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LoRa-Based Wireless Sensor Network (WSN) Project

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1 Abstract:

This report presents the design and implementation of a LoRa-based Wireless Sensor Network (WSN) for the wireless transmission of environmental data, including temperature, humidity, and motion detection. The system consists of a transmitter node with LoRa, DHT11 sensor, and PIR sensor, and a receiver node with LoRa and an OLED display. The system uses LoRa's Chirp Spread Spectrum (CSS) modulation to enable long-range communication with low power consumption, making it ideal for smart agriculture, environmental monitoring, and remote data collection. The report includes a detailed explanation of the LoRa technology, its ISM bands, power consumption, and electromagnetic wave generation.

2 Introduction:

The proliferation of IoT (Internet of Things) applications has driven the need for low-power, long-range communication solutions. LoRa (Long Range) technology has emerged as a low-power, wide-area network (LPWAN) protocol, enabling reliable and scalable communication for remote sensors in various applications, including agriculture, environmental monitoring, and asset tracking. This report discusses the design and implementation of a LoRa-based Wireless Sensor Network (WSN) that uses LoRa modules to transmit sensor data over long distances with low power consumption.

3 System Design:

3.1 Overview of the System

The system consists of two main nodes:

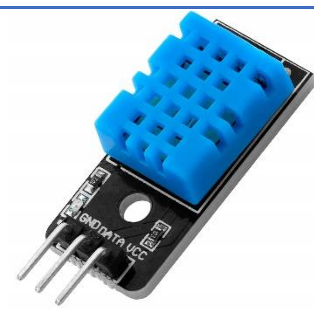
1. Transmitter Node:
   - The Arduino Uno collects data from the DHT11 (temperature and humidity sensor) and PIR motion sensor.
   - The LoRa SX1278 module is used to wirelessly transmit this data over long distances to the receiver node.
2. Receiver Node:
   - The Arduino Uno receives the data via the LoRa SX1278 module and displays it on the OLED display.

The system utilizes LoRa modules for low-power, long-range communication in the 433 MHz frequency band, enabling long-range communication in remote areas where traditional communication infrastructure like Wi-Fi or cellular networks are unavailable.

3.2 System Architecture

1. Data Collection: The Arduino reads data from the DHT11 (temperature and humidity) and PIR (motion) sensors.
2. Data Transmission: The LoRa module transmits the data wirelessly to the receiver node.
3. Data Reception: The receiver node receives the data via the LoRa module, and the Arduino displays the data on the OLED screen.

3.3 Components Used

Component	Description	Image
Arduino Uno	The microcontroller responsible for processing and controlling the sensors and LoRa communication.	
LoRa SX1278 Module	Provides long-range communication in the 433 MHz frequency band.	
DHT11	Measures temperature and humidity.	

PIR Motion Sensor	Detects motion.	
OLED Display	Displays received data on the receiver node.	
433 MHz Antenna	Enhances the range of the LoRa module.	

Figure 1: Components Used

4 LoRa Technology:

4.1 LoRa Modulation and Operation

LoRa uses a unique form of Chirp Spread Spectrum (CSS) modulation. CSS is a type of frequency modulation (FM) where the frequency of the signal continuously increases or decreases over time. This allows the signal to spread across a wide frequency band, increasing its resilience to interference and improving range.

- **Chirp Signal**: This is a signal whose frequency continuously increases or decreases, representing digital data. The ability of the LoRa system to spread this signal over a wide frequency range allows it to maintain robust communication, even in the presence of noise and interference.
- **Spreading Factor (SF)**: LoRa uses a Spreading Factor (SF) to adjust the balance between range and data rate. The higher the SF, the wider the chirp, leading to increased range but a reduced data rate. The typical range of SF is 7 to 12:
  - SF 7 offers faster data rates but shorter range.
  - SF 12 increases range significantly but reduces the data rate.

4.2 LoRa Communication Process

1. **Data Encoding**:
   - The Arduino encodes sensor data (e.g., temperature, humidity, and motion data from the DHT11 and PIR sensors) into digital bits.
   - These bits are modulated using CSS by the LoRa module into the chirped signal that can be transmitted over long distances.
2. **Transmission**:
   - The LoRa module transmits this modulated data using an RF signal. The data is spread over a wide frequency band due to CSS modulation, making the signal resistant to interference and capable of long-range communication.
3. **Reception**:
   - The receiver LoRa module receives the RF signal, demodulates the chirped signal, and extracts the original data.

4. **Display**:
   - The Arduino processes the received data and displays it on the OLED screen, providing the user with the sensor readings.

4.3 ISM Bands, Frequency, Range, and Power Consumption

LoRa operates in unlicensed ISM (Industrial, Scientific, and Medical) frequency bands, commonly used in IoT applications. The frequencies used vary by region:

- 433 MHz (used in Asia and parts of Europe)
- 868 MHz (used primarily in Europe)
- 915 MHz (used in North America and Australia)

In this project, we are using the 433 MHz frequency for long-range communication, providing up to 10 km in rural areas and 2-5 km in urban environments.

Transmission Power:

- LoRa modules typically transmit at 20-22 dBm (100 mW to 160 mW) at 433 MHz, but this can be adjusted.
- At this power level, LoRa provides long-range communication while minimizing power consumption.

Power Consumption:

- Sleep Mode: LoRa modules consume 1 µA in sleep mode, drastically extending battery life in low-power applications.
- Transmission Mode: During transmission, the power consumption is 20 mA to 120 mA, depending on the transmission power setting and the Spreading Factor (SF) used.

4.4 FPC and Antenna Design

In LoRa modules, an FPC (Flexible Printed Circuit) antenna is commonly used for its compact size, flexibility, and ability to integrate directly into the LoRa module. The FPC antenna is particularly suitable for IoT devices that require flexible designs and space efficiency.

- **Antenna Type**:
  - The LoRa SX1278 module typically uses a quarter-wave monopole antenna. The length of the antenna is approximately 0.17 meters for 433 MHz.
  - A quarter-wave monopole antenna is a simple antenna design, ideal for LoRa due to its ease of construction and good performance in the low-frequency range.
- **Impedance Matching**:
  - The LoRa module and FPC antenna are designed with a 50 Ω impedance, ensuring maximum power transfer between the module and the antenna. This is crucial because mismatched impedance can lead to signal loss and reduced communication efficiency.
- **Matching Network**:
  - A matching network is used to ensure that the LoRa module and antenna impedance are well-matched for optimal signal transmission and reception. The matching network may include components like capacitors and inductors that fine-tune the impedance at the desired operating frequency.

4.5 Electromagnetic Field (EMF) Generation

The LoRa module generates an RF signal using Chirp Spread Spectrum (CSS) modulation. This signal is then radiated as an electromagnetic wave by the antenna.

- **Electromagnetic Wave**:
  - The electromagnetic wave consists of two components: an electric field (E) and a magnetic field (B), which oscillate perpendicular to each other. These fields propagate through space and carry the modulated data from the transmitter to the receiver.
  - The FPC antenna radiates this electromagnetic wave, allowing for the wireless transmission of data over long distances.

- **Wavelength**:
  - The wavelength of the signal is determined by the frequency of the transmission. Using the formula:

$$\lambda = \frac{c}{f}$$

    Where:
  - $\boldsymbol{\lambda}$ = wavelength
  - $\boldsymbol{c}$ = speed of light (3×10^8 m/s)
  - $\boldsymbol{f}$ = frequency (433 MHz for this project)

The **wavelength** of the signal at **433 MHz** is:

$$\lambda = \frac{3 \times 10^8}{433 \times 10^6} = 0.692\ m$$

This corresponds to the physical length of the quarter-wave monopole antenna used in the LoRa module.

- **Bandwidth**:
  - The bandwidth of LoRa communication depends on the spreading factor (SF) and signal bandwidth settings. A higher SF results in a lower data rate but increased range, thus impacting the overall bandwidth available for transmission.

4.6 Power Consumption

The power consumption of LoRa modules is one of the key advantages of the technology, making it suitable for battery-powered applications.

- **Sleep Mode**: The LoRa module consumes as little as 1 µA, making it ideal for remote sensing where low power is crucial for prolonged battery life.
- **Transmission Mode**: During data transmission, the module draws 20 mA to 120 mA, depending on the power settings, the spreading factor (SF), and the distance over which data is being transmitted.

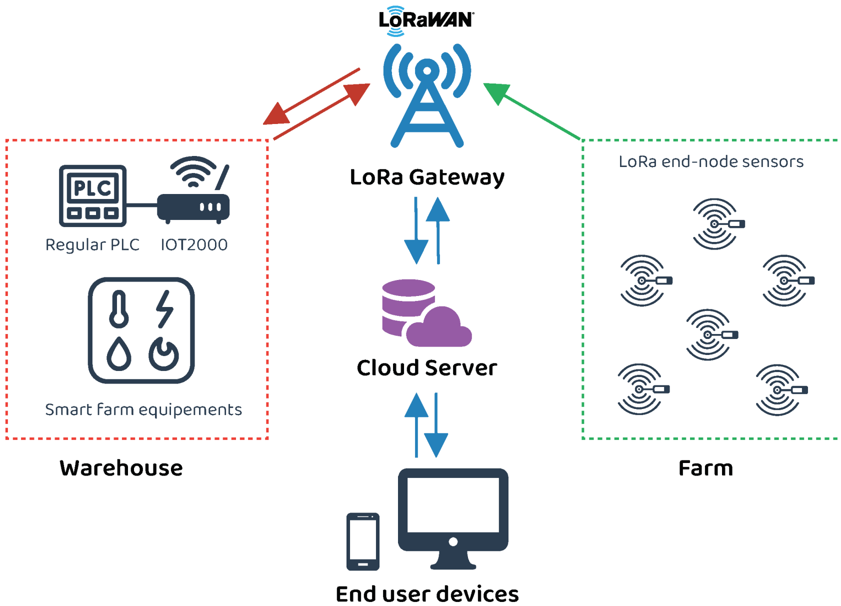


Figure 2: Operation diagram for LoRa

5 Components and Connections:

5.1 LoRa Module (SX1278)

- MISO → D12 on Arduino Uno (receive data).
- MOSI → D11 on Arduino Uno (send data).
- SCK → D13 on Arduino Uno (clock signal).
- NSS → D10 on Arduino Uno (chip select).
- RESET → D9 on Arduino Uno (reset module).
- DIO0 → D2 on Arduino Uno (packet transmission detection).
- Antenna → SMA connector on LoRa module.

5.2 Arduino Uno

- The central controller that reads data from the DHT11 and PIR sensors and communicates with the LoRa module.

5.3 DHT11 Sensor

- VCC → 5V on Arduino Uno.
- DATA → D3 on Arduino Uno.
- GND → GND on Arduino Uno.

5.4 PIR Motion Sensor

- VCC → 5V on Arduino Uno.
- OUT → D4 on Arduino Uno.
- GND → GND on Arduino Uno.

5.5 OLED Display

- VCC → 5V on Arduino Uno.
- SDA → A4 on Arduino Uno.
- SCL → A5 on Arduino Uno.
- GND → GND on Arduino Uno.

6 System Workflow:

6.1 Data Collection: How DHT11 and PIR Sensors Work

The process of collecting data starts with the sensors detecting environmental conditions and then converting that information into a digital format that can be processed by the Arduino. Let's explore this process for each sensor, step by step:

6.1.1 DHT11 Sensor: Temperature and Humidity Measurement

The DHT11 sensor is a digital sensor that measures temperature and humidity in the surrounding air. Though it measures analog data, it converts it to a digital signal using an internal microcontroller. Here's how it works:

1. Sensing the Analog Environment:

- The DHT11 sensor contains a humidity sensing component (usually a resistive element) that changes its electrical resistance in response to the moisture content in the air.
- Similarly, the temperature sensor inside the DHT11 (usually a thermistor) detects changes in resistance as the temperature varies in the environment.

2. Analog to Digital Conversion:

- The analog signals from the humidity sensor and temperature sensor are sent to an internal microcontroller within the DHT11.
- The microcontroller digitizes these analog readings using an Analog-to-Digital Converter (ADC), converting them into digital values that can be easily processed by the Arduino.

3. Data Transmission:

- The microcontroller then sends the digital data over the single-wire communication protocol to the Arduino. The data includes both temperature and humidity readings in digital form.
- The Arduino receives this data and processes it, extracting the temperature and humidity values from the digital signal.

6.1.2 PIR Motion Sensor: Motion Detection

The PIR motion sensor is designed to detect motion by measuring changes in the infrared radiation emitted by objects in its field of view. It operates in a different way than the DHT11 but still converts analog data to digital form for the Arduino to process. Here's how it works:

1. Sensing the Analog Environment:

- The PIR sensor detects infrared radiation from objects in its environment, primarily from humans or animals. It uses a pyroelectric sensor that responds to changes in infrared energy.
- When a warm body (such as a person) moves within the sensor's range, the sensor detects the variation in infrared radiation and produces a corresponding analog output signal.

2. Analog Signal Processing:

- The sensor converts the infrared radiation changes into an analog voltage.
- This analog voltage is then processed by the internal circuitry of the PIR sensor, which produces a HIGH signal when motion is detected and a LOW signal when no motion is detected.

3. Digital Output:

- The PIR sensor is a digital sensor by design, meaning it outputs either a HIGH (motion detected) or LOW (no motion detected) signal, which is easily read by the Arduino.
- The Arduino then interprets the signal, determining whether motion is detected or not.

6.2 Data Flow from Sensors to Arduino

Here's how the data flows from the DHT11 and PIR sensor to the Arduino for further processing:

1. **DHT11 Sensor:**
    - The humidity sensor and temperature sensor inside the DHT11 convert the analog signals into digital values.
    - These digital values are then sent over the single-wire bus to the Arduino, which reads the data using the DHT library and extracts the temperature and humidity values.
    - The Arduino processes this data, converting it into a readable format (e.g., displaying it on a screen or preparing it for wireless transmission).
2. **PIR Motion Sensor:**
    - The PIR sensor outputs a digital signal (either HIGH or LOW), which is read by the Arduino using a digital input pin (typically D4).
    - The Arduino checks the state of the signal to determine if motion is detected.
    - When the signal is HIGH (motion detected), the Arduino prepares to process or transmit this event (e.g., sending a notification or updating the display).

6.3 Data Encoding and Transmission

Once the Arduino has processed the data from the DHT11 and PIR sensors, it is ready to be transmitted over the LoRa module:

1. **Data Formatting:**
    - The Arduino formats the digital data into a string format that includes the temperature, humidity, and motion status (e.g., "Temp: 25°C, Hum: 60%, Motion: Detected").
2. **LoRa Transmission:**
    - The Arduino uses the LoRa module to send this formatted data wirelessly. The LoRa module uses CSS modulation to encode the digital data into an RF signal, which is transmitted over the air.

7 Block Diagram:

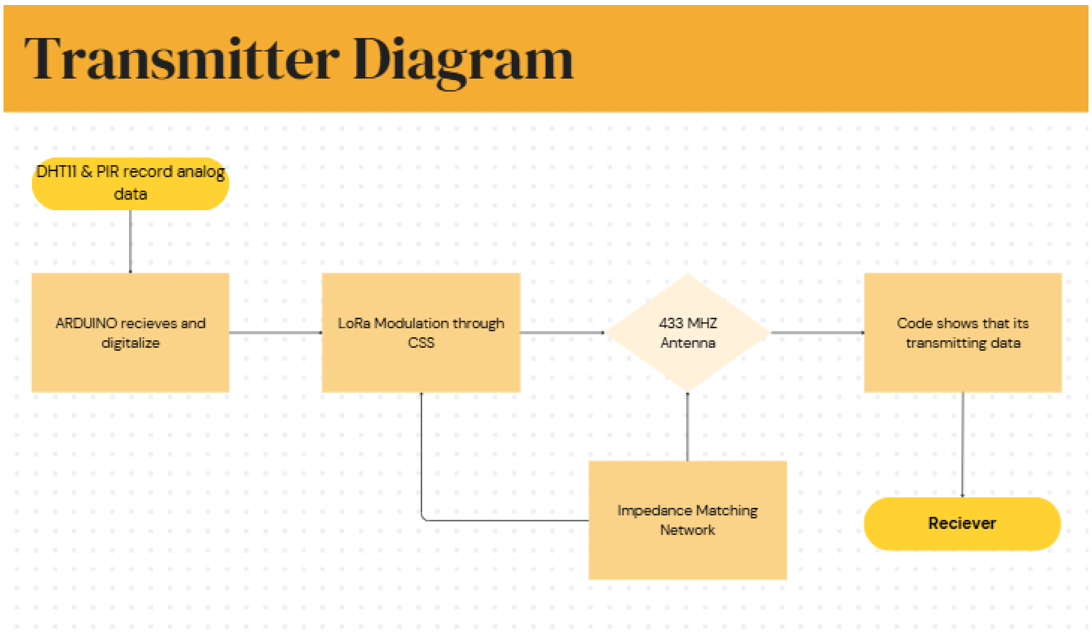


Figure 3.1: Transmitter Block Diagram

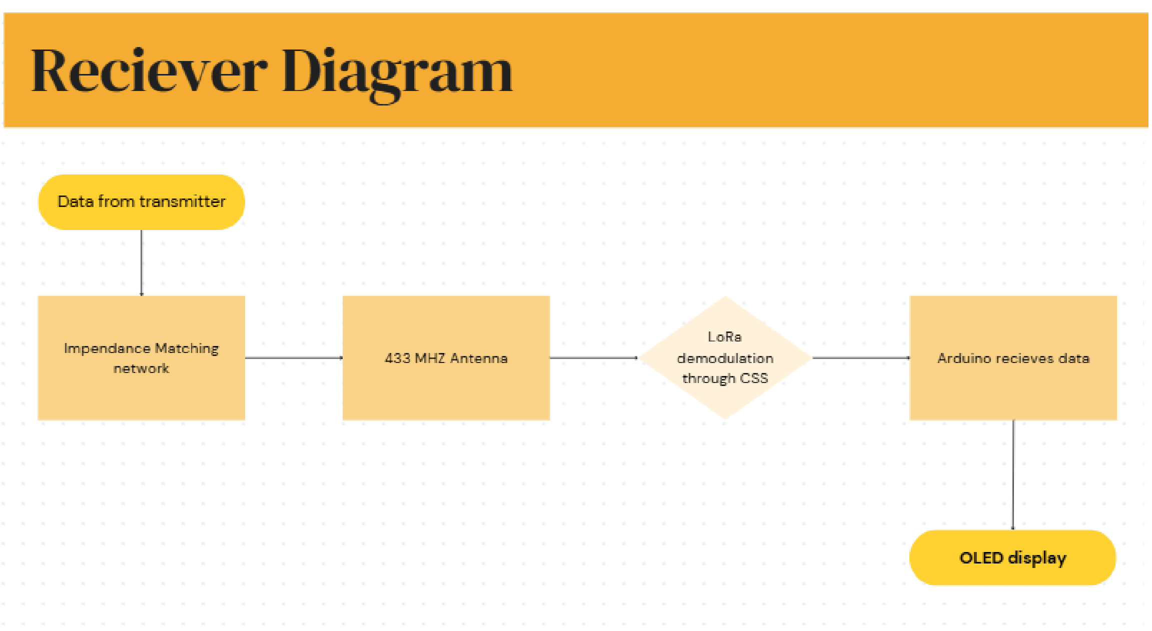


Figure 3.2: Receiver Block Diagram

8 Results:

8.1 Performance Evaluation

- Range Test: The system achieved successful communication over distances of up to 10 km in open rural areas and 2-5 km in urban environments.
- Power Consumption: The system demonstrated low power consumption, with the LoRa module consuming minimal power during idle and transmission modes, ensuring long battery life.

8.2 Range Test and Power Consumption

The system was able to communicate over long distances while consuming minimal power, making it ideal for remote locations.

8.3 Scalability and Applications

The system is easily scalable by adding more nodes for data collection and can be applied in smart agriculture, environmental monitoring, and IoT-based data collection.

LoRa Module

Figure 4: Video of how the project operates.

9 Conclusion:

This project successfully demonstrated the capabilities of LoRa technology in creating a low-power, long-range wireless sensor network. The system efficiently transmitted sensor data from the transmitter node to the receiver node, making it an excellent solution for remote monitoring and data collection in areas without traditional network infrastructure.

10 Future Work:

One potential enhancement for this system is the integration of Li-Fi (Light Fidelity) alongside LoRa to create a hybrid communication system. Li-Fi uses visible light to transmit data, offering high-speed communication compared to traditional radio frequency (RF) solutions like LoRa. Here's a breakdown of how Li-Fi can be integrated with LoRa and the benefits it would bring:

1. Understanding Li-Fi

Li-Fi is a wireless communication technology that uses visible light (typically from LEDs) to transmit data. It works by modulating the light emitted by LEDs at a high frequency, which can then be received by a photodetector and decoded into data. Unlike Wi-Fi that uses radio waves, Li-Fi is based on the principle of optical wireless communication.

- High-Speed Data Transmission: Li-Fi can theoretically support data rates of up to 100 Gbps under optimal conditions, which is significantly faster than the low data rates offered by LoRa.
- No Interference with RF Networks: Li-Fi operates in the visible light spectrum, so it does not interfere with RF communication systems like LoRa. This makes it an ideal complement to LoRa in environments where both high-speed and long-range communication are needed.
- Line-of-Sight Communication: Since Li-Fi relies on light, it requires a clear line of sight between the transmitter (LED) and receiver (photodetector). This can be a limitation in certain environments, but it can also provide a more secure communication channel compared to RF-based systems.

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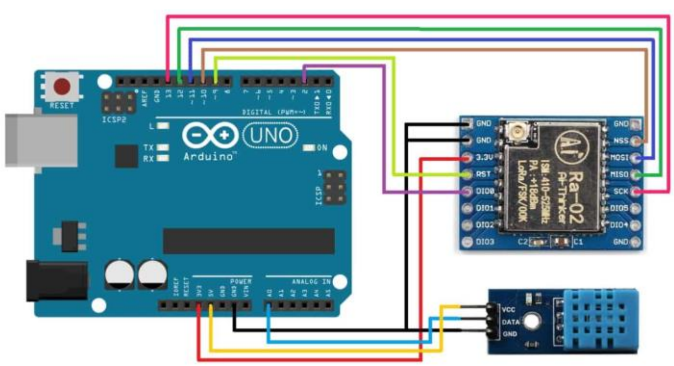
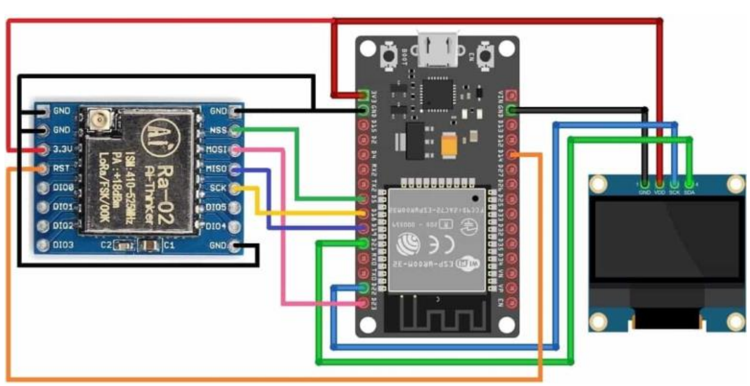
12 Appendices:

12.1 Circuit Diagram:



Appendix A: Transmitter example circuit diagram



Appendix B: Receiver example circuit diagram using ESP32 instead of Arduino

12.2 Arduino Code:

transmitter_DHT22_PIR.ino

Receiver_OLED.ino

Appendix C: Press to view Transmitter and Receiver codes in IDE