A Cost-Effective LoRa Gateway for Low-Density IoT Applications

Caio T. B. Costa, Anderson G. de Almeida, Vitória J. Baratella, Danilo H. Spadoti

***Abstract*— LoRaWAN gateways, typically costly and employing high-overhead protocols, pose challenges for low-density IoT deployments. Smart city applications and environmental monitoring demand extensive gateway coverage, particularly in rural areas. Additionally, building reliable LoRaWAN repeaters is intricate, necessitating more distributed gateways. This study introduces a novel LoRa-based device to alleviate these concerns, lowering gateway expenses, and improving reliability. The proposed solution substantially reduces costs compared to conventional LoRaWAN gateways, offering a promising alternative for IoT deployments.**

***Keywords*— LoRaWAN, Internet of Things, WSN**

I. Introduction

The increase in Internet of Things (IoT) applications has driven the need for efficient and low-cost communication solutions, particularly in the context of smart city deployments[1]. Traditional LoRaWAN (Long Range Wide Area Network) gateways, while effective in high-density scenarios, are often prohibitively expensive [2] and involve high communication overhead, of at least 13 bytes on every message [3]. Applications such as environmental sensing, river level monitoring, and other public infrastructure monitoring require widespread deployment over large areas, especially in rural regions where device density is low. This results in the necessity for numerous costly gateways, posing a significant financial burden. To address these challenges, this paper proposes a novel LoRa (Long Range) based protocol and gateway design aimed at mitigating high gateway costs, and incorporating basic mesh functionality to enhance network resilience and coverage area.

In regions like the Amazon, where the ecosystem's health is of global significance, the threat of wildfires looms large [4]. Efficient monitoring of these areas is crucial for early detection and mitigation of wildfires, safeguarding biodiversity and combating climate change. LoRa technology offers a promising solution for monitoring vast expanses of forest due to its long-range capabilities and low power consumption. By deploying LoRa-enabled sensors throughout the Amazon, authorities could establish a comprehensive wildfire detection network, providing real-time data on temperature, humidity, and air quality to aid in fire prevention and response efforts. This proactive approach is another example of a low density application that could benefit from lower infrastructure cost and the range extending nature of mesh networking [5].

This work presents both hardware and software developments that build on the knowledge acquired from our previous publications at SBrT 2022[6] and 2023[7]. The new hardware design features a solar-powered Maximum Power Point Tracking (MPPT) controller, a 4G LTE (Long Term Evolution) modem, and WiFi connectivity, integrated with a modern SX1262 Semtech LoRa transceiver. Compared to its predecessor, the SX1276, the SX1262 offers improved sensitivity, reduced power consumption, and better interference immunity, making it more suitable for robust IoT deployments[8]. The inclusion of a 4G LTE modem ensures redundancy and future-proofs the system as 2G and 3G networks are being phased out[9].

On the software side system runs on the STM32F103C8 microcontroller. The mesh network protocol is loosely based on the Ad hoc On-Demand Distance Vector (AODV) routing protocol. AODV is a reactive routing protocol that establishes routes between nodes only as needed, minimizing control traffic and reducing power consumption, which is crucial for battery-operated IoT devices. This approach allows the network to adapt dynamically to changes in topology, providing a flexible and reliable communication framework.

II. Design Requirements

The features typically found in traditional LoRaWAN gateways, such as multi-channel operation and robust CPU capabilities, are well-suited for dense urban environments where numerous devices communicate simultaneously. In those settings, the ability to handle multiple channels allows for efficient communication among a large number of devices, ensuring optimal network performance. Additionally, the inclusion of powerful CPUs enables gateways to manage complex routing tasks, process large volumes of data, and support advanced networking functionalities.

However, while these features are essential for high device count applications, they are often overkill for rural or low-density environments. Thus, the cost savings achieved by the proposed LoRa gateway primarily stem from two key components: the LoRa transceiver and the CPU.

Firstly, the LoRa transceiver selected for the gateway is the SX1262, operating on a single LoRa channel frequency. In contrast, traditional LoRaWAN gateways commonly utilize more expensive transceivers such as the SX1301 and SX1302, capable of handling up to 8 simultaneous channels.

Secondly, the CPU used in the proposed gateway design is intentionally minimalistic, focusing solely on relaying LoRa

Caio T. B. Costa, e-mail: caio.tacito@unifei.edu.br; Anderson G. de Almeida, e-mail: anderson.g.almeida@unifei.edu.br; Vitória J. Baratella, e-mail: vitoriajacomelli@gmail.com; Danilo H. Spadoti, e-mail: spadoti@unifei.edu.br, IESTI, Federal University of Itajubá (UNIFEI), Itajubá-Minas Gerais. The authors thank CAPES, CNPQ -402093/2022-4, FAPEMIG, FAPESP 2021/06569-1 and the entire team at LabTel-LAIoT UNIFEI for their support to the research.

packets to the internet without additional functionality. Unlike many LoRaWAN gateways on the market that feature robust operating systems, configurable web interfaces, integrated network and application servers, and router-like capabilities [10], the proposed gateway eschews these features. Instead, it relies on pre-configured external servers to handle processing tasks, thus eliminating the need for relatively powerful CPUs capable of running Unix-based operating systems and accompanying hardware such as DRAM and NAND-based storage. This minimalist approach further reduces costs while maintaining the essential functionality of relaying LoRa packets.

In terms of power consumption, the gateway must be engineered to operate efficiently on solar power, with no reliance on additional energy sources. Reliability is also paramount for the proposed gateway, especially considering its deployment in remote and inaccessible regions. It must be capable of continuous operation for extended periods of time without requiring manual intervention or maintenance. The gateway must also guarantee the integrity of transmitted data, ensuring that every packet received accurately reflects the information sent by the devices. To achieve this, error-checking and correction mechanisms should be employed to detect and rectify any data corruption or loss during transmission.

Redundancy is essential to maintain continuous internet connectivity. The gateway should incorporate redundant connectivity options such as WiFi and 4G with dual SIM failover capability.

III. Prototype and Assembly

A. Component selection

The selection of components for the proposed LoRa gateway prototype was guided by considerations of cost-effectiveness, reliability, and performance. The main processor chosen is the STM32F103C8T6 microcontroller, which features a 72 MHz ARM Cortex-M3 core, 64 KB of flash memory, and 20 KB of SRAM. This microcontroller offers a robust set of features, including multiple I/O ports and communication interfaces, while maintaining low power consumption. For the LoRa communication, the RAK Wireless RAK3172 module with the SX1262 Semtech chipset was selected due to its superior sensitivity of -148 dBm, reduced power consumption of 4.8 mA in receive mode, and enhanced interference immunity, ensuring reliable long-range communication. The SIMCom A7672 LTE module was chosen for cellular connectivity, supporting up to Cat-4 speeds with dual SIM failover capability, which is essential for maintaining continuous connectivity in remote areas as 2G networks are phased out. The ESP-12F module provides reliable WiFi connectivity, featuring an integrated TCP/IP stack, 4 MB of flash memory, and low power sleep modes, which enhance the gateway's ability to connect to local networks. Powering the gateway, the Samsung 30Q lithium cell with a capacity of 3000 mAh and an integrated protection circuit was selected for its high energy density, reliable performance, and safeguards against overcharging, over-discharging, and short circuits. This high-capacity battery ensures that the gateway can operate autonomously for extended periods, crucial for deployments in remote and hard-to-access locations. Each component was carefully chosen to balance cost, efficiency, and reliability, ensuring that the gateway delivers consistent performance even in challenging environments.

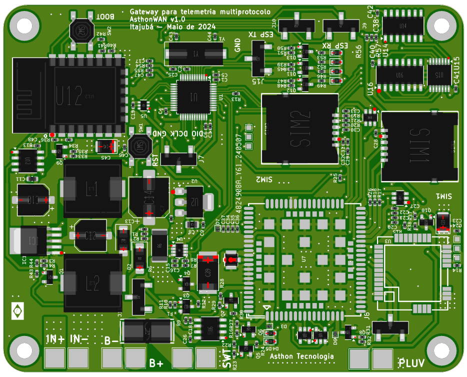

Fig. 1. PCB 3D render

B. PCB design

The PCB (Printed Circuit Board) design for the proposed LoRa gateway was crafted using KiCad, a powerful open-source electronics design automation (EDA) software suite. The layout includes 4 layers to accommodate the circuitry required for integrating the chosen components while ensuring signal integrity and minimizing interference. The design incorporates separate planes for power and ground to reduce noise and enhance stability. High-frequency traces, particularly those connected to the SX1262 and the ESP-12F modules, were carefully routed to minimize signal degradation. The 3D visual of the finished PCB, as shown in Figure 1, highlights the compact and efficient arrangement of components, optimizing space while maintaining accessibility for assembly and troubleshooting. Strategic placement of the LTE module, LoRa transceiver, and other critical components ensures optimal performance and ease of connectivity.

C. Software development

The software development for the proposed LoRa gateway follows a structured state machine, ensuring that every action is performed systematically and reliably. At the initial stage, the software begins by checking the hardware status, verifying the proper startup of all modules including the STM32F103C8T6 microcontroller, RAK3172 LoRa transceiver, SIMCom A7672 LTE module, and ESP-12F WiFi controller. Concurrently, it monitors voltages and currents to ensure all components are operating within their specified parameters, safeguarding against potential hardware issues.

Once the initial checks are completed and the hardware is confirmed to be functioning correctly, the gateway enters a waiting state, actively listening for incoming LoRa packets. Upon receiving a packet, the software performs a Cyclic Redundancy Check (CRC) to validate the integrity of the received data. If the CRC check fails, the packet is discarded to prevent corrupted data from being processed. If the CRC check passes, the entire payload is prepared for transmission to the internet, with no decoding performed on the gateway side to streamline processing and conserve resources.

The software then attempts to send the payload via WiFi, the preferred method of internet connectivity. It makes up to four attempts to establish a WiFi connection. If WiFi is unavailable after these attempts, the software switches to the 4G LTE modem. Within the 4G modem routine, the software first tries to connect using SIM1. If the connection fails, it switches to SIM2 and attempts the connection again. This redundancy ensures that the gateway has multiple opportunities to maintain internet connectivity.

If all connectivity attempts fail, the software initiates a reboot sequence to reset all modules and attempts the entire process from the beginning. This reboot strategy helps recover from transient errors and ensures the gateway makes a fresh attempt to establish a reliable connection. The state machine approach to software development ensures robust operation, systematically addressing hardware initialization, data integrity, and reliable data transmission over various communication interfaces.

The software development for the proposed LoRa gateway was carried out using PlatformIO, an integrated development environment (IDE) extension for Visual Studio Code (VSCode). PlatformIO provides a powerful and flexible environment for embedded development, supporting a wide range of microcontrollers and development boards. For this project, the ST STM32 Arduino core was utilized, enabling the use of familiar Arduino libraries and frameworks on the STM32F103C8T6 microcontroller.

D. Assembly

The assembly process for the proposed LoRa gateway involved using a 10x14 cm plastic project enclosure to house all the components securely. Waterproof IP68 connectors were used to ensure the gateway's durability and reliability in outdoor environments, protecting against dust and water ingress. The internal layout was organized with 3D-printed mounts and holders, designed to fit each component precisely, providing structural stability and ease of assembly.

IV. Test Methodology

The testing methodology for the proposed LoRa gateway aims to evaluate its performance in comparison with a commercially available off-the-shelf (COTS) LoRaWAN gateway. The primary focus of the tests will be on determining the maximum operational range and assessing packet loss across various distances within a real-world urban environment.

The experimental setup uses a transmitting unit based on our previous work, as documented in SBrT 2022 and 2023 [6] [7]. This unit features a SX1276 LoRa transceiver. For the purpose of testing, the unit will be configured with two different firmware options: one utilizing the LMIC IBM LoRaWAN library to operate within a standard LoRaWAN framework, and the other using a custom LoRa firmware based on the Arduino LoRa library, tailored specifically for our single-channel gateway design.

The testing process will be conducted in a typical urban environment to simulate real-world conditions. The transmit device will be placed at various predetermined distances from the gateway, and a series of packet transmissions will be initiated using each firmware. Transmission interval is 10 seconds, Spreading Factor will be set to 12, bandwitdh to 125kHz and the transmission frequency will be fixed at 916 MHz for both LoRa and LoRaWAN. Both gateways will be installed on the same facility with about 1m of distance from each other, and record the number of packets received for a period of 10 minutes, allowing for the calculation of packet loss at each distance measured. The satellite map on Figure 3 highlights all test locations and gateway positioning.

V. Results

The chart on Figure 2 illustrates how packet loss varies with distance for both communication protocols. It shows that as the distance increases, the packet loss tends to increase as well. Packet losses increase with distance due to signal attenuation, path loss, and interference. LoRa also loses more packets than LoRaWAN due to its transceiver's lower sensitivity, affecting its ability to detect weak signals at longer distances and increasing the likelihood of packet loss [11].

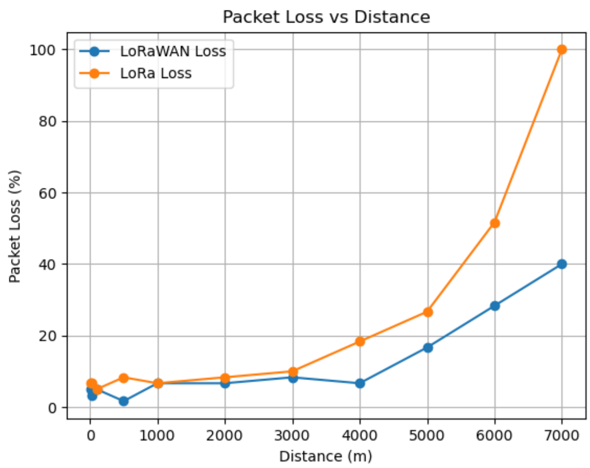

Fig. 2. Measured packet loss comparison between the commercial and developed gateways

Table I details the measurements obtained from the test. At short distances (5m to 20m), both gateways demonstrated strong signal strength and high SNR. For instance, at 5 meters, the LoRaWAN RSSI (Received Signal Strength Indicator) was -28 dBm with an SNR (Signal to noise ratio) of 20 dB, while the custom LoRa firmware showed an RSSI of -43 dBm and an SNR of 14 dB. Similarly, at 20 meters, the RSSI and SNR were -29 dBm and 10 dB for LoRaWAN, and -45 dBm and 7 dB for the custom LoRa firmware.

As the distance increased to 1000 meters, a more noticeable divergence in performance emerged. At 100 meters, the LoRaWAN configuration maintained a relatively strong RSSI of -31 dBm and an SNR of 4 dB, compared to -56 dBm and 2 dB for the custom LoRa firmware. At 1000 meters, the LoRaWAN

Distance m	**LoRaWAN RSSI dBm**	**LoRaWAN SNR dB**	**LoRaWAN Loss %**	**LoRa RSSI dBm**	**LoRa SNR dB**	**LoRa Loss %**
5	-28	20	5%	-43	14	6.67%
20	-29	11	3.33%	-45	7	6.67%
100	-31	4	5%	-56	2	5%
500	-34	1	1.67%	-59	-4	8.33%
1000	-67	-3	6.67%	-63	-6	6.67%
2000	-75	-5	6.67%	-75	-8	8.33%
3000	-81	-6	8.33%	-94	-10	10%
4000	-99	-6	6.67%	-97	-12	18.33%
5000	-103	-10	16.67%	-105	-16	26.67%
6000	-107	-12	28.33%	-114	-17	51.67%
7000	-112	-14	40%			100%

TABLE I
TEST RESULTS

RSSI and SNR dropped to -67 dBm and -3 dB, while the custom LoRa firmware showed values of -63 dBm and -6 dB.

Beyond 1000 meters, the signal degradation became more pronounced. At 2000 meters, the LoRaWAN gateway recorded an RSSI of -75 dBm and an SNR of -5 dB, whereas the custom LoRa firmware measured -75 dBm and -8 dB. At 3000 meters, the LoRaWAN RSSI was -81 dBm with an SNR of -6 dB, compared to -94 dBm and -10 dB for the custom firmware. At 4000 meters, the values were -99 dBm and -6 dB for LoRaWAN, and -97 dBm and -12 dB for the custom firmware.

At the furthest distance of 7000 meters, the LoRaWAN gateway could still receive packets with an RSSI of -112 dBm and an SNR of -14 dB, though the custom LoRa firmware did not register a signal at this range, indicating a significant drop-off in performance.

Component	**Description**	**Price (USD)**
LoRa Transceiver	SX1262	5.99
Main Processor	STM32F103C8T6	1.19
LTE Controller	SIMCom A7672	4.79
WiFi Controller	ESP-12F	1.95
Battery	Samsung 30Q 3000 mAh	3.50
Enclosure	Plastic Project Box	3.00
Miscellaneous	Connectors, Power Supply, etc.	20.00
Total Cost		**40.42**

TABLE II
COMPONENT PRICING FOR DEVELOPED LORA GATEWAY

Table II gives an overview for the pricing of the developed gateway components, according to market rates as of June, 2024. Table III compares the developed gateway cost with a few of the market available gateways.

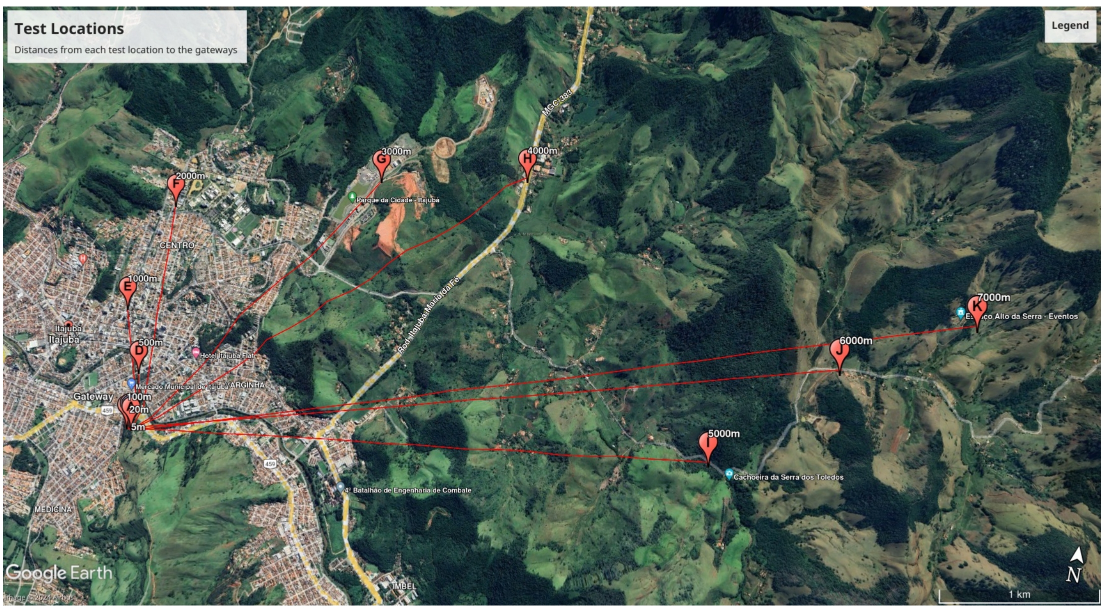

Fig. 3. Map detailing test locations and distances to gateway

Gateway	Price (USD)
Developed LoRa Gateway	**40.42**
Manufacturer 1	325.00
Manufacturer 2	179.00
Manufacturer 3	499.00
Manufacturer 4	599.00
Manufacturer 5	699.00
Manufacturer 6	349.00

TABLE III

COMPARISON OF DEVELOPED LORA GATEWAY WITH COMMERCIAL LORAWAN GATEWAYS

VI. CONCLUSION

In summary, the results indicate that while the custom single-channel LoRa gateway performs adequately at shorter ranges, the LoRaWAN gateway outperforms it at greater distances, maintaining stronger signal strength and better signal-to-noise ratios. Specifically, at distances up to 1000 meters, the custom gateway showed comparable performance to the commercial unit, though its effectiveness diminished at longer ranges. This divergence highlights the inherent advantages of the LoRaWAN gateway's multi-channel capabilities and robust processing power. However, these features, which include operating systems, integrated network servers, and powerful CPUs, also contribute to the high cost and complexity of commercial gateways.

In terms of cost-effectiveness, the developed gateway offers a significant advantage. While a commercial LoRaWAN gateway, including the necessary supporting equipment for deployment, can cost around 4000 reais, the low-cost gateway developed in this project can be produced for as little as 200 reais. This dramatic reduction in cost makes it an attractive solution for low-density, rural, or budget-constrained IoT applications.

In conclusion, the developed low-cost LoRa gateway presents a compelling price-to-performance ratio, making it an ideal choice for specific IoT applications that do not require the extensive capabilities of commercial LoRaWAN gateways. While it does not achieve the absolute maximum range of a commercial unit, its cost-effectiveness, coupled with adequate performance for low-density deployments, positions it as a viable alternative. This project demonstrates that with careful component selection, efficient design, and targeted functionality, significant cost savings can be achieved, making advanced IoT deployments more accessible and sustainable.

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