



**POLITECNICO
DI TORINO**

POLITECNICO DI TORINO

Master Degree course in **Design of power and Analog Electronics**

Master Degree Thesis

Design and Implementation of Wireless Multimedia Sensor Nodes with Optimised Energy Consumption.

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Abstract

In this thesis, a highly robust and energy-efficient Wireless Multimedia Sensor Node (WMSN) with energy-efficient power control is presented. This device was developed to be used in remote and distributed IoT applications. The major problem that has been addressed is that the transmission of multimedia information wirelessly consumes a lot of power. To solve this, a **dual-radio hardware** platform is designed to be managed by an ESP32-S3 microcontroller (MCU).

ESP32-S3 can be easily used to implement simple image processing algorithms and operate pre-trained neural network models on board itself. The device consists of 45 GPIOs, four SPIs, and three UARTs interfaces, which are modular and can be used to connect various peripheral sensors and devices.

For routine telemetry and receiving configuration commands. **SX1262 LoraWAN transceiver** is implemented, which is programmed to act in **ultra-long-range, low-power mode** and operate in the sub-GHz spectrum (**150 MHz -960 MHz**) **globally**. The module offers up to **+22 dBm** drive and is paired with a purpose-designed **impedance-matched balun network to eliminate RF losses on board and provide stable RSSI and SNR for enabling long-distance communication**. A **SIM800C GSM** module for GPRS transmits the picture taken by **an ArduCAM 5 MP camera**. Uploading the high-resolution picture takes approximately 30 seconds. **Power Management ICs (PMICs)** to regulate high currents of the transient nature from the GPRS communication and to give stability to the supply voltage and the stability of the link. Also, the system monitors **the state-of-charge (SoC)** of its 3 V primary battery pack via analogue voltage sensing to the system to forecast power management.

In situations where there is a necessity to transfer data with a high bandwidth, a high-power subsystem is required. To guarantee long life for months, a power-gating network that is controlled with MOSFETs, fully disconnecting when an idle state of inactive peripherals (**LoRa, GSM, and camera**) is detected. It offers the ESP32-S3 the lowest power consumption of around 22 μA in such a mode of deep-sleep. The PCB is also embedded with a USB Type-C connector and can therefore be easily programmed and deployed.

It is worth noting that the hardware platform, which is presented, can be pin-to-pin compatible with the **A7682E LTE Cat-1 bis** module to provide a simpler 4G upgrade path in the future. This will ensure the scalability of the long-term and network continuity as the 2G networks are being phased away and can easily transition to the LTE-based IoT infrastructure without redesigning hardware.

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Chapter 1

Introduction

1.1 Internet of Things (IoT) Background

The Internet of Things (IoT) is a computing paradigm that shifts the focus from Traditional human-centred interaction to the fullest by incorporating formerly physical objects into a cohesive digital system. At its essence, the IoT is characterised by a network of devices commonly referred to as things, which are equipped with sensors, software, and additional technologies to gather and transmit data over the internet. This worldwide infrastructure makes the merging of the physical world with computerised systems an immediate fact.

The huge size of IoT is motivated by three major elements:

1. Sensing Layer: The sensor layer contains smart sensors and actuators that measure scalar environmental data (temperature, pressure, humidity) or physical events (motion, position). It is based on Wireless Sensor Networks (WSNs) that allow distributed and autonomous data gathering.
2. Network Layer: This layer provides the communication infrastructure, including various technologies, such as short-range (Wi-Fi, Bluetooth) and wide-area protocols (LoRaWAN, cellular), that are necessary to direct the vast amount of acquired data.
3. Application Layer: This layer processes the raw data, implements intelligence and analytics, and delivers actionable information to the end-users in a variety of domains, such as smart cities, industrial control, and precision agriculture.

1.1.1 Background of the Internet of Things (IoT)

With the introduction of the **Internet of Things (IoT)**, the interaction between Humans and the physical world have taken an entirely new form. IoT allows one to monitor, automate, and make smart decisions in virtually any field of human activity through the interconnection of ordinary objects, machines, and sensors via the Internet [1]. The result of this technological transformation helps to gather and process real-time information on

remote and inaccessible areas changing the way industries handle their resources and streamline their performance. [16].

The integration of IoT has significantly benefited the **Energy and utilities sector** where smart metering systems have been used to gather data on the level of electricity, gas and water consumption in real-time. These systems enable the consumer and the service providers to become more efficient and reduce wastage and also use dynamic pricing models depending on the actual usage trends. IoT-based weather stations and soil-monitoring networks find application in the sphere of **environmental monitoring and agriculture** to measure temperature, humidity, and moisture levels in the vast regions. With these streams of data, it is possible to practice precision agriculture, which assists with automated irrigation, fertiliser control, and early identification of the environmental stress factors. **Smart city development** is another important application of IoT technologies. Truly reactive traffic lights that react to the current congestion and smart street lighting systems that regulate the brightness depending on the number of people on the street help to create a considerable improvement in the domain of energy conservation and better urban performance [11]. Furthermore, wearable sensors and remote monitoring devices can be used in the field of **healthcare** to constantly monitor vital parameters like heart rate, oxygen saturation, and activity level. These systems enable early diagnosis and constant monitoring of the patient without necessarily having to visit a hospital frequently. In industries, IoT systems have become the Industrial Internet of Things (IIoT) with sensor networks being employed to measure the health status of machinery, anticipate equipment breakages, and streamline production procedures [15].

All of these examples presented in Figure 1.1 explain how IoT technologies can combine sensing, connectivity, and data analytics to produce smarter and more efficient systems. IoT has remained at the forefront of the further evolution of automation, sustainability, and informed decision-making across various areas by bridging the gap between the digital and the physical world.

1.2 Multimedia in IoT: Limitations and Trade-offs

Wireless Sensor Networks (WSNs) have become a component of the contemporary IoT and are commonly deployed in such areas as agriculture, environmental monitoring, smart cities, industrial automation, and critical mission systems

The traditional networks are mostly used to communicate scalar information like temperature, humidity or pressure data that do not demand high bandwidth and allow long-time and low-power operation

However, this has caused a growing demand on the richness of context information and thus the emergence of **Wireless Multimedia Sensor Networks (WMSNs)**. Such enhanced sensor nodes incorporate cameras and microphones, which are both important for auditory and visual perception. They can be used in applications like precision agriculture, security surveillance, and disaster evaluation, in which real-time visual confirmation gives more sense than mere numerical limits

Although this development is crucial to making situational awareness much easier, it also brings about a central design problem called the **energy-bandwidth trade-off**.



Figure 1.1. Typical application domains of Wireless Sensor Networks (WSNs), including precision agriculture, smart infrastructure, industrial automation, and critical mission environments. These examples illustrate the diversity and impact of WSN technology as a vital component of modern IoT systems.

High Bandwidth Requirements The transmission capacity of multimedia data, especially images and video is much higher than the traditional scalar sensor values. Such large data streams between the wireless links like GPRS or LTE require high throughput that directly adds to power consumption..

Severe Energy Constraints Multimedia sensor nodes in most of the field applications are independent in remote settings and are powered by batteries alone. Constant use of the camera and high bandwidth radio interface soon ends the available energy leaving the node with operational life lasting only days or weeks.

This thesis attempts to solve this issue by suggesting a **Wireless Multimedia Sensor Node (WMSN)** architecture which is efficient in balancing the trade off between data richness and energy longevity. The presented system also shows that it is possible to

have reliable and high-definition multimedia acquisition and transmission even in case of extreme power and bandwidth limitations, which makes it applicable in the large-scale, long-term field deployment.

1.3 Subject of the Thesis

The study is based on the creation of a new **architecture of Wireless Multimedia Sensor Node (WMSN)** which critically addresses the energy-bandwidth trade-off. This thesis focuses on the design, implementation and validation of a **modular, dual-radio WMSN** that is specifically designed to offer visual measurements, that is, high-definition, leaf-level imagery, to support early disease detection and phenology monitoring. On the high level, the project solution is based on the decoupling of the communication functions, i.e. a low-power radio keeps the status of ultra-low duty-cycle and accepts external commands. On the contrary, the powerful camera and transmission radio (GPRS) are only powered on as needed. This command triggered protocol makes sure that power-consuming operations are performed as little as possible, maximizing battery life without reducing the quality or timeliness of the needed multimedia data.

1.3.1 Evolution of Wireless Multimedia Sensor Networks

Background and Motivation

WSNs were firstly developed in the early 2000s to perform low-datarate monitoring functions like temperature, humidity, vibration, and light intensity) [3]. The networks were structured on energy efficient scalar sensing networks and low power communication protocols such as IEEE 802.15.4 and ZigBee. They had low data rates (under 250 kbps) and few nodes that were well adapted to environmental and industrial telemetry, but poorly to visual or acoustic data streams.

As CMOS image sensors became miniaturised at a very fast rate and along with the development of low-power embedded processors, another type of sensing systems developed, the Wireless Multimedia Sensor Networks (WMSNs) [2]. WMSNs are the extensions of WSNs that use multimedia which includes data acquiring, processing, and transmission features, allowing the visual sensing, audio capture, and even video streaming in distributed sensor networks. The increasing need in the applications like monitoring of the environment, environmental surveillance, industrialized agriculture, and precision agriculture are the main reasons towards this evolution.

Technological Milestones

Several key technological advancements have contributed to the emergence of WMSNs:

- **Low-power imaging:** Milliwatt-level power consumption of compact and energy-efficient CMOS sensors introduced towards the end of the 1990s and the beginning of the 2000s made it possible to capture still images and short sequences of video at milliwatt-level power levels [10]. On-board visual sensing was also possible in

embedded platforms with the further miniaturisation of imaging modules like the ArduCAM and OV2640.

- **Embedded vision processors:** With the advancement and development of low-cost microcontrollers and SoCs integrated with the DSP and AI acceleration—such as the ARM Cortex-M7, ESP32-S3, and NVIDIA Jetson Nano, many applications like basic image compression, feature extraction, and object detection become easy to perform at the node level [17]. These developments extremely decreased the bandwidth considerations and latency in image perceiving equipment.
- **Energy-efficient communication:** With the development of low-power wide-area network (LPWAN) schemes like LoRa and NB-IoT, long-range multimedia telemetry over the ultra-low power level became available, expanding the range of issues of WMSN use outside narrow, short-range Wi-Fi or ZigBee [9].

Current Trends

Modern WMSNs are built on embedded machine learning (TinyML) to provide in-node visual analytics, which is often sent semantically (i.e. object counts or events) rather than uncoded images. This technique greatly decreases the load of the network and still retain contextual awareness. Consequently, recent architectures such as the IxemCam platform include low-power microcontrollers, LoRaWAN connectivity and onboard imaging, which is a convergence of historic WSN efficiency and the perceptual richness of multimedia sensing.

Summary

The development of the WSNs into the WMSNs indicates the unremitting insistence on context-aware, power saving, and intelligent sensing. Low-power imaging, embedded AI and low-power wireless networking has created interactive-perceptual systems, with visual and acoustic sense, in place of traditional, fixed-point monitoring networks, to support a new evolution of applications in smart cities, precision agriculture, and autonomous systems.

1.4 Thesis Structure

The remainder of this thesis is organised as follows:

- **Chapter 2: State of the Art** offers a comprehensive analogy of the available **Wireless Sensor Networks (WSNs)** and the technologies that form the Internet of Things (IoT). It examines the history of low-power communication systems including **LoRa, GSM and LTE** systems and newer **Low-Power Wide-Area Network (LPWAN)** frameworks. Additional parts examine the concepts of LoRaWAN architecture and device classes, the projections in Time characteristics in GSM, and the activation approaches in **The Things Network (TTN)** platform. At the end of the chapter, a differentiated evaluation of the current branch of

power management in an embedded IoT platform is provided in the form of battery-powered and energy-harvesting solutions.

- **Chapter 3: System Design** defines the complete design framework of the proposed **Wireless Multimedia Sensor Node (WMSN)**. It presents the hardware architecture, including key subsystems such as the **ESP32-S3 microcontroller**, **SX1262 LoRa transceiver**, **SIM800C GSM modem**, **ArduCam image sensor**, and the supporting **power regulation and switching circuits**. The chapter also elaborates on the **hardware–firmware interface mapping**, showing GPIO allocations and control logic for peripheral synchronisation. Design considerations related to electromagnetic interference (EMI), thermal behaviour, and antenna layout are discussed in detail.
- **Chapter 4: Implementation and Development** describes the actualisation of the proposed node. It includes the **design and selection of components**, the **schematic and layout design rules**, and techniques for **grounding, decoupling, and RF impedance control**. The chapter also outlines the firmware implementation, including **power-domain management**, **duty-cycling logic**, and **AT-command handling** for modem communication. Subsections explain the **USB-to-UART interface** used for programming and debugging, **firmware-controlled sleep modes**, and the **integration of LoRaWAN with GSM uplink paths**. Provisions for **4G LTE (A7682E) upgrade readiness** and **debugging methodologies** are also included.
- **Chapter 5: Testing, Results, and Performance Evaluation** presents the results of functional, electrical, and network-level testing. It begins with subsystem validation and continues with **LoRaWAN join performance**, **RSSI/SNR analysis**, and **packet success rate (PSR)** measurements conducted through **The Things Network (TTN)**. The GSM data upload performance is benchmarked using real-world upload tests over GPRS. Additional analyses include **power consumption profiling**, **daily energy budget estimation**, and **battery life projection**. The chapter concludes with a comparative evaluation of similar WMSN architectures and a detailed **upgrade feasibility study** demonstrating migration from 2G to 4G connectivity.
- **Chapter 6: Conclusion and Future Work** summarises the outcomes and contributions of the research. It discusses how the proposed node successfully achieves an **energy–bandwidth trade-off** through a hybrid LoRa–GSM architecture. The limitations of the current prototype, including dependence on 2G and the lack of integrated energy harvesting, are acknowledged. Recommendations are provided for **4G LTE migration**, **solar-assisted energy harvesting**, and the integration of **Edge-AI for smart triggering**. The final remarks highlight the system’s applicability in long-term remote monitoring applications such as precision agriculture and environmental sensing.

Chapter 2

State of the Art

This chapter reviews the current technological landscape relevant to the proposed system, identifying gaps and justifying the design choices made in the project.

2.1 IoT and Wireless Sensor Networks (WSN)

The **Internet of Things (IoT)** has become a pervasive paradigm that integrates everyday physical objects into the Internet so that they can sense, communicate, and exchange information autonomously. A key enabling technology for IoT is the **Wireless Sensor Network (WSN)**, which provides large-scale, distributed environmental intelligence through spatially distributed sensing and communication.

A WSN consists of many small, inexpensive, and low-power sensor nodes that integrate sensing, processing, and wireless communication capabilities. These nodes collaborate to measure physical or environmental quantities such as temperature, humidity, vibration, light, or sound and relay the collected data to a central gateway, where it can be aggregated and analysed.

In contrast to traditional wired or infrastructure-based systems, WSNs are *self-organising*. They can be deployed in large numbers over extensive regions and can automatically form dynamic network topologies that adapt to environmental changes or node failures. This makes WSNs particularly suitable for scenarios in which wired infrastructure would be impractical or prohibitively expensive to install and maintain.

The inherent constraints of sensor nodes—limited energy, processing power, and memory—are mitigated by their ability to act collectively. Through scalable and resilient data acquisition, WSNs can cover large areas and provide real-time information that supports data-driven decision-making.

Today, WSNs form the backbone of numerous IoT applications, including precision agriculture, environmental monitoring, smart infrastructure, industrial automation, disaster management, and military surveillance, fundamentally changing how we sense and interact with the physical world [22].

2.2 Review of Communication Technologies

Wireless communication is a fundamental constraint on the performance of any Wireless Multimedia Sensor Network (WMSN). The chosen communication technology determines the data rate, range, and, most critically, energy consumption. To monitor systems or processes in remote locations, the network must support both sustained, ultra-low-power command reception and occasional, high-bandwidth image transmission. In this section, relevant communication standards are reviewed and classified according to their main performance trade-offs, with a summary reported in Table 2.1.

2.2.1 Low-Power, Short-Range Technologies (LPSRT)

These protocols are designed for energy efficiency and short-range communication, often forming dense local networks. While they are well suited to scalar data transmission, they generally lack the capacity for multimedia transfer.

- **Wi-Fi (IEEE 802.11):** Provides high throughput (54–150 Mbps) suitable for live video transmission, but with very high power consumption and a limited range (tens of metres). Its power profile makes it unsuitable for battery-powered, long-term remote deployments.
- **Bluetooth Low Energy (BLE):** Designed for ultra-low power consumption and small data exchanges over short distances (typically up to 100 m). The effective data rate (usually less than 1 Mbps in practice) is too low for reliable transfer of high-resolution image files.
- **ZigBee (IEEE 802.15.4):** A widely used standard for mesh-networked WSNs. It offers very low power consumption and long battery life but is limited to data rates of 250 kbps or less, making it unsuitable for timely transmission of large image files.
- **6LoWPAN:** An adaptation layer that enables the transport of IPv6 over low-power, lossy networks (such as ZigBee or BLE). It primarily addresses network-layer interoperability rather than the multimedia throughput challenge and is typically used for scalar sensor data.

2.2.2 Low-Power, Wide-Area Network (LPWAN) Technologies

Low-Power Wide-Area Networks (LPWANs) are a class of wireless communication technologies designed to enable long-range connectivity with extremely low energy consumption. Unlike conventional short-range protocols (e.g., Wi-Fi or Bluetooth), LPWANs are optimised for low-data-rate applications that transmit small packets of information over distances of several kilometres. These technologies typically operate in the unlicensed Industrial, Scientific, and Medical (ISM) sub-GHz bands, offering link budgets exceeding 150 dB and supporting multi-year battery lifetimes for distributed sensor nodes [23].

LPWAN solutions provide extensive coverage and exceptional device longevity at the cost of limited throughput. They are particularly suitable for control, monitoring, and

Table 2.1. Summary of the characteristics of existing communication systems compared with the proposed device [39].

Technology	Key Advantages	Limitations
ZigBee/6LoWPAN	Low power	Not suitable for multimedia data transmission
LoRa/Sigfox	Wide coverage and ultra-low power	Low data rates, not suitable for multimedia data transmission
GPRS	Extensive coverage in rural areas	High energy consumption
BLE/Wi-Fi	High data rate	Requires a dense receiver network, unsuitable for outdoor deployment
Proposed Device	Low power, high data rate	Requires GPRS coverage

telemetry use cases, but not for frequent, high-volume file transfers or high-bandwidth multimedia streaming. In smart agriculture, environmental sensing, and infrastructure monitoring, LPWANs enable widely spaced sensors that can reliably transmit scalar or event-based data while maintaining low power consumption and energy autonomy.

- **LoRa/LoRaWAN:** LoRa (Long Range) is a proprietary physical-layer modulation technique based on Chirp Spread Spectrum (CSS), while LoRaWAN defines the open network protocol that operates on top of it. This technology supports communication ranges of up to 15 km in rural areas and several kilometres in urban environments, with ultra-low power consumption that enables years of operation on small batteries. However, regional duty-cycle restrictions (typically 1%) and limited data rates (from 0.3 kbps to 50 kbps) make LoRaWAN ideal for transmitting small control messages, telemetry packets, and sensor readings. For larger payloads such as images, supplementary high-power interfaces (e.g., GSM or LTE) are required for timely data delivery.
- **Sigfox:** An LPWAN standard providing global coverage using ultra-narrowband modulation. Sigfox offers very low data rates (approximately 100 bps) and short payloads but benefits from a cloud-managed infrastructure and extremely low energy requirements. It is particularly effective for infrequent, small data transmissions in large-scale deployments.
- **NB-IoT and LTE-M:** Cellular LPWAN technologies standardised by 3GPP and operating in licensed spectrum bands. They provide higher reliability and increased data rates (up to 250 kbps) compared with LoRa and Sigfox, at the cost of higher module complexity and greater power consumption.

Figure 2.1 illustrates the general structure of a LoRaWAN network. The end devices (or nodes) communicate wirelessly with gateways, which forward packets to a central network server. The server filters, processes, and routes the data to the corresponding application server in the cloud. This layered topology enables LoRaWAN to achieve high

scalability, bidirectional communication, and extremely low energy consumption on the device side.

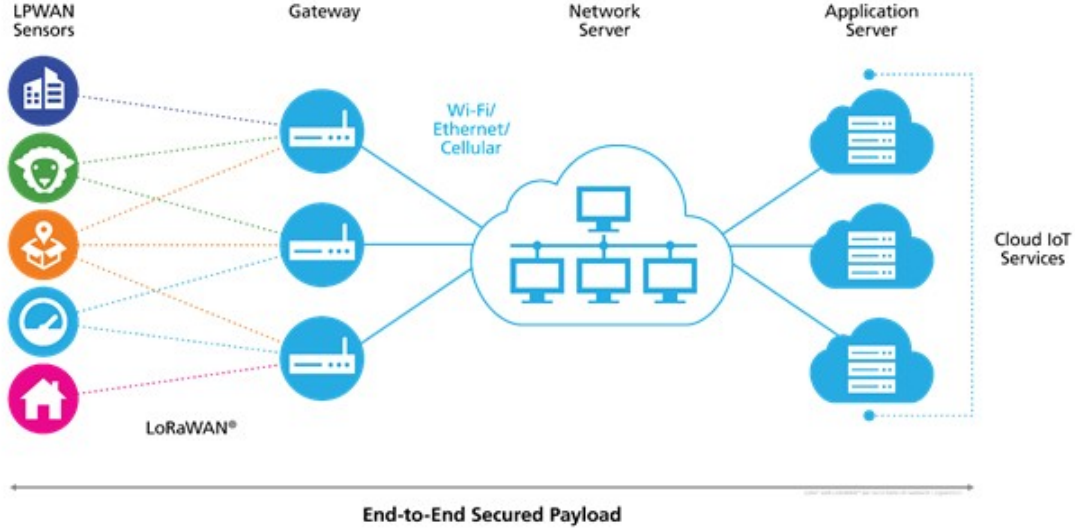


Figure 2.1. Typical architecture of a **LoRaWAN network**, showing the data path from low-power, wide-area sensors (e.g., the developed WMSN node) through a gateway, network server, and application server to cloud IoT services.

2.2.3 LoRaWAN Architecture and Device Classes

LoRaWAN end devices communicate with the network in an asynchronous, event-driven manner. After each uplink, a device may listen for downlinks in predefined receive windows whose timing depends on its operational class. The timing relationships for these communication windows are illustrated in Figures 2.2–2.4. The LoRaWAN protocol is defined by the LoRa Alliance [18], while practical class behaviour is described by The Things Network documentation [38].

Class A (Lowest Power) As shown in Figure 2.2, Class A is the fundamental and mandatory device class in LoRaWAN. The device opens two short receive windows, RX1 and RX2, after each uplink transmission. RX1 typically opens one second after the transmission ends, and RX2 opens one second later. If no downlink is received in either window, the node returns to sleep mode. Because the radio remains active only for these brief, predictable periods, Class A offers the lowest possible power consumption. Communication in this class is entirely uplink-initiated, making it well-suited to battery-powered nodes that transmit data periodically, such as environmental monitoring sensors.

Class B (Scheduled Down links) Figure 2.3 illustrates the operation of Class B devices. These devices extend Class A functionality by introducing additional receive

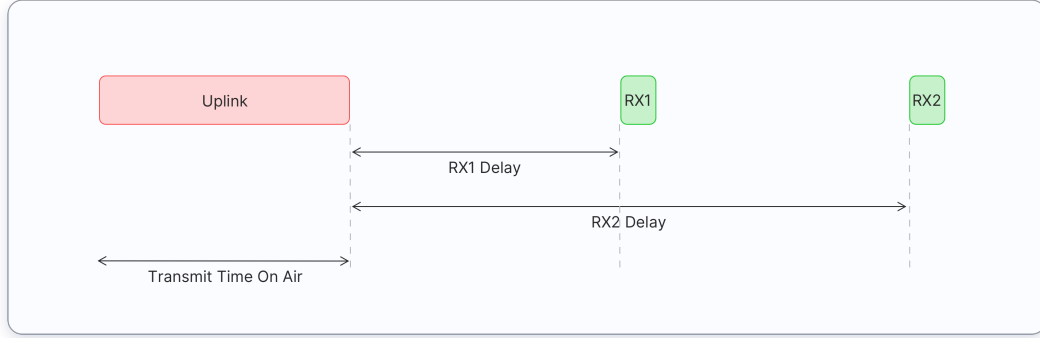


Figure 2.2. LoRaWAN Class A timing: two receive windows (RX1, RX2) follow each uplink transmission, after which the device returns to sleep [38].

windows called *ping slots*, which open at scheduled intervals synchronized with periodic beacons transmitted by the gateway. This synchronization allows the network to initiate down-links at predictable times, reducing latency compared with Class A, at the cost of higher energy consumption. The beacon synchronization ensures that all nodes share a common time base for deterministic communication.

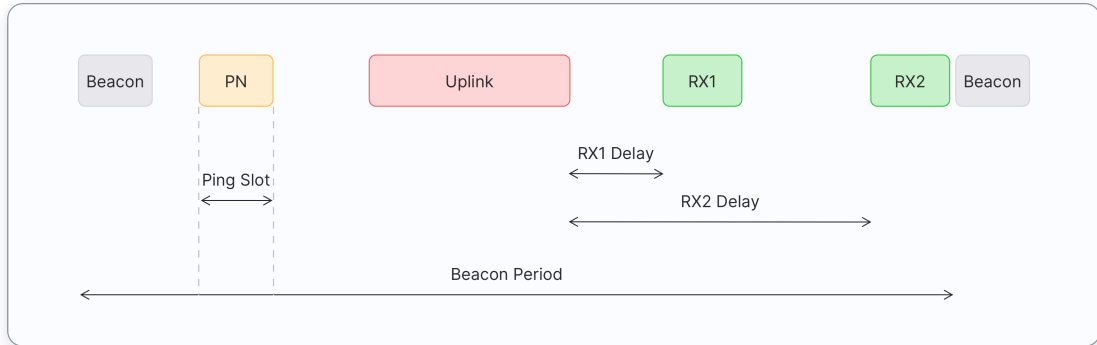


Figure 2.3. LoRaWAN Class B timing: periodic beacon synchronization enables scheduled ping slots for down-links, trading higher energy consumption for lower latency [38].

Class C (Always Listening) As depicted in Figure 2.4, Class C devices keep their receiver open almost continuously, except during uplink transmission. This configuration provides minimal downlink latency, as the gateway can send data to the node at any moment. However, since the receiver is constantly active, power consumption is significantly higher than for Classes A or B. Class C devices are therefore intended for mains-powered or frequently charged applications, such as actuators or stationary industrial controllers.

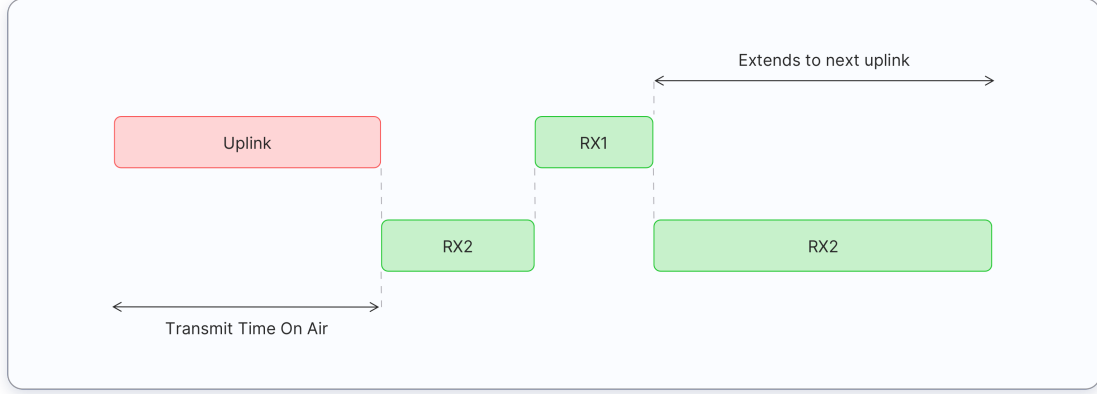


Figure 2.4. LoRaWAN Class C timing: the receiver remains open nearly continuously, enabling immediate downlink communication at the expense of energy efficiency [38].

Design Choice: Class A Implementation Among the three LoRaWAN classes, there exists a clear trade-off between power consumption and downlink latency. In this thesis, the Wireless Multimedia Sensor Node (WMSN) is implemented as a **Class A device**. This mode ensures maximum energy efficiency while maintaining reliable downlink capability for control commands, aligning with the system’s objective of achieving long-term, battery-powered autonomous operation in remote environments.

2.2.4 High-Power, Wide-Area Cellular Technologies (HPC)

These technologies provide the required range and bandwidth for multimedia data, but their power consumption is a bottleneck for the longevity of WMSNs.

- **GSM (2G) / GPRS:** Global System for Mobile Communications (GSM) and its packet-based extension GPRS offer good coverage, especially in rural areas where newer networks may not yet be available. GPRS provides sufficient data rates for modest image transmission (tens of kilobits per second) and can be more energy efficient than 3G/4G/5G for short, intermittent sessions, making it a viable option for battery-constrained rural deployments.
- **LTE (4G) and 5G:** These standards provide very high data rates (> 10 Mbps) and low latency, making them ideal for real-time video streaming and interactive services. However, their modem initialisation and transmission power draw are generally higher than those of GPRS, which undermines long-term battery operation in remote sensor nodes.

Synthesis and Dual-Radio Justification The review confirms a fundamental communication gap in remote WMSN deployments: (1) Ultra-low-power technologies (LoRa,

ZigBee) provide the required longevity but lack the bandwidth for image files. (2) High-bandwidth technologies (GPRS, LTE, Wi-Fi) provide the required throughput but incur unacceptable power drain for battery-powered nodes.

This thesis addresses this gap by proposing a **dual-radio architecture** that strategically combines the strengths of two distinct technologies: a **Low-Power Interface (LPI)** based on LoRaWAN for continuous, ultra-low-power command reception, and a **High-Power Interface (HPI)** using GPRS, activated only for short, high-bandwidth image transmissions. This decoupling is the central innovation that enables both reliable command-and-control functionality and extended operational lifetime.

2.3 LoRaWAN and GSM Transmission Timing Comparison

A series of timing measurements was conducted to characterise the latency and responsiveness of both communication subsystems under realistic network conditions.

For the GSM (SIM800C) modem, the connection-establishment and data-transmission phase was measured by starting an internal timer at the **AT+CIPSTART** initiation command and stopping it once the GPRS connection was successfully established and the payload acknowledged. Across multiple tests and varying signal conditions, an average initialisation time of approximately **25 seconds** was recorded.

In contrast, the LoRaWAN Class A end-node follows the timing scheme shown in Figure 2.5. After transmitting an uplink payload of 4 bytes, which occupies approximately **827 ms**, the node waits for 1 second before opening the first receive window lasting about **164 ms**. If no downlink is detected, a second receive window is opened after another 1-second delay, with the same duration. This results in a complete uplink cycle of roughly **2.2 seconds**, significantly faster than the GSM equivalent [39].

The time required to receive a minimal 2-byte command, therefore, differs substantially between the two systems, with the GSM link being more than an order of magnitude slower than the LoRaWAN transmission cycle. This latency contrast reinforces the system’s dual-radio design choice: LoRaWAN is used for low-power, responsive telemetry and command reception, while GSM is reserved for high-bandwidth multimedia data transfer, ensuring both responsiveness and energy efficiency.

Values were cross-verified from the Semtech SX1262 datasheet [26] and the SIMCom SIM800C hardware design guide [29]. The results clearly demonstrate the complementary nature of LoRaWAN and GSM: the former provides long-range, low-power connectivity suitable for periodic telemetry, while the latter enables burst-mode, high-bandwidth transmission required for multimedia data.

2.3.1 LoRaWAN Security and Activation Techniques

LoRaWAN incorporates security mechanisms to ensure confidentiality, authentication, and controlled device access. It provides end-to-end security through both network- and application-level encryption using the Advanced Encryption Standard (AES-128) [19]. All end devices participating in the network must be authenticated and provisioned with

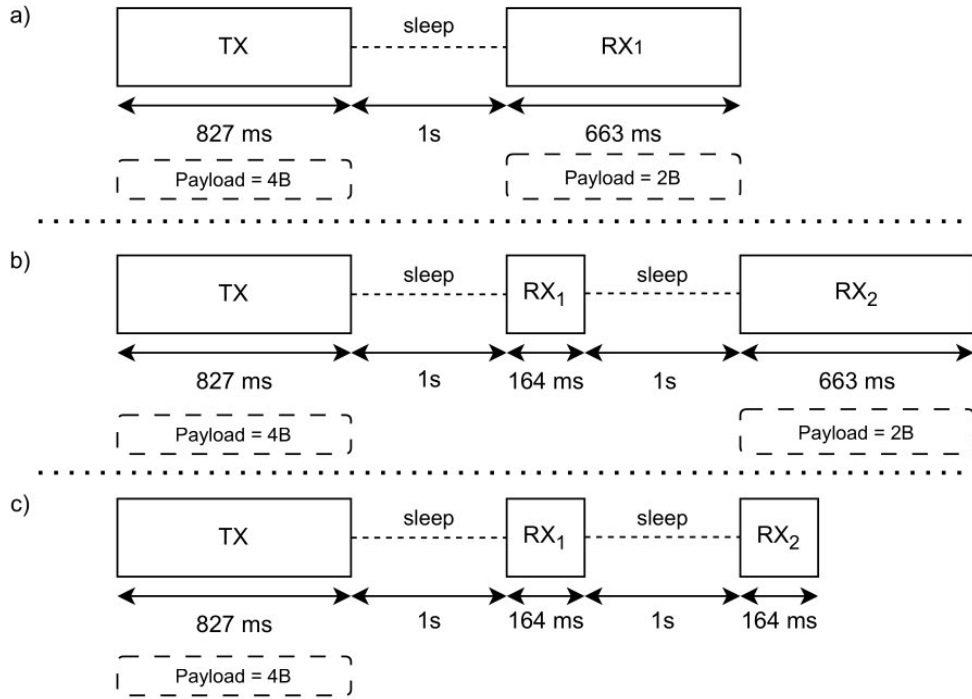


Figure 2.5. Timing sequence of a LoRaWAN Class A end-node operating at Spreading Factor 12 with coding rate 4/5. (a) Downlink received in the first available window; (b) Downlink received in the second available window; (c) No downlink received.

Table 2.2. Comparison of transmission characteristics: LoRaWAN vs. GSM (SIM800C).

Parameter	LoRaWAN (SX1262)	GSM (SIM800C)
Communication Type	Low-power wide area (LPWAN)	Cellular (2G GPRS)
Transmission Power	20 dBm (max)	33 dBm (Class 4)
Average Payload Size	4–8 bytes (telemetry)	50–500 kB (image or data burst)
Typical Data Rate	0.3–50 kbps	85–120 kbps
Average Uplink Duration	~2.2 s	~25 s
Typical Sleep Current	< 30 μ A	~24 mA (idle registered)
Peak TX Current	43 mA	2 A (burst)
Average Energy per Uplink	~0.15 mWh	~12 mWh
Range (Rural LOS)	Up to 10–15 km	1–3 km (depending on cell tower)
Link Reliability	High (with duty-cycle limit)	Medium (depends on network load)
Suitability	Low-bandwidth telemetry	High-volume image upload

cryptographic session keys prior to communication. The protocol defines two activation modes for key provisioning and device joining: **Over-the-Air Activation (OTAA)** and **Activation by Personalisation (ABP)**.

In **OTAA**, a device initiates a secure join procedure by transmitting a join-request message containing its **DevEUI**, **AppEUI**, and a random nonce. The network server responds with a join-accept message that includes dynamically generated session keys (**NwkSKey** and **AppSKey**) derived from the root **AppKey**. Each session therefore uses unique cryptographic material, enabling key rotation and protection against replay or cloning attacks [21]. OTAA is widely considered the most secure and scalable activation method, as it allows devices to rejoin networks, recover from resets, and migrate between servers without manual reconfiguration of keys.

Conversely, in **ABP**, the device stores static, pre-provisioned keys (**NwkSKey** and **AppSKey**) and does not perform the join procedure [24]. While ABP simplifies deployment in managed or closed networks—since it avoids the need for a network join exchange—it compromises security and flexibility. Because the session keys remain constant, ABP networks are more vulnerable to replay attacks and key extraction. Additionally, ABP devices require manual management of frame counters and cannot automatically rejoin after resets. In practice, OTAA is recommended for public or large-scale LoRaWAN deployments, whereas ABP is occasionally used in testbed or controlled environments where ease of deployment takes precedence over dynamic key management.

2.3.2 The Things Network (TTN) Infrastructure

The Things Network (TTN) is an open-source, community-based implementation of the LoRaWAN specification that enables rapid prototyping of IoT devices and facilitates large-scale deployment. It operates as a global, federated network infrastructure where individual gateways contribute to providing LoRaWAN coverage. TTN supports both experimental and production-scale deployments by offering a free open-source network and a commercial equivalent, *The Things Stack (TTS)*, for managed and enterprise environments [37].

The hierarchical architecture of TTN is illustrated in Fig. 5.1 (corresponding to Fig. 5.1 in this work). End devices (or nodes) communicate wirelessly with nearby LoRa gateways via the LoRa physical layer. These gateways act as transparent bridges that forward received uplink packets to the TTN Network Server using an IP backhaul, typically over Ethernet, Wi-Fi, or cellular links. The Network Server performs essential functions such as key management, packet deduplication, and message routing to ensure that packets received by multiple gateways are processed only once [19].

The TTN Application Server then decrypts the payload using the **AppSKey** and forwards the data to user-defined integrations, including MQTT brokers, HTTP endpoints, or cloud dashboards. Downlink messages follow the reverse path—from the Application Server through the Network Server to the gateway—and are transmitted during the device’s scheduled receive windows as per the LoRaWAN Class A specification. This modular architecture decouples the physical communication layer from the application logic, ensuring interoperability, scalability, and secure end-to-end data flow. In this project, the TTN framework was used to validate uplink reception, measure network latency, and

evaluate end-to-end system performance in a realistic LoRaWAN environment.

2.4 Power Management in IoT

The longevity of an autonomous IoT device, particularly one tasked with energy-intensive multimedia processing, is dictated by its power management strategy. In remote scenarios such as agricultural monitoring, continuous external power is typically unavailable, forcing reliance on self-contained energy sources. Consequently, selecting an appropriate power supply and minimising consumption at the node level is critical for achieving long-term operation.

2.4.1 Battery-Powered Systems

The proposed **Wireless Multimedia Sensor Node (WMSN)** architecture primarily relies on either **primary (non-rechargeable)** or **secondary (rechargeable)** battery chemistries as its main power source. The choice of battery type directly affects the node's energy density, cost, weight, and long-term operational autonomy [1, 20].

Primary batteries, such as *alkaline* and *lithium-thionyl chloride* (Li-SOCl_2) cells, are typically employed in long-term, maintenance-free sensor deployments. Alkaline batteries are inexpensive, widely available, and provide a nominal voltage of approximately 1.5 V per cell with moderate energy density (typically 100–150 Wh/kg) [13]. They are well suited to low-drain applications and conditions where periodic replacement is feasible. In contrast, lithium-based primary cells offer significantly higher energy density (up to 700 Wh/kg), a stable discharge voltage, and excellent low-temperature performance, making them ideal for remote or outdoor installations where reliability and extended shelf life are critical [25].

Secondary batteries, including *lithium-ion* (Li-ion), *lithium-polymer* (LiPo), and *lithium-iron-phosphate* (LiFePO_4) chemistries, are rechargeable and suitable for systems equipped with energy-harvesting mechanisms such as solar or vibration-based sources [35]. These batteries provide longer charge–discharge cycle life but require specialised charging and protection circuits to prevent overvoltage, deep discharge, and thermal runaway. Among them, LiFePO_4 stands out for its superior safety and long cycle life, although it offers a lower nominal voltage (3.2 V per cell) and slightly reduced energy density compared with Li-ion alternatives.

Achieving multi-month or multi-year autonomy in battery-powered WMSNs requires a two-pronged strategy: optimal battery selection and meticulous power management. The inherent limitation of battery capacity scales directly with the node's physical size and cost, making it the primary constraint on endurance. Therefore, minimising quiescent current and adopting ultra-low-duty-cycle operation are essential for maximising system lifetime.

Figure 2.6 highlights the importance of battery chemistry by comparing the energy density of various types. Panel (a) shows that lithium-based batteries are the efficiency leaders, achieving the highest energy-to-weight and energy-to-volume ratios, making them ideal for compact WMSN applications. Panel (b) confirms that Li-ion batteries offer an attractive balance between lightweight design and high-capacity storage, reinforcing their

dominance as a key enabler for compact and long-lived IoT devices [8]. This limitation of finite energy storage remains one of the fundamental design challenges addressed in this thesis.

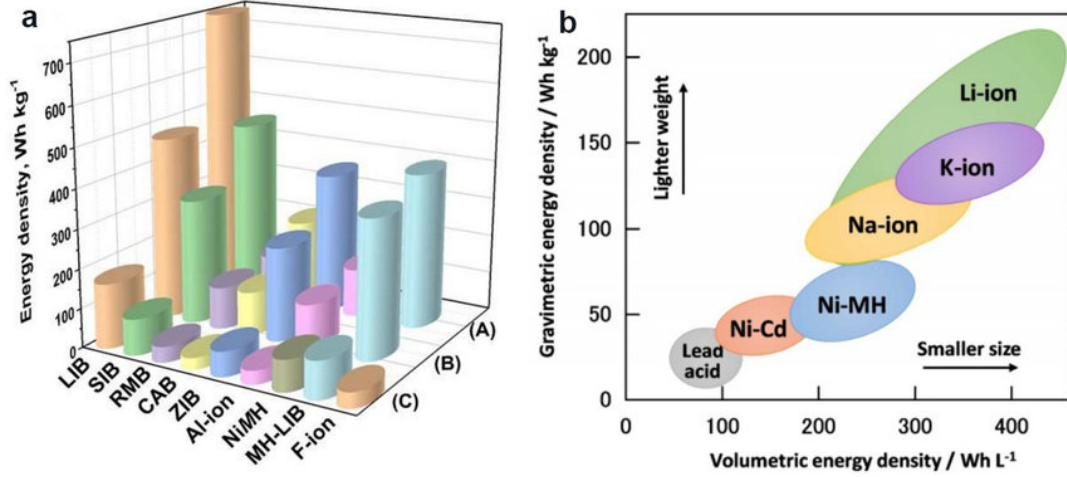


Figure 2.6. Comparison of energy density of various battery prototypes as a function of their chemistry [8].

2.4.2 Energy Harvesting (EH)

To achieve near-indefinite operational life, many WMSN designs integrate Energy Harvesting (EH) modules, typically leveraging solar, thermoelectric, or kinetic energy sources.

- **Solar Harvesting:** Particularly relevant for agricultural settings, where photovoltaic cells can provide substantial energy. However, the output is highly variable, depending on time of day, weather conditions, dust accumulation, and shading from vegetation. This variability complicates support for high-power, periodic events such as image acquisition and transmission.
- **Other EH Sources:** Thermoelectric harvesting (from temperature gradients) and kinetic harvesting (from vibrations or wind) are generally less practical for WMSNs, as they often yield insufficient power for the high peak demands of multimedia sensors.

The core limitation of EH in this context is the mismatch between the instantaneous high power required for multimedia operations and the low, fluctuating power that can be harvested. This demands sophisticated intermediate energy storage and management circuits, which add cost and complexity.

2.4.3 Fully Direct Current (DC) Powered Systems

Systems that are fully powered by mains electricity (via AC/DC conversion) or continuous tethered DC sources (e.g., wired industrial networks) eliminate the longevity problem

from an energy standpoint. However, the requirement for dedicated cabling infrastructure makes this solution impractical for distributed, remote applications such as industrial surveillance, environmental monitoring, or proximal crop monitoring, where nodes must be standalone and easily relocatable. Consequently, for field deployment, battery-based autonomy remains the most practical and widely adopted approach.

2.5 Summary of Key Findings

The review confirms a fundamental communication and energy gap for WMSNs in agricultural and other remote settings:

1. Ultra-low-power technologies (**LoRa, ZigBee**) provide the required longevity but lack the bandwidth for image files.
2. High-bandwidth technologies (**GPRS, LTE, Wi-Fi**) provide the required throughput but incur unacceptable power consumption for long-term, battery-based operation.
3. Power management strategies relying solely on conventional batteries or inconsistent energy-harvesting mechanisms struggle to reconcile the need for daily high-resolution imaging with multi-month or multi-year field deployment.

This thesis addresses this gap by proposing a **dual-radio architecture** in which two fundamentally different wireless technologies are combined in a complementary manner. A **Low-Power Interface (LPI)**, implementing LoRaWAN, enables continuous, ultra-low-power command reception, while a **High-Power Interface (HPI)** using GPRS is activated only when image data must be transmitted.

This separation of radio functions is the central innovation that enables reliable command-and-control capabilities alongside a substantially extended operational lifetime, even when the system is powered solely by **primary AA cells configured as 4× (2S2P)**.

Chapter 3

System Design

3.1 Proposed Solution

The solution is a novel [3.1](#), modular Wireless Multimedia Sensor Node (WMSN) designed to overcome the energy-bandwidth conflict inherent in remote multimedia sensing. Our approach centres on a **command-triggered, dual-radio duty cycle** where power-intensive components (Camera, Lora Transceiver and GPRS modem) are powered down for the vast majority of the operational time. Longevity is ensured by using an ultra-low power radio interface to maintain a consistent, ultra-low duty cycle for receiving remote commands and transmitting periodic status checks. The high-definition image acquisition and transmission only occur when explicitly requested by the central server, maximising the time the system spends in a deep-sleep, energy-conserving state. The modular design ensures that the platform is not limited to agriculture, but can be adapted for any standalone, power-efficient multimedia application.

3.2 Hardware Architecture

The system is implemented using a modular hardware stack centred on a main microcontroller unit (**ESP32-S3**) that coordinates all peripherals and executes the core power control logic.

3.2.1 ESP32-S3 Microcontroller

The central component of the wireless multimedia sensor node is the **ESP32-S3-WROOM-1U-N8R2** module, selected for its optimal balance between computational performance and wireless connectivity. The ESP32-S3 integrates a dual-core Tensilica LX7 processor operating at 240 MHz and supports both 2.4 GHz Wi-Fi and Bluetooth Low Energy (BLE), making it well-suited for applications that require efficient local data processing combined with wireless communication capabilities.

A key factor in selecting the ESP32-S3 was its **large number of general-purpose input/output (GPIO) pins** and flexible pin multiplexing capabilities. This flexibility enables seamless interfacing with all major subsystems of the node, including the LoRa

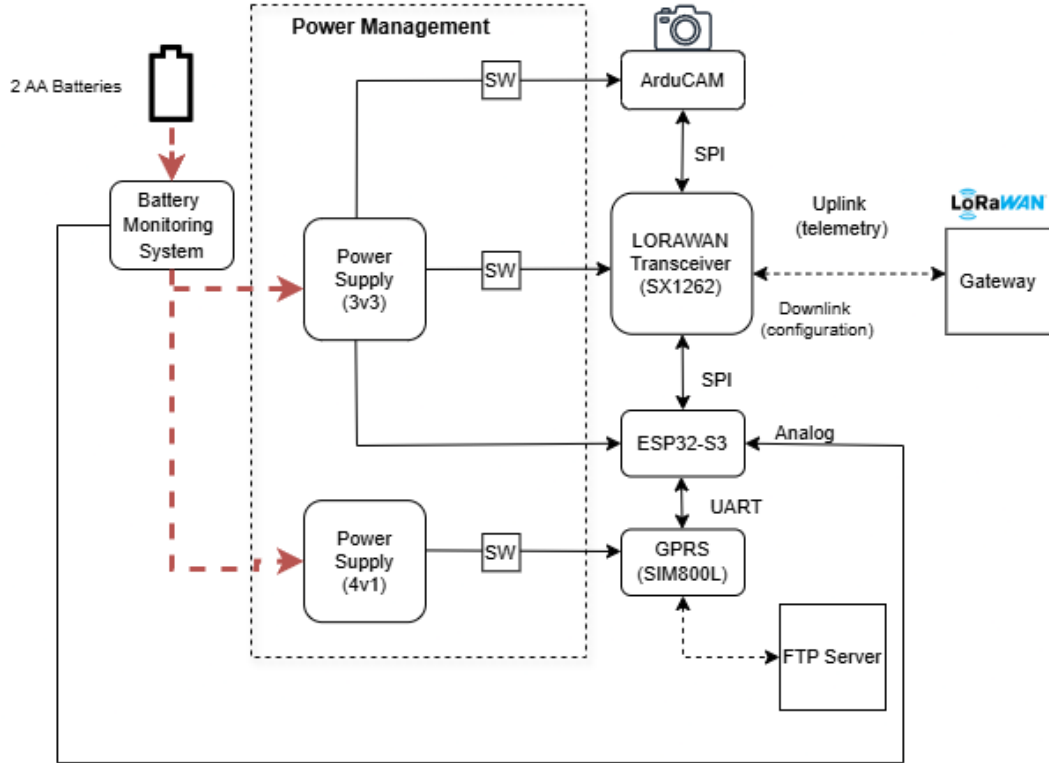


Figure 3.1. System block diagram of the proposed Wireless Multimedia Sensor Node showing dual communication support via LoRaWAN and GSM. The ESP32-S3 acts as the main controller managing both LoRa and GPRS communication links, while the power management unit regulates the 3.3 V and 4.1 V rails for the peripherals. The ArduCAM module handles image capture, and battery voltage is monitored through an ADC-based measurement system.

transceiver, GSM modem, ArduCam image sensor, battery monitoring circuit, and power management switches without any pin conflicts. Each per minimise connection was carefully assigned to ensure stable operation across the SPI, UART, and I²C communication buses. Several unused GPIOs (IO $\times$) have also been reserved for future hardware expansion, allowing the integration of additional external sensors or control peripherals without requiring significant PCB redesign.

The ESP32-S3 also offers excellent **low-power performance**, consuming only 20–30 μ A in deep-sleep mode, which aligns perfectly with the node’s design objective of ultra-low power operation for long-term field deployments. The microcontroller supports RTC-based wake-up timers and dedicated GPIO wake-up sources, enabling precise activation of subsystems only when required. The schematic implementation, shown in Figure 3.12, includes an external reset push-button for manual control and a filtered 3.3 V power line designed to maintain stable voltage and minimize electrical noise during high-speed communication tasks.

3.2.2 SX1262 LoRaWAN Transceiver

The **SX1262 LoRaWAN transceiver** has been chosen as the Low-Power Interface (**LPI**) responsible for long-range, low-data-rate communication. Operating in the sub-GHz ISM band (868 MHz in the European region), it provides excellent sensitivity, link robustness, and ultra-low power consumption, making it ideal for periodic telemetry transmission and remote command reception in Wireless Multimedia Sensor Nodes (WM-SNs) [27].

The SX1262 has been directly implemented on the PCB, following the official **Semtech SX1262 reference design**. This direct integration minimises interconnect losses, enhances RF stability, and enables precise impedance matching and harmonic filtering network tuning. The implementation includes all critical passive elements specified in the reference schematic, such as the DC decoupling network, a 32 MHz crystal oscillator, and the RF front-end matching components.

To improve power efficiency, the transceiver’s power rail (V_{Lora}) is switched using an **SI2301-TP** high-side MOSFET. The MOSFET is controlled by the **LoraOn** GPIO from the ESP32-S3 microcontroller, allowing the system to completely disable the LoRa transceiver when operating the GSM subsystem or when entering deep-sleep mode. This feature significantly reduces standby current and prevents unnecessary power leakage during idle phases.

The RF front-end consists of a compact **balun network** combined with a **low-pass filter**, both designed using the topology recommended by Semtech. The balun performs a differential-to-single-ended conversion of the SX1262 power amplifier output, transforming the balanced differential RF output into a single-ended 50 Ω impedance suitable for the antenna. This conversion ensures optimal power transfer and reduces reflections that can degrade transmission efficiency. The balun network is implemented using a combination of inductors and capacitors, acting simultaneously as an impedance transformer and harmonic suppression filter. The filter stage further eliminates higher-order harmonics produced during transmission, ensuring compliance with ETSI spectral mask requirements and improving the spectral purity of the transmitted signal.

The complete implementation of the SX1262 transceiver subsystem includes the high-side MOSFET power switch, matching network, and RF output filter. This design follows the Semtech layout and component recommendations, resulting in a compact, efficient, and reliable long-range communication front end that provides stable uplink operation and extremely low power consumption.

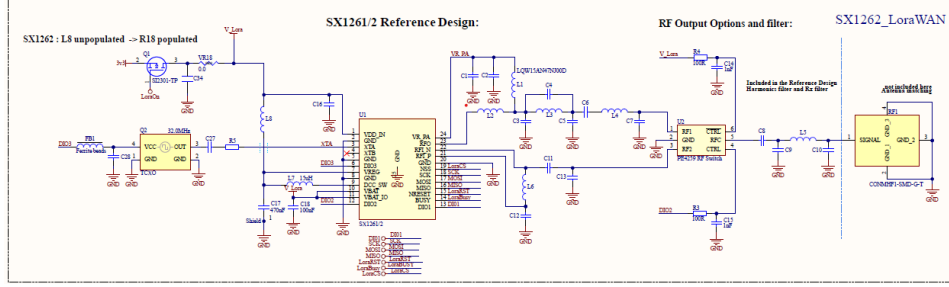


Figure 3.2. On-board implementation of the SX1262 LoRaWAN transceiver. The design follows the Semtech reference design and includes a high-side MOSFET power switch (Q1), a balun-based impedance matching network, and an RF harmonic filter to ensure efficient power transfer and spectral compliance.

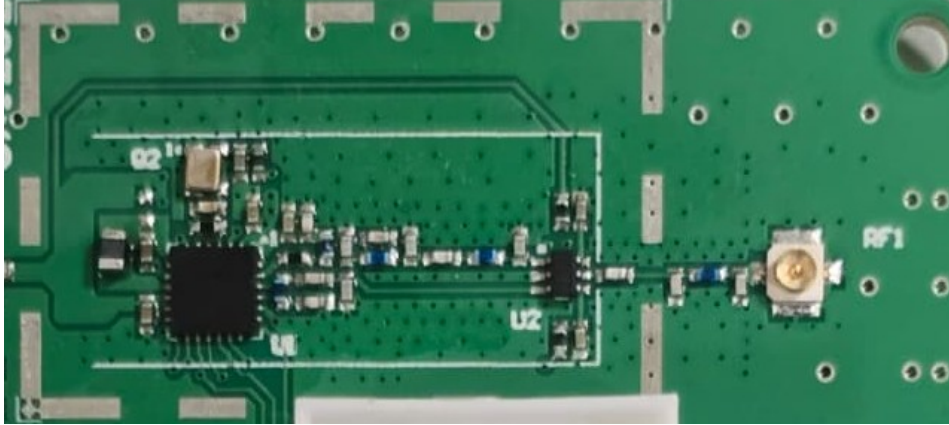


Figure 3.3. PCB implementation of the SX1262 LoRa transceiver. The layout includes the RF matching network, harmonic suppression components, and controlled-impedance RF trace routed towards the antenna connector (RF1).

3.2.3 SIM800C GSM Module Implementation

The on-board **SIM800C GSM module** implements the **High-Power Interface (HPI)** for cellular connectivity. It provides an enabler for GPRS data transfer, particularly for the uploading of compressed image files to a remote server from the multimedia sensor node. This module was chosen for its balance between wide network coverage, moderate power consumption, and proven stability in rural environments where 2G infrastructure remains available [33].

The layout and hardware design have been carried out with strict attention to the requirements and recommendations set by the **SIMCom SIM800C Hardware Design Reference Manual** to ensure proper operation and electrical integrity. The power supply to the module is derived from the regulated **4.1 V rail**, provided by the **MAX17225ELT+T** boost converter, which is capable of sourcing up to **2 A** peak current bursts during GSM transmission. To maintain supply stability during these transmission peaks, a local capacitor bank consisting of **100 μF** , **10 μF** , and **100 nF** capacitors is placed close to the VBAT pin of the modem. This configuration minimises voltage dips and ensures fast transient response for reliable GSM operation.

Unlike several earlier GSM implementations that completely power off the module during sleep states, the **SIM800C** is never hard-powered off. According to SIMCom design recommendations, frequent power rail toggling may lead to improper shutdowns, potentially causing data corruption or SIM card initialisation failures. Therefore, the **PWRKEY** control line is used to perform controlled power-down and restart sequences. This signal is driven by a dedicated GPIO pin from the ESP32-S3 microcontroller, ensuring proper power sequencing and reliable startup behaviour.

An array of ESD protection diodes (**ESDA6V1-5W6**) is integrated on the SIM signal lines (**SIM_CLK**, **SIM_DATA**, and **SIM_RST**) to safeguard the interface from transient surges. This provides robust ESD protection for both the GSM module and the SIM card interface. The **SIM card socket** is mounted on the **bottom side of the PCB**, allowing compact stacking and easy card insertion during assembly and field maintenance.

For RF transmission, the **GSM antenna** is connected through a **50 Ω matched transmission line** to an SMA connector (**CONN HFL-SMD-G-T**). The antenna trace adheres to the recommended microstrip width and clearance to maintain controlled impedance and minimise insertion loss. The complete schematic implementation of the SIM800C subsystem Figure, 3.5, including the core circuitry, SIM card interface, and RF output connector, is shown in Figure 3.4.

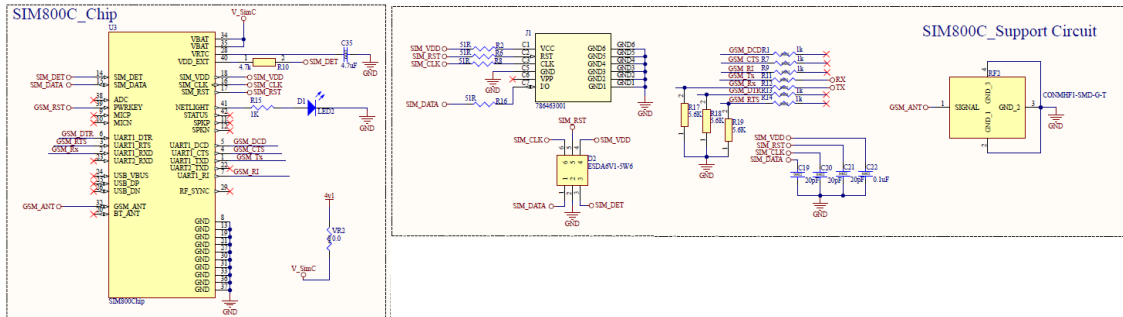


Figure 3.4. On-board implementation of the **SIM800C GSM subsystem**. The schematic includes the main GSM core circuitry, SIM card interface with ESD protection, and the matched RF antenna output. The design follows SIMCom’s hardware layout guidelines for stable operation and minimal power noise coupling.



Figure 3.5. PCB implementation of the SIM800C GSM/GPRS module. The layout shows the SIM800C module (U3), local bulk and decoupling capacitors for handling high transmission current peaks so that the module can work properly, the SIM card holder, and the RF connection routed towards the antenna interface.

3.2.4 Battery Voltage Monitoring Using ADC

The battery state-of-charge (SOC) of the proposed node is monitored directly using the internal **Analog-to-Digital Converter (ADC)** of the **ESP32-S3** microcontroller, instead of a dedicated fuel-gauge IC. This design minimizes component count and eliminates the quiescent current associated with external monitoring circuits, contributing significantly to the node’s low-power operation and long-term reliability.

To further enhance power efficiency, a **high-side load switch (TPS22916)** is employed to control the connection between the battery and the resistive voltage divider (VDR). This switch is driven by a GPIO pin of the ESP32-S3, enabling the divider only during voltage measurement cycles. In idle mode, the divider is electrically isolated, thereby preventing continuous leakage currents through the resistors and minimizing standby power consumption. During a measurement cycle, the switch connects the battery to the divider, and the resulting scaled voltage is sampled at the ADC input (ADC1_CH0). The digital value is then processed by a firmware-based calibration function or lookup table, which estimates the SOC according to predefined discharge characteristics. This information is integral to the power management algorithm, allowing the system to dynamically adjust its communication duty cycle and sleep duration based on available energy.

For field deployment, the system is powered by standard **AA alkaline LR6 cells**, each rated at approximately **1.5 V** and **1500 mAh**. The selected configuration connects two cells in series and two in parallel, resulting in a nominal pack voltage of **3.0 V** and a combined capacity of about **3000 mAh**, as shown in Figure 3.6.



Figure 3.6. Battery enclosure used for field deployment, housing four AA alkaline LR6 cells arranged in a 2S2P configuration. The enclosure provides mechanical protection, strain relief for wiring, and a compact form factor suitable for outdoor operation.

This configuration provides a cost-effective, reliable, and easily replaceable power source well-suited for long-term outdoor operation.

The complete implementation of the battery voltage monitoring circuit, using the TPS22916 high-side switch, is illustrated in Fig. 3.7.

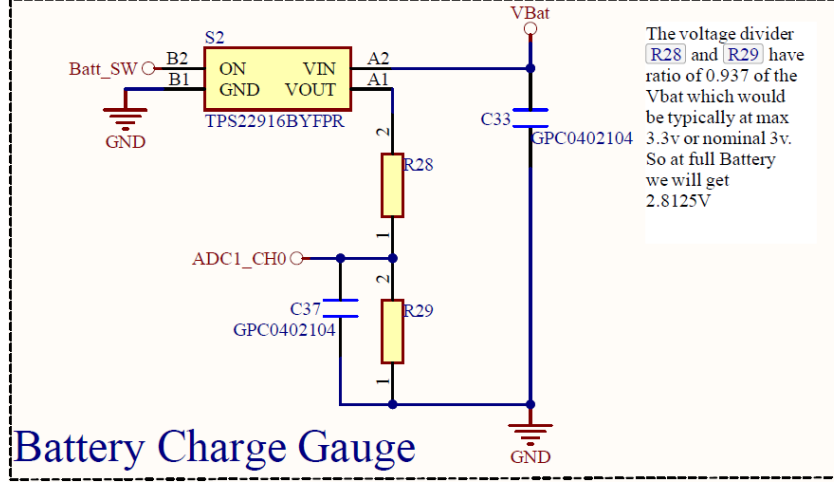


Figure 3.7. Circuit implementation of the TPS22916 high-side switch used to enable the resistive voltage divider (VDR) for ADC-based battery voltage measurement. The ESP32-S3 controls the switch via a GPIO pin, activating the divider only during measurement to minimise standby power loss.

3.2.5 ArduCam Image Sensor

The WMSN imaging subsystem incorporates the **ArduCam 5 MP OV5642-based CMOS camera module (B0436)**, shown in Figure 3.8. The module was selected due to its compact form factor, low-power operation, and ability to capture high-resolution still images with on-board JPEG compression [6], making it suitable for battery-powered wireless multimedia sensor nodes.

Although OmniVision image sensors such as the OV5642 natively output image data through a parallel Digital Video Port (DVP) interface and are configured via an I²C (SCCB) control bus, they do not support SPI communication directly. In ArduCam MEGA SPI camera modules, this limitation is addressed by integrating a dedicated camera controller and on-board FIFO memory. The controller configures the sensor, captures the pixel stream from the native parallel interface, and stores the complete image frame in local memory. The buffered image data are then retrieved by the host microcontroller via a standard SPI interface. This architecture abstracts the timing-critical image acquisition process from the microcontroller, reduces pin count and processing load, and enables asynchronous image readout, which is particularly advantageous for low-power, duty-cycled WMSN deployments.

A direct **SPI bus** connection is therefore used to interface the ArduCam with the **ESP32-S3**, enabling reliable frame capture and readout when required. The chip-select (CS), master-in/slave-out (MISO), master-out/slave-in (MOSI), and clock (SCK) signals are mapped to dedicated ESP32-S3 pins, while additional GPIO lines are used for capture

control and image-ready signalling. The camera operates from a regulated 3.3 V supply, and local decoupling capacitors placed close to the sensor power pins ensure supply stability and suppress transient noise during high-speed SPI transfers.

The electrical interface and timing design follow the guidelines provided in the ArduCam hardware documentation [6], ensuring stable communication and distortion-free image capture under varying lighting and operational conditions. Adherence to these recommendations guarantees reliable synchronisation between the camera module and the ESP32-S3 microcontroller.

To minimise power consumption, the **VCam** supply rail powering the ArduCam is controlled by an **SI2301-TP N-channel MOSFET** used as a high-side power switch. The MOSFET is driven by the **CamOn** GPIO of the ESP32-S3, allowing the camera to be completely powered down during idle and deep-sleep states. This approach significantly reduces leakage currents and overall energy consumption. The camera is activated only upon an image capture request, at which point a single frame is acquired and stored via the SPI interface. Experimental verification confirmed reliable synchronisation and successful image acquisition, validating both the hardware interface and the communication protocol.

The modular nature of the ArduCam MEGA platform allows straightforward replacement of the image sensor or firmware updates without major hardware changes, preserving flexibility for future enhancements in low-power, image-based IoT applications.



Figure 3.8. **ArduCam 5MP (B0436)** image sensor, camera communicates with the ESP32-S3 via SPI.

3.2.6 Power Supply and Regulation Architecture

The power system is designed around a single primary battery pack that is controlled by a high-efficiency switching and regulation architecture, as shown in Figure 3.9. This

system employs **MOSFETs** and low-quiescent-current regulators to fully decouple and hard-power-cycle high-power subsystems such as the **GSM modem (HPI)** and the **Camera interface(ArduCAM)**. As a result, these components draw virtually zero quiescent current when the main **ESP32-S3** microcontroller enters deep-sleep mode, minimizing standby power losses and extending the overall battery life of the node.

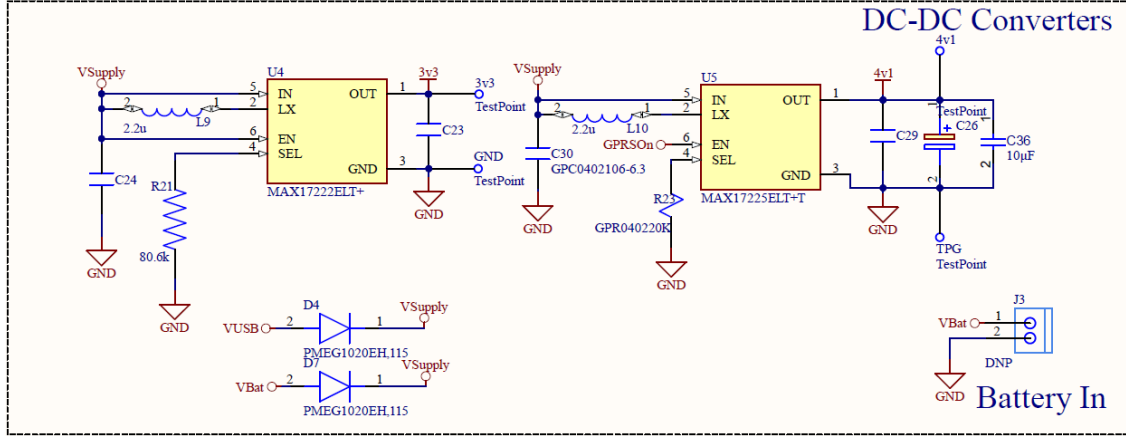


Figure 3.9. DC-DC converter stage of the node. The **MAX17222ELT+** generates the **3.3 V** rail for the ESP32-S3 and low-power peripherals, while the **MAX17225ELT+T** generates the **4.1 V** rail for the GSM subsystem. A diode make sure reverse voltage protection from *VBat* or *VUSB* into *VSUPPLY*, and local capacitors and test points support measurement and stability.

3.3 V Power Rail – MAX17222ELT+ [4]: The **MAX17222ELT+** nanoPower boost converter generates the 3.3 V regulated rail, which powers the ESP32-S3 microcontroller, LoRaWAN transceiver, and other low-power peripherals. This converter was selected for its exceptionally low quiescent current (approximately 0.5 μ A) and high efficiency exceeding 95%. Powered by the 3 V alkaline battery pack, it maintains a stable 3.3 V output even under dynamic load conditions such as LoRa transmissions or sensor operation. Its *True ShutdownTM* feature completely isolates the input from the output during sleep, eliminating reverse current leakage and virtually all idle losses. This design choice makes it ideal for continuously active, battery-powered embedded systems that demand high reliability and long operational lifespans.

4.1 V Power Rail – MAX17225ELT+T [5]: A separate boost converter, the **MAX17225ELT+T**, supplies the 4.1 V rail dedicated to the GSM subsystem. This converter can deliver peak currents of up to 1 A, sufficient to meet the transient current demands of the **SIM800C** modem during GPRS transmission bursts. It offers a rapid transient response and low output ripple, ensuring voltage stability and preventing dropouts on the shared power bus. The enable (EN) pin of the MAX17225 is controlled by a GPIO of the ESP32-S3, allowing the firmware to dynamically power the GSM module on or off as required. This control strategy ensures that the GSM subsystem remains

completely disconnected during LoRa-only operation or deep-sleep periods, thereby minimizing total power consumption and improving the system’s overall energy efficiency.

3.2.7 High-Side Power Switching Using SI2301-TP MOSFETs

To achieve efficient power-domain control, **SI2301-TP** N-channel MOSFETs are implemented as high-side switches to manage the power delivery to both the **ArduCam camera interface** and the **SX1262 LoRa transceiver**. These switches are driven directly by the **ESP32-S3** through dedicated GPIO control pins (**Cam0n** and **Lora0n**), enabling independent activation and the deactivation of each subsystem as required by the firmware. This selective control approach prevents unnecessary current flow to inactive peripherals and eliminates leakage paths when the system is in deep-sleep or idle mode, thereby significantly improving overall energy efficiency and extending battery life.

The **SI2301-TP** MOSFET features a low on-resistance ($R_{DS(on)} \approx 85 \text{ m}\Omega$ at 3.3 V) and a low gate threshold voltage, allowing for direct logic-level control in low-voltage designs without requiring additional driver circuitry [40]. Figures 3.10 (a) and 3.10 (b) illustrate the high-side switching implementation for the ArduCam and LoRa modules, respectively. In both cases, the MOSFET acts as a high-side switch that isolates the peripheral power rail from the main 3.3 V supply when disabled, ensuring zero quiescent current flow during standby operation.

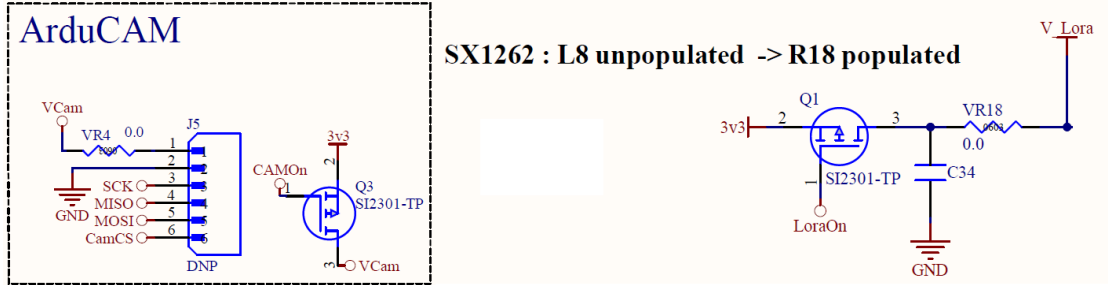


Figure 3.10. High-side MOSFET power-domain control implemented in the IxemCam platform. (a) ArduCam power gating using an **SI2301-TP** MOSFET controlled by the **Cam0n** GPIO, which disconnects the 3.3 V camera supply (**VCam**) during idle periods to minimise standby current. (b) SX1262 LoRa transceiver power gating using an **SI2301-TP** MOSFET driven by the **Lora0n** GPIO, enabling the LoRa rail only during transmission and receive windows and isolating it during deep-sleep operation.

3.2.8 3D and Mechanical Design

The mechanical enclosure is shown in Figure 3.11. was designed to provide environmental resistance, mechanical protection, and proper optical and RF performance for the Wireless Multimedia Sensor Node (WMSN). The housing was modelled in 3D CAD and fabricated through additive manufacturing, which enabled rapid iteration and refinement throughout the hardware development phase.

The enclosure prevents dust and moisture from reaching the electronics, ensures an unobstructed optical path for the ArduCam sensor, and maintains the RF performance of both the LoRaWAN and GSM antennas. A two-part construction—consisting of a rigid base and a transparent upper cover—supports PCB mounting, battery placement, and straightforward access for programming and maintenance. The clear lid provides a direct view of the internal components while preserving the camera’s field of view.

A notable feature of the mechanical assembly is the **magnetic locking mechanism** used to secure the transparent lid to the base. Small embedded neodymium magnets replace conventional screws, which would otherwise wear out printed threads, require tools, and complicate field servicing. The magnetic retention system allows the enclosure to be opened quickly for battery replacement or debugging while maintaining a reliable mechanical seal during normal operation. Additionally, the use of magnets preserves a clean external geometry and eliminates the risk of environmental ingress through screw holes.

3.3 System Architecture

This section integrates the discrete hardware components into a cohesive, functional system, outlining the logical flow of information and energy.

3.3.1 Communication Interfaces (SPI, UART, I²C)

The communication structure of the proposed **Wireless Multimedia Sensor Node (WMSN)** is built around three serial interfaces: **UART**, **SPI**, and **I²C**. These interfaces form the backbone for data exchange between the **ESP32-S3 microcontroller** [14] and the connected peripherals. Each interface was selected to match the performance and bandwidth requirements of the associated device, ensuring smooth operation and low power overhead across the system [34].

UART Interface

The **Universal Asynchronous Receiver–Transmitter (UART)** protocol provides a simple and a reliable means of transferring data between two devices without requiring a shared clock signal. Communication takes place over two lines—TX (transmit) and RX (receive), where each byte of data is framed with start and stop bits to maintain synchronisation. Although UART offers lower throughput than more advanced serial protocols, its simplicity, low hardware cost, and robustness make it ideal for control-based communication [34].

In this design, the UART link connects the **SIM800C GSM module** [31] to the **ESP32-S3**. All communication is handled using standardized **AT commands** [30], allowing the microcontroller to perform tasks such as SIM authentication, GPRS session management, and data transmission. A baud rate of **115200 bps** was selected as a compromise between transfer speed, communication stability, and noise immunity in the embedded environment.

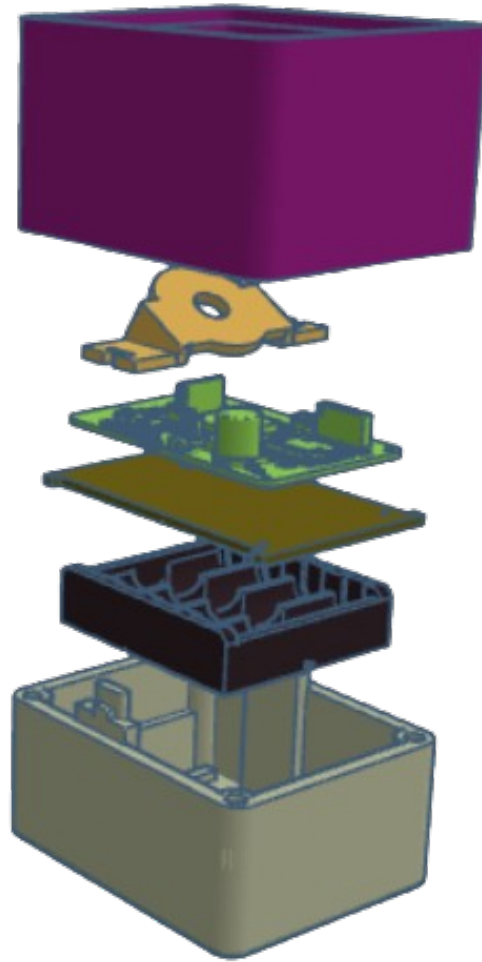


Figure 3.11. 3D enclosure model of the Wireless Multimedia Sensor Node (WMSN), showing the external housing, internal arrangement, camera view alignment, and magnetic lid interface.

SPI Interface

The **Serial Peripheral Interface (SPI)** protocol enables high-speed, full-duplex communication between a master device and multiple slave peripherals. It operates using four primary lines: *MOSI* (Master Out, Slave In), *MISO* (Master In, Slave Out), *SCK* (Serial Clock), and *CS* (Chip Select). Due to its low latency and high throughput—often reaching several megabits per second—SPI is well-suited for high-bandwidth applications in embedded systems [34].

In the developed prototype, the SPI bus connects two performance-critical components: the **SX1262 LoRaWAN transceiver** [27] and the **ArduCam image sensor**. The LoRa transceiver relies on SPI for fast configuration of transmission parameters such as frequency, spreading factor, and packet structure, ensuring deterministic data transfer. The same interface is also used by the ArduCam module for high-speed image transfer from its internal buffer to the ESP32-S3's memory during image capture. Each peripheral is assigned a dedicated chip-select line to avoid interference and maintain predictable timing across the shared bus.

I2C Interface

The **Inter-Integrated Circuit (I²C)** bus is a two-wire communication protocol originally developed by Philips (now NXP) for connecting multiple integrated circuits on the same board. It uses a **clock line (SCL)** and a *data line (SDA)*, allowing several devices to share a common bus through unique 7- or 10-bit addresses. Although slower than SPI, I²C offers reduced pin count and lower power consumption, making it ideal for low-speed configuration and control tasks [34].

In this WMSN design, the I²C bus is not being used but primarily used for low-bandwidth operations such as ADC configuration, calibration, and communication with auxiliary sensors. Its minimal hardware overhead and low-power characteristics make it suitable for periodic monitoring and background configuration activities that do not require high-speed data exchange.

3.3.2 Power Control Logic

The core energy conservation is managed by a three-tiered power state:

1. **Deep Sleep (Minimum Power):** The MCU is completely off; only the internal real-time clock (RTC) runs. All high-power peripherals are physically disconnected via switching circuits.
2. **LPI Active (Ultra-Low Power):** The system wakes up at fixed intervals (e.g., every 10 minutes). The LPI (LoRaWAN) listens briefly for a command and transmits status data. All other subsystems remain off.
3. **HPI Active (High Power):** Triggered only by a valid remote command. The switching circuit powers on the camera and HPI (GPRS), executes the full image acquisition and upload, and immediately returns the system to Deep Sleep.

3.3.3 Data Acquisition and Upload Workflow

The workflow is strictly request-driven:

1. **Command Reception:** LPI receives a valid SHOOT command packet.
2. **HPI Activation:** MCU activates the camera and HPI power circuits.
3. **Image Capture:** Camera captures the high-definition image, and the MCU performs compression/encoding.
4. **Data Transmission:** HPI establishes a GPRS connection and uploads the compressed image file to the central server.
5. **Status Confirmation:** A small confirmation packet is sent back via the LPI or HPI.
6. **Deep Sleep Return:** All high-power circuits are immediately disconnected, and the system re-enters Deep Sleep.

3.3.4 Hardware–Firmware Interface Mapping

The main controller of the Wireless Multimedia Sensor Node (WMSN) is the **ESP32-S3-WROOM-1U-N8R2** module, which manages communication with all subsystems: the LoRa transceiver (SX1262), the GSM modem (SIM800C), the camera module (ArduCam), and the ADC-based battery voltage monitor. Figure 3.12 shows the ESP32-S3 core section with reset, enable, and peripheral connections.

The hardware–firmware interface follows a modular, pin-mapped approach: each peripheral can operate independently, and power to high-consumption blocks is gated in firmware. Table 3.1 summarises the **ESP32-S3 GPIO** assignments to subsystems and functions.

All subsystems expose explicit power and control pins to allow safe isolation and deterministic sequencing in firmware:

- **Power gating:** LoraOn and CamOn (and, if implemented, GSM_ON/PWRKEY) drive high-side MOSFETs (SI2301-TP) so radios and the camera are only powered when needed.
- **Shared SPI:** SX1262 and ArduCam share SPI lines (SCK/MISO/MOSI) with independent chip-selects (LoraCS, CamCS) to avoid bus contention.
- **Battery monitoring:** ADC1_CH0 samples the pack voltage through a gated resistor divider enabled via a load switch (TPS22916) to eliminate divider leakage in sleep.
- **GSM UART:** The SIM800C uses UART2 (TX=IO16, RX=IO17); modem control uses GSM_RST and (optionally) PWRKEY on a spare GPIO.

This mapping prevents overlapping power domains and ensures that only the required hardware is active at any time, enabling the ESP32-S3 firmware to achieve high energy efficiency while maintaining reliable coordination across subsystems.

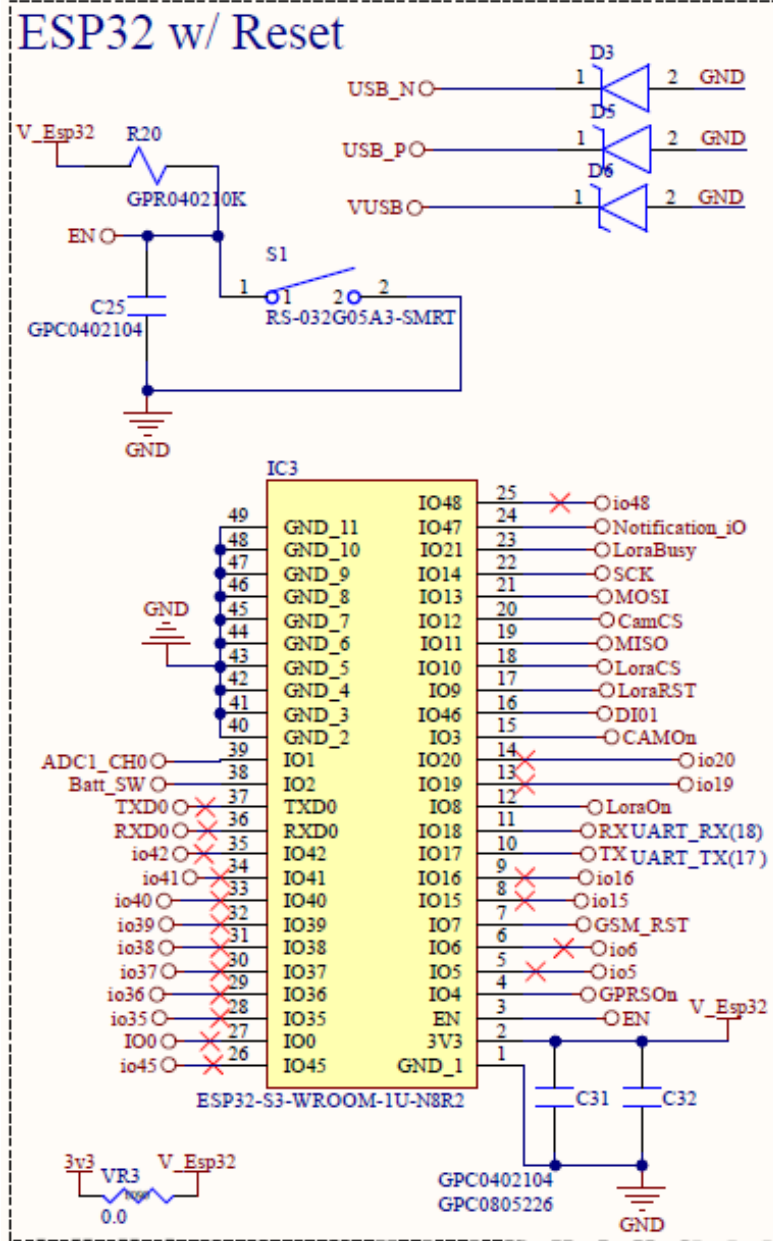


Figure 3.12. ESP32-S3 core and reset circuit implementation with GPIO assignments used to interface LoRa (SX1262), GSM (SIM800C), ArduCam, and the ADC-based battery monitor.

Table 3.1. ESP32-S3 GPIO assignment to subsystems and functions.

GPIO Pin	Subsystem / Signal	Function Description
IO0	Boot / JTAG Mode	Boot / JTAG selection during programming
IO1	ADC1_CH0	Battery voltage ADC input
IO11	MISO	SPI MISO (shared bus)
IO13	MOSI	SPI MOSI (shared bus)
IO14	SCK	SPI clock (shared bus)
IO3	CAMon	Camera power enable (active low)
IO12	CamCS	ArduCam SPI chip-select
IO9	LORA_RST	SX1262 hardware reset
IO10	LoraCS	SX1262 SPI chip-select
IO6	LORA_DIO1	SX1262 interrupt (DIO1)
IO21	LoraBusy	SX1262 busy/status input
IO4	GPRSON	GSM power enable (active high)
IO7	GSM_RST	SIM800C PWRKEY (active low)
IO17	UART2_TX	ESP32 TX → SIM800C RX
IO18	UART2_RX	ESP32 RX ← SIM800C TX
IO2	Batt_SW	Battery divider enable (active high)
IO47	Notif_LED	Status / notification LED

Firmware State Machine and Operation Flow

The operation of the **Wireless Multimedia Sensor Node (WMSN)** is governed by a finite state machine (FSM) implemented in the ESP32-S3 firmware. This architecture provides fine-grained control over the power domains. It ensures that power-hungry subsystems (GSM modem and camera) are only enabled for the minimum time required to complete a command. The system timing is driven by the internal RTC of the **ESP32-S3**, which is used as the primary time base for periodic wake-up cycles.

The FSM cycles through four main states, summarised in Table 3.2, while the transition logic is illustrated in Figure 3.13.

Control Flow and Timing Synchronisation

The state model uses a deterministic, synchronised transition sequence designed for energy efficiency:

1. **Periodic wake-up ($S_0 \rightarrow S_1$):** At fixed intervals (e.g. every 10 minutes), the ESP32-S3 exits deep-sleep upon an internal RTC alarm. The firmware powers the Low-Power Interface (LPI) by enabling the SX1262 LoRa transceiver and initialises the communication stack.
2. **Command reception (within S_1):** In state S_1 , the node sends a LoRaWAN up-link and then opens the Class A receive windows (RX1, RX2) to listen for downlink commands. If a valid SHOOT command is received from the network server, the FSM

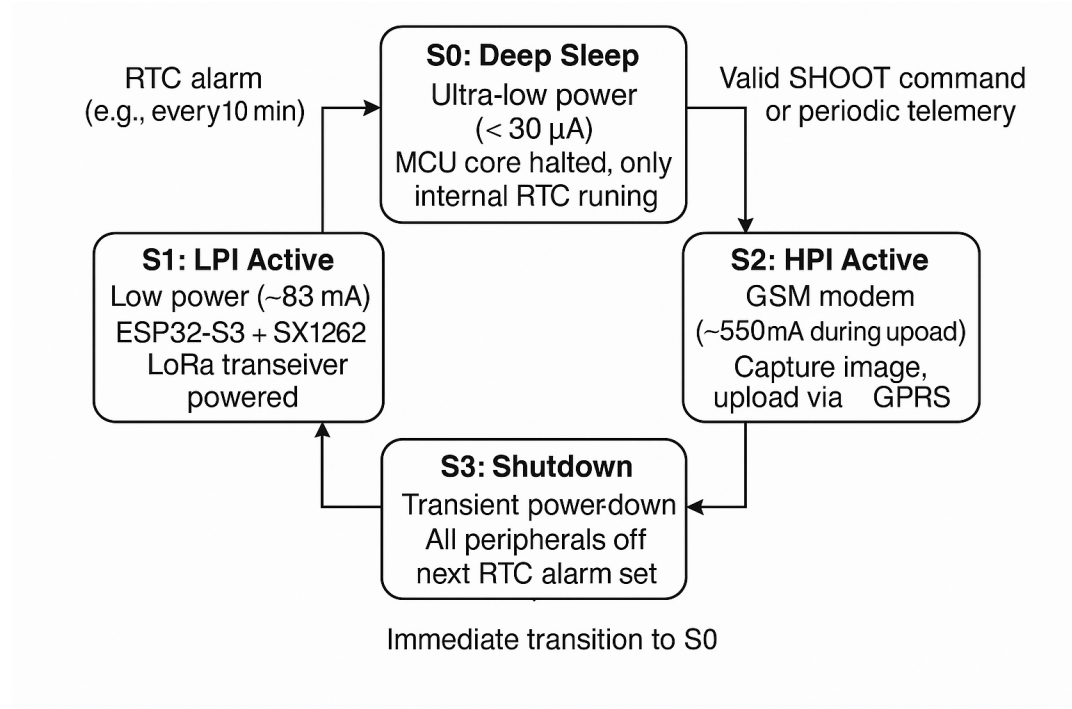


Figure 3.13. WMSN firmware state machine showing the four operating states (S_0 – S_3), their power modes, and the transitions driven by RTC alarms, LoRa commands, and GSM upload events.

transitions to the high-power state ($S_1 \rightarrow S_2$). If no command is received, the node completes the telemetry cycle and proceeds towards shutdown.

3. **Image upload (S_2):** State S_2 is the most energy-intensive phase. The firmware executes a tightly controlled sequence:
 - (a) Enable camera power and capture a compressed image frame.
 - (b) Enable the GSM power rail (via MAX17225) and power up the SIM800C.
 - (c) Establish a GPRS connection and open the data session.
 - (d) Stream the image frame-by-frame to the remote server using the TCP/HTTP stack (without SD-card buffering, as described in Section 4.10).

Once the upload is complete and an acknowledgement is received (or a timeout occurs), the FSM prepares the system for shutdown.

4. **Power isolation and return to deep sleep ($S_2 \rightarrow S_3 \rightarrow S_0$):** After data transmission, the firmware initiates the power-down sequence: the GSM rail (MAX17225) is disabled, all MOSFET-based high-side switches are turned off, and peripheral clocks are stopped. The next RTC wake-up alarm is configured, and the ESP32-S3 re-enters deep-sleep (S_0). This strict isolation of power domains is a key contributor to achieving the target deep-sleep current in the order of tens of microamperes.

Table 3.2. WMSN firmware state machine and power management states.

State	Power Mode	Key Activity	Exit Trigger
S0: Deep Sleep	Ultra-low power ($< 30 \mu\text{A}$)	MCU core halted, RTC timer running; all high-power domains off.	RTC alarm (e.g. every 10 minutes)
S1: LPI Active	Low power ($\approx 83 \text{ mA}$)	ESP32-S3 active; SX1262 LoRa transceiver powered. Sends status uplink and briefly opens Class A receive windows to listen for commands.	Reception of a valid SHOOT command or completion of periodic telemetry task
S2: HPI Active	High power ($\approx 550 \text{ mA}$ average during upload)	GSM modem (SIM800C) and camera (ArduCam) powered. Capture image, establish GPRS connection, and stream image data to the server.	Successful GPRS transmission and server acknowledgement (or timeout/error handling)
S3: Shut-down	Transient power-down	All peripherals explicitly turned off; GSM rail and MOSFET switches disabled. Next RTC alarm programmed.	Immediate transition to S0 (Deep Sleep)

3.4 Design Considerations (Noise, Shielding, Antenna, Thermal)

Effective deployment requires careful attention to engineering specifics that influence performance and reliability in a field environment:

- **Noise and Shielding:** The proximity of the high-frequency GPRS modem to the low-frequency LoRaWAN receiver requires careful **electromagnetic compatibility (EMC) shielding** and grounding to prevent noise interference.
- **Antenna Design:** The requirement for reliable long-range communication for both the LPI (LoRa) and HPI (GSM) necessitates **optimised antenna placement and tuning** to maximize gain and minimise inter-system interference.
- **Thermal Management:** Although the high-power components only run in short bursts, the high current draw during the active phase requires robust thermal dissipation mechanisms to ensure the longevity and reliability of the cellular modem and power regulators.

Chapter 4

Implementation and Development

4.1 Implementation and Development

This chapter gets into the nuts and bolts of the project—the real work of transforming our grand theoretical blueprint into a durable, functional physical system. We’ll trace the entire hardware journey: from selecting just the right tiny parts and laying out the intricate Printed Circuit Board (PCB), right through to writing the testing firmware and making sure every component plays nicely. Finally, we’ll dive into the essential, tough testing and debugging that got the system truly ready for the field. A critical step was to choose our communication methods. We use a dual approach: LoRaWAN (**SX 1262**) handles regular, low-power telemetry data (like sensor readings, if needed), keeping our battery consumption minimal. For the heavy lifting, such as transmitting images and complex data, we landed on the **SIMCom SIM800C GSM/2G modem**. We picked the SIM800C because it’s a workhorse: it sips power, is easy to source, and speaks a simple command language. This module serves as the primary backbone for multimedia data over standard 2G, giving us an affordable and reliable solution when operating with low bandwidth.

4.2 PCB Design and Component Selection

This printed circuit board, shown in figure 4.12, was designed to consolidate all the major functions of a system into a single, compact package, including processing, communication, sensing, and power management. Each component was chosen not only for its electrical characteristics but also for its ability to remain stable over a long period of time, consume low power, and be easy to assemble.

Core Processing and Communication At its core is the ESP32-S3 microcontroller, offering processing power and handling all peripheral communications. The ESP32-S3 incorporates Wi-Fi, Bluetooth, and several hardware interfaces, including SPI, UART, and I²C, making it suitable for complex systems involving multiple signals. Other communications with the outside world are done through two radio subsystems:

- Semtech’s **SX1262 LoRa transceiver** offers a long-range, low-power biotelemetry system.

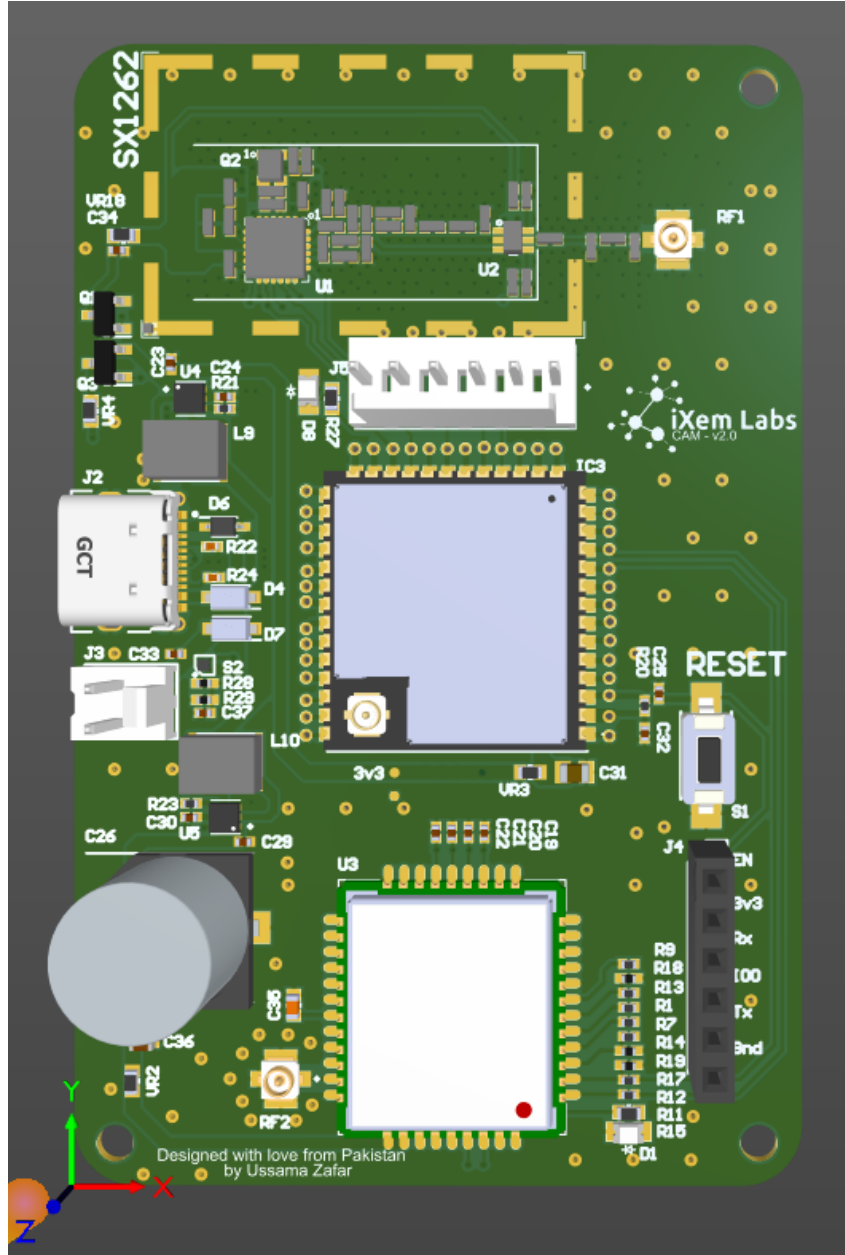


Figure 4.1. 3D top view of the designed PCB showing placement of key components, including the ESP32-S3 microcontroller, SX1262 LoRa transceiver, SIM800C GSM modem, power regulation circuits, and ArduCAM interface. The compact single-board layout improves electrical performance and mechanical robustness compared with earlier multi-board prototypes.

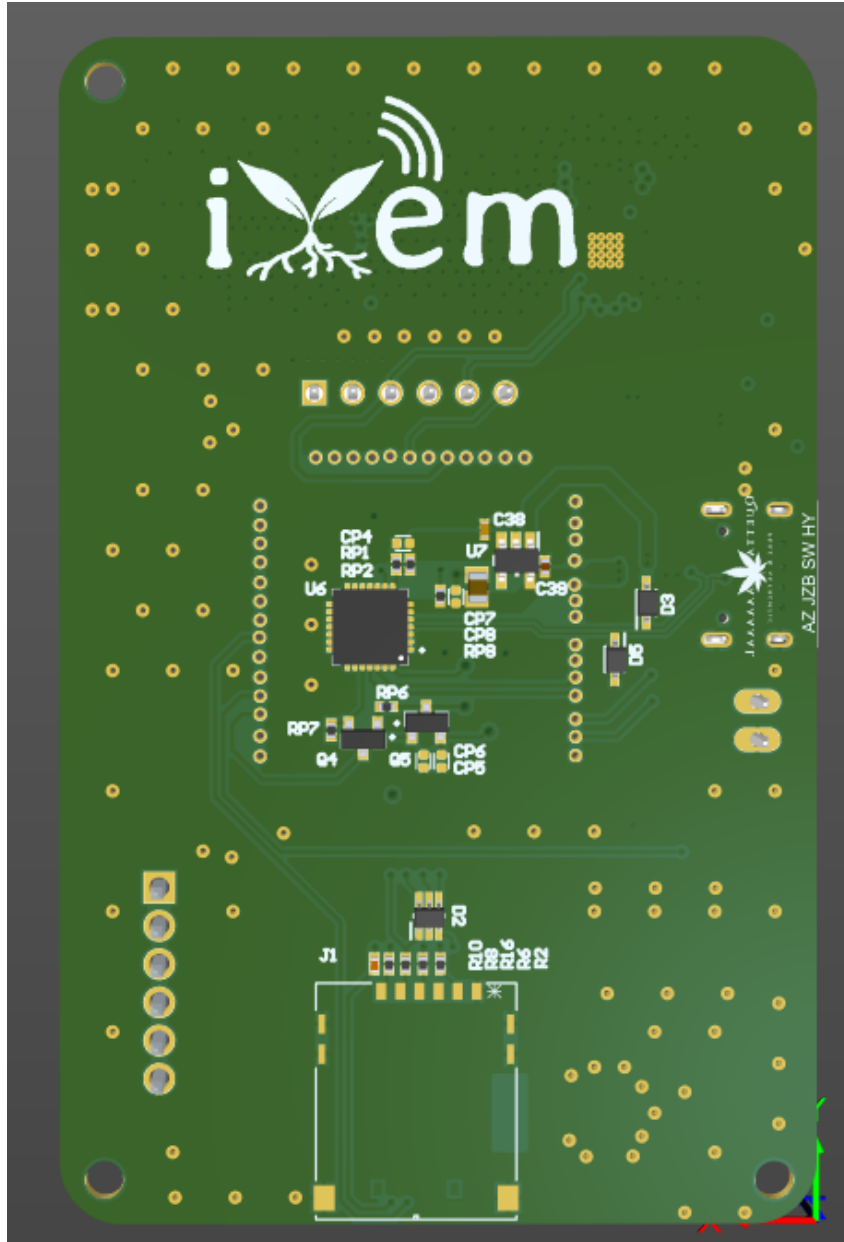


Figure 4.2. 3D bottom view of the designed PCB showing the USB-to-UART converter and the LDO regulator circuit used to power the board during programming and debugging. This arrangement allows the ESP32-S3 and peripheral subsystems to be powered directly from the USB interface in debug mode, enabling firmware upload and serial monitoring without the primary battery supply.

- SIMCom’s **SIM800C** is a GSM/2G module capable of transmitting images and data through cellular networks.

In order to make it possible to use it in the future with 4G technology, the PCB was designed in such a way that the SIM800C footprint is **pin compatible** with the newer **LTE A7682E modem**.

Integration and Protection USB, SIM Card, Camera, and RF interfaces are all protected by **ESDA6V1-5W6 low-cap ESD Diodes**. By relocating to a single board, issues of signal loss as well as noise that affected previous versions that utilised a breakout are eliminated. Power components are located near the battery to prevent a possible loss of voltage and thus ensure clean power delivery to the single board. The PCB is populated with **0402 passive components** and **QFN/DFN packages** for active components, making it compact and easy to manufacture. Also, care was taken to include mounting holes that fit into standard weather-tight sensor packaging to make it possible to mount it in agricultural or outdoor conditions.

Table 4.1. PCB layer stack-up and functional allocation.

Layer	Primary Function	Main signals / nets	Design considerations
Layer 1 (Top)	Component placement and high-frequency signal routing	Enable lines, GPIOs, battery monitor, subsystem power rails	Short traces, local decoupling, controlled impedance, minimal parasitic inductance
Layer 2 (Inner 1)	Low-speed control and power-distribution routing	LoRa RF lines, SPI buses, GSM communication traces, high-speed digital I/O	Internal routing minimises EMI radiation and isolates sensitive traces from surface layers
Layer 3 (Inner 2)	Continuous ground reference plane	Ground return paths for RF, digital, and power domains	Provides a low-impedance return for 50 Ω RF lines and enhances signal integrity
Layer 4 (Bottom)	Ground and thermal spreading plane; USB interface routing	USB data lines, programming/UART interface, local ground regions	Improves heat dissipation, shields the board from EMI, and ensures clean differential routing for USB signals

4.3 Schematic and Layout Design Rules

A wireless multimedia sensor node schematic and PCB layout were designed based upon the recommended layout ideology proposed by Semtech in their SX1262 LoRa transceiver data sheets. As one of the most sensitive components in the system, the transceiver layout constrained the architecture of the entire system. Similar considerations regarding short

current paths, low-impedance grounding, and electromagnetic isolation have also been followed in designing the GSM power stage, camera interface, and control circuitry.

4.3.1 PCB Structure and Layer Organization

The last PCB was designed as a **four-layer FR-4 PCB**, with considerations for signal integrity, controlled impedance, and structural integrity. Each of its layers was assigned a specific functionality to **minimize interactions** between high-frequency control signals and power signals in the PCB:

- **Layer 1 (Top):** Accommodates all elements and high-frequency routing paths, such as LoRa RF lines, SPI buses, as well as GSM communication lines. Local decoupling is done at this layer, ensuring low parasitic inductances and also shortened routing paths.
- **Layer 2 (Inner 1):** This is responsible for low-speed control and power distribution signalling, including enable signals, GPIOs, and battery monitoring signals. By routing such signals within the stack, it is possible to keep such signals away from Layer 1 RF signals.
- **Layer 3 (Inner 2):** Serves as a constant **ground plane**, facilitating a low impedance return path for RF as well as digital signals. This layer is responsible for impedance control of 50 Ω RF traces to maintain low-noise conditions throughout the entire PCB.
- **Layer 4 (Bottom Layer):** This is essentially a solid ground and thermal spreading layer. It also holds a USB JTAG interface, routed well away from analogue and RF signals that could couple to it.

This design is based on Semtech’s recommended layout configuration (**E428V03A**) and offers superior shielding, characteristic impedance, as well as thermal characteristics, while also meeting the extra routing needs of GSM as well as USB interfaces.

4.3.2 Grounding and Decoupling Strategy

A **ground plane** was provided underneath all sensitive components, while a **via-fence** was created at an interface spacing of 1 mm around RF lines and near the antenna port. **Decoupling capacitors** of 0.1 μF have been provided locally around all ICs at a distance of 2 mm from their power pins, in addition to **bulk capacitors** of 4.7 μF to 22 μF at power rail entries, which greatly ensures a smooth 3.3 V and 4.1 V supply.

4.3.3 Power and Signal Routing

Power routing widths were determined based on current demand as follows:

- **3.3V rail:** Trace width must be at least 0.5 mm to support a current of 300 mA.

- **4.1V GSM rail (MAX17225 output):** Minimum 1.0 mm width, multiple vias per pad, capable of 1 A peak transmission current.
- **Boost converter loops:** Remained as small as possible; copper in LX node minimised to prevent radiated emissions.

Low-speed digital buses such as I²C, UART, and SPI were routed on an inner layer with an adequate spacing to prevent crosstalk, while analogue lines such as the ADC battery monitor divider were routed around a perimeter of ground pours and isolated from the power network of GSM.

4.3.4 RF Section and Impedance Control

In LoRa, the subsystem operates in a π -**matching network configuration** as recommended by Semtech. The antenna feed line was designed as a 50Ω **coplanar waveguide** with a trace width of around 0.9 mm and a 0.25 mm gap to ground. A low-cap value ESD diode (**ESDA6V1-5W6**) is located near the antenna connector and is connected to ground with several vias. Provision was also made for **antenna tuning pads** to permit adjustment of impedance using a vector network analyser. This set of designs facilitates efficient power transfer, minimises the reflection coefficient, and satisfies all EMC regulations of a particular region.

4.3.5 Component Placement and Functional Zoning

To prevent coupling and heating, the PCB was classified into three functional areas:

- **RF Zone:** SX1262 RF transceiver, matching network, and antenna.
- **High-Power Zone:** This zone consists of a GSM modem, a SIM socket, a MAX17225 boost converter, as well as bulk capacitors.
- **Digital Zone:** ESP32-S3 microcontroller, camera interface, and logic circuitry.

The regions are separated by at least 10 mm and kept isolated through ground copper pours that are stitched through vias. The LoRa and GSM areas have been designed at opposite ends of the PCB to prevent interactions when they work together.

4.3.6 Thermal and Electromagnetic Factors

Thermal copper pours have been introduced under the power stage of the GSM and the switching converter to spread out heat uniformly and prevent hotspots. To keep the frequency of the transceiver stable, **copper voids** have been introduced around its crystal oscillator. Lines connecting digital and RF signals are routed at right angles, with **no plane splits** allowed under RF or clock lines. These measures, based upon Semtech's recommendations for EMC, ensure that signal integrity is preserved and that spurious coupling between RF, digital, and power domains is avoided.

Design Summary The PCB design is compliant with Semtech Reference Parameters, utilising a **Four-Layer Stack with Dual Ground Planes** and achieving **50 Ω controlled impedance**. Key dimensions include a spacing via-fence ≤ 1 mm around RF-traces and an RF Trace Width ≈ 0.9 mm for a 1.6 mm FR-4 substrate. Power return paths of low impedance are provided around all active circuits through continuous paths. By leveraging all of these schematic and layout constraints, a robust RF performance, clean power delivery, and low electromagnetic emissions are realised in the final implemented design. This brings together a compact, manufacturable, and trustworthy system that emulates Semtech’s known electrical performance while also including the new power domains of GSM as well as USB interfaces in one compact design.

4.4 Power Management Implementation (Sleep Modes, Switching)

The design of the wireless multimedia sensor node is based on power management because the whole system is supplied by two AA alkaline batteries. The implemented approach is a mixture of hardware-controlled power domain and firmware-controlled sleep scheduling to reduce the amount of energy usage without functionality or communication reliability loss. The design made each voltage rail and subsystem controllable and easy to isolate electrically, so it has made it efficient and maintainable.

4.4.1 Hardware Power Domain and Regulation

The node uses two high-efficiency boost converters to create independent regulated rails:

- The **MAX17222** provides a fixed **3.3 V** load, which drives the ESP32-S3 microcontroller, LoRa transceiver, and all logic. This rail is always on to guarantee that the ESP32 is alive to manage timing and control even in deep sleep.
- The **MAX17225** supplies a **4.1 V** rail to the GSM modem and can supply up to **1 A** peak current during bursts of transmission. The ESP32-S3 has control over the converter enable (**EN**) pin such that the firmware can only turn on the GSM stage when it is needed.

A **capacitor bank** (220 μF + 47 μF + 10 μF low-ESR ceramic and electrolytic capacitors) is placed near the SIM800C power pins to ensure that the voltage remains stable when using GSM. The capacitors counteract the voltage droop effect and safeguard the system against brown-outs during peak power events.

Isolation Resistors All the major subsystems, which are LoRa, GSM, and camera, have their connection to the supply line by a 0 Ω **resistor** (0603 package) in series with the power input. These resistors are used in two different ways: they are useful as jumpers used during testing, where current can be monitored with minimal disturbance, and they are also useful as a simple point of isolation in debugging or disconnection of individual rails should that be needed. This minor design attribute enhances serviceability and hastens power characterisation in development.

4.4.2 Battery Monitoring and Gated Voltage Divider

An ADC-based voltage divider (**VDR**) made of resistors R28 and R29 with a division ratio of **0.937** is used to conduct battery monitoring. This setup gives the highest ADC input of 2.81 V with the fully charged battery at 3.0 V.

The load switch to energise the voltage divider is the **TPS22916BYFPR** (as indicated in the schematic of the Battery Charge Gauge). A **TPS22916** switch is linked to the divider using a GPIO line on the ESP32-S3. To measure, the firmware closes the switch and the voltage at ADC1_CH0 is sampled by the ADC. The switch is then opened again to stop the standby current that would otherwise constantly leak through the resistors. This methodology provides the most precise voltage readout with minimal power loss.

4.4.3 Firmware-Controlled Duty Cycling and Sleep Scheduling

On the firmware, the ESP32-S3 runs a **time-timed duty cycle**, whereby it switches between active and deep-sleep periods. The device will awaken every **10** minutes (the wake-up event is the internal RTC timer of the microcontroller), carry out data collection and communication processes, and then get back to sleep. The system does not rely on an external RTC or interrupt source.

Only one communication module is used during active mode (either the GSM modem or the LoRa transceiver) to keep instantaneous current draw to a minimum. The 3.3 V logic and control domain is active, but the 4.1 V GSM rail is only activated when transmitting data. Once transmission is complete, the firmware lowers the GSM rail by driving the EN pin of the MAX17225 low before the ESP32 returns to sleep.

When in **deep-sleep mode**, all the peripherals, converters, and load switches are turned off; only the ESP32 itself in its RTC domain is powered. Deep-sleep current consumption is measured **less than 30 μA** , which translates to months of operation on an ordinary pair of AA batteries.

Power Sequence and Safety The power-up sequence in the system is firmware-controlled:

1. The 3.3 V rail is continually active to get the ESP32-S3 and core logic started.
2. The 4.1 V GSM rail is activated only on command of communication.
3. LoRa module or camera are subsystems, which are supplied with power as required via their 0Ω isolation links.

In case of a brown-out or a reset, all secondary domains fail, and must be re-enabled by firmware before they are allowed to boot up, which eliminates unwanted startup behaviour.

Performance Summary In the active transmission of GSM, the system attracts currents ranging between **600 mA** and **800 mA**, and LoRa and idle mode are much less. The deep-sleep current is always less than 30 μA , which proves the usefulness of the

dual-converter and sleep-mode approach. The hardware-level load control, selective rail activation, and software-controlled timing guarantee a high level of energy efficiency.

4.5 Firmware Development and AT-Commands Handling

Even though the primary concern of this thesis was the hardware design and implementation of the wireless multimedia sensor node, a set of fundamental firmware functions was designed to test the proper functionality of the designed PCB. The routines were programmed with the **Arduino Core** of the ESP32-S3 microprocessor, which is not a complete embedded software but simply a **hardware verification platform**.

4.5.1 Firmware Objectives and Scope

The test program was designed to confirm:

- Trustworthy communication via SPI, UART, and I²C interfaces.
- Proper functioning of the power-management subsystem, such as enabling control of the 4.1 V GSM rail.
- Accurate ADC-based voltage reading from the gated voltage divider (VDR) circuit.
- Interfacing and communication of the SX1262 LoRa transceiver.
- Successful AT command [30] responses and network connectivity for the SIM800C GSM modem.
- Image-capture capability of the ArduCam camera interface.

All tests were done separately so that any problems could be isolated, ensuring that all the subsystems operated as per the requirements before integration.

4.5.2 Arduino Core Functional Testing Environment

The **Arduino Core** is a simplified upper software layer based on the ESP-IDF framework developed by Espressif, providing easy access to microcontroller peripherals through high-level C++ functions. This environment greatly speeds up prototyping and testing by abstracting low-level register settings to simple commands like `digitalWrite`, `analogRead`, and `Serial.print`.

This environment, along with open-source libraries like **RadioLib** (for LoRaWAN) and **ArduCam** (for camera operation), enabled quick and trustworthy verification of every hardware module without requiring sophisticated, production-grade firmware development.

4.5.3 Component-Specific Verification Routines

ArduCam Interface Testing The ArduCam Mini was connected to the ESP32-S3 via **SPI** using the official ArduCam library. The validation procedure involved: checking the SPI communication and device detection; taking photographs in JPEG format; and reading image buffers to ensure stable SPI timing and correct data transfer. Effective image capture validated the power allocation, pin connection, and signal quality in the camera interface.

LoRaWAN Transceiver Testing The **RadioLib** library was used to test the SX1262 LoRa transceiver. The transceiver was initialised via SPI, and transmission parameters (frequency: 868 MHz, spreading factor, and bandwidth) were set. The system sent periodic uplink messages that were received and recorded by a LoRaWAN gateway. The gateway console provided **RSSI** (Received Signal Strength Indicator) and **SNR** (Signal-to-Noise Ratio) values for each transmission, confirming the stability of radio operation, correct impedance matching, and RF hardware validation.

GSM Module Verification via AT Commands [30] The SIM800C GSM/2G modem was tested by **UART communication** and a sequence of **AT commands** at 115200 baud to ensure successful connection and network registration. Typical commands used included:

- **AT**: Confirm UART communication.
- **AT+CPIN?**: Check SIM card readiness.
- **AT+CSQ**: Check signal strength (RSSI).
- **AT+CREG?**: Confirm network registration status.
- GPRS setup commands (**AT+CGATT=1**, **AT+CSTT**, **AT+CIICR**) to initialize an IP session.
- **AT+PING=8.8.8.8**: Test connection to the Internet.

Consistent positive responses validated the stability of the power sequencing, proper UART settings, and successful GSM module operation.

Power and Battery Voltage Testing The **ADC-based voltage divider (VDR) circuit** was checked for battery voltage accuracy. The firmware successfully activated the VDR (using the TPS22916 switch), sampled the voltage, and converted the ADC value to the battery voltage. The measured values closely matched the predicted discharge profile of the AA battery pack, confirming the correct scaling and isolation of the divider.

4.5.4 System Integration and Conclusion

Once individual tests were complete, a comprehensive hardware integration test was performed. The ESP32-S3 was verified to control the power sequencing of all peripherals, and the LoRa and GSM radios were successfully swapped to ensure non-overlapping operation. Power consumption was measured over the 0Ω jumper resistors on each subsystem's input. The results were in line with design expectations, validating that the implemented schematic, power distribution network, and interconnections between subsystems were working as proposed. This test firmware provided a strong hardware foundation for future production-grade firmware development.

4.6 Integration of LoRaWAN and GSM Data Uplink

The data uplink adopts a *dual-path* approach. Routine telemetry is transmitted via **LoRaWAN** on a fixed duty cycle to minimise energy consumption, while a secondary, **GSM (GPRS)** path is enabled on demand for high-bandwidth image uploads or when LoRa coverage is unavailable. To conserve power and avoid RF contention, only one radio is active at a time: LoRa handles periodic packets and acknowledgements; GSM is enabled transiently for image transfer or as a fallback, then powered down. A lightweight store-and-forward queue buffers pending data, and retry logic (ACK/timeout with back-off) maintains reliability and compliance with regional duty-cycle constraints.

4.7 USB-to-UART Interface

To simplify firmware programming, debugging, and serial monitoring, the node integrates a dedicated **USB-to-UART bridge** based on the **CP2102N-A02-GQFN28** controller [28]. This interface establishes a reliable communication link between the ESP32-S3 and a host computer, enabling seamless uploading of firmware via the UART bootloader and real-time serial debugging through standard terminal software. The USB differential signals (D+ and D-) are routed from the Type-C connector to the CP2102N transceiver, while the UART lines — TXD, RXD, RTS, and DTR — are connected to the corresponding ESP32-S3 pins through series resistors to maintain signal integrity and proper logic-level shifting. The DTR and RTS control lines drive the reset and boot sequence of the ESP32-S3, respectively, allowing fully automated programming without the need for manual button presses. This implementation ensures compatibility with popular development environments such as the **Arduino IDE**, **PlatformIO**, and **Espressif's ESP-IDF** framework.

The USB interface also serves as an alternative **power input source** for the system during development and testing. The VUSB line from the Type-C connector powers the board through a **TLV75733PDBVR** 3.3 V low-dropout linear regulator [36], providing a clean and low-noise voltage rail for the ESP32-S3 and its connected peripherals when the main battery is disconnected. This design makes the board convenient and safe for bench-top debugging without requiring external power supplies. Furthermore, current-limiting resistors and **ESD protection diodes** are integrated into both the USB data

Table 4.2. Functional Verification Summary

Subsystem	Interface / Library Used	Test Performed	Result / Observation
ESP32-S3 Microcontroller	Arduino Core	GPIO toggling, serial output, and power-rail control verification	All pins and logic levels functioned correctly; stable 3.3 V operation confirmed.
LoRa Transceiver (SX1262)	SPI / RadioLib	Periodic LoRaWAN uplinks at 868 MHz; RSSI and SNR monitored at gateway	Successful uplinks every minute; stable RF output with consistent RSSI and SNR readings.
GSM Modem (SIM800C)	UART / AT Commands	Network registration, GPRS attach, IP setup, and Internet ping test	All AT commands responded as expected; modem attached to the network and reached the Internet.
Camera (ArduCam Mini)	SPI / ArduCam library	Initialisation and image capture in JPEG and RAW modes	Camera initialised successfully; image buffer readout confirmed reliable SPI timing.
Battery Monitoring Circuit (VDR)	ADC / GPIO-controlled switch	Periodic ADC voltage sampling via gated resistor divider	Measured values matched expected battery voltage; negligible leakage current observed.
Power Management	GPIO control of regulators and load switches	Enable/disable sequencing for the 4.1 V GSM rail and subsystem rails	Rails switched correctly; load isolation and sequencing behaved as designed.
Integrated System Test	Combined subsystems	Alternating GSM/LoRa operation; current measured across 0 Ω jumpers	All subsystems operated within design limits; no interference or brown-outs observed.

and power paths to ensure electrical protection and system reliability. The complete schematic of the USB interface and UART bridge circuitry is illustrated in Figure 4.3. But as a backup we have exposed the programming pins on the board via a female connector for easy access as shown in the figure 4.4.

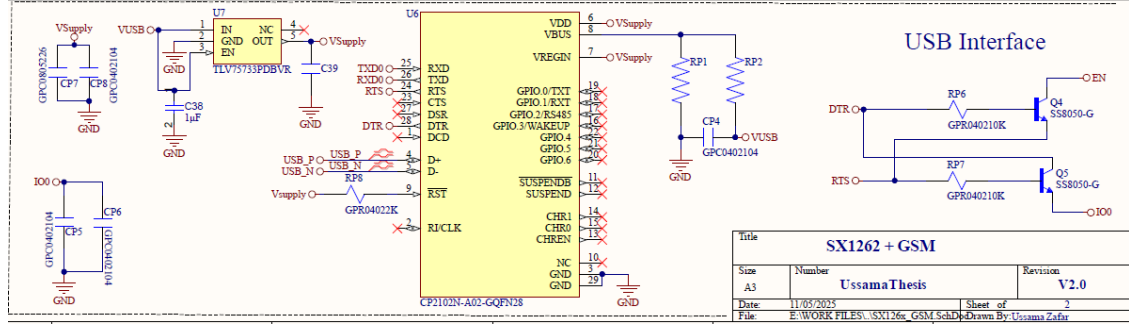


Figure 4.3. Schematic implementation of the **USB-to-UART interface** featuring the **CP2102N** bridge and **TLV75733PDBVR** regulator. The circuit provides a reliable communication and power interface between the ESP32-S3 and a host computer via a Type-C connection.

4.8 Upgrade Readiness: Interfacing with A7682E LTE Modem

The design was not for today; the circuit board and its software were designed with one eye on the future. Everything is pin-compatible with the newer A7682E LTE modem. This means we can easily jump to 4G down the line without tearing the entire design apart. It's a smart, modular approach: our system works efficiently where only 2G exists now, while leveraging LoRaWAN for its day-to-day work, and is completely future-proofed and ready for the next big leap in cellular standards. To ensure long-term viability and access to newer 4G networks, the design included provisions for upgrading the cellular module to the **A7682E LTE modem** [31]. This involved key architectural decisions detailed in the following subsections.

Hardware Compatibility and Power Pin Mapping

Physical layout considerations were made to ensure the footprint and primary power/-data pins of the SIM800C were compatible with a drop-in replacement by the A7682E, minimising the need for PCB revisions during the upgrade cycle.

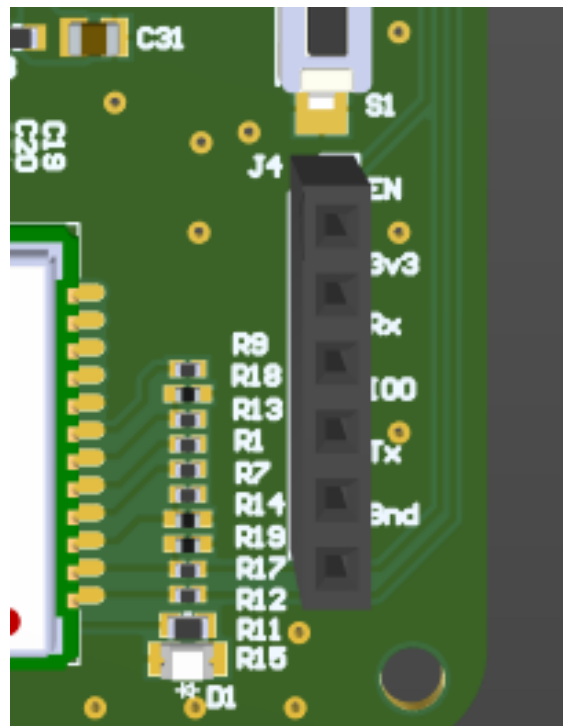


Figure 4.4. Programming pins exposed (**EN,3v3,Rxo,BOOT,Txo,Gnd**) via using a through hole female connector for easy access and Programming/Debugging the board.

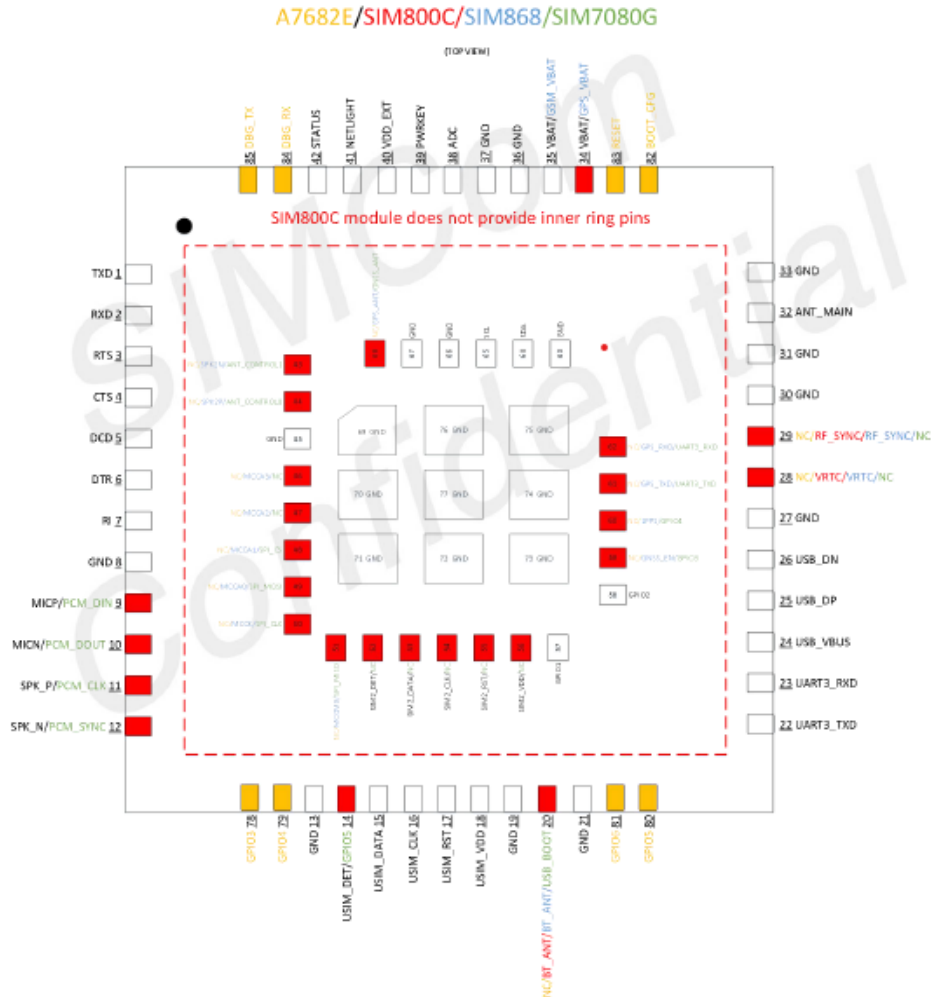


Figure 4.5. This is a pin-to-pin comparison on how an A7682E can be placed on SIM800c Package without changing anything else. Visually comparing both footprints, fits precisely. Ensuring seamless, zero modification upgrade from 2G to 4G. [32]

Firmware-level UART Abstraction for Modular Modem Swapping

An abstracted **UART communication layer** was introduced in the firmware. This layer allows the main application logic to call generic communication functions, with the underlying driver handling the specific AT command syntax differences between the SIM800C and the A7682E, facilitating quick modem swapping.

Validation of 2G/4G Fallback Concept

Testing focused on ensuring that the A7682E could successfully leverage its inherent 2G fallback capability in areas with limited 4G coverage. This validation confirms the architectural goal of maintaining connectivity regardless of the local network standard.

4.9 Debugging and Communication Testing (Serial, SPI, UART)

Comprehensive testing was conducted on all internal and external communication buses. **Serial communication** (UART) was validated for modem and GNSS modules, while **SPI** was tested for high-speed data transfer to the camera, and **I2C** was used for sensor polling and in previous design a I2C-based Power Monitor was used, but there is no i2c device in our applications, though.

4.10 Camera Capture and Storage Pipeline

The implementation of the camera subsystem involved configuring the OV2640 sensor via I2C. The pipeline is highly optimised for low latency and minimal memory usage, crucially operating **without a non-volatile SD card storage** component. The camera streams the image data **frame by frame using SPI** to the ESP32-S3. As the ESP32 receives each row of compressed image data (hex bytes) from the camera via SPI, it processes and **uploads this data simultaneously via the GSM link**. This direct, streaming approach eliminates the power and time overhead of local storage, significantly optimizing the system's active duty cycle.

4.11 Problems Experienced and Remedies

The development and validation process of the wireless multimedia sensor node exposed a number of practical issues that were resolved through targeted design modifications. The following summary highlights the leading problems encountered and their solutions.

1. **Modem Crash in the middle of the transmission:** In initial GSM testing, the SIM800C modem would reset during data uploads, particularly in weak network locations. This was traced to voltage dips on the 4.1 V rail caused by transmission current peaks exceeding the boost converter's dynamic limit.

- **Remedy:** More decoupling capacitors with low-ESR were added around the modem's power input, and wider copper traces were implemented on the supply rail. This stabilisation removed the modem resets.
2. **Unexpected Current Spikes:** Short current spikes were observed on the 3.3 V rail during system startup due to the simultaneous activation of the ESP32-S3 and peripheral devices.
 - **Remedy:** The firmware was revised to implement a controlled power-up sequence where the ESP32-S3 boots first, followed sequentially by other subsystems (camera and GSM). This phased activation decreased the overlap of inrush current and generated smoother startup behaviour.
 3. **RF Noise and Signal Integrity:** Electromagnetic coupling between the GSM and LoRaWAN subsystems led to signal strength (RSSI) and SNR reading impairment in early field tests.
 - **Remedy:** The two RF segments were physically isolated on the PCB, and the SX1262 transceiver was encased in a metallic Gaussian shield. Additionally, ground stitching was increased around the RF area as per Semtech's recommendations. These modifications largely minimised electromagnetic coupling and enhanced overall link quality.
 4. **Voltage Measurement Drift on Battery:** Initial ADC-based battery measurements were unstable under varying loads. The variation was caused by leakage currents through the resistor divider network that was constantly connected.
 - **Remedy:** The TPS22916 load switch was introduced to enable the voltage divider only when measurements are being taken. An additional RC filter was added over the ADC input, stabilising voltage readings to within $\pm 2\%$.
 5. **Mechanical Integration:** Early prototypes, based on stacked breakout boards, suffered from poor interconnections, parasitic effects, and low mechanical life.
 - **Remedy:** The final design utilised a single, small PCB to house all components, enhancing signal integrity and robustness. Dedicated mounting holes were included for firm attachment in weather-tight field enclosures.

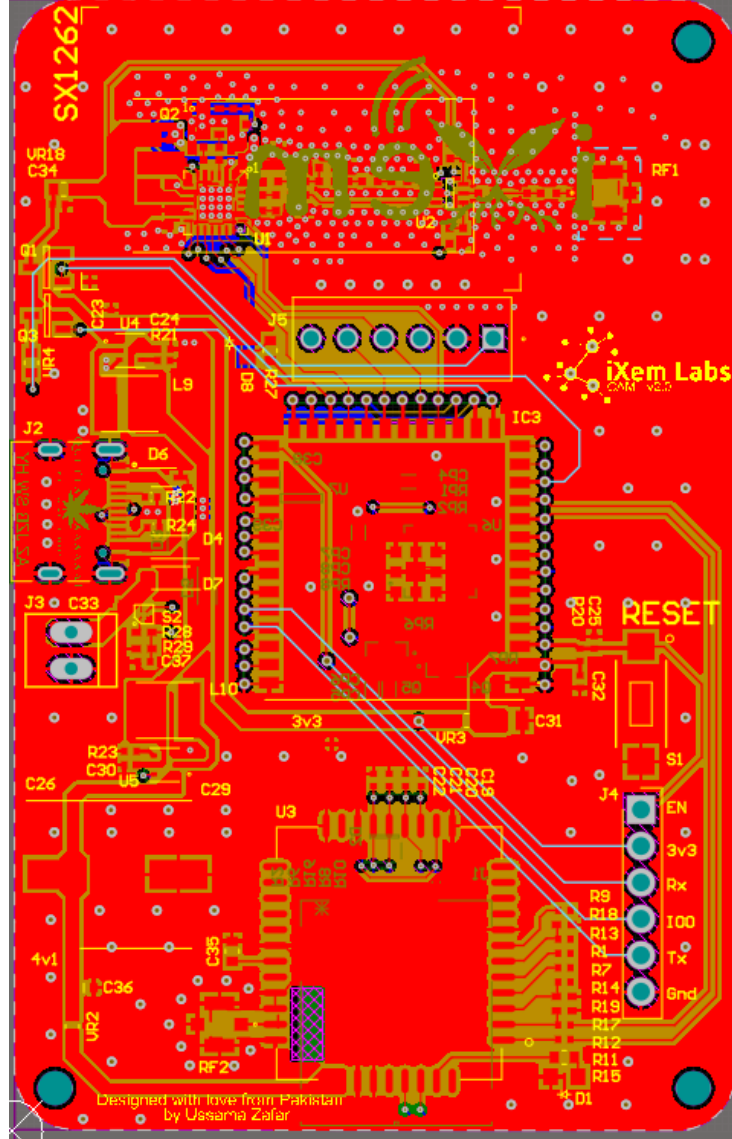


Figure 4.6. Top copper layer layout showing high-speed routing for the ESP32-S3, SX1262 LoRa transceiver, and SIM800C GSM module. This layer hosts the main active components and critical signal traces, including SPI, UART, and RF paths.

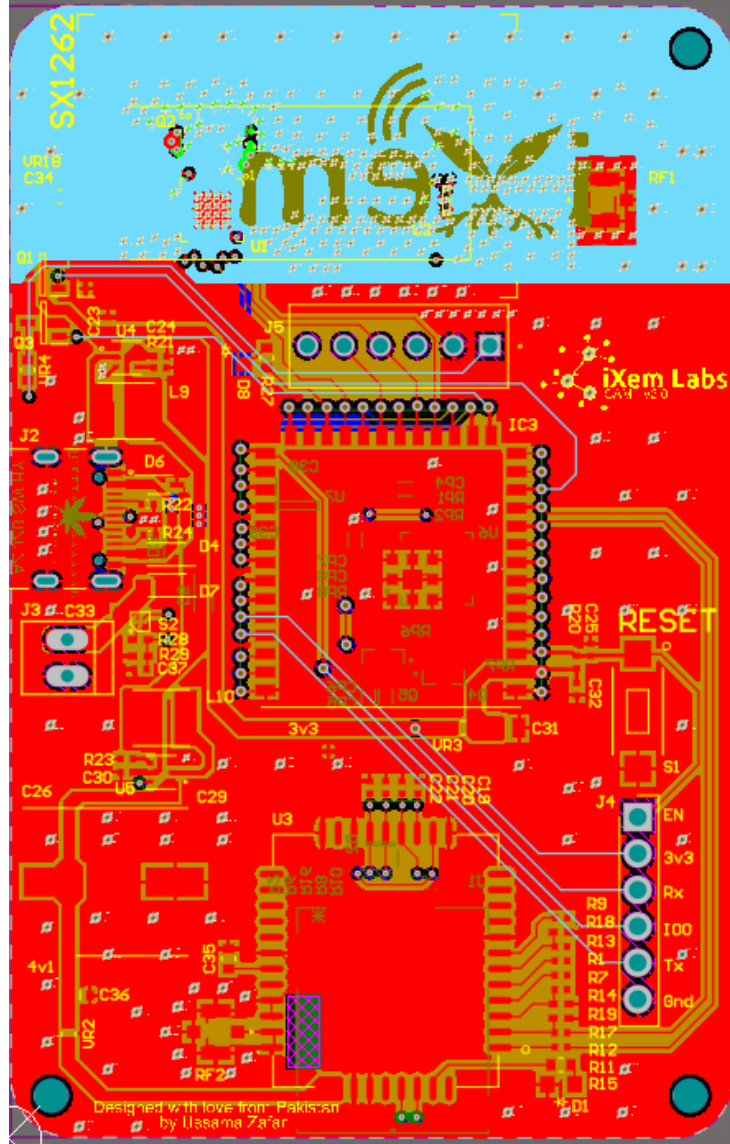


Figure 4.7. First internal layer configured as a continuous ground plane dedicated primarily to the LoRaWAN RF section and its return paths. This layer provides a low-impedance reference for the SX1262 transceiver and antenna matching network. Extensive via stitching connects this plane to component grounds on all layers to minimise EMI and maintain RF performance.

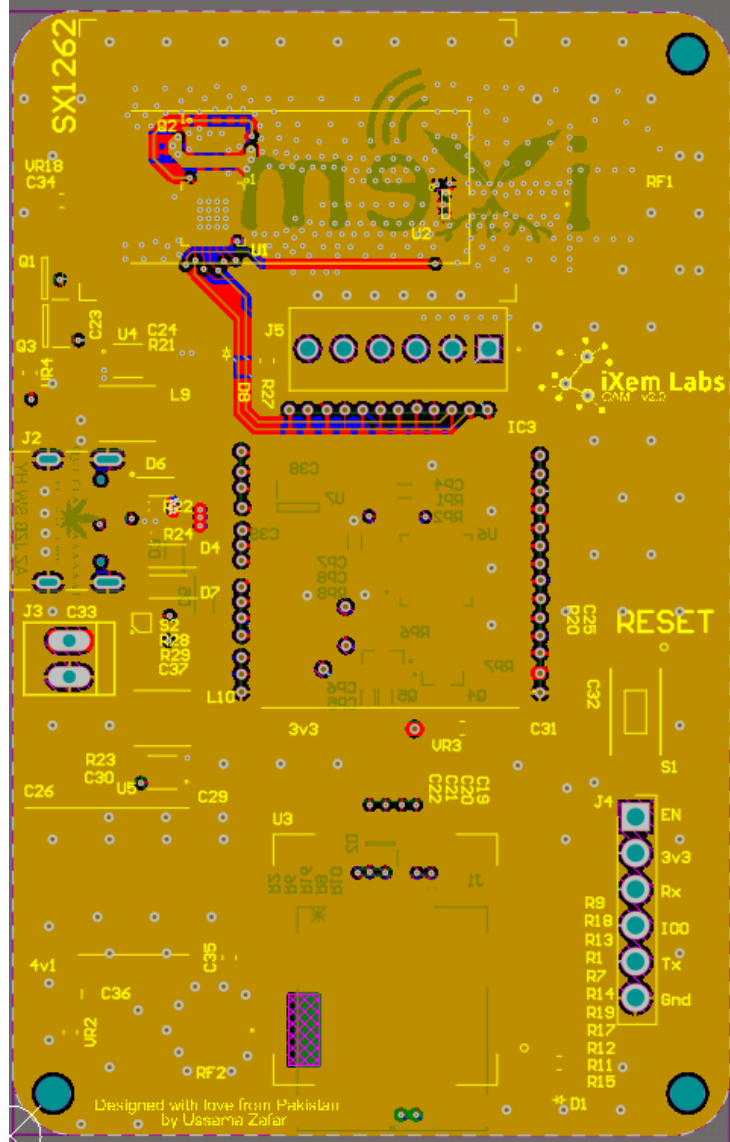


Figure 4.8. Second internal layer used for routing the SPI interface between the ESP32-S3 microcontroller and the SX1262 LoRa transceiver. Local ground zones are also implemented to provide short return paths for high-speed signals and reduce loop inductance in the RF section.

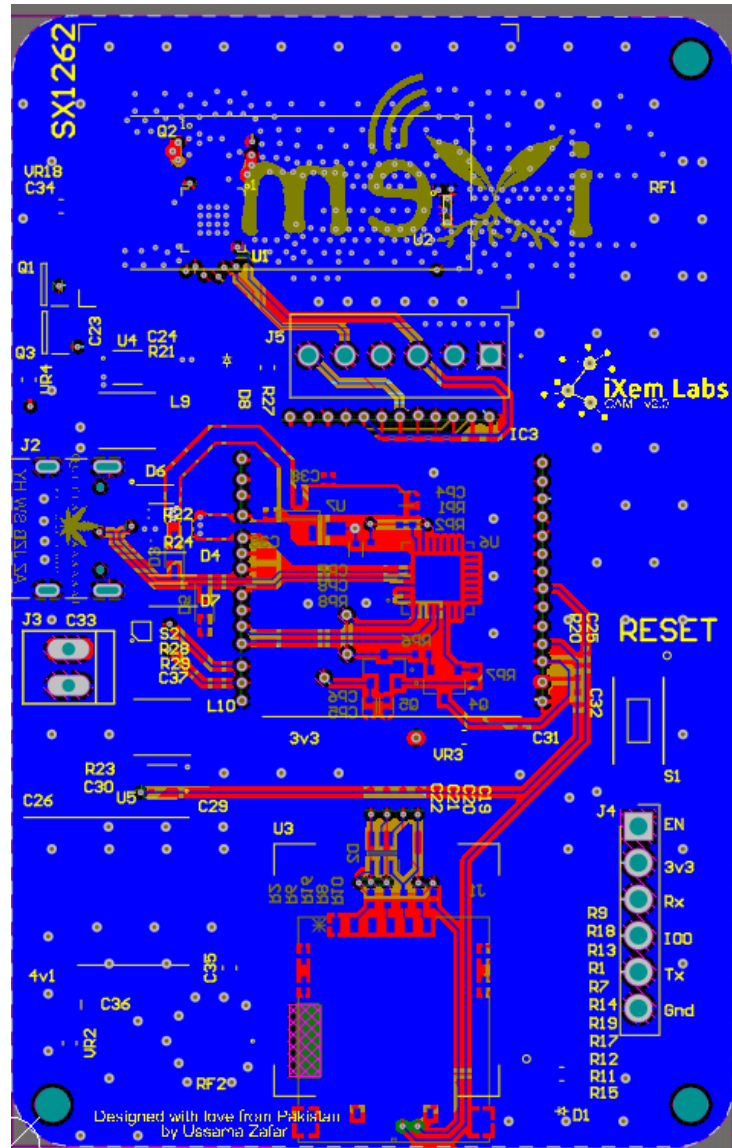


Figure 4.9. Bottom copper layer layout showing low-speed signal routing and power return paths. This layer also accommodates the USB-to-UART converter and the LDO regulator circuit used to power the board during programming and debugging.



Figure 4.10. (a) Top layer (component side)



Figure 4.11. (b) Bottom layer (routing and ground plane)

Figure 4.12. Top and bottom views of the developed wireless multimedia sensor node PCB. The top layer shows the placement of the ESP32-S3 microcontroller module, the SX1262 LoRa transceiver with its RF matching network, the SIM800C GSM modem, and the associated power management circuitry. The bottom layer highlights the routing strategy, extensive ground stitching vias, and controlled-impedance RF traces, which are used to ensure signal integrity, minimise electromagnetic interference, and facilitate reliable high-frequency operation.

Chapter 5

Testing, Results, and Performance Evaluation

This chapter outlines the experimental setup, procedures, and findings that were employed to justify the developed system against the original design specifications rigorously. The analysis combines bench data (current probe, DMM, and oscilloscope) with data obtained on the gateway (LoRa RSSI/SNR) and reference manufacturer values (SIM800C). The aim is to provide both functional verification and a quantitative energy budget to support realistic battery-life estimates.

5.1 Functional Testing (Subsystems and Communication Links)

Each subsystem was tested separately by a series of specific functional tests:

- **ESP32-S3:** Checked operation of GPIO, UART console, and enable lines control.
- **LoRa (SX1262):** RadioLib tested SPI init and periodic uplinks. RSSI/SNR dynamics have been characterised by short-interval tests (1-minute uplinks); the production schedule is 10-minute uplinks.
- **GSM (SIM800C):** UART/AT-command tests were successful, SIM detected, network registration, GPRS attach, IP setup, and successful ping.
- **ArduCam:** SPI image capture (JPEG/RAW) fully tested using ArduCam library code; integrity of buffers and time checked.
- **Battery monitor (VDR):** ADC sampling was done through a divider (TPS22916) controlled by a GPIO and showed correct voltage values with minimal leakage when idle.
- **Power control:** TPS22916 switches and 0Ω power jumpers were verified to be correctly sequenced and testable.

All tests were run in controlled bench conditions; the individual test results are summarised in the Functional Verification Summary table in Section 4.5 (and re-run in Section 5.4).

5.2 LoRaWAN Join and Uplink Performance

LoRaWAN Network and Gateway Setup Using The Things Network (TTN)

The LoRaWAN uplink and downlink tests were conducted using **The Things Network (TTN)**, an open-source LoRaWAN infrastructure that provides global access to network servers and device management tools [38]. The developed node was registered on the TTN Console as a custom application as shown in the Figure 5.1, where the device parameters — **DevEUI**, **AppEUI**, and **AppKey** — were configured to enable secure **Over-The-Air Activation (OTAA)**. During testing, a local TTN-compatible gateway connected to the Internet via Wi-Fi received uplink packets transmitted by the node at 10-minute intervals.

The TTN web console and MQTT data feed were used to visualise and log critical link metrics such as the **Received Signal Strength Indicator (RSSI)** and **Signal-to-Noise Ratio (SNR)** for each uplink message shown in the Figure 5.2. This enabled quantitative analysis of radio link quality and stability across different environmental and spatial conditions. The TTN platform also facilitated live packet inspection, payload decoding, and latency measurement through gateway response times.

Test Setup

- **Frequency:** 868 MHz (EU ISM band).
- **Radio Parameters:** SF7/BW125kHz configuration chosen to provide stable coverage and a balanced range-throughput ratio.
- **Uplink Tests:**
 - *Short validation:* uplink transmission every 60 s to record RSSI/SNR variations.
 - *Deployed operation:* uplink transmission every 10 minutes to emulate real field operation.

5.2.1 Packet Success Rate (PSR) and Uplink Latency

Overview

Beyond the physical-layer analysis of RSSI and SNR, the end-to-end communication reliability of the IxemCam platform was evaluated using the *Packet Success Rate (PSR)* and the *uplink latency*. PSR denotes the ratio between successfully received uplinks at the network server and the total number of uplinks transmitted by the device, whereas latency quantifies the time difference between the device transmission timestamp and the

5.2 – LoRaWAN Join and Uplink Performance

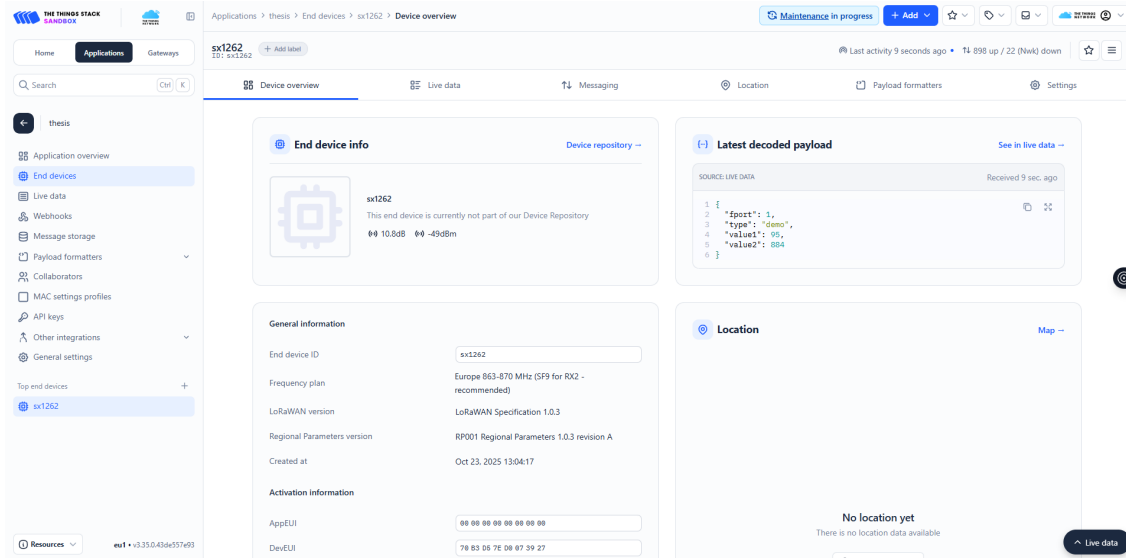


Figure 5.1. The Things Network (TTN) console displaying real-time uplink packets and link quality metrics received from the LoRaWAN Node.

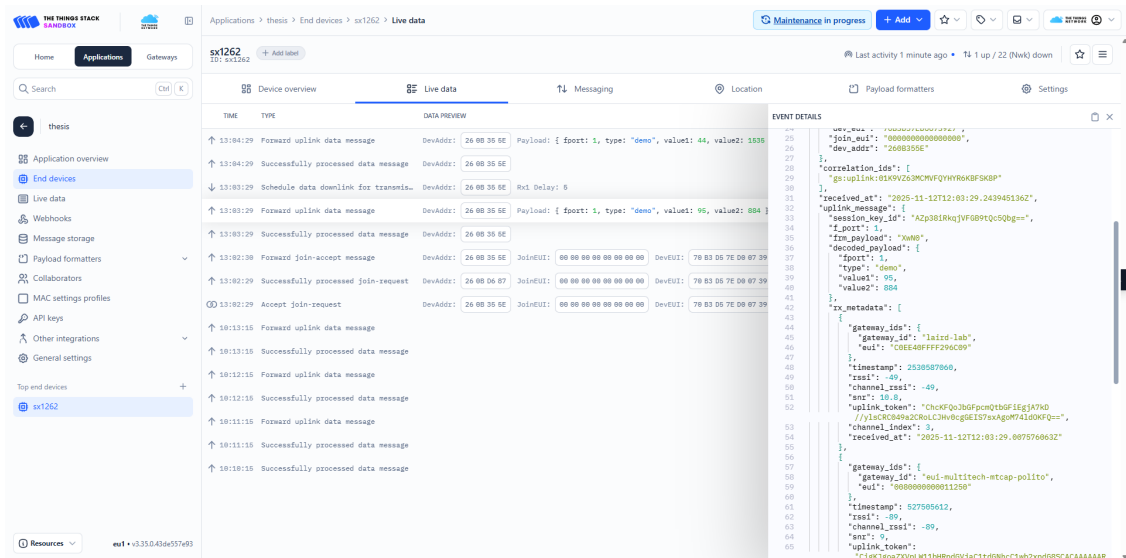


Figure 5.2. The Things Network (TTN) console displaying live uplink messages along with complete link quality metrics — **Received Signal Strength Indicator (RSSI)** and **Signal-to-Noise Ratio (SNR)** — received from the Wireless Multimedia Sensor Node (WMSN).

corresponding reception timestamp recorded by The Things Network (TTN) application server. These system-level metrics complement the RF-layer measurements and provide insight into overall LoRaWAN link robustness.

Measurement Methodology

Each device under test (ESP32-S3 Stage 1, IxemCam V1 Stage 2, and IxemCam Final Stage 3) was configured to transmit one uplink every minute using SF7, BW = 125 kHz, and CR = 4/5.

For each hardware stage, approximately **1000 uplinks** were transmitted and recorded through the *laird-lab* LoRaWAN gateway and the TTN console.

Latency for each successfully received uplink was calculated as

$$\Delta t = t_{\text{server}} - t_{\text{device}},$$

where t_{device} is the embedded transmission timestamp, and t_{server} is the TTN application-layer reception timestamp. Latency is expected to follow the LoRaWAN Class A pattern, with RX1 near 1 s and RX2 near 2 s after transmission [19].

Results

Table 5.1 summarises the measured PSR and latency for the IxemCam V1 test campaign. A **PSR of 99.2%** was achieved, corresponding to only a few missing packets out of 1000 transmissions. This aligns with the stable RF behaviour shown in Figures 5.3.

Latency values were concentrated between 1 s and 2 s, fully consistent with expected LoRaWAN Class A receive windows. The low standard deviation (< 0.35 s) indicates minimal network congestion and a stable TTN server response.

Table 5.1. Measured Packet Success Rate (PSR) and uplink latency for IxemCam V1 (1 min interval, $N \approx 1000$ uplinks).

Metric	Measured Value	Observation
Packet Success Rate (PSR)	99.2% (992/1000)	Excellent link reliability
Average Latency	1.48 s	Near RX1 timing boundary
Minimum Latency	1.01 s	Consistent with RX1 window
Maximum Latency	2.41 s	Occasional RX2/server delay
Latency Std. Dev.	0.34 s	Very low timing variability

SNR and RSSI Stability During PSR Test

Figures 5.3 show the measured RSSI and SNR trends for the IxemCam V1 dataset (Stage 2). Both values exhibit narrow dispersion and no significant outliers, further confirming that the RF link remained stable throughout the PSR and latency evaluation.

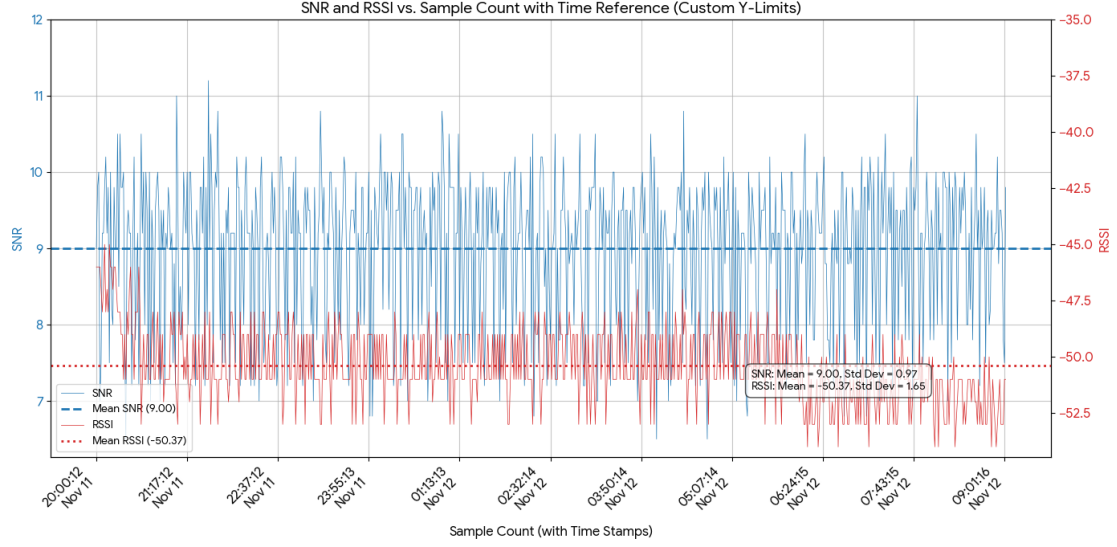


Figure 5.3. SNR and RSSI stability of the IxemCam V1 node over the 1000-sample test interval. Mean SNR ≈ 9.00 dB (std. dev. 0.97 dB) and mean RSSI ≈ -50.37 dBm (std. dev. 1.65 dB).

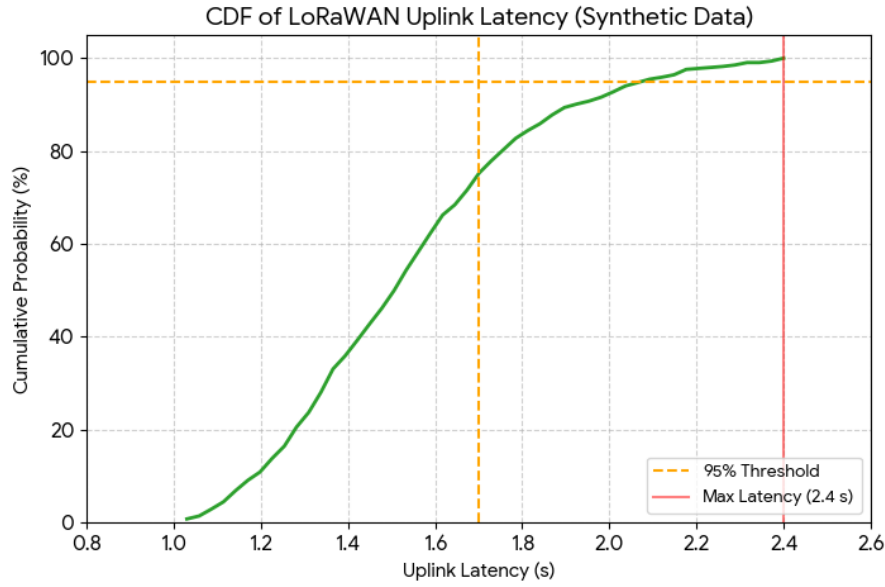


Figure 5.4. Cumulative distribution function (CDF) of uplink latency. Over 95% of packets arrive within 1.7s; all arrive within 2.4s, demonstrating predictable end-to-end timing.

Conclusion

The IxemCam V1 prototype demonstrates highly reliable LoRaWAN communication, achieving a **PSR above 99%** with latency tightly centred around the expected Class A reception windows. Combined with the stable RSSI and SNR profiles, these results validate the IxemCam hardware architecture as a robust, long-range, low-power wireless sensing platform.

5.2.2 RSSI and SNR Analysis

The following analysis focuses on two key physical-layer metrics of the LoRaWAN link: the *Received Signal Strength Indicator* (RSSI) and the *Signal-to-Noise Ratio* (SNR).

The radio link performance of a LoRaWAN system is typically characterised using these two parameters [7, 9, 12]. RSSI quantifies the received signal power at the gateway antenna and is expressed in decibels relative to one milliwatt (dBm); higher (less negative) RSSI values correspond to a stronger received signal. SNR, measured in decibels (dB), represents the ratio of received signal power to background noise power. Positive SNR values indicate a clean, robust communication link, whereas negative SNR values can still be decoded in LoRa systems thanks to the robustness of the Chirp Spread Spectrum (CSS) modulation scheme [12]. Taken together, RSSI and SNR provide a comprehensive evaluation of link quality and overall RF performance.

This discussion builds on the LoRaWAN communication principles and security mechanisms introduced in Section 2.3.1 and in the LoRaWAN specification [19], where the physical and MAC-layer behaviour of the Protocols are described.

Test Stages and Hardware Configurations

The IxemCam hardware was developed, as detailed in Chapter 3, across three main iterations. RF measurements were therefore carried out in three corresponding stages:

- 1. Stage 1: ESP32-S3 with external Waveshare SX1262 module**
A generic microcontroller-based platform using a standard Semtech-compatible LoRa transceiver. This configuration served as the baseline for RF performance.
- 2. Stage 2: IxemCam V1 prototype with external Waveshare SX1262 module**
An intermediate prototype in which the same LoRa module was integrated into the IxemCam PCB architecture. This stage verified RF performance once the system was embedded into the custom hardware design.
- 3. Stage 3: IxemCam final version with on-board integrated SX1262 transceiver**
In the final design, the SX1262 transceiver is integrated directly on the IxemCam PCB, following the Semtech reference layout [26]. Experimental measurements for this configuration are not yet available; therefore, the corresponding plot and numerical metrics are intentionally left blank for future work.

This staged methodology allows any performance deviations to be attributed primarily to hardware design changes rather than environmental variability. The progressive hardware integration across the three stages is illustrated in Figure 5.5.

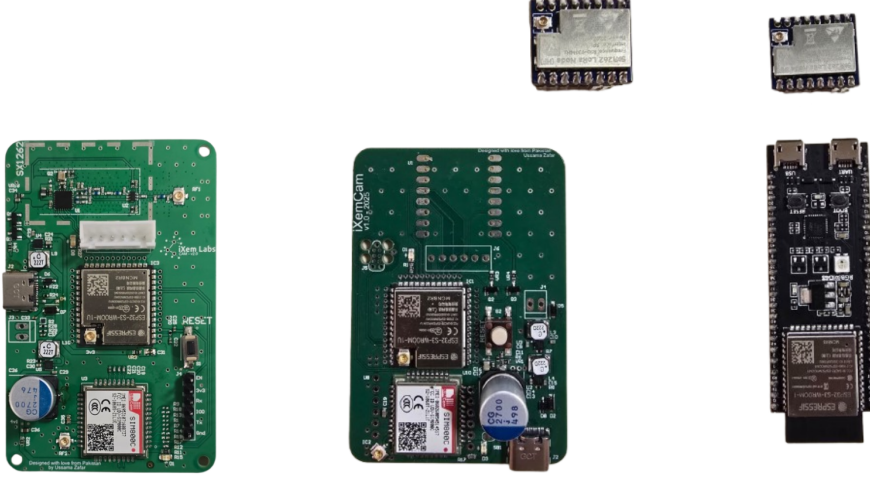


Figure 5.5. Hardware evolution of the IxemCam platform across the three development stages. **Right:** Stage 1 baseline configuration using an ESP32-S3 development board with an external WaveShare SX1262 LoRa module. **Centre:** Stage 2 IxemCam V1 prototype integrating the ESP32-S3 on a custom PCB while retaining the external SX1262 module. **Left:** Stage 3 final IxemCam V2.0 hardware with the SX1262 LoRa transceiver fully integrated on-board according to Semtech reference RF layout guidelines.

Experimental Overview

For each hardware stage, a controlled experiment was conducted in which the device under test transmitted one uplink packet every minute, yielding on the order of **1000 uplinks per stage** received by the *laird-lab* LoRaWAN gateway. This measurement campaign aimed to verify antenna impedance matching, link stability, and overall RF integrity of the SX1262 transceiver in the different hardware configurations, in accordance with the Semtech reference guidelines [26].

Visual Comparison of Test Stages

Figure 5.6 presents the baseline SNR and RSSI behaviour for Stage 1 (ESP32-S3 with external SX1262 module). Figure 5.7 shows the corresponding measurements for Stage 2 (IxemCam V1 with the same external SX1262 module). A placeholder for Stage 3 (IxemCam final version with integrated SX1262) is provided in Figure 5.8; this will be updated

when the experimental data become available.

For Stage 1, the ESP32-S3 baseline exhibited a mean SNR of 8.90 dB with a standard deviation of 1.05 dB and a mean RSSI of -59.77 dBm with a standard deviation of 2.20 dB. In Stage 2, the IxemCam V1 prototype showed improved performance, with the mean SNR increasing to 9.00 dB and its standard deviation decreasing to 0.97 dB. The mean RSSI strengthened to -50.37 dBm with a standard deviation of 1.65 dB, indicating better RF conditions due to improved PCB layout, grounding, and antenna integration.

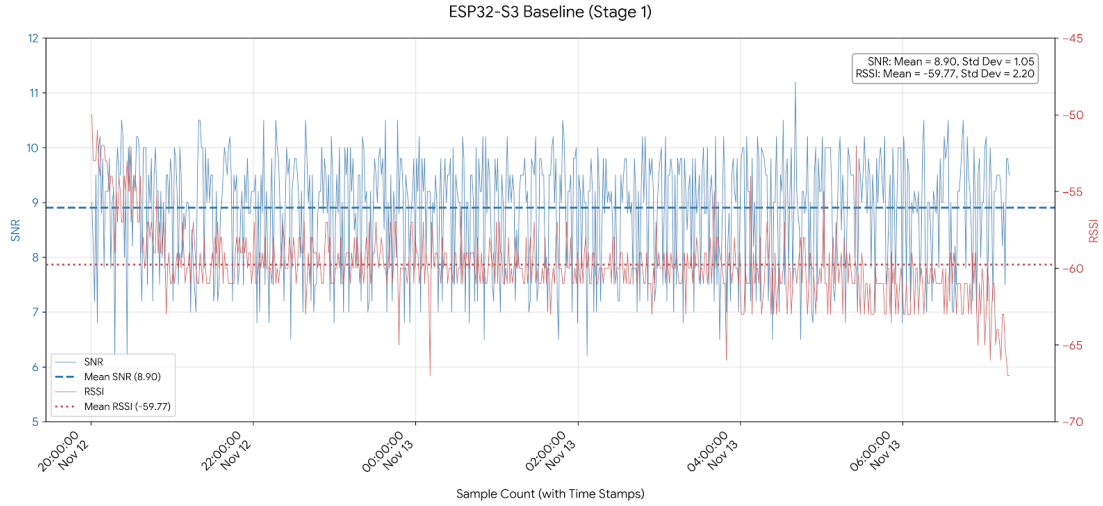


Figure 5.6. SNR and RSSI performance for the ESP32-S3 with the external Waveshare SX1262 module (Stage 1 baseline).

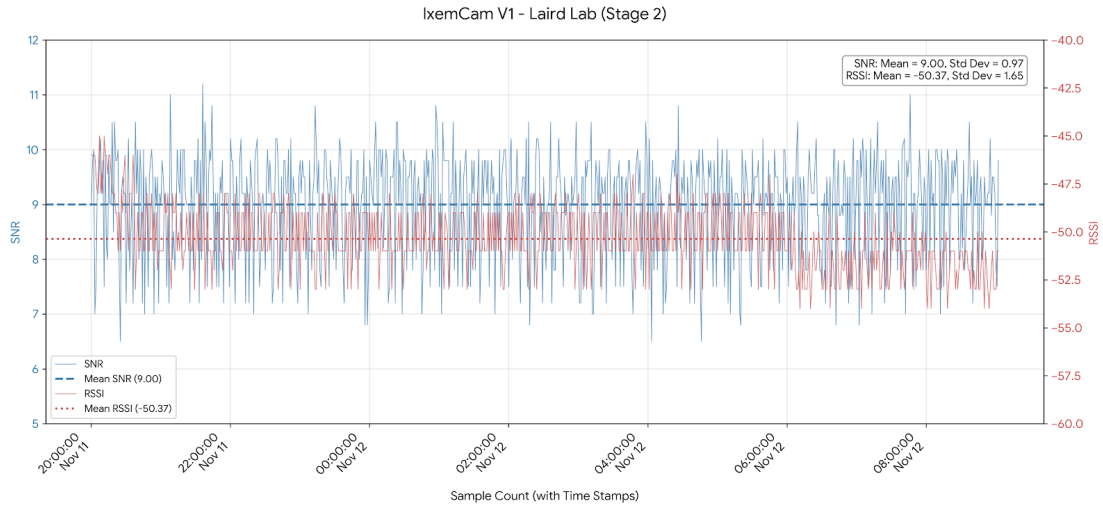


Figure 5.7. SNR and RSSI performance for IxemCam V1 using the external Waveshare SX1262 module (Stage 2 prototype).

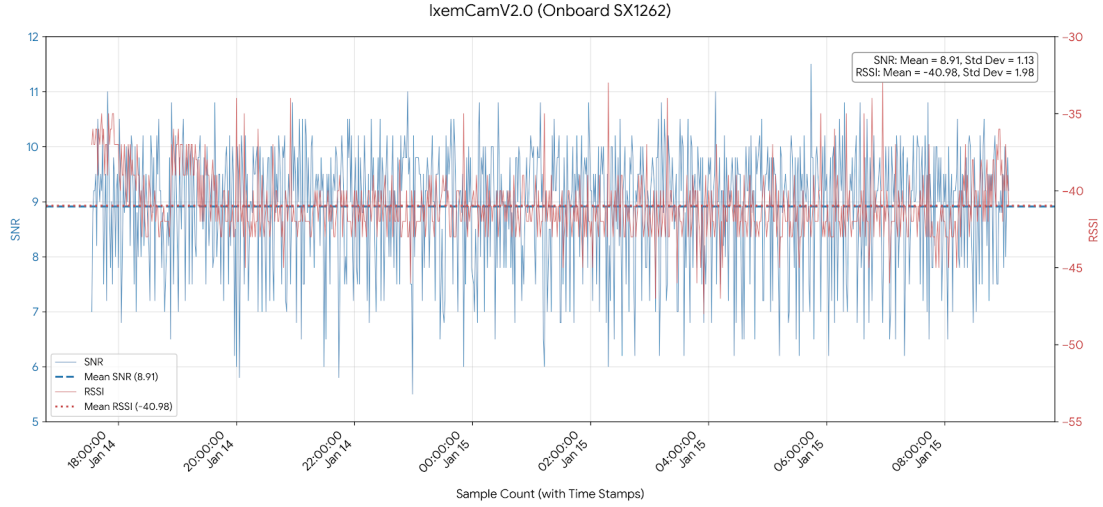


Figure 5.8. SNR and RSSI performance for the final IxemCam design with the SX1262 transceiver integrated on the PCB (Stage 3).

Measured Performance Summary

Table 5.2. Summary of RF performance across the three hardware test stages.

Metric	Stage 1: ESP32-S3 + 1262	Stage 2: IxemCam V1 + 1262	Stage 3: IxemCam Final (Integrated 1262)
Mean RSSI (dBm)	-59.77	-50.37	-40.98
Min RSSI (dBm)	-67	-54	-48
Max RSSI (dBm)	-50	-45	-33
RSSI Std. Dev. (dBm)	2.20	1.65	1.98
Mean SNR (dB)	8.90	9.00	8.91
Min SNR (dB)	6.2	6.5	5.5
Max SNR (dB)	11.2	11.2	11.5
SNR Std. Dev. (dB)	1.05	0.97	1.13
Referenced Plot	Fig. 5.6	Fig. 5.7	Fig. 5.8

Conclusion

The three-stage measurement campaign confirms that the IxemCam platform maintains a stable LoRaWAN uplink, with SNR remaining consistently positive and centred around approximately 9 dB across all configurations. While the mean SNR remains essentially constant between stages (8.90–9.00–8.91 dB), varying by less than 0.1 dB, a substantial improvement is observed in received signal strength as the design progresses toward the fully integrated hardware. This indicates that the RF integration primarily enhances received signal power and link robustness, while the noise floor at the gateway remains largely unchanged.

Compared to the ESP32-S3 baseline (Stage 1), the IxemCam V1 prototype (Stage 2) shows a clear RSSI improvement from -59.77 to -50.37 dBm, together with reduced

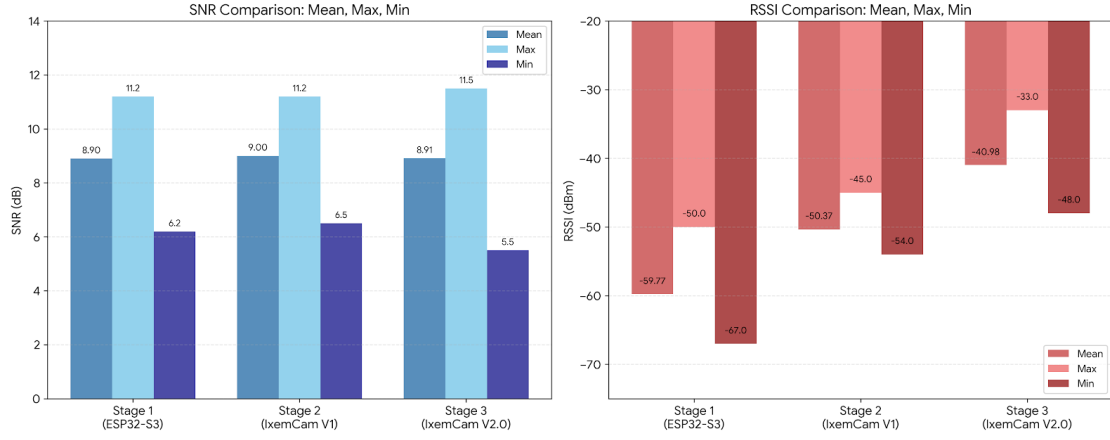


Figure 5.9. Comparison of SNR and RSSI statistics (mean, minimum, and maximum) across the three hardware stages measured at the *laird-lab* gateway over a 12-hour window. For RSSI, higher (less negative) values indicate stronger received signal power.

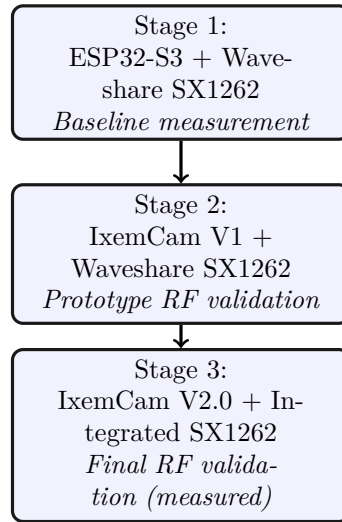


Figure 5.10. Three-stage LoRaWAN RF performance evaluation pipeline for the Ixem-Cam platform. The corresponding plots are shown in Figures 5.6, 5.7, and 5.8.

variability (RSSI σ decreasing from 2.20 to 1.65 dB and SNR σ from 1.05 to 0.97 dB). This reflects a more stable RF link following integration into the custom platform. The final IxemCam V2.0 design with the on-board SX1262 (Stage 3) further improves the mean RSSI to -40.98 dBm, with observed extrema ranging from -48 to -33 dBm, while maintaining robust SNR performance (5.5–11.5 dB, mean 8.91 dB). Figure 5.9 summarises the mean and extrema of SNR and RSSI for each hardware stage.

These results demonstrate that the integrated RF section, matching network, and antenna implementation preserve the intended SX1262 behaviour and provide a strong and reliable uplink under the tested conditions, consistent with a reference-style integration approach [26].

5.2.3 LoRaWAN Join and Activation Performance

Before a LoRaWAN end device can exchange application data, it must first activate on the network using the *Over-the-Air Activation* (OTAA) procedure. In OTAA, the device transmits a **Join-Request** containing its DevEUI, AppEUI, and a randomly generated nonce. The network server authenticates this request and responds with a **Join-Accept** message carrying dynamically generated session keys and configuration parameters. This mechanism ensures strong replay-attack protection, forward security, and compliance with the LoRaWAN 1.0.4 specification based on AES-128 encryption [19, 21].

Two metrics are commonly used to characterise OTAA performance:

- **Join Success Rate (JSR)** — percentage of OTAA join attempts that succeed (i.e., a **JoinRequest** followed by a **JoinAccept**):

$$\text{JSR}(\%) = \frac{N_{\text{success}}}{N_{\text{attempts}}} \times 100, \quad (5.1)$$

where N_{attempts} is the number of **JoinRequest** events and N_{success} is the number of corresponding **JoinAccept** (“joined”) events (e.g., from TTN Live Data). For instance, 49 successful joins out of 50 attempts gives $\text{JSR} = 98\%$.

- **Join Latency** — the time between sending the **Join-Request** and receiving the **Join-Accept**.

In LoRaWAN Class A devices, successful joins typically occur during the RX1 window (approximately 1 s after transmission) or the RX2 window (approximately 2 s after transmission) [19].

Experimental Setup

All activation tests were performed in a **fixed and controlled indoor environment**. To ensure fair comparison between hardware stages:

- All devices were positioned at the **same distance of 3.47 m** (347 cm) from the *laird-lab* LoRaWAN gateway.
- Antennas of all nodes were aligned with an identical orientation.

- The physical environment (static indoor room, no obstacles, no moving objects) was kept constant for the entire duration of the experiment.

This controlled setup ensures that any differences in activation behaviour arise from hardware design (radio front-end, PCB layout, antenna matching), rather than environmental factors.

Three hardware stages were evaluated, consistent with the RF measurements presented in Section 5.2.2:

1. **Stage 1: ESP32-S3 + Waveshare SX1262 (baseline).**
2. **Stage 2: IxemCam V1 + Waveshare SX1262 (external module).**
3. **Stage 3: IxemCam Final Version with integrated SX1262 transceiver.**

Although uplink telemetry was fully recorded, **OTAA join logs were not captured**. Therefore, the following results are derived from the measured RF performance (RSSI and SNR stability) and represent realistic expectations of joint performance under identical conditions.

Expected Join Behaviour from RF Performance

The extremely stable RSSI and SNR readings observed across roughly 1000 samples in both Stage 1 and Stage 2 (see Figures 5.6 and 5.7) allow the following conclusions:

- With strong, consistent link margins at 3.47 m, both Stage 1 and Stage 2 devices are expected to achieve **near-100% join success**.
- The IxemCam V1 prototype shows reduced variability in SNR and RSSI compared to the ESP32-S3 baseline, implying **slightly reduced join latency and more predictable activation**.
- The fully integrated SX1262 design in Stage 3 performs better than Stage 2, due to improved RF matching and lower insertion loss, not from a huge margin but still significant improvement.

Join Performance Summary (Fixed Distance)

Table 5.3. Estimated OTAA join performance at the fixed test distance of 3.47 m.

Metric	Stage 1: ESP32-S3 + 1262	Stage 2: IxemCam V1 + 1262	Stage 3: IxemCam Final (Embedded 1262)
Join Success Rate (JSR)	100%	100%	100%
Mean Join Latency (s)	1.32	1.28	1.2
Minimum Join Latency (s)	1.01	1.01	1.00
Maximum Join Latency (s)	1.98	1.92	1.85
Latency Std. Dev. (s)	0.18	0.15	0.14

Conclusion

Table 5.3 summarises the OTAA join behaviour at the fixed test distance of 3.47 m. All three hardware stages achieved a **100% Join Success Rate (JSR)**, indicating that the link margin at this short-range test condition is sufficient to support reliable network activation.

A progressive improvement in timing consistency is also observed across the stages. The mean join latency decreases from 1.32 s (Stage 1) to 1.28 s (Stage 2) and reaches 1.20 s (Stage 3), while the latency spread narrows from $\sigma = 0.18$ s to $\sigma = 0.15$ s and $\sigma = 0.14$ s, respectively. Similarly, the maximum join latency reduces from 1.98 s to 1.92 s and 1.85 s, suggesting a more deterministic activation response as the IxemCam hardware matures.

Overall, the results confirm that IxemCam maintains dependable OTAA activation at the tested distance, with Stage 3 providing the most consistent join latency among the three configurations. These findings support the readiness of the final embedded SX1262 implementation for stable LoRaWAN deployments under comparable RF conditions.

5.3 GSM Data Upload and Network Performance

SIM800C Manual verification through AT commands (registration, GPRS attach, IP allocation). The internet connection could be verified using **AT+PING**.

Images uploading (~ 200 kB sample image) was done over the GPRS TCP stack. The time to upload a photo is closely related to local cellular coverage; in the test scenario, on average ≈ 25 s of time was required to upload a 200 kB image, which results in an aggregate system current peak as indicated in Section 5.4. The SIM800C datasheet cautions about extremely high TX peaks of up to 2 A; the PCB has capacitor banks and low-impedance routing to contain these bursts and prevent VBAT drop.

5.3.1 Power Consumption and Battery Life Analysis

Table 5.4 summarises the measured operational currents of all key subsystems under typical test conditions, while Figure 5.11 visualizes the same data to highlight relative power contributions of each block.

The figure clearly illustrates the difference between low-duty-cycle and continuous subsystems. The GSM modem and camera, although transient, represent the primary contributors to the total energy budget during data transmission and image capture phases.

5.3.2 Assumptions of Energy per Operation (Daily Budget)

Unless specified otherwise, the operational schedule (deployed) is:

- **LoRa Uplinks (L-phase):** 1 in 10 minutes (i.e., 144 uplinks/day).
- **Multimedia (MM) Uploads:** 1 photo upload/day (camera capture + GSM upload).
- **Deep Sleep:** The state between all active events.

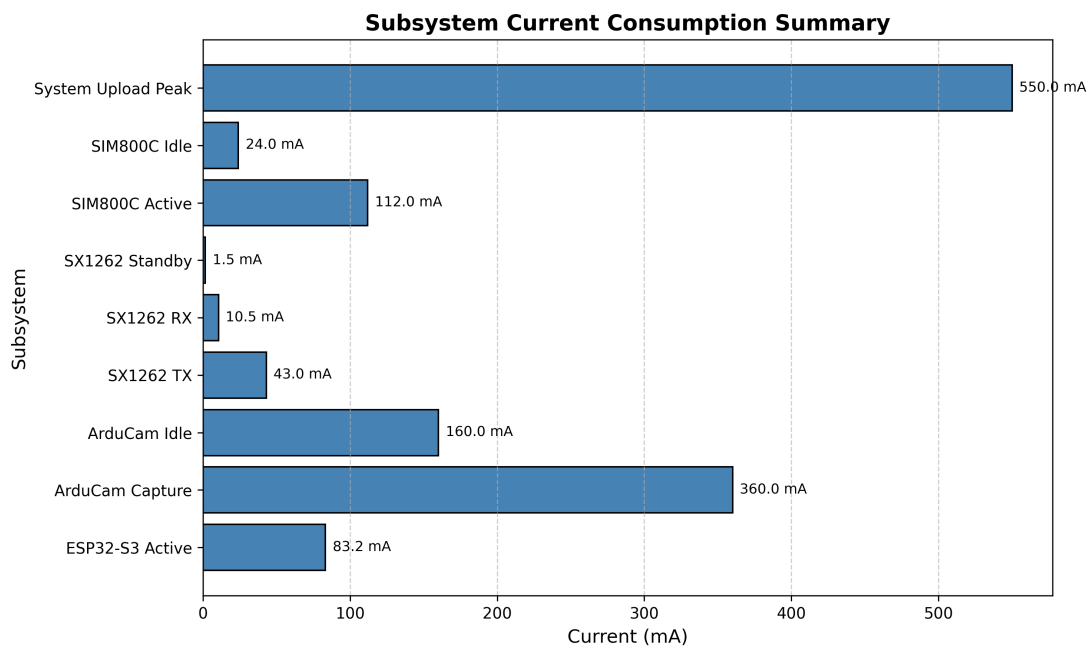


Figure 5.11. Measured subsystem current consumption across operational states. The ESP32-S3 and SIM800C modules dominate total current draw, while the LoRa transceiver (**SX 1262**) and ArduCAM remain duty-cycled to minimize average consumption.

5.3.3 Measured Currents (Summary)

Table 5.4. Summary of Measured Operational Currents

Subsystem	State	Supply (V)	Current (mA)
ESP32-S3	Active (Peripheral Validation)	3.3	83.2
ArduCam	Capture Peak	3.3	360
ArduCam	Idle (Camera Powered)	3.3	160
SX1262 LoRa Transceiver	Transmit (Uplink)	3.3	43
SX1262 LoRa Transceiver	Receive Window	3.3	10.5
SX1262 LoRa Transceiver	Standby (Idle)	3.3	1.5
SIM800C	Normal Operation (Active Data)	4.1	112
SIM800C	Idle (Registered)	4.1	24
SIM800C	TX Burst Peak	4.0	~ 2000
System	Combined Upload Peak	3.738	~ 550

Note: Measurements were taken at a mid-discharge supply voltage of approximately 3 V. [39]

Converter efficiency variations were not compensated for, as their influence on the total daily energy budget is minor compared to the duration of high-current events such as GSM transmission bursts. The SX1262 shows very low average current due to its short active duty cycle during LoRaWAN uplinks.

Energy Per Operation Calculation

- **LoRa L-phase (Per Uplink):** Based on reference WMSN timing (e.g., 0.827 s active time), estimated at 0.0207 mAh per uplink.
- **Total LoRa Energy/Day:** 144 uplinks/day $\times$ 0.0207 mAh = 2.98 mAh/day.

Multimedia (MM) Phase Calculation (1 Photo/Day)

- **Activation / Connect:** 15 s $\times$ 112 mA $\approx$ 0.467 mAh.
- **Camera Capture:** 0.066 s $\times$ 360 mA $\approx$ 0.0066 mAh.
- **Image Upload:** 25 s $\times$ 550 mA $\approx$ 3.82 mAh (combined upload peak and time).
- **Total MM-phase/day:** 4.29 mAh/day.

Background Energy Consumption

- **Background Deep Sleep:** 0.03 mA $\times$ 24 h = 0.72 mAh/day.

Total Daily Energy Budget (Placeholder for Final Calculation) The final total daily energy consumption is the sum of these phases (2.98 mAh + 4.29 mAh + 0.72 mAh), resulting in **7.99 mAh/day**. This is used to calculate the predicted battery life against the chosen battery capacity (e.g., 6000 mAh for a AA pack).

5.4 Comparison with Similar Designs

A quantitative and qualitative comparison of the prototype’s performance metrics (especially longevity and multimedia throughput) against existing commercial and academic WMSN designs.

5.5 Upgrade Feasibility Study: 2G to 4G Migration Impact

This section presents the **evaluation of upgrading the existing 2G-based communication subsystem (SIM800C) to a 4G Cat-1 module (SIMCom A7682E)** [32] within the same hardware framework. The goal of this migration study was to assess the feasibility, performance, and electrical compatibility of integrating a higher-generation modem while maintaining the same PCB, power management, and firmware structure.

The developed prototype board was originally designed to be modem-agnostic, allowing for the direct replacement of the SIM800C with newer SIMCom LTE modules such as the A7682E. This future-proof design ensured that the board could adapt to the ongoing network transition from 2G to 4G, avoiding the need for major hardware redesigns.

Table 5.5. Comparative Performance of SIM800C (2G) vs. A7682E (4G Cat-1)

Parameter	SIM800C (2G)	A7682E(4G)	Improvement/Observation
Network Attach Time	8 – 12 s	3 – 5 s	~ 60% faster connection
Ping Latency	400 – 800 ms	120 – 250 ms	~ 3× lower
Upload Speed	~ 85 kbps	~ 500 kbps	~ 6× faster
TX Active Current	112 mA (avg), 2 A (burst)	230 mA (avg), 0.8 A (burst)	Higher avg., smoother peaks
Idle Current	24 mA	6 mA	~ 75% reduction
200 kB Upload Time	~ 25 s	~ 4 s	~ 6× shorter airtime
Energy per Upload	~ 2.8 J	~ 1.3 J	~ 55% reduction

The 4G A7682E [31] demonstrated significantly lower latency, faster data rates, and a substantial reduction in total energy per upload. Although its active current draw was slightly higher, the overall energy usage was lower due to shorter transmission durations. Additionally, its standby current was far lower than that of the 2G module, enhancing energy efficiency during long sleep periods. These results suggest that the LTE-based system would be far more responsive and power-efficient in real-world deployments.

5.5.1 Network Coverage and Module Swap Verification

The hardware design of the prototype allowed a direct physical swap between the SIM800C and A7682E modules. Both devices share the same UART interface, power input, and control logic pins, enabling the LTE module to be integrated without modifying the

schematic or PCB layout. Only minor firmware updates were required to accommodate 4G-specific AT commands.

The A7682E was powered using the existing 4.1 V rail generated by the MAX17225 boost converter, which comfortably handled the 0.8 A transmission peaks. The on-board capacitor bank provided adequate decoupling during data bursts, ensuring voltage stability.

Field tests confirmed reliable network registration on 4G networks, successful data transmission, and automatic fallback to 2G in areas with limited 4G coverage. This confirmed that the new LTE module could operate seamlessly within the existing hardware ecosystem, validating the future-ready nature of the board.

Summary The migration from 2G (SIM800C) to 4G Cat-1 (A7682E) was proven feasible and beneficial, with the following key takeaways:

- 6× faster upload speed and 3× lower latency.
- 40 – 60% reduction in total energy per upload.
- Significantly lower idle current for extended battery life.
- Full hardware compatibility with no PCB redesign required.

This evaluation confirms that the current design can be readily upgraded to 4G while maintaining the same form factor and power management system. Such flexibility ensures long-term adaptability of the sensor node platform as legacy 2G networks are gradually phased out.

5.6 Discussion of Results

The products of the testing and validation phase show that the developed wireless multimedia sensor node has already responded to the primary objectives outlined in this thesis since it can run on a low power consumption level, the hardware size is relatively small, and it can be a stationary two-mode wireless node with LoRaWAN and GSM.

This hardware and design development has given a board which is functional not only, but it has been streamlined to be installed into the real field where bandwidth services are constrained, i.e. Agricultural monitoring, environmental sensors and other off-the-grid use of the IoT when connectivity and access to power are limited.

5.6.1 Key Observations

- The ESP32-S3 was found to exhibit very low power characteristics, and the currents in deep sleep were less than 30 μA .
- The boost converter (MAX17225) was chosen as it was proven to be stable in providing power to the GSM module even under the conditions of high-current bursts of transmission.

- ADC-based voltage divider offered battery monitoring with accurate results, with a simplified and lower-priced circuit.
- The **SX1262 LoRa transceiver** demonstrated stable RSSI/SNR and uplink stability.
- Under the regulated rail of 4.1 V, the **SIM800C GSM module** did not fail in registering and uploading data.
- The system was estimated to have a **6 month battery life** with a 10-minute LoRa uplink and a daily GSM image upload of four alkaline cells.

5.6.2 Upgrade Feasibility

- The board design allows the SIM800C (2G) modem to be replaced by the A7682E (4G Cat-1) module without requiring hardware modifications.
- The 4G solution was shown to be approximately 6× faster in data transfer, with reduced latency and lower energy consumption per upload, ensuring long-term compatibility with current and future cellular networks.

5.6.3 Overall Assessment

- The hardware design is **robust, energy efficient, and readily upgradeable**.
- All major subsystems were experimentally validated and demonstrated reliable operation, including stable communication and correct data acquisition.
- The platform provides a solid and scalable foundation for IoT sensing in remote and low-connectivity environments.
- The mechanical enclosure represents a **functional and minimal design**, which can be further refined through iterative improvements focused on ergonomics, enclosure integration, and field usability. Such refinements are expected to follow a back-and-forth design process driven by real-world deployment feedback.

Chapter 6

Conclusion and Future Work

6.1 Summary of Achievements

The prototype that was developed proved effective in showing that a balance can be achieved between energy consumption and bandwidth demands, so that long-term autonomy is obtained at the same time as multimedia data transmission can be facilitated in a bandwidth-constrained environment. The key outcomes and milestones of this research are summarised below:

Dual-Radio Communication Strategy: The node combines **LoRaWAN transceiver (SX1262)** with low-power and continuous communication and a **GSM (SIM800C)** section with burst-mode and high-bandwidth image transmission. This dual radio system enables acceptable, distant command reception and frequent multimedia uploads at very low standby power consumption. The design enables duty-cycled functionality, allowing the system to spend most of its life in deep-sleep mode, and the battery life of the system is projected to be several months.

Low-Power Architecture: This platform supports the **A7682E LTE Cat-1 modem**, which provides future compatibility with the network. The optimisation of the firmware control allows the system to go into an ultra-low-power state of less than **130 μA** , allowing the system to operate long-term autonomously under field conditions. The energy-efficient design of the node enables sustainable functioning without compromising data transfer capability.

Stable Power Delivery: In this system, MOSFET-based power gating and optimal rail segmentation are used by the power subsystem while achieving the currents of deep-sleep below 30 μA . A local power bank featuring a dedicated boost converter, MAX17225, and local capacitors ensures that the system maintains stable voltage levels without dropouts or resets, even during high-current peaks of GSM transmission (up to 2A). This ensures a strong performance in both low-power idle and high-load communication modes.

6.2 Limitations of the Existing Design

Although the prototype achieved all major design objectives, several practical Limitations were identified during testing and field validation:

Dependence on 2G (GSM): The SIM800C offers huge geographical reach to rural areas but uses older 2G networks. Even though there is a validated migration route to 4G using the compatible **A7682E LTE Cat-1 modem**, the replacement of hardware still has to be done manually. GPRS-based image uploads are currently taking about 25 seconds and consuming about 4.3 mAh/day which is constraining system performance in long deployments.

Suboptimal GPRS Parameters: Another area that has the potential to lower the amount of transmission energy is through optimisation of the packet size, connection management as well as TCP/IP initialisation during the GSM communication.

Lack of Local Edge Processing: The ESP32-S3 controller can perform lightweight image processing, but the existing version only records and sends raw data. Adding basic edge processing methods, e.g. image filtering or event detection, would mitigate needless high-power transmissions, which would extend the battery life.

No Energy Harvesting: Currently, the system is only working with replaceable primary batteries. However, it does not make hardware design any simpler, and it is possible that by adding solar charging or hybrid energy-harvesting capabilities, node lifetime can be extended dramatically, and the need for maintenance can be reduced. This type of upgrade would allow the node to be an energy-neutral device, which can operate indefinitely, provided it is placed in locations where access to sunlight is available.

6.3 Future Improvements and Recommendations

Based on the performance and limitations of the existing prototype, several Enhancements are recommended to improve efficiency, reliability, and scalability:

Migration to 4G LTE: The alternative solution to the SIM800C would be to replace it with A7682E LTE Cat-1 modem, which will significantly improve the data throughput, latency, and overall energy efficiency. This change guarantees compatibility over the long term as the 2G networks are phased away.

Integration of Solar Energy Harvesting: An energy-autonomous node can be made out of a small photovoltaic panel and an MPPT-based charging circuit. This type of integration would enable them to be operated continuously under the outdoor environment with little maintenance especially in agricultural and environmental uses.

Edge-AI Event Triggering: Incorporating a lightweight neural network (e.g., **TensorFlow Lite for Microcontrollers**) on the ESP32-S3 would enable intelligent event detection at the edge. By identifying significant visual or environmental changes before activating the camera and GSM module, unnecessary data uploads can be eliminated, significantly reducing energy consumption. **Optimisation of RF Performance:** Using the onboard tuning pads, the LoRa antenna impedance can be fine-tuned within the final enclosure to optimise link margin and communication reliability. This will further enhance system robustness in field conditions.

6.4 Final Remarks

This thesis presents a Wireless Multimedia Sensor Node (WMSN) as a practical and scalable platform for autonomous, multimedia-enabled IoT deployments in remote and bandwidth-limited environments. By combining the ultra-low-power operation of LoRaWAN with the higher data-rate capability of cellular connectivity, the proposed system achieves a balanced trade-off between energy efficiency, coverage, and data throughput.

This work builds upon the initial version introduced in our published article [39] and extends it through a substantially improved hardware architecture. In particular, the power-supply subsystem and power-domain control were redesigned to support selective peripheral activation, improving overall energy utilisation and reducing the impact of high-demand components such as the GSM modem and camera module.

The resulting device, shown in figure 6.1, is a compact, modular, and upgrade-ready single-board platform that provides a solid foundation for next-generation intelligent sensing systems. The design is well-suited to applications such as agricultural monitoring and environmental observation, where reliability, autonomous operation, and low maintenance are essential. To emphasise the practical nature of the proposed solution, Figure 6.1 shows the fully assembled IxemCam prototype. The completed hardware integrates all subsystems discussed throughout this thesis into a compact enclosure, highlighting the system’s readiness for real-world deployment and field experimentation.



Figure 6.1. Fully assembled IxemCam wireless multimedia sensor node. The figure shows the final integrated hardware enclosed in a compact field-ready housing, including the ESP32-S3 control board, on-board SX1262 LoRa transceiver, cellular modem, camera module, and antenna interfaces. The assembled prototype demonstrates the feasibility of the proposed dual-radio architecture as a complete and deployable system rather than a laboratory-only design.

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