EXTEND LOW-POWER LORAWAN COVERAGE DEVICE FOR IoT APPLICATIONS

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Abstract - The advent of Long Range Wide Area Network (LoRaWAN) has significantly enhanced Internet of Things (IoT) applications, particularly in Smart Cities, with its broad coverage and energy efficiency. However, in areas with blind spots and obstacles, the conventional star network has limitations in coverage. To overcome this, researchers conducted a study to explore the potential of LoRaWAN extenders with multiple relays, focusing on coverage, performance, and power consumption. The study involved designing and deploying a relay system aligned with protocol of LoRaWAN to extend the reach of a standard LoRaWAN gateway. Strategically placed relays addressed areas beyond the gateway's coverage. Performance was measured by the longest communication distance achieved by each relay, packet loss ratio, and latency. Power consumption was also monitored. The results demonstrate the practicality and effectiveness of the proposed multiple relay design, expanding the capabilities of LoRaWAN network.

Key words - Smart city; Relay; LoRaWAN; Internet of Things; low-power; coverage.

1. Introduction

Low Power Wide Area Network (LPWAN) is a wireless technology that provides an excellent solution for Internet of Things (IoT) applications, thanks to its long-range capabilities, energy efficiency, and cost-effectiveness. LPWAN encompasses various technologies, operating in both unlicensed frequency spectrums and licensed bands. Notably, NB-IoT, Sigfox, and LoRaWAN are the most prominent and distinct technologies in this domain [1, 2]. Among these, the LoRaWAN protocol [3, 4] stands out as the most widely adopted LPWAN technology. Its star-of-star topology ensures that all end-devices require only one Gateway to connect to the network server, facilitating seamless communication and connectivity within the LPWAN network.

LoRaWAN end-devices are capable of transmitting packets over distances exceeding 15 km [5]. However, in specific environments such as underground areas, deep forest regions near rivers, or places with numerous obstacles, additional gateways need to be installed to expand the network's coverage and improve connectivity in blind spots. This requirement results in a more complex infrastructure and increased costs.

The concept of using repeating nodes, referred to as Relays, as transparent and cost-effective LoRaWAN extenders, was introduced [6]. The research presents an innovative LoRaWAN extender based on an enhanced LoRaWAN node, demonstrating the effectiveness of this approach. Moreover, a multi-hop communication system between LoRaWAN end-devices was implemented, resulting in a significant improvement in packet delivery rate, with up to 2.47 times improvement observed in indoor environments [7]. Another study detailed the protocol specifications, provided a prototype implementation, and presented experimental performance results related to extending LoRaWAN coverage [8]. However, many of these studies lack the design and evaluation of power consumption for extender devices, which is a crucial factor to consider for their deployment in environments without a power supply. Additionally, the performance of multiple-relay in terms of relay coverage, latency and packet delivery rate (PDR) requires further investigation.

The objective of this research is to establish a LoRaWAN communication network using multiple relays to extend the LoRaWAN of gateway. These relays are strategically located along river to address real-world areas not covered by the gateway. The study also examines the performance differences with varying numbers of relays, delay times, and packet delivery rates. Furthermore, experiments were conducted to measure the power consumption of the relays, assessing their feasibility for long-term deployment. The main contributions of this paper are as follows. First, Design and implementation of hardware for single Relay and relay-to-relay applications. Secondly, deployment and evaluation of a multiple relay system in practical environments beyond the coverage of the LoRaWAN Gateway. Third, assessment of the battery lifetime feasibility in relay-to-relay applications.

2. Relay coverage extender

2.1. Relay design

The primary goal of designing the Relay is to enable the reception and re-transmission of packets on a single channel within the LoRaWAN network. Consequently, the essential components required for the Relay device include a microcontroller and a LoRa Transceiver. In this study, we employed the RF200 Relay kit, as depicted in Figure 1. This kit boasts dimensions measuring 94 mm x 94 mm x 45 mm and comprises a low-power STM32L4 microcontroller from STMicro-electronics, as well as a Semtech SX1262 LoRa module. To cater to environmental monitoring applications, the main board of the kit integrates a GPS module and environmental sensors. The device is powered by two parallel 3000 mAh batteries and is housed within a compact, waterproof polycarbonate plastic casing. In scenarios involving network expansion, the ex- tenders are strategically positioned between the end devices and the gateway. In these use cases, antennas with an omnidirectional radiation pattern are typically preferred. However, given that the proposed system is intended to be installed at the bottom of a dry riverbed, where the ground and river banks can obstruct signals, a wide-beam, high-efficiency antenna becomes essential. Figure 2 depicts the antenna design integrated with the RF200 kit, which is a low-profile tri-filar circular polarization antenna capable of delivering up to a 3- dBic peak gain and featuring a 115-degree beam width [9], [10].

Figure 1. *Relay device*

2.2. Multiple Relay

Figure 3 presents the schematic diagram depicting the multiple Relays utilized in this research. These Relays function as intermediaries in the communication process between the source or end-devices and the destination, which is the Gateway. Each Relay is equipped with LoRa transceiver modules designed to work seamlessly with the LoRaWAN protocol, enabling them to both receive and transmit packets to other Relays within their respective coverage zones.

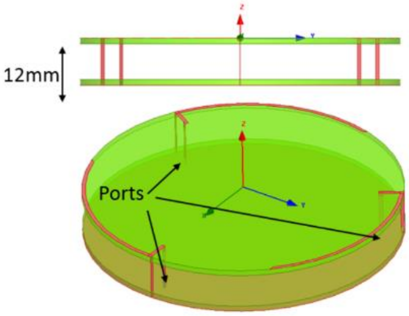

Figure 2. *Antenna design [9]*

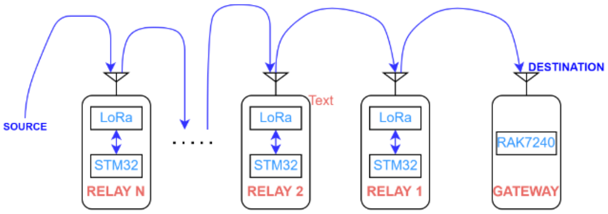

Figure 3. *Multiple relay*

Upon receiving packets, each Relay conducts a thorough examination of the packet header to determine whether it should retransmit the packet or not. This packet inspection process entails scrutinizing various fields, including CRC, Device address, Frame counter, and Network key comparison. It's worth noting that these specified fields are not encrypted in standard LoRaWAN packets, ensuring that the inspection process does not compromise security aspects.

3. Experimental methods

3.1. Experiment scenario

Several experimental scenarios have been conducted in previous studies. In the study referenced as [8], the experiment was conducted within an industrial laboratory situated in one of the buildings of the Engineering Faculty at the University of Brescia. In this experiment, an extended LoRaWAN system was used to establish signal connectivity between the basement and various floors. Another research study, as cited in [9], implemented a multi-hop communication setup within different areas on the same floor, including elevators, staircases, restrooms, and more. Most of these prior research efforts were conducted indoors. However, in our current study, we have deployed our experiment in an outdoor environment along the river, which presents a more challenging and complex testing environment. Nevertheless, our research aims to demonstrate the practicality and effectiveness of the proposed multiple relay design, which enhances the capabilities of the LoRaWAN network when deployed in outdoor settings.

Figure 4. *Deployment of relays along the beach in Danang city*

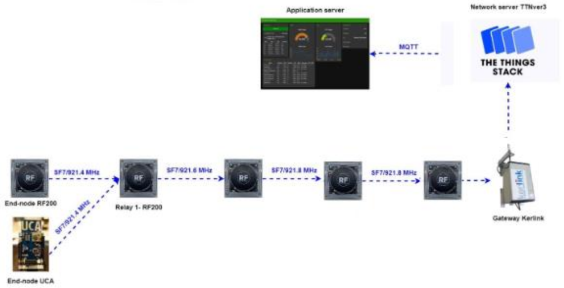

Figure 5. *Relays deployment diagram*

In our study, we conducted a demonstration to showcase the enhanced coverage capabilities. This demonstration involved the use of one outdoor Kerlink Gateway, four Relays, and one end-device. The Gateway was positioned at the summit of Son Tra mountain in Danang, Vietnam. The four Relays were strategically placed along a 2-kilometer stretch along the Cu De river, as depicted in Figure 4. These Relays were situated in different locations along the river, which presented various obstacles that hindered direct coverage from the Gateway to the end-device. For a visual representation of the system, please refer to Figure 5.

3.2. Relay configuration

In order to facilitate compatibility with existing LoRaWAN devices, the relays employed an identical LoRaWAN radio driver. These relays have their parameters configured to align with Channel 3 of the AS923 frequency plans, which are permitted for use in Vietnam, as specified in reference [11]. Detailed parameters are shown in Table 1. The relay deployment diagram was shown in Figure 8. Each relay was designed preamble time so that it can detect the LoRa packet form each other as shown in Figure 6.

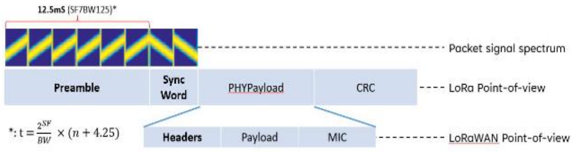

Figure 6. *Relay protocol*

Every relay is equipped with a temperature sensor, allowing for temperature monitoring on each individual relay. At regular 60-second intervals, the relay temporarily suspends its packet reception function to measure the environmental temperature. This temperature data is then transmitted alongside other relay-specific information in a status packet. The format of the relay status packet is illustrated in Table 2.

Table 1. *Relay parameters*

FC (Frequency)	921.4 Mhz
SF (Spreading Factor)	SF7
BW (Bandwidth)	125kHz
CR (Coding Rate)	4/5

Table 2. *Status of Relay packet frame*

Coordinates of	8 bytes
Temperature	2 bytes
Volage of Battery	2 bytes
Duration of status sending	4 bytes
Duration of repeating packet	4 bytes
Last RSSI received	2 bytes
Counter of Relay status	4 bytes

4. Experimental results

4.1. Coverage

The findings from Table 3 illustrate that incorporating the Relay significantly enhances the coverage range. In this setup, the end-device's signal is received exclusively by Relay-1, and subsequently, the packet was sent to the Gateway via Relay-4. The average of Received Signal Strength Indicator (RSSI) for relay, denoted as Avg. Relay RSSI, and the average coverage distance for each Relay (Avg. Coverage), are presented in Table 3. Based on these results, it is evident that without Relay 2 to Relay-4, the LoRaWAN Gateway cannot provide coverage to the end-device. In particular, the LoRaWAN Gateway exclusively received the packet sent by Relay 4, registering an RSSI of -110 dBm, and did not pick up any packets from the remaining Relays. The effective communication range between the Relays (Average Coverage) varies between 175 meters and 587 meters, contingent upon the terrain's intricacy.

Table 3. *Relays coverage in experimental scenario*

Relay	**Coverage**	**Relay RSSI**	**Gateway RSSI**
Relay-4	587 m	-dBm	-110 dBm
Relay-3	315 m	-92 dBm	-dBm
Relay-2	254 m	-97 dBm	-dBm
Relay-1	197 m	-103 dBm	-dBm
End-device	175 m	-95 dBm	-dBm

Comparing with the LoRa coverage in [12] and [13], in our experiment, the distances are much shorter, ranging from 175m to 587m. This disparity can be attributed to the fact that research conducted their experiment using a Gateway, whereas in our experiment, we utilized a Relay device similar to an end-device. Consequently, our coverage distance cannot match that of the Gateway. Furthermore, our experiment was deployed in complex areas with numerous obstacles, resulting in non-line-of-sight conditions, unlike the coverage distance in these research. So, These outcomes focus on the demonstrate the efficacy of the Relay in extending the Gateway's coverage.

4.2. Power consumption

To assess the power usage and battery longevity of the suggested system, numerous tests were performed on the relays. These assessments were carried out utilizing the Otti Arc power analyzer and a precise measurement system located in the LEAT Laboratory in France.

The average of measurement outcomes of operating duration and current in various working modes of the relay are presented in Table 4 The measurement process involved utilizing both the Otii device and Otii software. The Otii device was used to supply power to the relay, and it was connected to a computer through a USB cable. Subsequently, the Otii software was employed to monitor the relay's operation, including its duration and power consumption, as depicted in Figure 7.

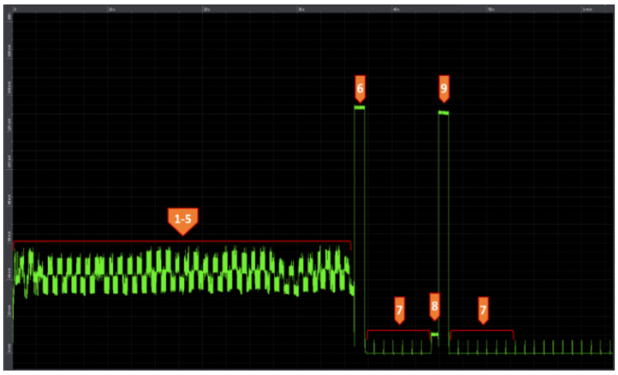

Figure 7. *Relay power consumption measurement with OTI*

The relay operation comprises two distinct states: the system initialization and running state. The initialization state encompasses Modes from one to five, which was executed when relay is powered on. On the other hand, Modes 6 to 9 constitute running state, which continuously loops to ensure the core operation of relay.

Table 4. *Average current and duration of Relay operating modes*

Modes	Avg of current	Avg of duration
Initialization of GPIO	6.3 mA	2 ms
Initialization of Sensors	22.9 mA	98.0 ms
Initialization of GPS	48.0 mA	190 ms
Initialization of LoRa	39.6 mA	469 ms
Fixing of GPS	41.6 mA	30400 ms
Status packet sending	129.5 mA	1199 ms
Packet listening	65.0 uA	(Randomly)
Receiving of packet	99.0 mA	786 ms
Packet repeating	128.8 mA	1098 ms

During running state, relay initiates by transmitting a status packet, conveying information about coordinates, battery level and the number of successful packets from the previous running state. Subsequently, the relay enters a receiving mode, where the LoRa chip is configured to CAD (Channel Activity Detect). To conserve power, the micro-controller and the other electronic components are in sleep mode and are only awakened when an incoming signal is detected, allowing the relay to repeat the packet as required.

Table 5 illustrates the relationship between sensitivity, power consumption, and spreading factor in a 1-second receiver duty cycle. This result was measured from a laboratory in France designed to isolate electromagnetic waves which is illustrated in Figure 8 Results are taken from wave analysis software combined with measurements on Relay.

Table 5. *Sensitivity measurement and power consumption of Relay*

Speading Factor	**Energy**	**Sensitivity**	**Current**
SF7	91.3 uWh	-123 dBm	64 uA
SF9	105 uWh	-129 dBm	145 uA
SF12	193 uWh	-135 dBm	1200 uA

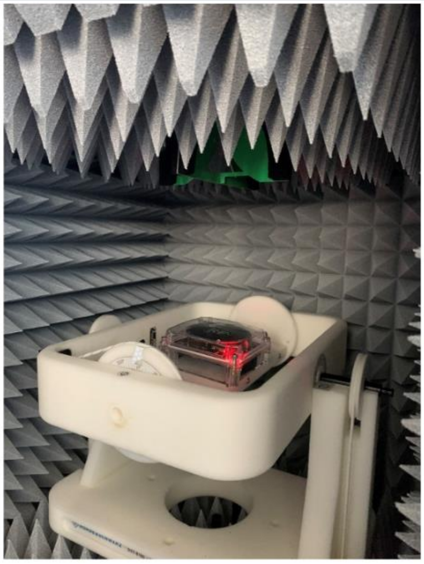

Figure 8. *Relays sensitivity measurement in the LEAT laboratory, France*

This measurement demonstrates how the spreading factor impacts the energy efficiency and sensitivity of the relay. A trade-off exists between energy consumption and sensitivity. For instance, when choosing SF12, the sensitivity is at its lowest, enabling the relay to receive signals from a greater distance. On the other hand, SF7 consumes the least energy but has the highest sensitivity, limiting its ability to detect packets transmitted at distances greater than SF12 and SF9.

Battery life estimation can be achieved by considering the count of iterations and states duration. The formula used to calculate the count of iterations for given capacity of battery, as below:

$$N = \frac{BC - C_{Init}}{C_{Init}}$$

Where:

- N is a count of iterations;
- BC is the capacity of battery mAh;
- C_{Init} and C_{Runin} are initialization and running state current, respectively, which were calculated by multiplying the average current and duration of modes.

Figure 9 illustrates the estimation of battery life using two parallel batteries 18650, which have a capacity 3000 mAh. Relay's lifetime was determined by multiplying the duration of state and the count of iterations. For example, according to Table 4, the initialization state comprises the initialization of GPIO, sensors, GPS, and LoRa. C_{Init} was calculated as the sum of the average current multiplied by the duration of these initializations. The running state includes GPS fixing, sending status packet, listenning for packet, receiving packet and repeat packet. C_{Runing} also was calculated similar with C_{Init}. In the case of the proposed system with four relays, the relay closest to the gateway is expected to have a battery life of approximately one year, while the furthest relay can achieve a battery life of over three years.

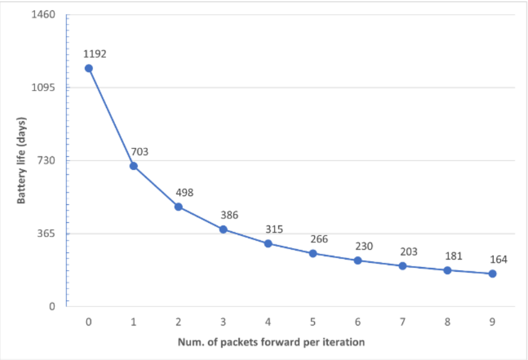

Figure 9. *Battery life estimation*

4.3. Network performance

Figure 10 presents the performance of network metrics, involving the packet delivery rate and the delay time. These results were obtained during the deployment of the system in the Cu De river area. For the data collection, each relay was programmed to send status packets at fixed intervals of 60 seconds, with a total of 500 packets sent during the recorded time.

Analysis of the recorded status packets revealed an average packet sending time of 1056 ms. The time required for each relay, receiving and re-transmitting a status of packet from another relay, was measured at 1587 ms. Consequently, the frequency channel or delay of each uplink packet through the multiple relay system was calculated as the formula below:

$$DelayTime(ms = 1056 + NumberOfRelay * 1587$$

Despite lacking a packet congestion control algorithm, the relay proposed in this research achieved a successful uplink rate of 71.49 % and an average sending delay time of 5 seconds for the relay located farthest from the gateway.

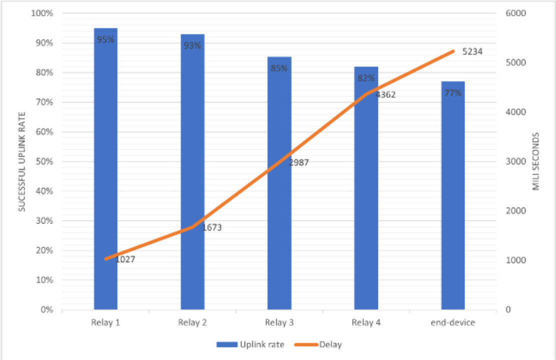

Figure 10. *Packet delivery rate and delay comparison*

Deploying multiple relays or using a relay-to-relay configuration can enhance LoRaWAN coverage in complex areas where LoRaWAN Gateway faces limitations. This setup is optimized for scenarios where devices are linearly positioned to extend in a specific direction, as seen in applications like water monitoring of river. The relays have low power consumption, enabling the hardware system to operate for up to a year in a 4-relay setup, each equipped with dual 3000 mAh batteries. In a 4-relay system, the delay for forwarding a packet is roughly 5 seconds, and the packet delivery rate is 77%. However, the packet delivery rate can be improved by using random delay before re-transmitting each relay packet, without causing any issues with the compatibility of the LoRaWAN network. There is a trade-off between packet delivery rate and delay offers a way to optimize the relay system's performance based on specific needs.

5. Conclusion

Deploying multiple relays or using a relay-to-relay configuration can enhance LoRaWAN coverage in complex areas where LoRaWAN Gateway faces limitations. This setup is optimized for scenarios where devices are linearly positioned to extend in a specific direction, as seen in applications like water monitoring of river. The relays have low power consumption, enabling the hardware system to operate for up to a year in a 4-relay setup, each equipped with dual 3000 mAh batteries. In a 4-relay system, the delay for forwarding a packet is roughly 5 seconds, and the packet delivery rate is 77%. However, the packet delivery rate can be improved by using random delay before re-transmitting each relay packet, without causing any issues with the compatibility of the LoRaWAN network. There is a trade-off between packet delivery rate and delay offers a way to optimize the relay system's performance based on specific needs.

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