IoT module operating at 923.2 MHz with a 125 kHz bandwidth. The data are received by a LoRa gateway and forwarded to the network and application servers for processing. To balance long-range reliability and energy efficiency, the system employs CSS modulation with SF10 and a coding rate of 4/5, providing robust communication under low RSSI conditions while maintaining a time-on-air of approximately 452.6 ms per 30-byte packet.

II. PATH LOSS AND LINK BUDGET

This section presents the calculation of the free-space path loss and the link budget for the proposed communication system. The free-space path loss model is employed for the analysis, as the communication scenario is characterized by a point-to-point line-of-sight (LoS) environment with no physical obstructions between the transmitter and receiver. Operating in the 900 MHz frequency band, the system may be subject to attenuation effects such as rain fade; however, these are considered minimal for the purposes of this model [23], [24], [25]. The theoretical results obtained from the link budget and path loss calculations are subsequently compared with the experimentally measured Received Signal Strength Indicator (RSSI) values to validate the accuracy of the model under practical deployment conditions.

To evaluate the performance of the LoRa-based communication system, we calculate the free-space path loss (FSPL) and the link budget using the system parameters. The FSPL is computed using the equation (1) [26].

$$FSPL = 20\log_{10}(d) + 20\log_{10}(f) + 20\log_{10}\left(\frac{4\pi}{c}\right) - G_{Tx} - G_{Rx} \quad (1)$$

d is the distance linking the antennas; f denotes the transmitting frequency. G_{Tx} is the gain of the transmitting antenna, while G_{Rx} represents the gain of the receiving antenna, and c is the speed of light in a vacuum (meters per second).

The link budget, which estimates the received signal power at the receiver, is calculated as equation (2) [27].

$$P_{Rx} = P_{Tx} + G_{Tx} + G_{Rx} - FSPL \quad (2)$$

The design and calculations presented in this study are based on the system parameters summarized in Table I. Fig. 2 illustrates the communication channel model, depicting the free-space path loss (FSPL) between the transmitter and the receiver.

Based on the system parameters outlined in Table 1, the free-space path loss (FSPL) was calculated using the standard logarithmic model, yielding a value of 97.76 dB over a 2 km line-of-sight distance at a frequency of 923.2 MHz. Utilizing this path loss value, the link budget was computed to estimate the received signal power at the receiver. With a transmit power of 14 dBm, a transmit antenna gain of 3 dBi, and a receive antenna gain of 8 dBi, the resulting received signal strength was determined to be –72.76 dBm.

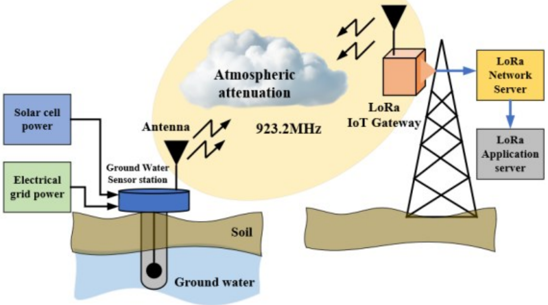

Fig.1 A diagram of a communication system in research.

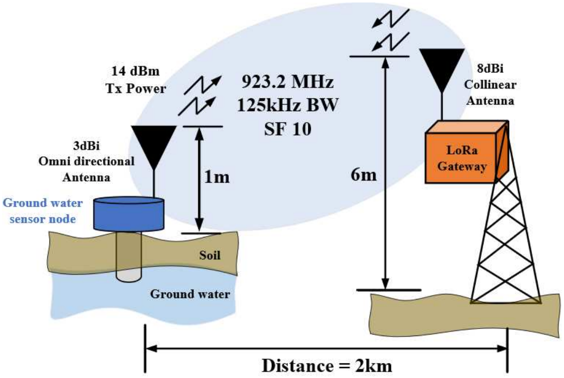

Fig 2. Communication channel diagram illustrates the free-space path loss (FSPL) model between the transmitter and receiver under line-of-sight (LoS) conditions.

TABLE I. PARAMETERS USED IN THE LINK BUDGET AND FREE-SPACE PATH LOSS (FSPL) ANALYSIS FOR THE LORA-BASED COMMUNICATION SYSTEM.

PARAMETER	VALUE	UNIT
Transmission frequency (f)	923.2	MHz
Distance between nodes (d)	2	km
Transmit power (P_{Tx}) (SX1276 Chip) [12]	14	dBm
Transmit antenna gain (G_{Tx})	3	dBi
Receive antenna gain (G_{Rx})	8	dBi
Tx antenna height	1	m
Rx antenna height	6	m
Bandwidth	125	kHz
Spreading factor (SF)	10	-
Modulation scheme	CSS	-

III. SIMULATION AND EXPERIMENT RESULTS

This section presents a comparison between the simulated and experimental results of the communication system. The free-space path loss (FSPL) model was simulated using Keysight Advanced Design System (ADS) software to analyze the expected signal behavior under ideal line-of-sight conditions. The simulation results were then compared with empirical measurements obtained from the actual communication setup, where the received signal strength was measured using an RF spectrum analyzer. This comparison aims to validate the accuracy of the FSPL model in representing the real-world performance of the system.

A. FSPL simulation and measurement results

Fig. 3 illustrates the simulation environment for the RSSI at the receiver for the FSPL. The figure shows the simulation result with the received power at the receiver at approximately -72.77dBm, which is consistent with the calculation result from the FSPL model.

Fig. 4 presents the experimental results of RSSI measurements at the receiver over 2 km from the transmitter. A total of 20 measurements were conducted, yielding an average RSSI value of -108 dBm. The measured results exhibit a notable deviation from the simulated and theoretical values derived from the FSPL model, indicating the influence of environmental factors and potential signal degradation not accounted for in the idealized simulation.

However, the observed discrepancy between the measured RSSI (–108 dBm) and the simulated value (–72.77 dBm) can be attributed to several real-world factors not considered in the ideal FSPL model. One primary factor is ground reflection and multipath fading, which can significantly attenuate signal strength in near-ground, long-range communication scenarios.

B. Packet delivery analysis and latency considerations

To evaluate the reliability of the LoRa communication system, 100 data packets (30 bytes each) were transmitted from the IoT node to the gateway, as shown in Fig. 5. With 95 packets successfully received, the system achieved a packet delivery ratio (PDR) of 95%, as calculated by (3). This high reliability is notable given the RSSI of –108 dBm, which approaches the receiver's sensitivity threshold under CSS modulation. Despite operating near this limit, the system maintained stable performance with minimal packet loss.

In addition to packet delivery performance, latency is a critical factor in assessing the suitability of LoRa technology for smart grid and environmental monitoring applications. Operating at a transmit power of 14 dBm and under a low duty cycle, the system achieves low energy consumption per transmission, making it well-suited for battery- or solar-powered IoT nodes deployed in remote environments. With a payload size of 30 bytes and a bandwidth of 125 kHz using CSS modulation, the estimated time-on-air per packet is relatively 0.45 s for SF10, which minimizes channel occupancy and enhances energy efficiency. This balance of low latency and low-power operation reinforces the viability of LoRa for long-range, energy-constrained monitoring systems.

$$Packet\ Delivery\ Ratio = \left(\frac{Number\ of\ received\ packets}{Number\ of\ transmitted\ packets}\right)\times 100\% \quad (3)$$

In evaluating the performance of the LoRa communication system, latency is a critical metric, particularly for time-sensitive applications such as environmental monitoring and smart grid control. Using Chirp Spread Spectrum (CSS) modulation with a bandwidth of 125 kHz, the time-on-air (ToA) for a single packet with a payload size of 30 bytes (240 bits) was estimated. The resulting transmission time can be calculated as (4) and (5) [11].

$$ToA = T_{pre} + N_{payload} T_s \quad (4)$$

Where $T_s=2^{SF}/BW$, Preamble time (default $T_{pre}=8$), Payload symbols (explicit header $H=0$, CRC on, coding-rate parameter $CR=1$ for 4/5, low-data-rate $DE=0$ at SF10/125kHz)

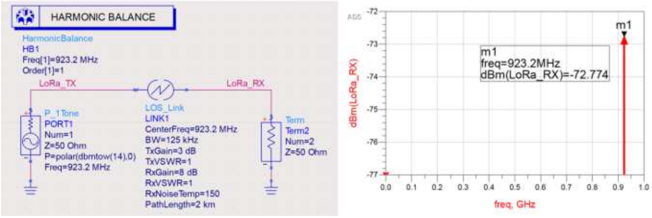

Fig 3. depicts the Keysight ADS simulation outcomes of the RSSI at the receiver.

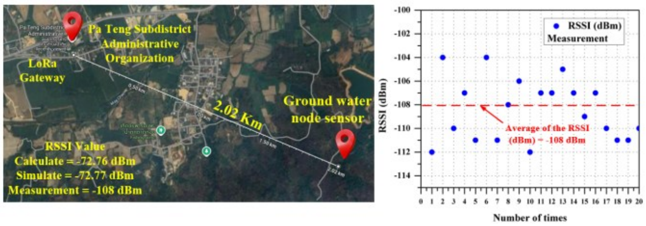

Fig. 4 depicts the measurement results of the RSSI at 2km.

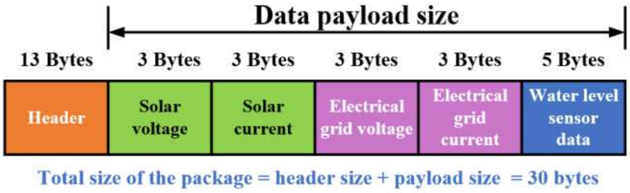

Fig. 5 The total data packets' payload size.

Fig. 6 The deployment of the sensor node and LoRa gateway in the real environment setup.

$$N_{payload} = 8 + \max\left(\left\lceil \frac{8PL - 4SF + 28 + 16CRC - 20H}{4(SF - 2DE)} \right\rceil .(CR+4), 0\right) \quad (5)$$

Each packet requires approximately 452.6 ms for transmission, demonstrating the low-latency characteristics of CSS modulation in the proposed LoRa link. This short time-on-air reduces channel occupancy and energy consumption, making the system suitable for battery- or solar-powered deployments. System-level performance was validated through field experiments and analytical evaluation. A packet delivery rate (PDR) of 95% was achieved by transmitting 100 packets (30 bytes each) over a 2 km line-of-sight link at an average RSSI of –108 dBm, close to the receiver sensitivity threshold. The maximum stable communication range was 2 km, while low-duty-cycle operation with 14 dBm transmit power ensures low average energy consumption, confirming the reliability and energy efficiency of the proposed LoRa-based monitoring

The monitoring station is powered by a solar-cell–based micro smart grid (MSG) that supplies continuous DC power to the sensing unit and LoRa communication module (Fig. 1 and Fig. 6). The MSG combines renewable energy generation with local energy storage and grid support to enable autonomous operation in remote groundwater monitoring sites. Energy efficiency is achieved through low-duty-cycle LoRa operation, in which compact 30-byte payloads are transmitted while the node remains in idle or sleep states between transmissions. Using CSS modulation at 14 dBm transmit power, the system limits active transmission time, with a measured time-on-air of approximately 452.6 ms per packet, thereby reducing average power consumption. Owing to the short transmission duration and infrequent reporting intervals, the node's energy demand remains within the MSG power budget, supporting continuous long-term operation in solar-powered deployments.

IV. CONCLUSION

This study presents the design, implementation, and evaluation of a LoRa-based IoT communication system integrated with a micro smart grid for groundwater quality monitoring. The system utilizes low-power wide-area network (LPWAN) technology operating in the 923.2 MHz band with CSS modulation schemes to enable reliable data transmission between remote sensor nodes and a centralized application server.

Through theoretical analysis and experimental validation, the free-space path loss (FSPL) and link budget were calculated and compared with real-world RSSI measurements over a 2 km communication link. Simulation using Keysight ADS confirmed the accuracy of the FSPL model, while empirical results revealed performance differences due to environmental factors. Despite these variations, the system achieved a high packet delivery rate of 95%, with a measured RSSI of –108 dBm, demonstrating strong communication reliability even near the receiver sensitivity threshold.

Additionally, performance evaluations indicate that the system maintains low latency and energy consumption. For example, CSS modulation a transmission time of approximately 452.6 ms per packet, resulting in minimal energy use per transmission. These findings highlight the suitability of the proposed solution for long-term, low-power operation in remote environments.

Overall, the integration of LoRa communication with micro smart grid technology provides an effective and scalable approach for environmental monitoring applications, supporting real-time data acquisition, energy efficiency, and robust long-range communication in resource-constrained settings.

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TABLE II. QUANTITATIVE PERFORMANCE SUMMARY

Metric	Measured / Calculated Value	Conditions
Packet Delivery Rate (PDR)	95%	100 packets, 30-byte payload
Communication Range	2 km (stable)	Outdoor LoS deployment
Average RSSI	–108 dBm	Near receiver sensitivity
Latency (Time-on-Air)	≈ 452.6 ms / packet	SF10, BW 125 kHz, CSS
Transmit Power	14 dBm	SX1276 LoRa module
Energy Operation Mode	Low duty cycle	Solar-powered micro smart grid

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