Wireless Sensor Network Performance Analysis for Indoor Air Quality Monitoring

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Abstract

Air pollution involves physical, chemical, and biological substances that can harm health and cause disease in living beings. Therefore, understanding air quality is very important. This research aims to design and develop a prototype of a web-based air quality monitoring system using Wireless Sensor Network (WSN) technology. Communication between the client and the server uses WebSocket.io protocols to reduce latency in the network. The system design is divided into two parts: the design of the server hardware and software, the microcontroller, as well as the user client interface. The study involves evaluating key performance metrics such as data reliability, latency, and power efficiency. Various sensor nodes are used to measure parameters including temperature, humidity, volatile organic compounds (VOCs), and particulate matter (PM). The nodes communicate with the central coordinator nodes, forming a mesh network topology to ensure reliable data transmission and coverage. The results of the performance analysis demonstrate the effectiveness of WSN in providing accurate and timely indoor air quality (IAQ) data. Challenges such as signal interference and node placement optimization are addressed to improve network reliability and coverage. The insights gained from this study contribute to the development of a more efficient IAQ monitoring system, encourage a healthier indoor environment and improve overall well-being.

Keywords: *Performance; Quality Monitoring; Wireless Sensor Network*

Introduction

Indoor air quality significantly affects the health and comfort of residents. With the increasing awareness of the importance of indoor air quality management, the demand for monitoring systems that provide accurate and real-time information about indoor air conditions is increasing. One of the technologies used to meet this need is Wireless Sensor Networks (WSN), which consists of sensors that are wirelessly connected to measure important parameters such as temperature, humidity, dust particle concentration, and hazardous gases. Although WSN promises effective and comprehensive monitoring, the reliability and effectiveness of these systems require in-depth analysis. Key factors such as the quality of communication between sensors, the effect of distance on measurement quality, and interference from other environmental sources need to be carefully considered to ensure the accuracy of air quality measurements, (Wibowo et al, 2017).

This study aims to conduct a comprehensive analysis of WSN performance in the context of indoor air quality monitoring. By understanding the factors that affect the performance of WSN, it is hoped that more effective methods and techniques can be developed to maintain air quality and improve the welfare of residents. In the development of indoor air quality monitoring technology, Wireless Sensor Networks (WSNs) offer a promising solution. The WSN consists of wirelessly connected sensors capable of measuring various parameters such as temperature, humidity, dust particles and harmful gases at multiple indoor points. The main advantage of WSN is its ability to provide real-time and continuous information, allowing users to respond quickly to adverse weather conditions or other potential hazards. (Rahmaniar et al, 2023).

However, to ensure the reliability and accuracy of the measurements, an in-depth analysis of the WSN's performance is required. This includes evaluating the quality of communication between sensors, assessing the impact of distance on measurement quality, and identifying possible interference from ambient sources. This kind of analysis not only ensures accurate data but also facilitates the development of optimal calibration or setting methods to improve the overall performance of the system. (Tharo et al, 2022)

This research is expected to provide a better understanding of the optimal use of WSN in the context of indoor air quality monitoring. As a result, more effective and efficient technical solutions can be found to maintain the health and comfort of indoor residents. In addition, the findings of this study have the potential to be the basis for the development of advanced technologies in the future, making a positive contribution to environmental sustainability and public welfare. The results of this study not only aim to increase public awareness of the importance of indoor air quality management but also lay the foundation for the development of more advanced technologies that have the potential to improve the health and comfort of indoor residents. (Hamdani et al, 2020).

Literature Review

2.1 IoT (Internet of Things)

Is a concept that leverages internet connectivity to

connect physical devices equipped with sensors and actuators. These devices can autonomously collect data, process it, and respond or take action in real-time. The basic concept of IoT involves the integration of physical devices with sensors, internet connectivity, and data centers that can be on local servers or in the cloud. (Hamdani et al, 2023)

In practice, IoT devices connected to the internet collect large amounts of data, which is often referred to as "big data". This data can be processed and analyzed by various parties such as companies or government agencies according to their needs. IoT implementations can provide a variety of benefits, such as improving operational efficiency, enabling remote monitoring, and optimizing decision-making based on the data collected.

2.2 Arduino

Is an open-source physical computing platform, primarily known for its simple input-output board. The platform enables the development of interactive physical systems that can detect and respond to real-world situations and conditions using software and hardware. Arduino refers not only to the board itself, but also to its programming language and software, as well as the Integrated Development Environment (IDE) [5]. There are many different types of Arduino modules available, and in this study, the Arduino Uno was used as a microcontroller that connects the hardware to the computer interface. For example, the Arduino Uno uses the ATmega328 microcontroller and is the successor to the Arduino Duemilanove. The Arduino Uno is equipped with 14 digital I/O pins, of which 6 input pins can be used as PWM outputs, and 6 analog input pins. The Arduino Uno also includes a 16 MHz crystal oscillator, a USB connection, a power jack, an ICSP header, and a reset button. (Rahmaniar et al, 2023)

Arduino uses its own compiler with the C/C++ programming language, adopting the concept of Object-Oriented Programming (OOP). The compiler is free and can be downloaded from arduino.cc website. One of the advantages of the Arduino compiler is its cross-platform capabilities, since it can run on different operating systems such as Windows, Linux, and macOS, allowing users of different operating systems to take advantage of these devices.

Figure 1. Arduino UNO ATmega 328

The advantages of Arduino compared to other hardware microcontroller platforms include:

1. The Arduino IDE is multiplatform, capable of running on a variety of operating systems such as Windows and Linux.
2. Arduino programming uses a USB cable to upload programs, not a serial port.
3. Arduino is open-source, allowing users to download software and circuit designs at no cost.
4. It does not require a separate chip programmer because it comes with a bootloader that handles the process of uploading programs from the computer.
5. It comes with a USB connection, allowing laptop users who don't have a serial/RS323 port to use it.
6. The programming language is easy to understand and supported by a comprehensive library.
7. There are ready-made modules (shields) that can be installed on an Arduino board, such as GPS, Ethernet, SD Card, and more.

2.3 Sensors in Electronic Systems

Sensors function to convert physical quantities into electrical signals that can be processed by digital systems or electrical circuits. The types of sensors are divided into physical sensors and chemical sensors, depending on the variables detected. Physical sensors detect based on physical principles such as light, sound, and temperature, while chemical sensors detect amounts of chemicals such as pH, gas, and oxygen. (Faludi, 2011)

DHT11 is a temperature and humidity sensor module with a temperature measurement range of 0 - 50°C and a humidity measurement range of 20 - 95% RH. This sensor module has a temperature measurement accuracy of about ±2°C and a humidity measurement accuracy of about ±5%.

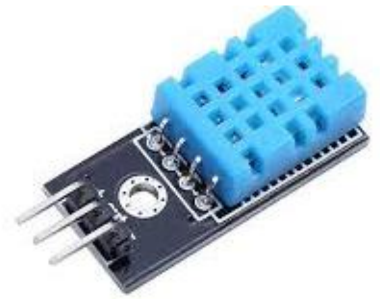

Figure 2. DHT11 humidity sensor

The specification of DHT11 is as follows:

a. Supply Voltage: +5V
b. Temperature Range: 0 – 50°C with an accuracy of ±2°C
c. Humidity Range: 20 - 90 % RH with ±5% accuracy
d. Output: Digital signal

The DHT11 is a sensor with calibrated digital signal capabilities that provides temperature and humidity information. These sensors are stable, have fast response times, and are affordable. DHT11 uses resistive elements and NTC temperature sensors. These sensors are equipped with highly accurate calibration with calibration coefficients stored in the sensor's program memory. When the sensor detects something, the module reads the sensor coefficient to provide more accurate results. With these characteristics, DHT11 is well-suited for a wide range of temperature and humidity measurement applications.

The LM35DZ temperature sensor is an electronic component used to convert temperature into an electrical signal in the form of voltage. These sensors are known for their high accuracy and ease of use.

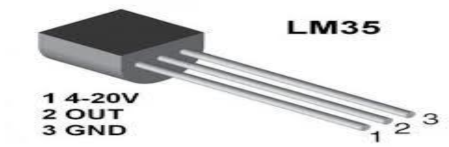

Figure 3. LM35DZ Temperature Sensor

The LM35DZ temperature sensor has 3 pins: Vs (supply voltage), GND (ground), and Output. The specifications of the LM35DZ temperature sensor are as follows:

a. Sensitivity: 10 mV/°C, providing a linear output voltage proportional to the temperature in Celsius.
b. Calibration accuracy: about ±0.5°C at 25°C.
c. Operating temperature range: from 0°C to 100°C.
d. Operating voltage range: from 4 to 30 Volts.
e. Low current consumption: about 60 µA.
f. Low output impedance: about 0.1 Ω for a current load of 1 mA.
g. Nonlinearity: about ±1/40°C.

The LM35DZ sensor is a good choice for applications that require high-precision temperature monitoring, such as in temperature control systems, environmental monitoring, and IoT applications that require accurate temperature measurements

2.4 ZigBee

Is a specification for high-level communication protocols based on the IEEE 802.15.4 standard, which is specifically designed for Wireless Personal Area Networks (WPANs). ZigBee has low power consumption and is adapted for private networks with low power requirements. This technology is widely used to control other devices and is often applied as a wireless sensor. ZigBee has the ability to autonomously manage the network and manage data exchange within the network. (Kinney, 2003)

2.4.1 ZigBee Architecture

The ZigBee Alliance works closely with IEEE to create a network capable of low power consumption with optimal performance. ZigBee is designed for use in small networks with low power consumption, which is especially beneficial for Wireless Sensor Network (WSN) applications. ZigBee provides certification and testing for devices that use ZigBee to ensure they meet the desired application requirements. (Ahamed, 2005)

2.4.2 Characteristics of ZigBee

Here are some of the characteristics of ZigBee:

1. It operates on the frequency bands of 2.4 GHz, 868 MHz, and 915 MHz. These frequency ranges are unlicensed: 2.4-2.4835 GHz, 868-870 MHz, and 902-928 MHz. These frequency bands are divided into 16 channels. The 2.4 GHz frequency is used almost all over the world, while the 868 MHz frequency is used in Europe, and the 915 MHz frequency is used in North America, Australia, and several other regions.
2. Low power consumption.
3. Maximum transfer rate for each data bandwidth: 250 Kbps for 2.4 GHz, 40 Kbps for 915 MHz, and 20 Kbps for 868 MHz.
4. High throughput and low latency for small duty cycles.
5. Reliable data transmission due to the handshake protocol for data transfer.
6. Supports a wide range of network topologies such as peer-to-peer, mesh, and star.
7. ZigBee is an efficient and effective technology for wireless sensor network applications, offering low power consumption and reliable network management capabilities.

2.5 XBee S2C

Is a wireless communication module manufactured by Digi International, supporting various communication protocols including IEEE 802.15.4 and ZigBee, and can be used as a replacement for serial cables (Djuandi, 2018). XBee has advanced RF modules that serve as a reliable solution for building Wireless Sensor Networks (WSNs). The XBee module communicates with the microcontroller via UART serial communication and has additional pins that can be used for standalone XBee applications, such as building a router node without a microcontroller.

XBee is designed to reduce costs and provide low-power connectivity for battery-operated devices to operate for months to several years, although it does not require high data transfer speeds. The XBee module is divided into two versions: XBee and XBee-Pro. The XBee-Pro consumes more power but offers a greater communication range than the XBee.

XBee S2C is a type of XBee module developed by Digi International that supports the ZigBee communication protocol [11]. Unlike the previous XBee S1 series which can only communicate in peer-to-peer and star topologies, XBee S2C supports communication networks in peer-to-peer, star, and mesh topologies. The XBee S2C display can be seen in Figure 4.

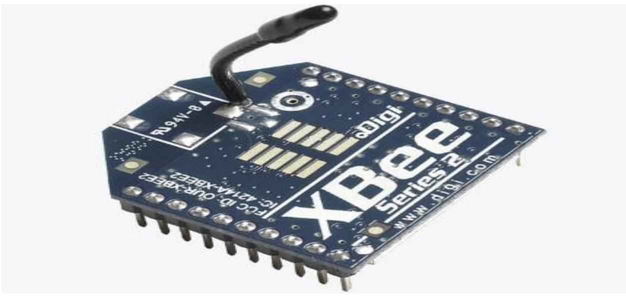

Figure 3. XBee S2C

XBee S2C Specification
1. RF Data Rate: 250 Kbps
2. Indoor/Urban Range: 40 meters
3. Outdoor Range/RF LOS: 120 meters
4. Transmit Power: 1.25 mW (+1 dBm) / 2 mW (+3 dBm)
5. Frequency Band: ISM 2.4 GHz
6. Interference Immunity: DSSS
7. Antenna: Wire
8. Supply Voltage: 2.1 – 3.6 VDC
9. Transmit Current: 35 mA / 45 mA (boost mode @ 3.3 VDC)
10. Receiving Current: 38 mA / 40 mA (boost mode @ 3.3 VDC)

The above specifications indicate that the XBee S2C has an RF data rate of 250 Kbps, an indoor/urban range of up to 40 meters, and an outdoor/RF Line-of-Sight (LOS) range of up to 120 meters. This module operates with a transmit power of 1.25 mW (+1 dBm) or 2 mW (+3 dBm) in the 2.4 GHz ISM frequency band, and has interference immunity with DSSS technology. The XBee S2C is equipped with a wire antenna and operates at a supply voltage between 2.1 to 3.6 VDC. The transmit current consumption is 35 mA or 45 mA in boost mode at 3.3 VDC, while the receive current consumption is 38 mA or 40 mA in boost mode at 3.3 VDC.

Mode of Operation:

There are five operating modes on the XBee, each of which serves a different purpose:
1. Idle Mode: In idle mode, the RF module is not actively receiving or sending data.
2. Transmit Mode: When the serial data is received and ready to be packaged, the RF module comes out of idle mode and tries to send data. The destination address determines which node will receive the data.
3. Receive Mode: If a valid data packet is received by the antenna, it is sent to the serial transmit buffer.
4. Sleep mode: Sleep mode allows the RF module to conserve energy when not in use.
5. Command Mode: To configure or query the parameters of the RF module, the module must be in command mode.

Each mode of operation plays a crucial role in ensuring efficient and effective communication with the XBee module.

2.6 Network Topology

In a ZigBee network, nodes can be connected in various network topology structures, as illustrated in Figure. This network topology shows how the RF transceiver modules are logically connected to each other. Some network topologies include:
1. Peer-to-Peer: A simple network consisting of two nodes, where one node acts as the coordinating node that makes up the network, and the other node is configured as a router or end device.

2. Star: In a star network, the nodes are connected to a central coordinator node that is positioned as the network's hub. All data from the system to be sent must pass through this coordinator. A coordinator node handles decision-making, routing, and topology control.
3. Mesh: Mesh networks use routers to forward messages in the direction of the coordinator nodes. Router nodes can forward messages to other router nodes and end devices as needed. Each device can communicate directly with nearby devices and form a communication relationship. The coordinator node manages network configuration and routing.
4. Cluster Tree: In this network structure, the coordinator nodes form the initial network, and the router nodes form the branches to forward messages.

i. Each network topology has its own advantages and disadvantages, depending on the specific needs of the user and the usage scenario.

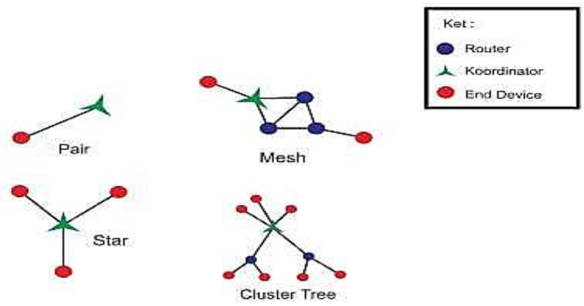

Figure 4. Network Topologies

2.7 XBee Network Concept

The concept of XBee networking is defined through three types of devices: coordinators, routers, and end devices.

Coordinator
Characteristic:
1. Select a channel and PAN ID to start the network.
2. Allows routers and end devices to join the network.
3. Cannot operate in sleep mode.

Router
Characteristic:
1. Send, receive, and route data within the same PAN ID.
2. Allows routers and end devices to join the network.
3. Helps in the data routing process.
4. Cannot operate in sleep mode.
5. Can store data packets for end devices in sleep mode.

Final Device
Characteristic:
1. Send and receive data in the same PAN ID.
2. Doesn't allow other devices to join the network.
3. Unable to route data.
4. It can save battery energy.

2.8 XBee Address and Channel

The data packets transmitted by the RF module contain the source and destination addresses. Each XBee module has a unique 64-bit permanent address provided by the XBee manufacturer. The XBee module also has a 16-bit address assigned within the network. The ZigBee network is also referred to as the Personal Area Network (PAN). An in-network PAN addressing system is defined by a unique and distinct PAN ID. To join a ZigBee network, a ZigBee device is configured with a PAN ID or finds a nearby network and selects a PAN ID to identify the network. Devices in the same ZigBee network must use the same 64-bit and 16-bit PAN IDs. If there are multiple ZigBee networks operating in different areas, each network must have a different PAN ID (Artanto, 2012).

Research Methods

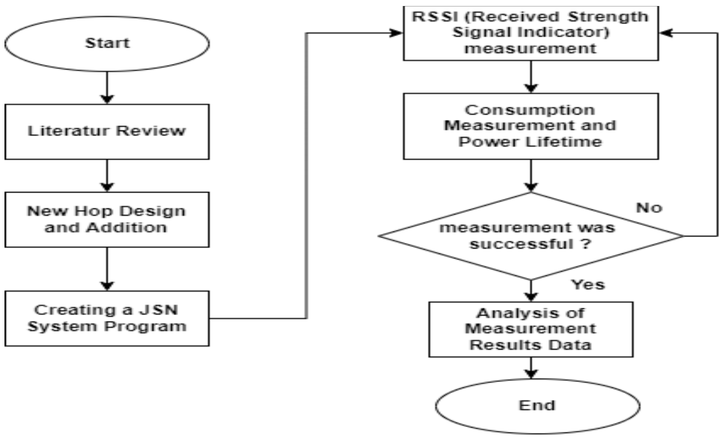

Figure 5. Research Flow Diagram

Result and Discussion

Design and Addition of New Hops in the JSN System

In the previous JSN system, a system has been created using 3 Hops to measure humidity and temperature at a specific reference point. In this study, one additional Hop was added to improve the performance of the previous JSN system. The addition of Nodal Sensors is useful for improving measurement parameters in JSN systems; the more Nodal Sensors installed in the measurement area, the more data can be obtained from that area. Figure 3.2 shows the components used to add the Nodal Sensor to the JSN System.

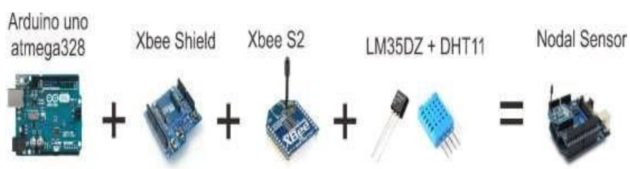

Figure 6. Nodal Sensor Device Components

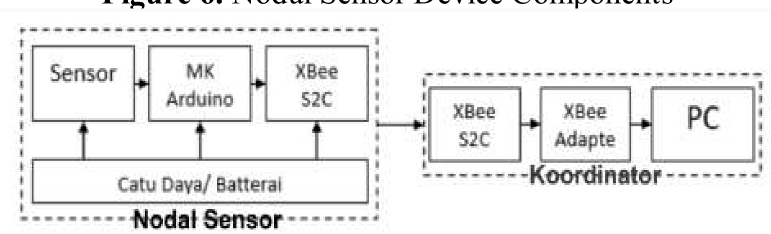

Figure 7. Wireless Sensor Network Block Diagram

Above the image, it can be seen that the wireless sensor network system is divided into two parts: nodal and coordinator sensors, which are connected wirelessly. The nodal sensor consists of a microcontroller, sensors, and an XBee S2C telemetry module that is connected to a power source. The coordinator consists of an adapter, an XBee S2C telemetry module connected to a Personal Computer as an interface, and a power source.

4.1 RSSI Scenario Design and Measurement

RSSI measurements are carried out in two conditions: indoor and outdoor, with several scenarios. The RSSI value is obtained from the ratio of the signal strength (-dBm) received at the receiver to a specific reference point. The following are the scenarios used for RSSI measurement in the JSN system:

1. RSSI Measurement with Point-to-Point Topology Testing.
2. RSSI Measurement with Star Topology Testing (4 Hops).
3. RSSI Measurement with Mesh Topology Testing (2 Hops) with one Router.
4. RSSI Measurement with Mesh Topology Testing (4 Hops) with two Routers.

4.2 RSSI Measurement with Point-to-Point Topology Testing

At this stage, measurements and tests are carried out by testing the Point-to-Point topology with one Nodal Sensor and one coordinator. RSSI Measurement with Mesh Topology Testing (4 Hops). At this stage, measurements and tests will be carried out on a mesh network with two routers and two end devices (4 Hops).

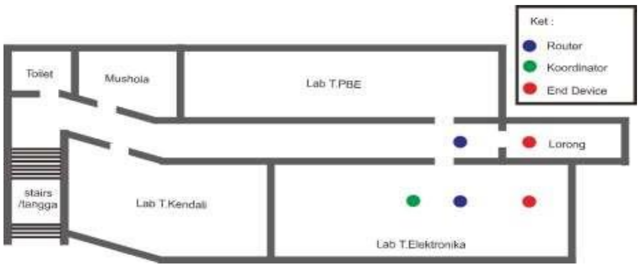

Figure 8. Nodal Sensor Placement

Here are the steps for a measurement and testing scenario using a mesh topology (2 Hops) with a single router:

1. Testing and measurements will be carried out on a mesh topology with 2 routers and 2 End Devices placed in one room, specifically the Electronics Laboratory.
2. The Router Node will only forward the data collected by the End Device (Nodal Sensor).
3. Data packets will be transmitted in byte format, with a total of 100 data packets.
4. The distance between the Nodal Sensors will be varied several times, ranging from 10 meters to 120 meters in outdoor conditions and from 5 meters to 40 meters in indoor conditions.
5. Baud rate is set at 9600.
6. The data packet delivery interval is 1 second (1 sec).

4.3 Power Consumption and Service Life Measurement

The power consumption measurement aims to determine the power consumption of the XBee S2C telemetry as a nodal sensor. Power consumption measurements are carried out on the nodal sensor, which consists of sensor components, Arduino Uno, XBee shield, and XBee S2C telemetry. Based on the measurement of the current obtained, the battery life can be predicted for the supply.

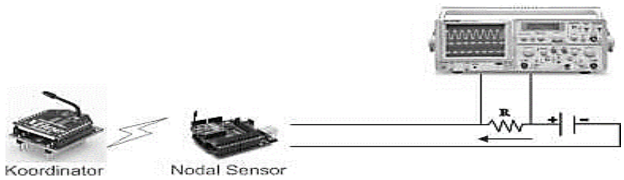

Figure 9. Power Consumption Measurement

Nodal sensor power, Power consumption measurement on the XBee S2C involves measuring the current during the transmission state and idle on the nodal sensor as the Final Device. In addition, the measurement of power consumption on the nodal sensor is carried out by measuring current consumption using Ohm's legal equations. Measurements were made using a digital oscilloscope as shown in this image.

Based on RSSI measurements and power consumption capacity, the XBee module is still suitable for Wireless Sensor Network (WSN) applications.

Table 1. Analysis of Battery Power Consumption Measurement Results

NO	Topology & Scenarios	Test Distance	RSSI value (± dBm)	Number of Hops	Number of Routers	Power Consumption (mA)	Battery Life (20,000 mAh)	Analysis
1	Point-to-point	Indoor: 5–25 m	-56 to 67	1 Hop	0	± 75 mA	± 13.83 days	RSSI is stable at short distances, suitable for confined room applications.
2	Star (4 Hops)	Indoor: 10–30 m	-58 to 70	4 Hops	0	± 76 mA	± 13 days	Data is sent through 4 nodes; The performance is still good, but there is a small delay between hops.
3	Mesh (2 Hops, 1 Router)	Indoor: 10–30 m	-60 to -72	2 Hops	1	± 78 mA	± 12.8 days	The router helps maintain signal stability in the medium range in an indoor environment.
4	Mesh (4 Hops, 2 Routers)	Indoor: 10–40 m	-62 to -74	4 Hops	2	± 80 mA	± 12.5 days	The most stable topology at a distance; slightly higher power consumption.
5	Mesh (4 Hops, 2 Routers) – Outdoor	Outdoor: 30–120 m	-58 to -70	4 Hops	2	± 80 mA	± 12.5 days	Excellent performance, wider range with signal gain through the router.

This table provides an analysis of the measurement results, covering the difference in RSSI values based on topology, the influence of distance and environmental conditions, as well as relevant aspects related to power consumption and battery life for Wireless Sensor Network (WSN) applications using the XBee S2C module.

Conclusion

The test results show that the type of network topology greatly affects the signal quality (RSSI) of the wireless sensor network. Point-to-point and star topologies show good performance at short distances, while mesh topologies are more stable at longer distances due to the presence of routers that help extend range and amplify signals. The RSSI value tends to decrease as the distance between sensors increases, and environmental conditions (indoor and outdoor) also affect the quality of the received signal.

In terms of power consumption, the nodal sensor is capable of operating for about 13.83 days with a 20,000 mAh battery and transmission intervals every 60 seconds. The life of this battery will be longer if the transmission interval is enlarged or the battery capacity is increased. Factors such as power usage efficiency, data transmission frequency, and hardware specifications are key determinants in the overall durability of the system.

Based on these results, the XBee S2C module has proven to be suitable for wireless sensor network applications in air quality monitoring. In addition to having a stable signal, the module is also energy efficient and flexible in a wide range of environmental conditions and network topologies. With these advantages, XBee S2C can be a reliable solution for the implementation of sensor-based monitoring systems both indoors and outdoors.

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