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Development of a Wireless Sensor Node Test Bed for Real-Time Environmental Monitoring

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Abstract –This paper presents the design and implementation of a low-cost, wireless environmental monitoring system using an ATmega328P microcontroller and nRF24L01 Radio Frequency (RF) module. The system comprises distributed sensor nodes capable of measuring temperature, humidity, light intensity, and dust density using DHT22, BH1750, and GP2Y1010AU0F sensors. Sensor data is wirelessly transmitted to a central base station, which logs the received data onto an SD card using the Serial Peripheral Interface (SPI) communication protocol and provides visual feedback via a Light Emitting Diode (LED) indicator. The system incorporates power-saving features, including sleep modes, to extend battery life. A mathematical battery consumption model was developed to estimate energy usage per transmission and predict battery longevity. Experimental results showed stable performance, with consistent voltage supply, accurate sensor readings, and effective data transmission across all environmental parameters. The system offers a scalable and energy-efficient solution for real-time environmental monitoring in both indoor and outdoor settings, making it suitable for smart agriculture, air quality assessment, and climate research applications

Keywords- Wireless sensor network; environmental monitoring; ATmega328P microcontroller; nRF24L01; low power consumption

I. INTRODUCTION

Environmental monitoring has become increasingly important in the context of climate change, urbanization, industrial pollution, and the need for sustainable resource management. Continuous assessment of environmental parameters such as temperature, humidity, air quality, and light intensity is essential for timely decision-making in areas such as agriculture, public health, disaster management, and urban planning [1]. Traditional methods of environmental monitoring often rely on manual data collection and isolated instruments, which are labor-intensive, limited in coverage, and incapable of providing real-time data. To address these limitations, Wireless Sensor Networks (WSNs) have emerged as a promising solution for automated, scalable, and remote environmental data acquisition systems [2].

WSNs consist of distributed sensor nodes equipped with sensing, processing, and communication capabilities [3]. These nodes collaborate to monitor environmental conditions and transmit data wirelessly to a central base station or server. However, the successful deployment of WSNs depends on effective integration of hardware and software components, energy efficiency, reliable communication, and data logging mechanisms. Telemetry, which refers to the automatic measurement and transmission of data from remote sources to receiving equipment for monitoring, has proven to be a critical enabler in real-time environmental monitoring systems [4].

This study presents the development of a telemetry-based wireless sensor node test bed designed to measure environmental parameters in real time. The system is built around the Atmega328p microcontroller, which serves as the central processing unit controlling three key operations: data acquisition from sensors, wireless transmission using nRF24L01 modules, and data logging. The choice of Atmega328p is motivated by its low power consumption, wide availability, and compatibility with the Arduino development environment, making it suitable for cost-effective environmental monitoring applications [5].

The sensor node is equipped with a suite of environmental sensors capable of measuring temperature, humidity, air quality, light intensity, and voltage drop. These readings are collected and transmitted wirelessly to a base station using the nRF24L01 transceiver module operating at 2.4 GHz.

This module was chosen for its high data rate, low power consumption, and robust signal integrity over short distances, making it ideal for indoor and semi-outdoor deployments [6].

Real-time data visualization is achieved using PLX-DAQ, a powerful data acquisition tool that integrates with Microsoft Excel through serial communication. This enables immediate viewing and recording of transmitted sensor data without requiring additional software development. Time synchronization and interval-based recording are facilitated using the DS3231 Real-Time Clock (RTC) module, which maintains accurate timestamps even during power disruptions. Furthermore, a Micro SD card module is integrated at the base station to ensure persistent data logging at one-minute intervals, enabling long-term analysis and interpretation of environmental trends.

The telemetry-based design eliminates the need for continuous human supervision, enhancing system autonomy and reliability. Its modular and low-cost structure also allows for easy scalability and customization based on specific environmental monitoring needs. As a result, this system offers a practical and efficient solution for real-time environmental monitoring, particularly in remote or resource-constrained areas where traditional monitoring methods are not feasible [7].

II. Related Works

Environmental monitoring systems have evolved significantly in recent years, driven by increasing awareness of climate change, pollution, and the urgent need for sustainable development [8]. Various research efforts have focused on developing test beds and real-time monitoring platforms to continuously assess environmental parameters such as temperature, humidity, air quality, and light intensity. These platforms are often deployed in urban centers, agricultural fields, and industrial zones to collect data that informs policy-making, disaster response, and resource management [9], [10]. Numerous test beds have been constructed using a range of sensors and microcontrollers, each aiming to provide real-time feedback and long-term data logging [11].

Earlier studies by [12] and [13] primarily relied on conventional data acquisition systems that were either manual or semi-automated, requiring considerable human effort. These systems often lacked scalability and failed to deliver real-time data effectively [14]. In an effort to improve upon these limitations, several researchers have designed wireless sensor network (WSN)-based test beds using popular microcontrollers such as the Arduino Uno and Atmega328p. These test beds typically include suites of sensors for environmental monitoring and are capable of transmitting data wirelessly to base stations or cloud storage platforms [15]. However, many of these implementations focused primarily on proof-of-concept designs or small-scale deployments, lacking robust telemetry capabilities for sustained real-time monitoring over extended periods [16].

Telemetry systems have been increasingly adopted in environmental monitoring due to their capacity to transmit data from remote locations to central hubs without the need for manual retrieval [17]. The integration of telemetry with WSNs allows for the seamless flow of data and improves decision-making processes in applications such as agriculture, air quality control, and disaster management [18]. Several studies have employed telemetry in the form of serial wireless transceivers, GSM/GPRS modules, and LoRa-based communication technologies [19], [20]. These telemetry modules serve as a communication bridge between the sensor node and the data logging platform. Despite these advancements, many of the existing telemetry systems are either too costly or complex to be adopted in low-resource settings [21].

One common approach to building cost-effective telemetry-enabled monitoring systems involves the use of the nRF24L01 communication module. This 2.4 GHz transceiver module is widely recognized for its low power consumption, high data transmission rate, and short-range wireless communication [22]. Researchers have adopted the nRF24L01 in various WSN implementations due to its simplicity and reliability for indoor and semi-outdoor use [23]. In particular, studies have shown its effectiveness in transmitting environmental sensor data to a base station, where further analysis and visualization can take place [24]. Nevertheless, limitations such as signal attenuation in open environments and limited communication range have also been noted in these studies [25].

In addition to communication modules, data acquisition tools have played a crucial role in the development of real-time monitoring platforms. One such tool is PLX-DAQ (Parallax Data Acquisition), which provides a seamless interface between Arduino-based systems and Microsoft Excel via serial communication. This integration enables real-time data visualization and storage without the need for additional software development [26]. Several researchers have used PLX-DAQ to simplify the data logging process and to provide time-stamped entries for environmental parameters. The simplicity of this solution has made it popular among academic and prototyping communities. However, its reliance on continuous PC connectivity limits its application in long-term autonomous deployments [27].

To address the need for time-based data logging, RTC modules such as the DS3231 have been widely integrated into environmental monitoring systems [28]. The DS3231 offers high accuracy and the ability to maintain timekeeping even when the main system is powered off, thanks to its onboard battery [29]. Studies have incorporated this module to enable interval-based recording of sensor data and to synchronize events across distributed nodes in a WSN. The use of RTC modules has enhanced the ability of environmental monitoring systems to timestamp sensor data, which is essential for trend analysis, anomaly detection, and decision support systems [30].

Furthermore, Micro SD card modules have been incorporated into several monitoring platforms to enable offline storage of sensor data. These modules allow for large-scale data retention, even in the absence of constant wireless connectivity [31]. When combined with RTC modules and telemetry systems, SD card storage facilitates a comprehensive data logging solution that ensures persistence and redundancy. Researchers have utilized these modules in various projects, particularly those deployed in remote areas with limited access to cloud-based services [32]. However, the integration of SD card modules often increases the power requirements and complexity of the system, which may affect long-term deployment in energy-constrained environments.

Despite the substantial progress made in the development of environmental monitoring platforms, several challenges remain unaddressed. A notable gap in the literature is the limited integration of low-cost serial communication systems with full data logging capabilities. Many existing platforms either rely heavily on PC-based interfaces like PLX-DAQ or employ expensive and power-hungry telemetry modules unsuitable for small-scale or rural deployments. Moreover, while individual components such as communication modules, RTCs, and SD card storage have been tested in isolation, comprehensive systems that bring together these elements into a cohesive, energy-efficient, and scalable platform remain scarce.

This study aims to bridge this gap by developing a telemetry-based wireless sensor node test bed that integrates low-cost serial communication (nRF24L01), accurate real-time data logging (DS3231 RTC), and persistent storage (Micro SD card module) into a single, compact design. The goal is to provide a scalable and autonomous solution for real-time environmental monitoring, particularly suited for low-resource or remote locations. By combining hardware and software in a modular, energy-efficient framework, this research seeks to address existing limitations and contribute a practical, cost-effective platform to the growing field of environmental monitoring technologies.

III. System Design Overview

There are many architectures for smart environmental monitoring device; in fact, the architecture, in most of the cases, is based on the application. However, in this section, presenting the most common architectures for smart environmental monitoring applications. As can be seen in Figure 1, there are four basic layers of the architecture, which are the physical layer, OS abstraction layer, middleware layer, and application components layer.

The physical layer consists of different components, including the smart devices and the communication interface. Smart devices could be smart sensors, such as humidity, light intensity, dust particle and temperature sensors. The communication component could be wired as in indoor applications or wireless as in outdoor applications. Smart environmental networks are usually utilizing the ZigBee and Bluetooth communication standards in addition to satellite communication, Radio Frequency will be the focus for this project. The OS abstraction layer is the kernel of any smart environmental monitoring in terms of including the basic required instructions for environment operations, it encompass and consist of the Microcontroller and Bootloader.

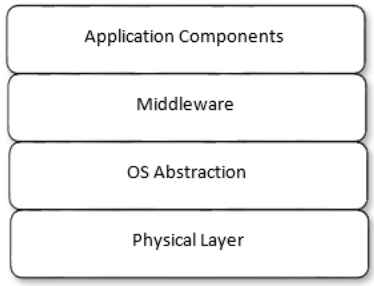

Figure 1. Systems Design Block Structure

Above the OS abstraction layer sits below the middleware layer, which includes the message controllers and communication channel identifier, it also consists of the datalogger in form of a Serial Disk and the Real time Clock which ensures that the data logged are serial arranged with the data collected. In addition, it is the interface between the application components and the OS abstraction layer in which different applications might require different requirements. The final layer is the application components layer, in which it is assumed that the application consists of many components that might be implemented separately. At the same time, these components can communicate to each other through the middleware layer, in context of this project the PLX-DAQ serves as master controller of the two sides of the project and ensures an applied or desired output of the entire environmental monitoring.

A. System Architecture

The proposed system is architecturally divided into two distinct components, each functioning as an integral part of a telemetry-based environmental monitoring framework. One part operates as the remote wireless sensor node responsible for sensing and transmitting environmental data, while the other functions as the base station that receives, logs, and visualizes the data in real time.

- **Sensor Node:** A wireless sensor node is composed of four primary subsystems: sensing, computation, communication, and power supply. The sensing subsystem interfaces with the environment by converting physical phenomena into electrical signals, which are processed by the microcontroller. The microcontroller, acting as the central processing unit (CPU), coordinates all node functions and supports multiple power modes active, idle, and sleep to minimize energy usage. The Basic architecture of the sensor node is shown Figure 2. The wireless communication module, typically a radio transceiver, handles data transmission and reception and is the most power-consuming component, especially when data is transmitted frequently or over long distances. Sampling intervals significantly affect power consumption; less frequent sampling reduces energy usage. The communication unit uses low-power RF modules that support adjustable data rates and ranges, making them ideal for diverse WSN applications. The power subsystem relies on batteries or supercapacitors, designed for long-term deployment in environments where maintenance is difficult or impractical. To extend operational life, the system employs energy-efficient designs and power management strategies, such as sleep mode scheduling. Some sensor platforms feature built-in sensors, while others offer ports for modular sensor integration, ensuring flexibility. Overall, the node design prioritizes low energy consumption and adaptability for real-time, remote environmental monitoring in varied and challenging settings.

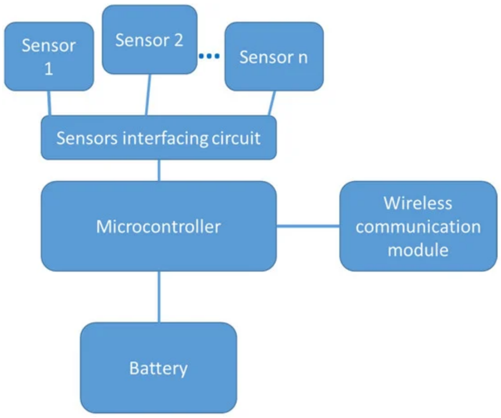

Figure 2. Basic architecture of the sensor node

- **Base Station:** The second part of the system is the base station (Receiver module), which is responsible for receiving, merging, and storing data packets transmitted by the wireless sensor node. It stores the data to the SD Card Module server using the Recommended Real Time Clock Standard (DS-1302) protocol to ensure that each packet is accurately time-stamped and up to date. This ensures chronological integrity of the monitored environmental data.

  Additionally, a desktop application module interfaces with the system by generating queries and sending requests to the PLX-DAQ tool, a data acquisition interface that integrates with Microsoft Excel. This tool processes the received data and presents it in a clear, user-friendly format, enabling system operators or personnel to easily interpret, analyze, and respond to real-time environmental conditions.

B. *Hardware Component Overview*

This is the concise explanation of the key components used in the design of the sensor node test bed for the environmental monitoring. Each component plays a crucial role in ensuring the device's functionality, user interaction, and overall performance.

1) **ATMEGA 328 Microcontroller**: Atmega-328 is an AVR family microcontroller with 28 pins. It has 6 analogue inputs and 13 digital input/output pins. A high-performance Microchip power in pico-watts 8-bit AVR RISC-based microcontroller combines 32KB ISP flash memory with read-while-write capabilities. It has a 1024B EEPROM, 2KB SRAM, 23 general-purpose I/O lines, 32 general purpose working registers, three flexible timer/counters with compare modes, internal and external interrupts as shown in Figure 3 [33]. It also has a serial programmable USART, a byte-oriented 2-wire serial interface, SPI serial port, a 6-channel 10-bit A/D converter (8-channels in TQFP and QFN/MLF packages), programmable watchdog timer with internal oscillator, and five software selectable power saving modes. The device operates between 2.5-5.5 volts.

   The Atmega328 microcontroller serves as the central processing unit in the design, managing sensor data acquisition, coordinating communication with the nRF24L01 transceiver, and controlling data logging processes. Its low power consumption and versatile functionality make it ideal for efficiently integrating sensing, transmission, and timing tasks within the wireless sensor node system.

Figure 3. ATMEGA328 Microcontroller

2) **NRF24L01 Transceiver**: The nRf24l01 is a single chip 8-pin radio transceiver module working in frequency of 2.4-2.4835 GHz ISM band with special pins that enable communication in all boards and microcontrollers. It is embedded with a baseband protocol engine known as Enhanced Shock Burst. It is generally used for low power wireless applications. Its maximum current consumption is 15mA. It can be operated using SPI (serial peripheral interface) using Master Out and Slave In (MOSI) and Master In and Slave Out (MISO) pins. The frequency channel, output power and the data rate can be configured depending upon the need. It supports a data rate of 250kbps, 1Mbps and 2Mbps. Overlapping channel spacing is 1 MHz and 2 MHz This transceiver module is composed of a frequency generator, beat controller, power amplifier, crystal oscillator modulator, and demodulator as shown in Figure 4 [34].

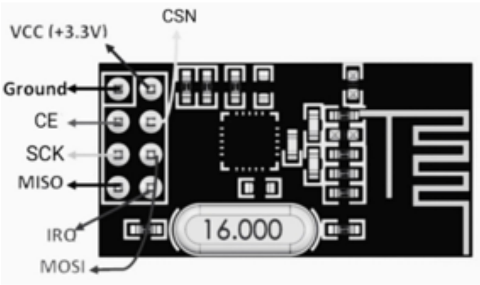

Figure 4. NRF24L01 Module

A single nrf module can connect with six (6) others modules as the transceiver. Utilizing and annexing the capability of the nrf can create a network of more than 3000 nodes using tree topology of 5 levels deep. Each node is assigned with address in the octal format defined by 15-bit address, allowing data transmission between devices and building mesh networks "one to many" or "many to many," increasing the communication range and providing network self-recovery capabilities in case of failure of one of the elements. The equations for Free Space Path Loss and Link Budget of the nRF24L01's wireless communication is given in following equations:

From Friis transmission equation (1):

$$L_{fs} = \left(\frac{4\pi df}{c}\right)^2 \quad (1)$$

Taken logarithm base 10 of equation 1 and then convert to dB (2) – (3):

$$L_{fs} = 20\log_{10}(d) + 20\log_{10}(f) + 20\log_{10}\left(\frac{4\pi}{c}\right) \quad (2)$$

$$L_{fs} = 20\log_{10}(d) + 20\log_{10}(f) + 32.44 \quad (3)$$

In the Free Space Path Loss (FSPL) model in equation 1 to 3, the distance f represents the separation between the transmitter and the receiver, measured in kilometers (km). The variable f denotes the frequency of operation, measured in megahertz (MHz). For the nRF24L01 module, which operates at a frequency of 2400 MHz (2.4 GHz), this value is substituted directly into the equation. The speed of light, represented by ccc, is a constant value equal to 3×108 meters per second (m/s). This parameter is used in the derivation of the FSPL formula to account for the propagation characteristics of electromagnetic waves in free space. The link budget is also given by (4):

$$P_{rx} = P_{tx} + G_{tx} + G_{rx} - L_{fs} - L_o \quad (4)$$

In the link budget equation for wireless communication, P_rxrepresents the received power in decibels-milliwatts (dBm), while P_tx denotes the transmitted power, also in dBm. The terms G_tx and G_rx refer to the antenna gains of the transmitter and receiver respectively, measured in decibels relative to an isotropic radiator (dBi). L_fs stands for the free space path loss, expressed in decibels (dB), which accounts for signal attenuation over distance due to the spreading of the wavefront in open space. Additionally, L_o represents other system losses, also in dB, which may include losses due to connectors, cables, environmental obstructions, or hardware inefficiencies. These parameters collectively determine the effective signal strength received by the nRF24L01 module in a wireless sensor network.

3) **Light Intensity Sensor (BH1750)**: The BH1750 is a low-cost digital light intensity sensor designed to measure ambient light levels with high precision and ease of integration. It communicates via the I2C protocol, making it highly compatible with a wide range of microcontrollers such as the ATmega328, commonly used in Arduino platforms.

As shown in Figure 5 [35], the sensor outputs direct lux values ranging from 1 to 65,535 lux, eliminating the need for complex calculations or analog-to-digital conversions. Operating at a voltage range between 2.4V and 3.6V and consuming only about 0.12mA of current, it is extremely power-efficient, making it ideal for battery-powered applications. It offers ±20% accuracy and is minimally affected by infrared radiation, ensuring stable and reliable light measurement. The BH1750 is commonly used in devices requiring automatic brightness adjustment, such as smart lighting systems, displays, and environmental monitoring setups, and is valued for its fast response, compact size, and straightforward integration.

Figure 5. BH1750 Module

4) **DHT 22 Module:** The humidity and temperature sensor (DHT22) shown in Figure 6 [36], also known as the RHT03, is a popular sensor used for measuring both humidity and temperature in various applications. It is a digital sensor that provides accurate and reliable measurements with a high degree of precision. Some key features and characteristics of the DHT22 sensor represented with measurement range: the DHT22 sensor can measure temperature in the

range of -40 °C to 125 °C (-40 °F to 257 °F) with an accuracy of ±0.5 °C, and humidity in the range of 0% to 100% with an accuracy of ±2%.

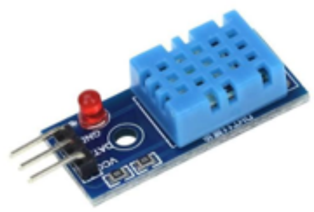

Figure 6. DHT22 Module

The DHT22 sensor is designed to operate with low power consumption, making it suitable for battery-powered applications or energy-efficient systems. The DHT22 sensor has a fast response time, typically around 2 seconds for temperature readings and 2-5 seconds for humidity. This allows for real-time monitoring and quick detection of changes in environmental conditions.

5) **Air Quality Module:** The study focuses on Particulate matter in respect to Air quality as the immediate environment is not an industrial or chemical based one. There are two categories of particle matter: the first are coarse dust particles between 2.5 and 10 micrometers (µm) in diameter, known as PM10. Examples of PM10 particles include dust, pollen, and mold. The second category includes fine particles with diameters of 2.5 µm or less, known as PM2.5. PM2.5 particles are produced from solid fuel combustion and industrial processes.

Sharp's GP2Y1010AU0F is an optical air quality sensor, designed to sense dust particles (PM10) as shown in Figure 7. An infrared emitting diode and a phototransistor are diagonally arranged into this device, to allow it to detect the reflected light of dust in air. It is especially effective in detecting very fine particles like cigarette smoke, and is commonly used in air purifier systems and environmental monitoring systems [37].

Figure 7. Air Quality Module

The sensor has a very low current consumption of 20mA maximum and 11mA typical, and can be powered with 4.5V to 5V (up to 7V DC).

The output of the sensor is an analog voltage proportional to the measured dust density.

C. Test Bed Prototype Implementation

The test bed prototype was implemented to validate the telemetry-based wireless sensor node system designed for real-time environmental monitoring. The system comprises two main modules: the transmitter (sensor node) and the receiver (base station). At the transmitter end, the Atmega328 microcontroller was programmed to collect data from connected sensors, including DHT11 for temperature and humidity, MQ135 for air quality, BH1750 for light intensity, and a voltage divider for battery status. These sensors were interfaced through analog and digital input pins of the microcontroller, and the data were processed and formatted for transmission. Communication between the sensor node and the receiver module was established using the nRF24L01 transceiver operating at 2.4 GHz, selected for its low power consumption and effective short-range transmission as shown in Figure 8.

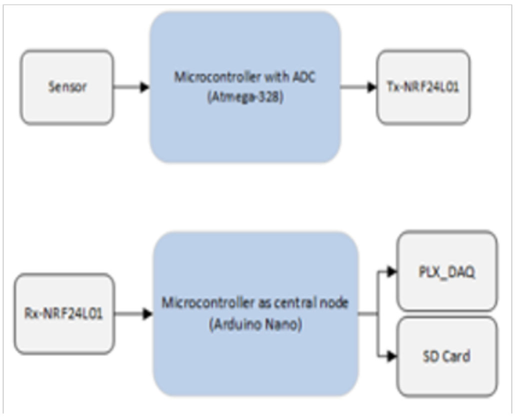

Figure 8. Sensor Node and Base Station Design Block Diagram

The receiver module was built around another Arduino Nano microcontroller, and responsible for capturing the transmitted data packets and forwarding them to a data logging system. The DS1302 RTC module was used to timestamp each data entry accurately. A MicroSD card module was integrated to provide non-volatile storage for long-term data logging. Additionally, PLX-DAQ, a Microsoft Excel-based serial data acquisition tool, was employed to visualize the received data in real time. This prototype demonstrated reliable operation and modular expandability for future enhancements. The hardware breadboard prototype is shown in Figure 9.

In the calibration process of our environmental monitoring system, we adopted a meticulous approach to ensure the accuracy and reliability of our sensor readings, drawing upon recent advancements and best practices in the field. The calibration involved comparing our system's sensor readings against those from selected commercial equipment known for their precision and reliability in measuring environmental parameters. The circuit diagram is shown in Figure 10.

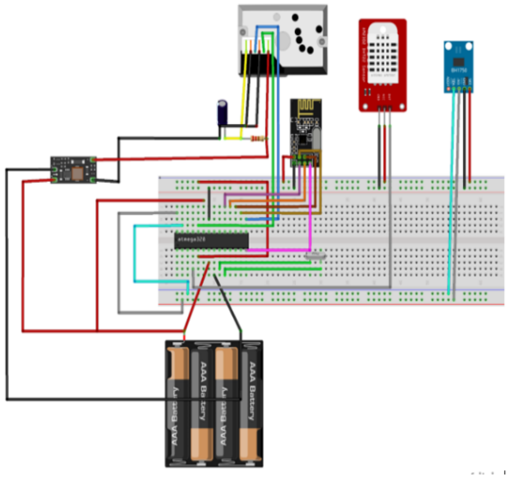

Figure 9. Hardware Breadboard Prototype

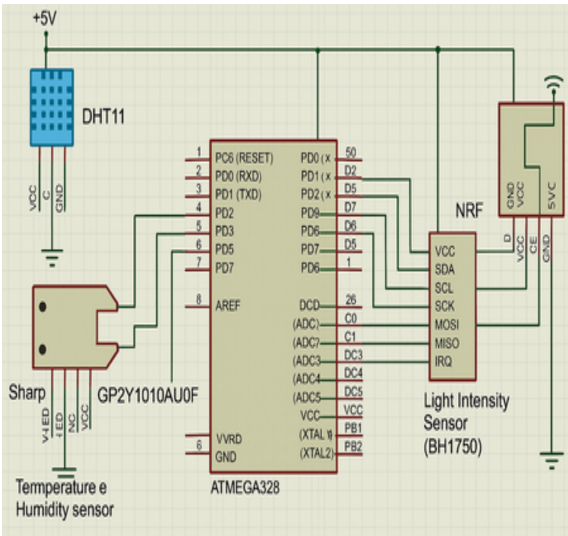

Figure 10. System Circuit Diagram

This approach allows for the correction of biases and enhancement of data reliability across different locations, making it possible to estimate environmental quality levels with greater precision. By integrating these advanced calibration techniques and carefully selecting reference equipment, we aimed to enhance the accuracy and reliability of our environmental monitoring system. This detailed calibration process, grounded in the latest research and best practices, ensures that our system can provide valuable and trustworthy data for environmental assessment and the hardware implementation of the sensor node is shown in Figure 11.

The proposed system includes two wirelessly connected modules: a sensor node and a base station. The sensor node, powered by an ATmega328P microcontroller, initializes communication interfaces, collects data from sensors like DHT22, BH1750, and GP2Y1010AU0F, processes it, and transmits it via the nRF24L01 module. After transmission, the system enters sleep mode to conserve power. At the base station, another ATmega328P initializes communication, listens for data, and logs received packets to an SD card using the DS1302 RTC for timestamping. The system confirms successful transmission through LED indicators and manages data reception errors using retry mechanisms and acknowledgment protocols to ensure reliability.

Figure 11. Environmental Monitoring Sensor Node

D. Developed Mathematical Model for Test Bed

A simple mathematical model was developed for the environmental monitoring sensor node Test Bed based on the key aspects of its operation battery power consumption.

Battery Power Consumption Model

To estimate the energy usage per transmission for each component in the wireless sensor node, the following formula is applied (5):

$$E_t = \frac{I \times T}{3600000} \quad (5)$$

Where E_t represents the energy consumption per transmission measured in milliampere-hours (mAh), I denotes the current draw of the component in milliamperes (mA), and T refers to the operating time of the component in milliseconds (ms).

The two modes for the power consumption are the active and standby modes. Let the battery level at time t in milliampere-hours (mAh) be denoted by $B(t)$ (6):

$$B(t) = Bo - (P_a \times A_t + P_s \times A_s) \quad (6)$$

Where Bo represents the initial battery level, measured in milliampere-hours (mAh). P_a denotes the active power consumption rate, given in milliampere-hours per minute (mAh/min). P_s refers to the standby power consumption rate, also in milliampere-hours per minute (mAh/min). A_t is the time spent in active mode, measured in minutes, while A_s is the time spent in standby mode, also measured in minutes.

IV. Testing and Result Analysis

The discussion was centered on the observations, modifications, and results obtained during the tests conducted. The wireless environmental monitoring system was successfully implemented and tested, with the following key outcomes observed:

1) **Power Efficiency:** The system's ability to adjust its transmission frequency based on voltage readings helped extend the battery life of the transmitter node. Additionally, implementing a sleep mode further reduced power consumption during periods of inactivity, ensuring the system could operate for extended periods without frequent battery replacements as shown in TABLE I.

TABLE I. COMPONENTS POWER CONSUMPTION

Component	Current Draw (mA)	Operating Time (ms)	Consumption per Transmission (mAh)
ATmega328P (Active mode)	15	2000	0.0083
nRF24L01 (Transmit Mode)	14	100	0.0004
DHT11 Sensor	0.5	1000	0.0001
DHT11 Sensor (LED)	10	2000	0.0056
BH1750 Light Sensor	0.12	100	0.000003
GP2Y1010AU0F Dust Sensor	20	1000	0.0056
LED (during blink)	20	200	0.0011
DS1302 RTC	3	2000	0.0017
Idle/Sleep Mode (ATmega328p)	0.05	3000	0.000042

2) **Data Transmission and Reception**: The transmitter was able to send data packets from the environmental sensors consistently to the receiver. By adjusting the transmission interval based on the voltage level of the power source, the system demonstrated adaptability to changing conditions, which helped conserve battery life. It was observed that data was consistently transmitted within a distance of $\leqslant$ 80m and at increased distance the frequency of transmission was unstable at 1 successful transmission per 6-8 seconds. And the graph of data frequency against distance is shown in Figure 12.

On successful reception, the receiver reliably captured the data packets, which included temperature, humidity, light intensity, and dust density readings. The use of an nRF24L01 module ensured that the data was transmitted over a considerable distance without significant loss or interference.

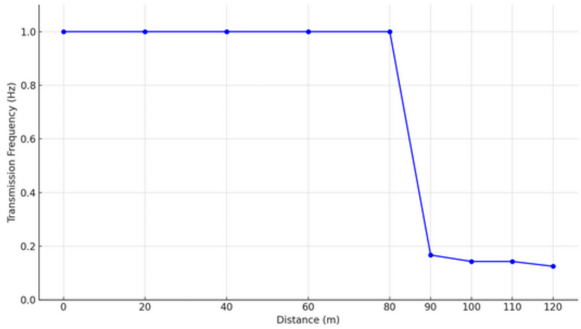

Figure 12. Graph of Data Frequency against Distance

3) **Data Logging and Visualization**: The SD card logging function in the receiver ensures that all received data is stored on an SD card, thereby creating a permanent and reliable record of environmental conditions over time. This logged data can be accessed later for in-depth analysis, offering valuable insights into trends and anomalies in the monitored environment. Additionally, the system incorporates a visual indicator in the form of an LED that blinks each time data is successfully received. This feature provides a straightforward and efficient means of confirming proper system operation without the need for continuous monitoring of the serial output as shown in Figure 13. The voltage analysis revealed that the system operated within a voltage range of 3.50V to 4.20V, with an average voltage of approximately 3.96V. This indicates that the battery provided stable power throughout the monitoring period, with only minor variations, suggesting efficient energy regulation by the power management system. Humidity readings ranged from 80% to 100%, with an average value of about 95%, reflecting a high-moisture environment typical of indoor spaces or humid climates. These readings showed normal fluctuations, consistent with environmental changes such as weather or indoor activities. Temperature analysis showed values between 15°C and 35°C, averaging at 25°C, which is close to typical room temperature.

The stability of the temperature readings, with no significant peaks or troughs, suggests a thermally stable environment. Light intensity ranged from 100 lux to 1000 lux, averaging around 550 lux, indicating a well-lit setting possibly due to proximity to natural or artificial light sources.

The variation in light levels reflects changing ambient conditions like time of day or lighting adjustments. Dust density measurements ranged from 500 to 2000 µg/m³, with an average of 569 µg/m³, representing a moderate particulate level. Fluctuations in dust levels may be linked to human activity, cleaning, or outdoor air infiltration.

Date	Time	Temperature °C)	Humidity (%)	Light Intensity (lx)	Air Quality (ug/m3)	Voltage Drop (V)
26/08/2024	00:42:23	27	95	77.50	396	3.96
26/08/2024	00:42:27	27	95	58.33	398	3.96
26/08/2024	00:42:34	27	95	0.00	402	3.95
26/08/2024	00:42:35	27	95	0.00	402	3.95
26/08/2024	00:42:36	27	95	0.00	402	3.96
26/08/2024	00:42:37	27	95	0.00	401	3.95
26/08/2024	00:42:44	27	95	0.00	395	3.95
26/08/2024	00:42:54	27	95	156.67	392	3.95
26/08/2024	00:43:00	27	95	270.00	395	3.95
26/08/2024	00:43:03	27	95	300.00	392	3.95
26/08/2024	00:43:05	27	95	300.00	504	3.95
26/08/2024	00:43:09	27	95	302.50	440	3.97
26/08/2024	00:43:13	27	95	300.83	395	3.95
26/08/2024	00:43:14	27	95	301.67	390	3.95
26/08/2024	00:43:15	27	95	300.83	387	3.95
26/08/2024	00:43:20	27	95	0.00	378	3.95
26/08/2024	00:43:27	27	95	0.00	361	3.95
26/08/2024	00:43:29	27	95	10.00	356	3.95
26/08/2024	00:43:50	27	95	98.33	361	3.95
26/08/2024	00:43:58	27	95	99.17	307	3.96

Figure 13. Data logging on SD Card at Base station

The results from the prototype implementation demonstrate the system's capability to reliably monitor and transmit environmental data using a low-power wireless sensor network. Voltage readings confirmed stable battery performance, supporting prolonged operation. Environmental parameters such as temperature, humidity, light intensity, and dust density were effectively captured, showing values within expected ranges for indoor environments. The LED indicator provided real-time visual confirmation of successful data transmission. Data logging on the SD card ensured accurate and retrievable records for analysis. Overall, the system functioned efficiently, validating its design and proving its potential for scalable deployment in environmental monitoring applications across various settings.

CONCLUSION

In conclusion, the development and implementation of the wireless environmental monitoring system demonstrated effective real-time data acquisition, processing, transmission, and storage using low-cost, energy-efficient components. The use of the ATmega328P microcontroller and nRF24L01 module enabled seamless wireless communication between sensor nodes and the base station. Sensors such as DHT22, BH1750, and GP2Y1010AU0F successfully measured key environmental parameters including temperature, humidity, light intensity, and dust density. The SD card module ensured reliable data logging for future analysis, while the LED indicator provided simple visual feedback on transmission status. The system proved stable, scalable, and suitable for deployment in both indoor and outdoor environments.

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