EAI Endorsed Transactions
on Internet of Things
Research Article EAI.EU

Research and Design a Low Power Electronic Shelf Label Based on E-paper Display and LoRa Technology

Le-Huy Trinh[1,*], Thanh-Tuan Phan[1], Fabien Ferrero[2], Nguyen Vu Truong[3]

[1]University of Information Technology, VNU-HCM, Linh Trung, Thu Duc, Ho Chi Minh City 71308, Vietnam
[2]Universite Cote d'Azur, CNRS - LEAT, 930 Route des Colles, Sophia Antipolis 06930, France
[3]National Institute of Applied Mechanics and Informatics - VAST, 291 Dien Bien Phu, Ho Chi Minh 70000, Vietnam

Abstract

Electronic Shelf Labels (ESL) are increasingly replacing traditional paper-based pricing systems due to their flexible update capabilities, ease of management, and environmental benefits. This paper presents the research and development of an optimized ESL device that incorporates LoRa technology and a 2.13-inch E-paper display, capable of low power consumption. By analyzing and considering design factors, the ESL device is engineered to achieve compact dimensions, low energy consumption, a long lifespan, and improved communication range. The paper also details an efficient operational workflow for integrating these devices into a system. The measurement results indicate that the ESL device can have a lifespan exceeding 5 years, highlighting its efficiency in energy consumption within an ESL system. The device described in this paper can operate reliably at distances of up to 23 meters in an obstacle-rich environment, achieving a packet delivery rate of over 96%.

Received on 05 June 2025; accepted on 16 August 2025; published on 10 October 2025

Keywords: Internet of Things, LoRaWAN, Miniature antenna, Low Power Wide Area Network, Electronic Shelf Label, E-paper

doi:10.4108/eetiot.9488

1. Introduction

The Internet of Things (IoT) has revolutionized various industries by enabling interconnected networks of devices that can share data and respond to real-time changes without human intervention [1, 2]. In the retail sector, IoT technologies have facilitated the way for innovations such as Electronic Shelf Labels (ESLs), which dynamically update product information, including prices and availability, throughout a store network [3, 4]. ESLs reduce manual effort, improve price accuracy, and enhance the shopping experience while providing retailers with valuable data-driven insights. However, challenges such as high power consumption, limited communication range, and scalability persist, particularly in large-scale deployments.

An Electronic Shelf Label (ESL) is a device mounted in front of products to provide shoppers with details like the product name, price, barcode, manufacturer, and expiration date. Commonly used in supermarkets and food retail outlets, ESLs are expected to grow rapidly in the coming years [5]. Due to the impracticality of wired connections in stores, these devices are battery-powered and utilize wireless communication to update and display product information [6]. In addition, keeping production costs low is crucial for feasibility in supermarkets with thousands of products.

Traditional paper price tags are still commonly used to display product information, which can lead to errors and confusion during price updates, requiring significant effort and human resources for each price change. ESLs can mitigate these problems by automatically updating prices and product information, thus saving time and money [7]. They enhance the customer experience by providing accurate and up-to-date information and are eco-friendly by eliminating the need for paper and saving energy.

A key element of ESLs is electronic paper display technology (e-paper), which mimics traditional paper while providing clear and sharp images and text. Widely used in e-readers and now in ESLs, e-paper allows for quick updates of product information, offering energy efficiency and durability that minimize replacement needs and reduce costs for retailers. Additionally, e-paper displays are readable in sunlight, making electronic price tags effective in various lighting conditions [8]. Thus, e-paper is an ideal solution for

*Corresponding author. Email: huytl@uit.edu.vn

ESLs, helping to lower environmental impact and save costs for merchants.

This study contributes to the growing field of IoT-based smart retail solutions by presenting:

- A comprehensive evaluation of the proposed ESL system;
- Hardware design;
- Software solution;
- Measurement and validation;

2. Related work

The findings highlight the practicality and scalability of LoRa and E-paper technologies in retail applications, offering a foundation for future developments in smart supermarkets and warehouses.

In general, Electronic Shelf Labels (ESLs) utilize standard technologies such as Bluetooth Low Energy (BLE) [9–11] and Zigbee [12, 13] for data transmission and reception. While these technologies have their advantages, they also come with limitations, particularly regarding communication distance and energy consumption. BLE and Zigbee are well-suited for small, easily maintained areas. However, in large-scale deployments involving numerous devices, deploying ESLs can be challenging due to their limited communication range and the need for frequent battery replacements.

To address these challenges, LoRa communication presents a promising alternative [14, 15]. This technology is advantageous for ESL systems because of its low energy consumption [16] and long communication range, making it feasible to expand the system to larger supermarkets or warehouses [5, 17]. In a study [18], LoRa technology was applied at a frequency of 433 MHz, enabling ESL devices to operate for over five years. However, this study did not evaluate a system with multiple devices, leaving the practical applicability of the proposal unproven.

In addition, to meet power consumption and communication distance requirements, an application network model is essential for an ESL system with multiple devices. The network structure proposed in [19] is a star architecture, commonly found in LoRa networks. This structure is well-suited for ESL applications, as it allows end devices to be distributed over a large area, enabling effective monitoring and data collection from devices located far apart. The LoRa star network architecture facilitates easy network expansion by adding new end devices and ensures high security during data transmission.

3. System Design

The packaging for the ESL system has been designed with functionality, durability, and efficiency, ensuring that it meets the practical needs of retail environments. The enclosure is made of robust materials such as ABS plastic, providing resistance to physical impacts, dust, and moisture while maintaining a lightweight structure. The design is compact and specifically engineered to fit internal components, such as the LoRa module, E-paper display, and battery holder, within a small form factor of approximately 60 mm x 34 mm. This ensures that the ESL seamlessly integrates into retail shelving systems without taking up unnecessary space. Fig.1.

Figure 1. The proposed ESL device with complete packaging.

The front face features prominently the 2.13-inch E-paper display, which is protected by a transparent, anti-glare cover to enhance readability under various lighting conditions. This cover also provides scratch resistance, preserving the professional appearance of the device during extended use. Inside the ESL, there will be a single PCB that controls its operation. The PCB will contain a LoRa module, which receives data and displays them on the E-ink screen using the SPI protocol. Additionally, the PCB includes power management sections for the ESL components and antennas for the LoRa module, allowing the ESL to operate without any external connections. The antenna, an essential component for LoRa communication, is compactly integrated into the design to ensure optimal signal reception while maintaining the device's slim profile.

For installation, ESL packaging had to be designed to incorporate flexible mounting mechanisms such as hooks, magnets, or adhesive mounts, making it easy to attach to different types of retail shelves. Accessibility has been considered in the design, with a simple closure mechanism that allows the device to be opened for maintenance or battery replacement, while ensuring it remains secure during use. This approach renders the ESL both user-friendly and robust, enabling it to endure the challenges associated with a retail environment.

3.1. Circuit Design

The circuit design for the ESL device revolves around the integration of the RAK3172 module, which is based on the STM32WLE5CC SoC contain of Arm® Cortex®-M4 core with LoRa communication capabilities. The circuit aims to achieve low power consumption while ensuring reliable performance for daily data transmission and display updates. Fig.2 illustrates the overall hardware architecture of the ESL device, highlighting the core components critical to its functionality: a LoRa-enabled microcontroller module, an E-paper display, and power management circuitry.

- **LoRa-enabled microcontroller module:** The central processor for the ESL device is the RAK3172 module, which integrates the STM32WLE5CC chip, which uses a 32-bit Arm® Cortex®-M4 core with an integrated LoRa transceiver developed by STMicroelectronics. The module combines microcontroller and RF in one chip, with a wide frequency range from 150 MHz to 960 MHz and Sub-GHz communication protocols such as LoRa, FSK, GFSK, MSK and BPSK. In addition, the STM32WLE5CC chip is also energy-saving with multiple deep sleep modes, supports 256-bit AES, a true random number generator (TRNG) for data security, and 256 KB Flash + 64 KB RAM, meeting the flexible processing needs of smart applications. This module, compatible with LoRaWAN protocol, enables efficient data transmission over long distances with low power consumption, making it particularly advantageous for Internet of Things (IoT) applications, especially within the domain of electronic shelf labeling.

- **E-paper Display:** A 2.13-inch e-paper display is used for its low energy consumption, as it only requires power during updates. The display is connected to the RAK3172 module via a 4-wire SPI interface, enabling quick data transfer for content updates. E-paper technology allows the display to retain information without continuous power, making it well-suited for battery-operated devices.

- **Power Management:** The system consists of two low-dropout (LDO) regulators (NCV8170), which supply a stable 2.8 V to the RAK3172 and the E-paper display. The LDOs are chosen for their low quiescent current, ensuring minimal energy wastage. Power is supplied by two CR2032 coin-cell batteries connected in parallel, providing a nominal voltage of 3 V and increased capacity for long-term operation. The power management system integrates an enable feature for the LDO powering the E-paper display, controlled directly by the RAK3172. This design ensures that the LDO is disabled during periods of inactivity, conserving energy.

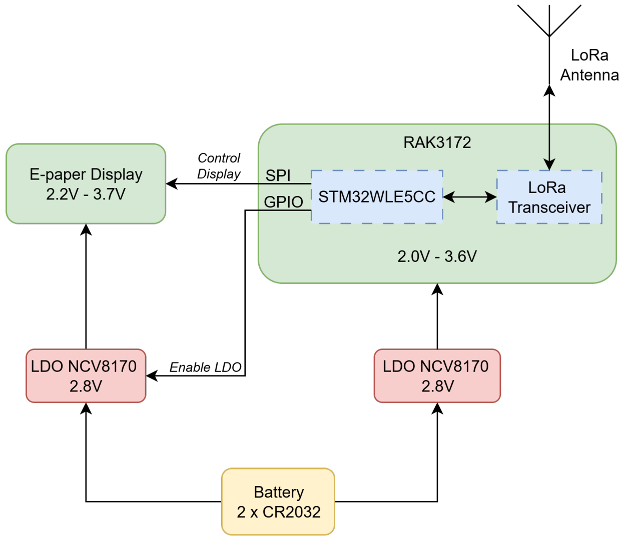

Figure 2. The proposed hardware architecture of the device.

The schematic and layout of the ESL device were designed in Altium Designer to ensure compact integration of all components. Key layout considerations included placing the LDOs close to their respective loads to minimize voltage drops, carefully routing the antenna path to maintain signal integrity, and positioning the e-paper display on the PCB edge for easy viewing.

The finalized PCB layout and 3D design are shown in Fig.3. The RAK3172 module will be placed in the right corner of the PCB, the right side of the RAK3172 module is the clearance for the LoRa antenna. The E-ink display connector is placed on the left side of the PCB to connect to the display located on the back of the PCB via an FFC cable. The center of the PCB is the area for the passive components for the E-ink display and the power management. The PCB is designed with two layers and vias all the areas without components to minimize noise and create a large enough GND for the antenna mounted on the PCB. All components on the PCB are placed in optimal positions for the ESL to have the best compactness and performance.

This circuit design enables the ESL device to perform core functionalities such as data transmission via LoRa, display updates, and optimized power management, making it a reliable and efficient solution for electronic shelf labeling in retail applications.

3.2. Antenna Design

The antenna is a critical component in the electronic shelf label (ESL) system, as it ensures efficient wireless communication between the device and the network gateway. For this project, a compact antenna operating at 923 MHz was designed and implemented. This frequency is within the AS923 band, which is compliant with regulations for low-power, long-range communications in Vietnam.

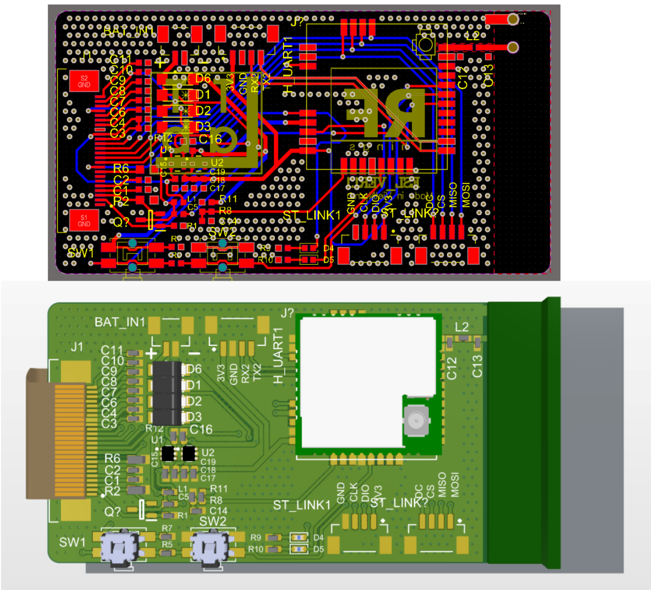

Figure 3. The proposed device layout with its 3D illustration image.

The antenna used in this project is the PIFA antenna. We have referred to the PIFA antenna design of the articles [21–28] with antennas for compact and high-performance devices. The design was aimed at optimizing energy efficiency, achieving robust signal strength, and maintaining compatibility with the compact form factor of the device.

The design began with theoretical calculations to determine the optimal antenna dimensions, considering the physical constraints of the ESL device. Using the equation for a quarter-wavelength antenna:

$$L = \frac{c}{4f\sqrt{\varepsilon}} \tag{1}$$

Where L is the antenna length, c is the speed of light, f is the operating frequency (923 MHz), and ε is the relative permittivity of the substrate. The calculated length was fine-tuned through simulations to account for the effects of the PCB ground plane and the dielectric properties of the FR4 substrate.

However, the antenna designs presented in the related articles are all flat, resulting in the antenna area occupying a large part of the devices. Therefore, we propose a PIFA antenna design that is placed vertically, rather than horizontally, to reduce that area. Moreover, most devices today must accommodate a certain thickness due to components such as batteries and screens. By utilizing this thickness to position the antenna vertically, we can minimize the overall area of the device while still meeting the performance requirements of the antenna. The design focuses on creating a compact and efficient antenna that aligns with the physical constraints of the ESL device. The vertical antenna placement is illustrated in Fig. 4, showing a portion of the antenna positioned perpendicular to the substrate and approximately the same height as the battery pack used in the ESL device.

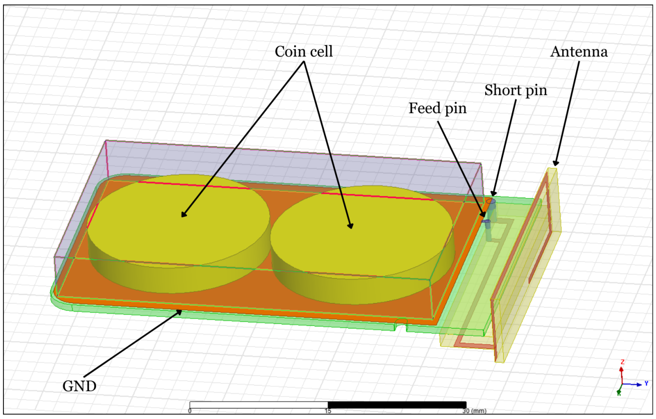

Figure 4. The proposed antenna structure in HFSS.

Fig. 5 illustrates the structure and dimensions of the designed antenna. The values of the geometric parameters of the antenna structure are shown in Table 2 The antenna consists of a radiating element and a feeding section optimized for the 923 MHz LoRa band. The compact design ensures that it integrates seamlessly into the ESL device while maintaining high efficiency.

By using ANSYS HFSS software, the proposed antenna was designed and simulated to meet the operational requirements of the ESL system, which relies on LoRa communication at 923 MHz. ANSYS HFSS is specialized in the design and analysis of electromagnetic systems, providing accurate tools for simulating antenna performance. The software enables detailed analysis of electric and magnetic fields, return loss, and radiation patterns, helping to optimize the antenna for efficient operation and robust signal transmission.

In Fig. 6, we varied the antenna length (i). The results indicate that the antenna length is inversely proportional to its operating frequency, as predicted by formula (1). Specifically, when i increases from 7.3 mm to 13.3 mm, the central operating frequency shifts from approximately 958 MHz to 858 MHz. By adjusting this parameter, the antenna can be tuned to operate in various LoRaWAN frequency bands, such as EU868 and US/AU915.

In addition to modifying the antenna length, we also adjusted the distance between the feed and short pins (w_4). This parameter directly influences the antenna impedance. As shown in Fig. 7, varying w_4 from 1 mm to 2 mm allows fine-tuning of the impedance to achieve optimal performance. With $w_4 = 1.6$ mm, the antenna exhibits an optimal impedance of 46.7 Ω, indicating the best impedance matching at the desired operating frequency.

The final simulation results are shown in Fig.8 indicated that the return loss (S_{11}) at 923 MHz was less than -35 dB, with the -10 dB bandwidth of 15 MHz (from 915 Mhz to 930 Mhz). This ensures excellent energy transfer between

Table 1. Summary of performance evaluation of the considered LoRa antennas.

Ref	Technique	Frequency (MHz)	Substrate	Dielectric (ε_r)	Gain (dBi)	Size in mm
[21]	PIFA	848-950	FR4	4.4	2.1	40 x 26 x 1.7
[22]	MPA	868	FR4	4.3	2.11	120 x 70 x 2.4
[23]	MPA/Slot	924	Rogers	NA	2.6	98 x 98 x 1.29
[24]	MPA/Slot	868	FR4	4.4	1.6	80 x 55 x 0.8
[25]	PIFA	868	FR4	4.4	1.92	100 x 40 x 1.6
[28]	PIFA	868	FR4	4.7	-2.8	78 x 88 x 1.6
[26]	PIFA	868	FR4	4.3	3.36	300 x 30 x 0.8
This work	3D PIFA	923	FR4	4.4	3.78	28 x 7 x 8

the transmission line and the antenna, minimizing signal reflections.

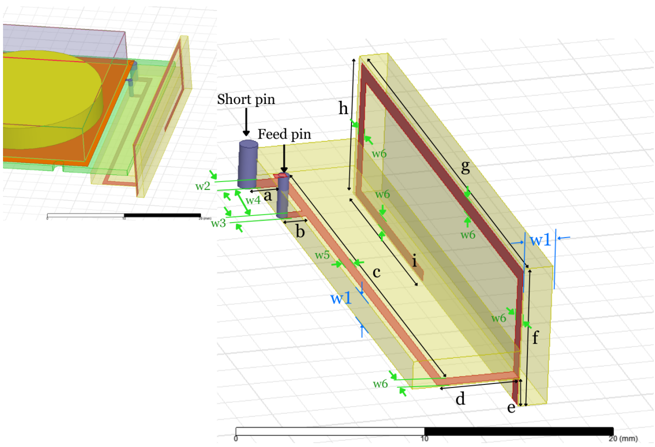

Figure 5. The proposed antenna structure.

Table 2. Key geometric parameters of the antenna.

Parameter	Value (mm)	Parameter	Value (mm)
a	1.83	h	7.7
b	1.25	w_1	1.6
c	26.55	w_2	1.0
d	4.6	w_3	0.65
e	1.6	w_4	1.6
f	7.8	w_5	0.5
g	27.45	w_6	0.8
i	10.3		

3.3. Software Design

The software design emphasizes energy efficiency and reliable communication, in accordance with the requirements of a LoRa-based Internet of Things (IoT) system. The device operates in Class A mode, facilitating event-driven communication to minimize power consumption. This

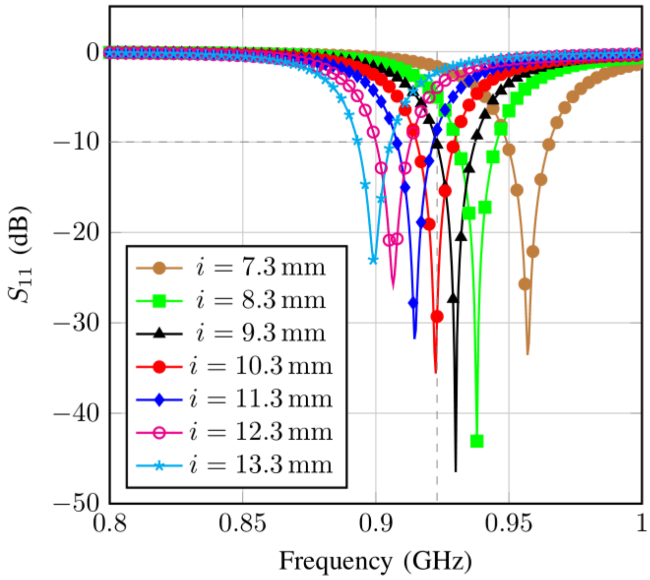

Figure 6. Simulation results for reflection coefficient under varying antenna length.

approach ensures that the device remains in a low-power state for the majority of its operational lifecycle, activating specific processes only as needed.

The device begins its operation in Sleep Mode, the default state, to conserve energy. A timer or external event triggers the device to wake up and transmit an uplink packet containing critical data, such as updated information, device status, and battery levels. The gateway processes uplink communication and, when necessary, transmits a downlink packet to the device for configuration updates or specific commands. Upon completion of the communication cycle, the device switches back to sleep mode. This state-based operation is critical to optimizing energy efficiency and ensuring robust communication reliability. Fig.9 presents the software flowchart, illustrating the logical transitions among

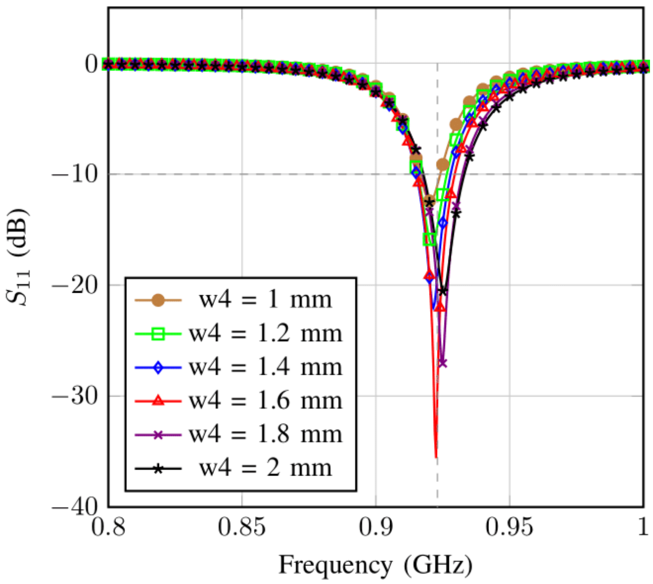

Figure 7. Simulation results for reflection coefficient under varying distance between feed and short pin.

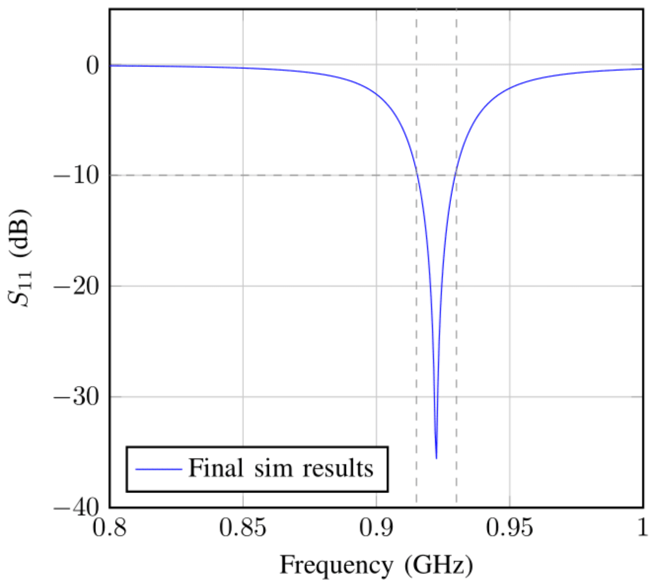

Figure 8. Simulated reflection coefficient of the proposed antenna.

sleep mode, uplink communication, data processing, and low-power mode. This structured state management is essential for maximizing battery life and ensuring reliable data exchange.

Secure and scalable communication is achieved through Over-The-Air Activation (OTAA) and encryption using an application key (AppKey). This approach ensures that all data transmitted between the device and The Things Network (TTN) are safeguarded against unauthorized access and tampering.

Real-time monitoring and remote management are enabled via the Losant IoT platform. This platform provides a

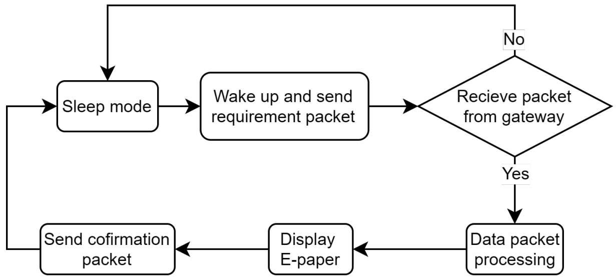

Figure 9. Flowchart illustrating the software's operational states and communication flow.

dashboard that displays critical metrics such as signal strength (RSSI), battery voltage, and device activity logs. This dashboard allows users to monitor device performance and interact with nodes in real time, facilitating the transmission of updates or commands directly to devices as necessary. The automation process within Losant, depicted in Fig. 10, illustrates the seamless integration of MQTT communication, data decoding, and conditional logic to optimize operations. This workflow highlights efficient data handling and automated responses to dynamic conditions within the IoT environment.

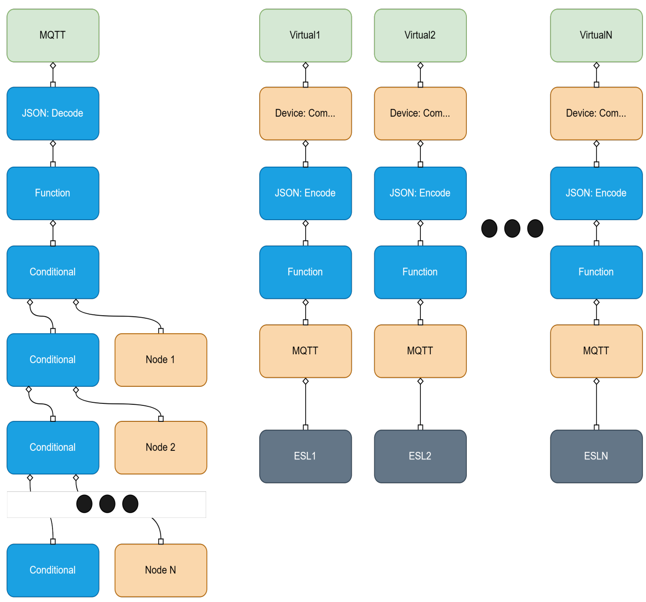

Figure 10. Losant workflow demonstrating MQTT communication, JSON decoding, and automation logic.

These visual aids provide an in-depth understanding of the logical structure and operation of the software. The design's focus on low power consumption, secure communication, and real-time functionality highlights its suitability for scalable IoT deployments.

4. Measurement Results and Discussions

4.1. Antenna Measurements

Following simulation, the designed antennas were fabricated and tested in a controlled environment to validate their performance. The antenna designs were carefully developed to meet the specific requirements for performance, size, and power efficiency of the ESL devices. The integration of simulation, material selection, and field testing ensured that the antennas delivered robust communication capabilities while seamlessly fitting into the overall system architecture. These designs not only optimized performance for the current application but also established a foundation for future iterations and applications of LoRa technology in IoT systems.

To assess the antenna performance for the ESL system operating within the LoRa 923 MHz band, a series of measurements were conducted. These measurements focused on key parameters such as S-parameters and radiation characteristics. The results will demonstrate that the antenna operates efficiently at 923 MHz, fulfilling the project's performance criteria for long-range, low-power communications. All measurements were performed using professional equipment within a controlled anechoic chamber environment to ensure the accuracy and reliability of the results.

To measure the S-parameter, we will use the NanoVNA Vector Network Analyzer to measure the S(11) value of the manufactured antenna. The measurement results are shown in Fig.11. With the results at 923 MHz, the antenna has the lowest reflection coefficient of -21.99 dB, and the -10 dB bandwidth is 15 MHz, which is similar to the simulation results in the Ansys HFSS software.

The setup for antenna testing, including the radiation characteristics, is illustrated in Fig. 12. The ESL device was positioned within an anechoic chamber, a specialized environment designed to eliminate external radio frequency interference and reflections. This configuration isolates the device, enabling precise measurement of the antenna's performance. The measurement results are presented in Fig. 13, which details the directivity, gain, and efficiency of the antenna. Within the –10 dB bandwidth of the antenna (915–930 MHz), the directivity ranges from 6.03 to 6.25 dBi, while the gain varies from 3.45 to 3.78 dBi. These values indicate that the antenna exhibits favorable directional characteristics and stable performance, particularly noteworthy given its compact size. Furthermore, the radiation efficiency ranges from –2.4 to –2.75 dB, suggesting that the antenna transmits signals effectively with minimal loss in the AS923 frequency band.

Fig. 14 illustrates the 3D radiation pattern of the antenna that was performed in the anechoic chamber. The pattern exhibits a quasi-omnidirectional shape, with strong radiation lobes distributed relatively evenly in multiple directions. This characteristic indicates that the antenna can effectively radiate signals across various orientations, allowing ESL devices equipped with this antenna to be positioned flexibly without the necessity for precise alignment. This versatility is particularly advantageous for large-scale deployments or complex environments.

Real-world testing of the antenna integrated into the ESL device confirmed stable connectivity to the LoRa gateway, thereby validating its suitability for deployment within the system. The measurement results, along with the relevant evaluations, are presented in Section 4.3.

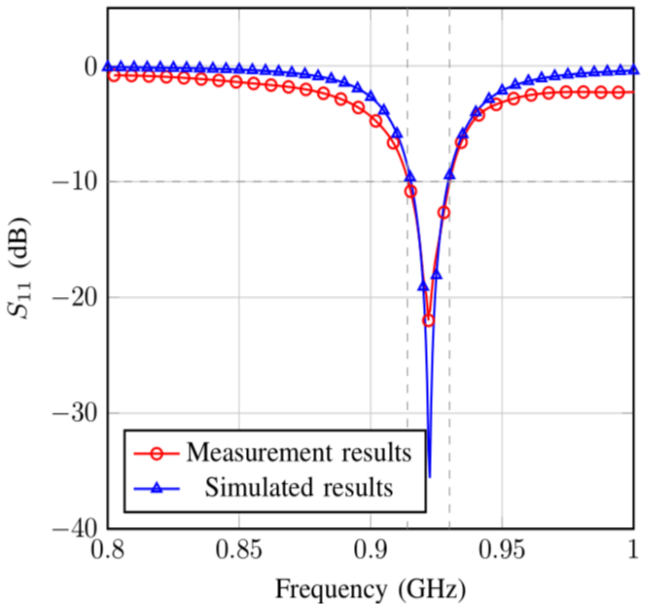

Figure 11. Measured reflection coefficient of the proposed antenna

Figure 12. Antenna measurement setup in anechoic chamber.

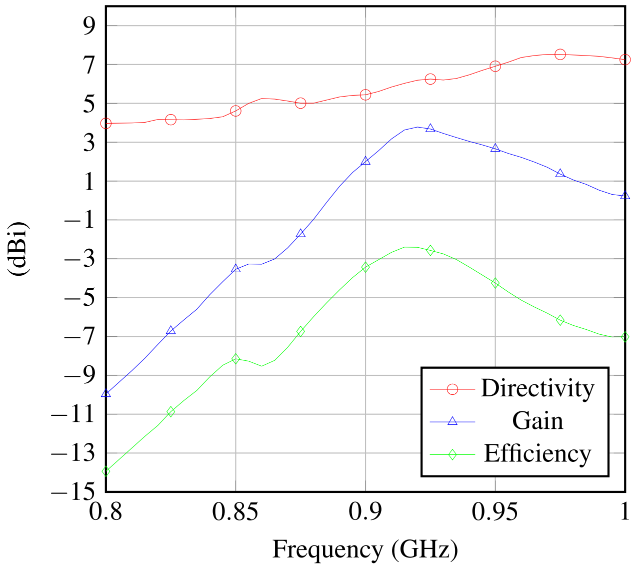

Figure 13. Antenna Performance Measurement: Directivity, Gain, and Efficiency

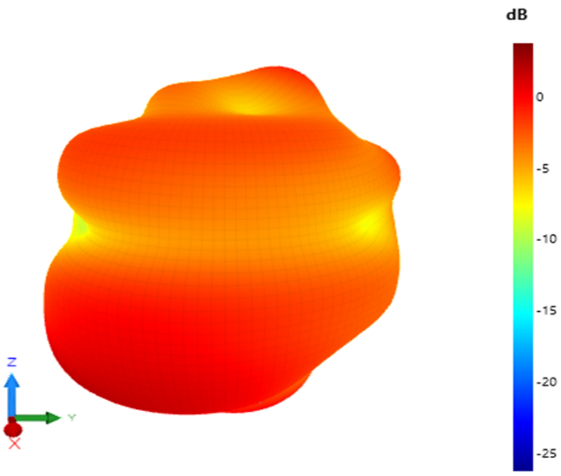

Figure 14. 3D Measured Radiation Pattern of the Antenna.

4.2. Circuit Measurement

Following the measurement of antenna parameters, the circuit's energy consumption was evaluated using the OTII ARC Power Analyzer. This instrument provided precise insights into the device's power draw across various operational states, including uplink, downlink, E-paper updates, and sleep mode. These measurements were essential for assessing whether the energy consumption objectives of the Electronic Shelf Label (ESL) system were achieved, particularly its target battery life of over 2 years with daily updates. The results of the ESL circuit test are illustrated in Fig.15, indicating an average current of 6.5 mA during typical operation and a sleep mode current of 6.25 µA. The energy measurements were analyzed under multiple conditions to estimate battery life and to understand the impact of various operating states.

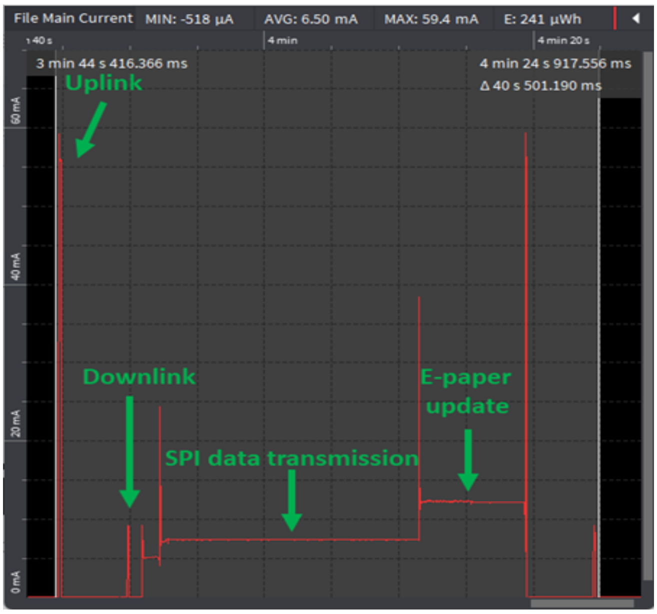

Figure 15. Battery Life Estimation for Different Update Frequencies

The energy consumption values of the Electronic Shelf Label (ESL) during specific operations — uplink, downlink, SPI data transmission, and E-paper updates — were systematically measured. Uplink transmission exhibited the highest energy consumption, peaking at 59.3 mA, while downlink operations averaged 5.0 mA. The SPI data transmission and E-paper update, which lasted approximately 28.5 seconds, consumed an average of 8.6 mA. Throughout this 40-second cycle, the average energy consumption was recorded at 6.5 mA, corresponding to a total of 241 µWh, with the device remaining in sleep mode for the remainder of the time, thereby exhibiting minimal power consumption.

Table 3 summarizes the energy consumption measurements of the Electronic Shelf Label (ESL) device developed during this research and provides a comparative analysis with the specifications outlined in the RAK3172 module's datasheet. Notably, the sleep current is slightly elevated, primarily due to the additional power consumption of components such as the Low Drop-Out (LDO) regulator and the E-Ink display, as illustrated in the hardware architecture shown in Fig.2.

Battery life was estimated using the Battery Life Estimator tool of the OTII Power Analyzer, as detailed in Fig. 16. The system is projected to achieve a lifespan of over six years with one daily update, although this lifespan decreases as the update frequency increases. These results indicate that the energy consumption of the ESL design is well-optimized, demonstrating performance efficiency that aligns closely with the project objectives. This comparison underscores the success of optimizing energy consumption within the constraints of system design.

Table 3. Energy Consumption for ESL System

Activity	Average Current	RAK3172
Sleep Mode	6.25 µA	1.69 µA
Uplink Transmission	47.3 mA (14 dBm)	39.1 mA (14 dBm)
Downlink Reception	5.0 mA	5.22 mA
E-paper Update	8.6 mA	N/A
Complete Update Cycle	6.5 mA	N/A

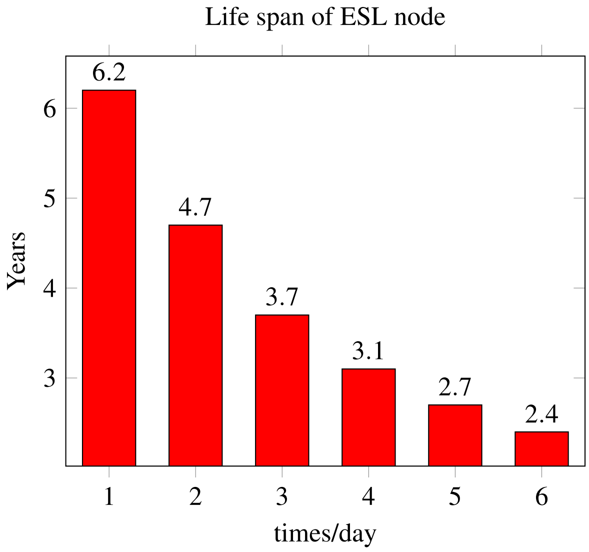

Figure 16. Battery Life Estimation for Different Update Frequencies

4.3. Communication Measurement

Communication measurements for the ESL system were conducted to evaluate the reliability and efficiency of data transmission over LoRa technology. This included an analysis of signal quality and packet transmission success rates during communication events. The measurements focused on key parameters such as signal strength, noise levels, and packet delivery rates, ensuring that the system met its intended design goals.

To carry out communication measurements, a test environment was established with 25 ESL nodes positioned under varying conditions, including indoor settings with obstacles and open-field scenarios. These nodes communicated with the RAK7240 gateway, operating at a frequency in the AS923 band and a transmission power of 14 dBm. The Adaptive Data Rate (ADR) functionality was enabled during testing to optimize communication performance based on environmental conditions. The gateway, centrally positioned, relayed messages between the nodes and The Things Network (TTN), which served as the network server.

The test setup included five distinct node groups (A, B, C, D, and E), strategically distributed at varying distances from the gateway. Fig.17 shows the placement of the node groups within the testing environment, while Fig.18 provides a detailed layout of the distances between the groups and the gateway. Groups A and C, located within 14 meters of the gateway, were closest, while Groups D and E were positioned further away at distances of 22-23 meters, introducing additional challenges such as obstructions.

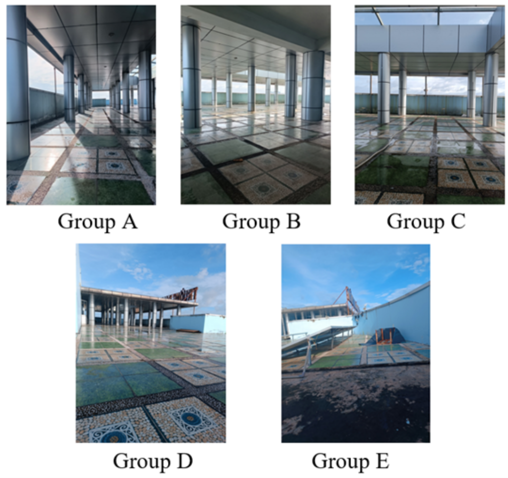

Figure 17. Views of the Node Groups.

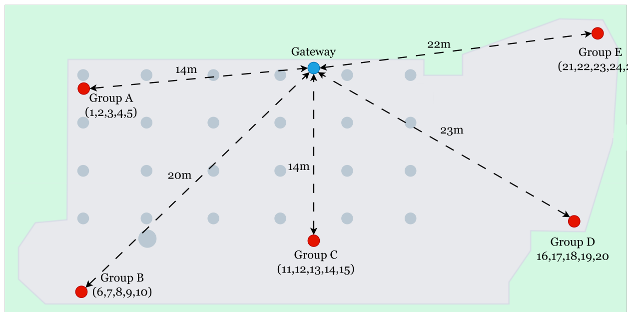

Figure 18. Layout of Node Groups and Distances from the Gateway.

The results of the measurements provided valuable insights into the communication capabilities of the system. The received signal strength indicator (RSSI) was recorded for all nodes, ranging from -70 dBm to -95 dBm in testing environments with physical obstructions. These values were well within acceptable ranges for LoRa communication, ensuring stable data transmission over distances of up to 23 meters indoors. The signal-to-noise ratio (SNR), another critical metric, averaged at 6.5 dB, indicating robust resistance to environmental noise and interference, even in challenging indoor conditions.

In terms of packet transmission, the ESL system demonstrated high reliability. The average packet delivery ratio (PDR) across all nodes was calculated at 96.46%, with a corresponding packet loss rate of 3.54%. The system's ability to maintain a consistent PDR, even under

Table 4. Packet Transmission and Loss Summary for Each Node

Group	Node ID	Packets Sent	Packets Received	Packets Lost	Packet Delivery Ratio (%)
A	1	2534	2451	83	96.72
	2	2564	2469	95	96.29
	3	2515	2425	90	96.42
	4	2533	2444	89	96.49
	5	2545	2457	88	96.54
B	6	2563	2470	93	96.37
	7	2569	2484	85	96.69
	8	2570	2481	89	96.54
	9	2519	2425	94	96.27
	10	2541	2452	89	96.50
C	11	2576	2477	99	96.16
	12	2535	2443	92	96.37
	13	2584	2495	89	96.56
	14	2574	2489	85	96.70
	15	2546	2458	88	96.54
D	16	2596	2507	89	96.57
	17	2584	2494	90	96.52
	18	2523	2435	88	96.51
	19	2542	2452	90	96.46
	20	2513	2424	89	96.46
E	21	2578	2489	89	96.55
	22	2514	2416	98	96.10
	23	2534	2449	85	96.65
	24	2572	2489	83	96.77
	25	2519	2412	107	95.75

obstruction conditions, highlights the effectiveness of the LoRa modulation technique and Adaptive Data Rate (ADR) in mitigating packet loss. A detailed summary of packet transmission and loss for each node is presented in Table 4.

Communication measurements underscore the feasibility of deploying the system in real-world scenarios. With reliable signal strength and minimal packet loss, the ESL nodes adequately meet the operational demands of smart retail environments. Although the observed packet delivery ratio (PDR) is within acceptable thresholds, further optimization can enhance system performance, particularly in more complex environments. Nevertheless, the measurements validate the design objectives and demonstrate the suitability of the ESL system for scalable and energy-efficient deployment.

5. Conclusion

The developed ESL system has successfully achieved its initial objectives, establishing a foundation for further research and development of efficient and scalable IoT solutions utilizing LoRa technology and E-paper displays. This work demonstrates the potential for integrating LoRa communication in practical applications, emphasizing its energy efficiency and reliability.

Future advancements are anticipated to enhance the performance and adaptability of ESL systems, thereby contributing to the broader adoption of LoRa technology and fostering innovation in smart retail. This progress will further advance the development of sustainable and intelligent technology ecosystems. Additionally, exploring energy harvesting from indoor light sources represents a promising avenue for extending the operational duration of ESL systems. This approach has the potential to significantly improve both the performance and sustainability of ESL implementations.

Acknowledgement. This research is funded by National Institute of Applied Mechanics and Informatics under grant number AMI.02/24-25.

References

[1] Atzori, L.; Iera, A.; Morabito,; G. (2010). The Internet of Things: A survey. Computer Networks, 54(15), 2787-2805.

[2] H. . Mroue, G. . Andrieux, E. . Motta Cruz, and G. . Rouyer, “Evaluation of LPWAN technology for Smart City”, EAI Endorsed Trans Smart Cities, vol. 2, no. 6, p. e3, Dec. 2017.

[3] Gubbi, J.; Buyya, R.; Marusic, S.; Palaniswami; M. (2013). Internet of Things (IoT): A vision, architectural elements, and future directions. Future Generation Computer Systems, 29(7), 1645-1660.

[4] K. Banakar and S. Shetty, “RapidNet IP: A synchronized, high throughput, low power wireless networking solution for ESL”, EAI Endorsed Trans Cloud Sys, vol. 5, no. 15, p. e2, Jul. 2019.

[5] M.A.A. Khan; X. Lian; I. Khan Mirani; L. Tan, "Research on Key Technologies of Electronic Shelf Labels Based on LoRa", Journal on Big Data, 2021. doi:10.32604/jbd.2021.016213

[6] J. -S. Park and B. -J. Jang, "Electronic shelf label system employing a visible light identification link," 2016 IEEE Radio and Wireless Symposium (RWS), Austin, TX, USA, 2016, pp. 219-222, doi: 10.1109/RWS.2016.7444409.

[7] Y. Kim, K. -H. Kim and W. -D. Cho, "Image Compression Using Chain Coding for Electronic Shelf Labels (ESL) Systems," in IEEE Access, vol. 9, pp. 8497-8511, 2021, doi: 10.1109/ACCESS.2021.3049868.

[8] X. Jin and G. Zhang, "Design and Realization of the electronic clock with E Ink screen," 2020 IEEE 4th Information Technology, Networking, Electronic and Automation Control Conference (ITNEC), Chongqing, China, 2020, pp. 2366-2369, doi: 10.1109/ITNEC48623.2020.9085017.

[9] H. -W. Tseng, H. Kao and C. -F. Kuo, "Adaptive Advertising Interval for Electronic Shelf Label System Based on Bluetooth Low Energy," in IEEE Sensors Journal, vol. 22, no. 12, pp. 12369-12385, 15 June15, 2022, doi: 10.1109/JSEN.2022.3172405.

[10] F. Zhang, "Design of electronic shelf label and bluetooth gateway based on electrophoretic display technology", Proc. SPIE 12250, International Symposium on Computer Applications and Information Systems (ISCAIS 2022), 1225017 (19 May 2022); https://doi.org/10.1117/12.2639700

[11] S. Shekhawat, "Decentralized Pricing on Mobile Phone-based ESLs," 2022 Sixth International Conference on I-SMAC (IoT in Social, Mobile, Analytics and Cloud) (I-SMAC), Dharan, Nepal, 2022, pp. 245-249, doi: 10.1109/I-SMAC55078.2022.9987339.

[12] Ying Wang and Yu Hu, "Design of electronic shelf label systems based on ZigBee," 2013 IEEE 4th International Conference on Software Engineering and Service Science, Beijing, 2013, pp. 415-418, doi: 10.1109/ICSESS.2013.6615337.

[13] Yanga, Runyu, Xuxiu Zhang, and Kaipu Caob. "Design of electronic shelf label and Zigbee gateway based on electrophoretic display technology." In Proceedings of the 2024 3rd International Conference on Artificial Intelligence, Internet and Digital Economy (ICAID 2024), vol. 11, p. 58. Springer Nature, 2024.

[14] Malak Abid Ali, Khan, Ma, Hongbin, Jin, Ying, Ma, Jingxiang, Rehman, Zia and Rahman, Mizanur. (2023). Analysis of LoRa for Electronic Shelf Labels Based on Distributed Machine Learning. 3229-3234. 10.23919/CCC58697.2023.10239831.

[15] A. Arnaud, M. Marioni, M. Ortiz, G. Vogel and M. R. Miguez, "LoRaWAN ESL for Food Retail and Logistics," in IEEE Journal on Emerging and Selected Topics in Circuits and Systems, vol. 11, no. 3, pp. 493-502, Sept. 2021, doi: 10.1109/JETCAS.2021.3101367.

[16] M. A. Jamshed, K. Ali, Q. H. Abbasi, M. A. Imran and M. Ur-Rehman, "Challenges, Applications, and Future of Wireless Sensors in Internet of Things: A Review," in IEEE Sensors Journal, vol. 22, no. 6, pp. 5482-5494, 15 March15, 2022, doi: 10.1109/JSEN.2022.3148128.

[17] A. Augustin, J. Yi, T. Clausen, and W. Townsley, “A study of LoRa: Long range & low power networks for the Internet of Things,” Sensors, vol. 16, no. 9, p. 1466, 2016.

[18] M. Miguez, M. Marioni, M. Ortiz, G. Vogel and A. Arnaud, "An IoT-based electronic price-tag for food retail," 2019 26th IEEE International Conference on Electronics, Circuits and Systems (ICECS), 2019, pp. 189-192, doi: 10.1109/ICECS46596.2019.8964686.

[19] Y. H. Tehrani, A. Amini and S. M. Atarodi, "A Tree-Structured LoRa Network for Energy Efficiency," in IEEE Internet of Things Journal, vol. 8, no. 7, pp. 6002-6011, 1 April1, 2021, doi: 10.1109/JIOT.2020.303414

[20] "RAK3172 | STM32WL | Module for LoRaWAN", RAKwireless Store, [online] Available: https://store.rakwireless.com/products/wisduo-lpwan-module-rak3172?variant=40014759297222.

[21] M. Tarbouch, A. Reha, A.E. Amri, Y. Mejdoub, A compact PIFA antenna for internet of things network LORAWAN at 900 Mhz band, in: Colloque sur les Objets et systèmes Connectés, IEEE, 2019.

[22] Dala, Aliyu, and Tughrul Arslan. "Design, implementation, and measurement procedure of underwater and water surface antenna for Lora communication." Sensors 21, no. 4 (2021): 1337.

[23] Putra, Naufal AH, Wahyudi Hasbi, Muhammad P. Manggala, Daffa U. Kusmara, Wiwit M. Putri, Raihan Triyogi, and Muhammad P. Wirakusuma. "Design of cubesat microstrip antenna with metamaterial structure for LoRa communication." In 2021 IEEE International Conference on Aerospace Electronics and Remote Sensing Technology (ICARES), pp. 1-5. IEEE, 2021.

[24] Haydhah, S.A., Ferrero, F., Lizzi, L., Sharawi, M.S. and Zerguine, A., 2021. A multifunctional compact pattern reconfigurable antenna with four radiation patterns for sub-GHz IoT applications. IEEE Open Journal of Antennas and Propagation, 2, pp.613-622.

[25] Reha, Abdelati, Mohamed Tarbouch, and Abdelkebir El Amri. "A dual band compact PIFA antenna for internet of things networks Sigfox, Lorawan And Zigbee." In Colloque sur les Objets et systèmes Connectés. 2019.

[26] Wang, Yibo, Luca Santamaria, Fabien Ferrero, and Leonardo Lizzi. "Design of a multi-antenna portable IoT terminal." In 2021 IEEE Conference on Antenna Measurements & Applications (CAMA), pp. 597-599. IEEE, 2021.

[27] Wang, Xiaoyan, Lei Xing, and Hailong Wang. "A wearable textile antenna for lora applications." In 2021 IEEE 4th International Conference on Electronic Information and Communication Technology (ICEICT), pp. 613-615. IEEE, 2021.

[28] Bouyedda, Abdellatif, Bruno Barelaud, and Laurent Gineste. "Design and realization of an UHF frequency reconfigurable antenna for hybrid connectivity LPWAN and LEO satellite networks." Sensors 21, no. 16 (2021): 5466.