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Integration of IoT Smart Irrigation into Renewable Rural Microgrids

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***Abstract*— Rural and remote agricultural areas often face critical challenges related to both water management and limited access to stable energy sources. This work presents the design and evaluation of a low-power Internet of Things (IoT) smart irrigation system integrated into a renewable rural energy context. Building on LoRaWAN technology, the proposed solution ensures long-range and low-energy communication between distributed sensor-actuator nodes and a centralized control dashboard. The system leverages RAK3172 modules based on STM32 microcontrollers that minimize energy consumption. Initial communication evaluation demonstrated robust performance over less than 1 km, achieving a Packet Delivery Rate (PDR) of approximately 83.17%, with a best-case Received Signal Strength Indicator (RSSI) of −54 dBm and a Signal-to-Noise Ratio (SNR) of +4 dB reported by the gateway. A photovoltaic (PV)-battery configuration is conceptually designed to power the end devices, enabling autonomous operation without dependence on the electrical grid. The article outlines the system architecture, communication stack, and the conceptual energy integration model, supported by comparative tables on LoRaWAN device classes and wireless technology trade-offs. This approach demonstrates how low-power IoT infrastructures can be effectively combined with renewable micro-sources to support sustainable precision agriculture in rural contexts.**

Keywords— **Smart Irrigation, LoRaWAN, Low Power IoT, Renewable Energy, PV-Battery Systems ,Microgrids.**

I. Introduction

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The agricultural sector faces increasing pressure to enhance productivity while ensuring the sustainable management of natural resources, particularly water and energy. In rural and remote areas, these challenges are further amplified by limited access to stable electricity and communication infrastructure. Traditional irrigation practices often result in water overuse and energy inefficiency, emphasizing the need for innovative, low-cost, and autonomous solutions capable of operating in off-grid environments [5,7].

Recent advancements in the Internet of Things (IoT) have created new opportunities for precision agriculture, enabling real-time monitoring and intelligent control of irrigation processes. Among various communication technologies, Low Power Wide Area Networks (LPWAN)—especially LoRaWAN—have gained significant attention due to their long-range coverage, low energy consumption, and minimal deployment cost. These features make LoRaWAN particularly suitable for rural areas where conventional cellular or Wi-Fi connectivity is often unavailable or unreliable [5,6,7].

In parallel, the integration of renewable energy sources, such as photovoltaic (PV) systems combined with battery storage, offers a viable means of powering distributed IoT devices in remote locations. By coupling low-power IoT architectures with locally available renewable energy, it becomes possible to deploy sustainable irrigation systems that minimize operational costs and environmental impact [8].

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This paper presents the design and evaluation of a low-power IoT smart irrigation system integrated into a renewable rural energy framework. The proposed solution leverages LoRaWAN Class A communication, STM32-based RAK3172 sensor–actuator nodes, and a cloud platform for data visualization and control. A PV–battery configuration is introduced to ensure the autonomous operation of field devices. The system architecture, communication strategy, and renewable energy integration concepts are detailed, supported by comparative tables and diagrams illustrating device consumption and network topology.

II. System Architecture and communication design

In rural agricultural settings, the suggested smart irrigation system is based on a low-power, modular Internet of Things architecture that facilitates effective data collection and remote actuation. To provide long- range connectivity with low energy consumption, it integrates distributed sensing and control nodes with a LoRaWAN-based communication infrastructure.

A. *Smart Irrigation Deployment Scenario*

A typical rural deployment scenario for the suggested smart irrigation system is shown in Figure 8. Multiple remote field devices, such as pumps and sensors, are dispersed throughout the agricultural area, a photovoltaic (PV) module powers the local communication unit, and a farmer house with a LoRaWAN gateway and monitoring interface. For long-term autonomous operation, each node depends on low-power components and energy-efficient communication.

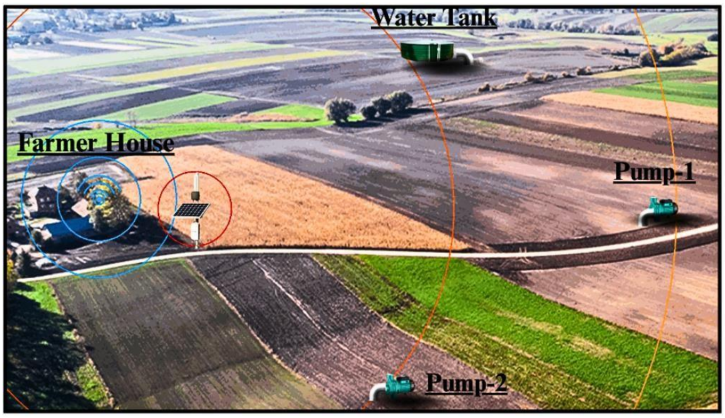

Fig. 1 Smart Irrigation for Farmland

B. *Overall System Architecture*

A star-of-stars topology is used by LoRaWAN networks, in which gateways serve as transparent conduits between a central network server and end devices, such as sensors or actuators. For long-range, low-power communication, the wireless link between end devices and gateways uses the LoRa physical layer, whereas the connection between gateways and the network server usually uses common IP-based backhaul technologies (e.g., Ethernet, 3G/4G, or Wi-Fi). The main components of a LoRaWAN architecture are:

- End Devices (Nodes): IoT devices that typically have a microcontroller and a LoRa transceiver. They use LoRa modulation to transmit directly to gateways within range after gathering sensor data or carrying out actuator commands [5,6].
- Gateways: devices that serve as protocol bridges, transforming end-user LoRa RF packets into IP packets that are sent to the network server. Typically, gateways are mains-powered, have high-sensitivity receivers, and can manage thousands of endpoints at once [4,7].
- Network Server: the main organization in charge of overseeing LoRaWAN network operations. It carries out security checks, adaptive data rate (ADR) control, packet deduplication, and message routing between application servers and devices. Both downlink (server-to-device) and uplink (device-to- server) communication are supported [7].

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- Application Server: integrates gathered IoT data into external systems or dashboards and hosts end- user applications. When required, it transmits commands back through the network server, processes incoming data and initiates alerts or actions

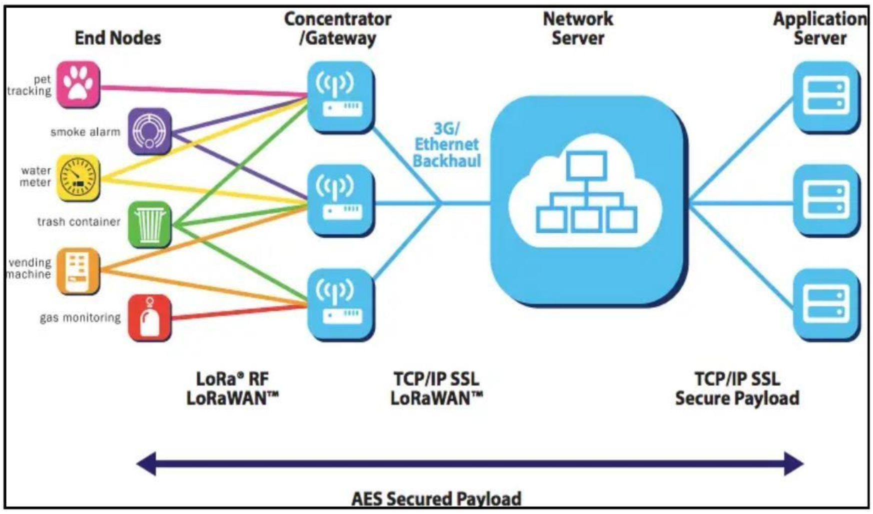

Fig. 2 Network architecture

C. Hardware Tool

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- RAK3172 Evolution Board is a compact LoRaWAN-enabled development board used as the main sensing and control node in the project. It integrates two key chips: the STM32WLE5CCU6 microcontroller [3] for processing and control, and the SX1262 LoRa radio [2] for LoRaWAN communication. Because of its ultra-low power consumption and ARM Cortex-M4 core, the STM32WLE5CCU6 is a perfect board for Internet of Things devices that run on batteries. Reliable communication with the RAK7289 gateway is made possible by the SX1262, which manages long-range, low-power LoRaWAN connectivity. For the project's sensing and control applications, this dual-chip architecture guarantees reliable wireless performance and effective processing.
- RAK7289 Gateway: Wide-area network coverage and dependable outdoor deployments are the goals of the RAK7289, an industrial-grade LoRaWAN gateway. It is appropriate for dense device networks due to its dual LoRa concentrators which support up to 16 channels. An integrated GPS module guarantees precise location and timing data, and it supports Ethernet, Wi-Fi, and LTE, a 4G cellular standard for high-speed internet access, for backhaul connectivity. Secure data transfer to cloud platforms is made possible by the gateway, which operates on an OpenWRT-based system with an integrated LoRaWAN network server and supports MQTT v3.1 bridging with TLS encryption [4]. Network security is improved by LoRa frame filtering and node while listing, and the firmware fully complies with the LoRaWAN 1.0.3 specifications.

D. Communication Protocols

LoRaWAN (Long Range Wide Area Network): Based on LoRa, LoRaWAN is a network protocol that specifies the communication framework and system architecture, as shown in Figure 1.11. It provides:

- Addressing and Devices Classes: Three classes (A, B, and C) and unique device addressing are used to balance communication requirements and power consumption (e.g., low power for Class A, real-time for Class C).
- Security: Data security at the network layer (between devices and gateways) and application layer (between devices and application servers) is achieved through end-to-end AES-128 encryption [5].
- Scalability: A star-of-stars topology, where multiple gateways relay data to a central network server, efficiently managing thousands of devices across wide areas.

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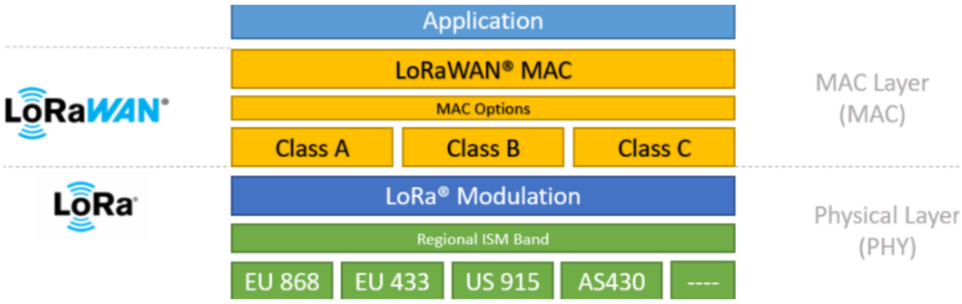

Fig. 3 Architecture of LoRa and LoRaWAN

LoRaWAN, by contrast, provides [1]:

- Coverage up to 10–15 km in rural areas.
- Battery life measured in years for end devices.
- No dependency on existing Wi-Fi infrastructure

III. Renewable Energy integration for IoT nodes

To ensure autonomous operation in remote agricultural areas, the proposed system integrates renewable energy sources to power field devices efficiently. This section outlines the energy requirements of the deployed IoT nodes and presents the conceptual design for photovoltaic (PV) and battery-based power supply.

A. Power Requirements of Field Devices

Table 1 summarizes the typical current and power consumption values of a single node according to the manufacturer's specifications [2,3]:

TABLE I
CURRENT AND POWER CONSUMPTION

Operating Mode	Typical Current (mA)	Voltage (V)	Power (mW)	Duration (per cycle)
Deep Sleep	0.002	3.3	0.0066	58 s
Transmit (TX)	125	3.3	412.5	1 s
Receive (RX)	10	3.3	33	1 s

The energy consumption for each operating mode is calculated by multiplying the Power (mW) by the Duration in hours (h). The general formula is:

$$Energy\ (mWh) = Power\ (mW) \times Duration(s)/3600 \quad (1)$$

The energy consumption for each mode:

TABLE I
CURRENT AND POWER CONSUMPTION

Mode	Power (mW)	Duration (s)	Energy per cycle (mWh)	Energy per cycle (µWh)
Deep Sleep	0.0066	58	0.0001063 mWh	0.1063 µWh
Transmit	412.5	1	0.1146 mWh	114.6 µWh
Receive	33	1	0.00917 mWh	9.17 µWh

This analysis shows that the energy consumption per transmission cycle remains extremely low, allowing the device to operate for several months on a small-capacity lithium battery or to be continuously powered by a compact PV module (e.g., 3–5 Wp). These low requirements form the basis for the renewable energy integration discussed in the following subsection.

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B. Photovoltaic (PV) and Battery Sizing Concept

To guarantee autonomous operation of the field nodes, a small-scale photovoltaic (PV) and battery system can be used to meet daily energy requirements. The total daily energy consumption Ed of a node is expressed as:

$$E_d = P_{avg} \times t_{day} \tag{2}$$

where P_{avg} represents the average power demand and t_{day} the daily operating duration. Assuming an average of 0.25 mWh per minute, the node requires less than 0.4 Wh per day. A 5 Wp PV module operating under 4 hours of effective sunlight can supply over 20 Wh/day, largely exceeding the device's need and allowing for energy storage. The required battery capacity Cb can be estimated as:

$$C_b = \left(V_{batt} \times \eta \times E_d \times N_{autonomy}\right) \tag{3}$$

where $N_{autonomy}$ is the number of autonomy days, V_{batt} the battery voltage, and η the system efficiency. This configuration ensures reliable operation even during cloudy periods, providing a robust power solution for isolated agricultural fields.

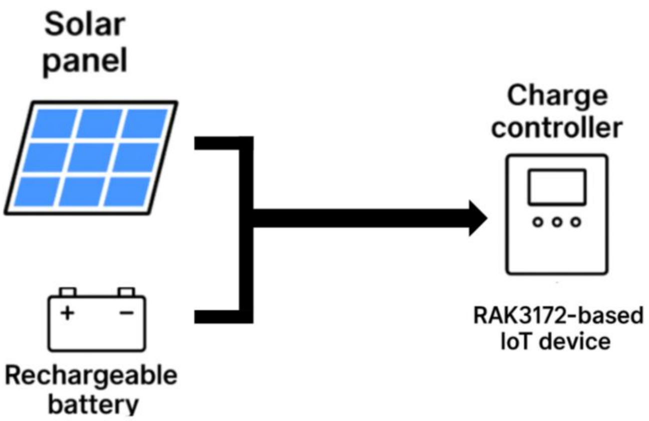

Fig. 4 Conceptual diagram of the PV-powered IoT node

The Figure 4 illustrates the energy supply configuration of a field node, which includes a small photovoltaic (PV) panel, a charge controller, a rechargeable battery, and the RAK3172-based IoT device. During daylight, the PV panel powers the node and charges the battery, while at night the stored energy maintains operation in low-power mode. This setup ensures continuous functionality and energy autonomy with minimal maintenance requirements

IV. EVALUATION AND DISCUSSION

The implemented system demonstrated reliable long-range communication between IoT field nodes and the central LoRaWAN gateway. Throughout the tests, stable data transmission was maintained, ensuring accurate and timely delivery of soil and environmental parameters to the cloud dashboard.

Packet Delivery and Link Quality: In LoRaWAN-based networks, *packet loss* represents the proportion of transmitted messages that fail to reach the application server. It is primarily influenced by signal strength, noise levels, and environmental interference.

The link quality of the deployed system was evaluated using two key indicators:

- RSSI (Received Signal Strength Indicator): measures the received signal power in dBm. Values better than −115 dBm are generally considered good, while values below −120 dBm indicate weak connectivity.
- SNR (Signal-to-Noise Ratio): quantifies the signal quality relative to background noise. Positive values correspond to clean, strong signals, whereas LoRa modulation remains functional even with SNR as low as −20 dB for higher spreading factors (eg.,SF12).

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Measured results (Field Test in Tunis):

- RSSI: -54dBm (best case observed)
- SNR: +4 dB (gateway-reported)
- Packet Delivery Ratio (PDR): ≈ 83.17 % over more than 150 000 transmitted packets.

V. Conclusions

This work presented the design and evaluation of a LoRaWAN-based IoT architecture for smart irrigation applications, emphasizing energy autonomy and sustainability through renewable integration. The proposed system demonstrated reliable long-range communication, efficient data visualization via the cloud platform, and low power consumption achieved with STM32-based RAK3172 nodes operating in LoRaWAN Class A mode. A compact photovoltaic (PV) energy supply was introduced to sustain continuous operation with minimal maintenance, confirming the feasibility of deploying such systems in rural or off-grid agricultural contexts. The results highlight the potential of combining low-power IoT technology with renewable micro-sources to advance precision agriculture and resource efficiency. Future work will focus on extended field testing, adaptive power management algorithms, and multi-sensor network scaling to further assess long-term reliability, scalability, and integration within larger renewable microgrid frameworks.

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