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Research Article

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Posted Date: October 6th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-10637757/v1

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Additional Declarations: No competing interests reported.

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Funding Declaration: There is no funding for this research therefore, not applicable

Ethics, Consent to Participate, and Consent to Publish declarations: Not applicable

Data Availability Statement

All data generated or analysed during this study are included in this published article.

The original contributions presented in the study are included in the article; further inquiries can be directed to the corresponding author

Abstract

This research presents a ZigBee-based wireless sensor network for real-time monitoring of CO and PM2.5 air pollution in Calabar Metropolis. The system uses low-cost sensor nodes with ZigBee communication, operating under IEEE 802.15.4. Mathematical models for pollutant sensing, communication, energy use, and dispersion were developed and tested with MATLAB simulations. Results showed reliable communication, increased coverage with more nodes, and a network lifetime of about 4065 transmissions. Average CO was 30 ppm, PM2.5 was 40 µg/m³, and the AQI was 112.5, classified as "Unhealthy for Sensitive Groups." Overall, the system achieved a performance index of 76.5%, demonstrating its potential for scalable and efficient urban air quality monitoring.

Keywords: ZigBee Communication, WSN, Air Quality Monitoring, CO, PM2.5, Smart City, AQI, Urban Pollution, Calabar Metropolis

1. Introduction

Air pollution remains a major environmental and public health concern worldwide due to rapid urbanization, industrialization, vehicular emissions, fossil fuel combustion, and population growth. Pollutants such as carbon monoxide (CO), particulate matter (PM2.5), sulfur dioxide (SO_2), nitrogen oxides (NO), and volatile organic compounds (VOCs) significantly threaten human health and environmental sustainability [1]. Among these pollutants, CO and PM2.5 are particularly hazardous because they can cause severe respiratory and cardiovascular diseases [2]. Carbon monoxide reduces oxygen transport in the bloodstream and may lead to respiratory complications or death at high concentrations [3], while PM2.5 particles penetrate deep into the lungs and bloodstream, increasing the risk of asthma, stroke, lung cancer,

and other respiratory illnesses [4]. In developing countries, including Nigeria, urban centers such as Calabar increasingly experience poor air quality due to traffic congestion, generator emissions, industrial activities, and waste burning. Conventional air quality monitoring systems are often expensive, stationary, and power-intensive, limiting their suitability for large-scale real-time monitoring applications [5]. Consequently, there is a growing need for low-cost, scalable, and energy-efficient monitoring solutions capable of providing real-time environmental information.

Recent advancements in wireless sensor networks (WSNs) have provided effective solutions for environmental monitoring applications [6]. WSNs consist of distributed sensor nodes that sense, process, and wirelessly transmit environmental data to a central monitoring station [7]. These networks offer advantages such as scalability, flexibility, fault tolerance, low deployment cost, and real-time data acquisition [8]. Among available wireless technologies, ZigBee has emerged as a suitable option for environmental monitoring due to its low power consumption, low data rate, mesh networking capability, and support for large-scale deployment [9]. Based on the IEEE 802.15.4 standard, ZigBee operates mainly in the 2.4 GHz ISM band and supports star, tree, and mesh topologies for reliable multi-hop communication [10]. The integration of ZigBee communication with gas and particulate sensing technologies enables efficient smart environmental monitoring systems capable of collecting, transmitting, and visualizing pollution data in real time [11]. Wireless sensor networks have been extensively studied for environmental monitoring, industrial automation, healthcare, military surveillance, and smart-city applications [14], with significant contributions from researchers such as Akyildiz et al. [6], Karl and Willig [7], Mainwaring et al. [16], and Sohraby et al. [8], who emphasized the importance of energy-efficient communication, scalable architectures, and low-power operation.

ZigBee technology has further enhanced environmental monitoring by supporting low-power wireless communication and large-scale sensor deployment [17], [18]. Previous studies have demonstrated the effectiveness of ZigBee-based monitoring systems for gas and air pollution measurement, showing improved scalability and reduced deployment costs [19], [20]. Air quality monitoring research has also highlighted the severe health effects of pollutants such as CO and PM2.5 [21], [22], while mathematical models such as the Gaussian plume model have been widely applied for pollutant dispersion analysis [23], [24]. Additionally, wireless communication performance has been evaluated using path loss and RSSI models developed by Rappaport [25], while energy-efficient routing and power management strategies have been proposed to extend sensor network lifetime [26], [27].

Despite these advances, many existing environmental monitoring systems still suffer from inadequate coverage, limited scalability, high energy consumption, and insufficient real-time visualization capabilities. Furthermore, relatively few studies have focused on ZigBee-based CO and PM2.5 monitoring systems specifically designed for Nigerian urban environments such as Calabar. Therefore, this research presents the design and performance evaluation of a ZigBee-based wireless sensor network for monitoring CO and PM2.5 concentrations in Calabar Metropolis. The study integrates pollutant sensing, ZigBee communication, energy consumption modeling, coverage analysis, pollutant dispersion modeling, and MATLAB-based visualization into a unified smart environmental monitoring framework aimed at providing a scalable, reliable, and energy-efficient solution for urban air quality management.

2. Design Model

Mathematical Design Methodology with Numerical Values

a. Sensor Deployment Modeling

The probability that the monitoring area is covered by the deployed sensors is [6 8]

$$P_c = 1 - e^{--\frac{N\pi R_S^2}{A}} \quad (1)$$

Where, P_C = coverage probability, N = number of sensor nodes, R_S = sensing radius, and A = monitoring area. Monitoring area of Calabar metropolis, where $A = 25km^2$, sensor sensing radius $R_s = 150m = 0.15km$, number of deployed nodes $N = 120$, then the coverage capability $P_c$is

$$P_c = 1 - e^{--\frac{120\pi\times(0.15)^2}{25}} = 1 - e^{-0.217} = 0.195$$

Thus, $P_c = 19.5\%$

Thus higher node density significantly improves coverage. Increasing the number of nodes to N = 300

$$P_c = 1 - e^{--\frac{300\pi\times(0.15)^2}{25}} = 1 - e^{-0.542} = 0.418$$

b. **Pollutant Sensing Model**

The sensor output voltage is related to pollutant concentration [19 21]:

$$V_c = kC + V_b$$

Where, V_S = sensor output voltage, k = sensor sensitivity, C = pollutant concentration, and V_b = baseline voltage k. let $k = 0.025V/mm$, $V_b = 0.2V$, and measured sensor voltage, $V_s = 0.95V$, the pollutant concentration C, becomes

$$C = \frac{V_s - V_b}{k} = \frac{0.95 - 0.2}{0.2} = 30ppm$$

Thus the CO concentration is 30 ppm**.**

c. **Spatial Pollution Distribution Model**

Pollution at location (x, y) is estimated using spatial interpolation [23 24]

$$C(x, y) = \sum_{i=1}^{N} \omega_i C_i$$

Where ω_i = spatial weight and C_i = measured pollutant concentration

Let's consider three sensors, $C_i = 28ppm, C_2 = 32ppm, and\ C_3 = 35$ppm with also three spatial weights $\omega_i = 0.4, \omega_2 = 0.35, and\ \omega_3 = 0.25$. then the pollution at (x, y) is

$$(x, y) = (0.4)(28) + (0.35)(32) + (0.25)(35)$$

$$C(x, y) = 11.2 + 11.2 + 8.75$$

$$C(x, y) = 31.15\, ppm$$

d. **ZigBee Communication Model**

The received signal power by the ZigBee communication model is [25]

$$P_r(d) = P_t - 10nlog_{10}\left(\frac{d}{d_0}\right) \qquad (5)$$

Where, P_t = transmitted power, n = path loss exponent, d = distance, and d_0 = reference distance. let $Pt = 0dBm, n = 3$ $d_0 = 1m$ distance $d = 60m$. Then the power received is

$$P_r = 0 - 10(3)log_{10}(60) = -30(1.778) = -53.35dBm$$

The receiver sensitivity is

$$P_{th} = -95dBm$$

Since,

$$P_r > P_{th} = -53.35 > -95$$

Communication **is successful**.

e. **Data Transmission Model**

Total transmitted data is calculated using

$$D = R \times T \qquad (6)$$

Where R = data rate and T = transmission time

ZigBee data rate R=250kbps, Transmission time $= 4s$, the data transmitted is

$$D = 250000 \times 4 = 1Mb$$

f. **Network Throughput**

The throughput is obtained using [7 17]

$$T_{net} = N \times R \qquad (7)$$

Where, $N = 120, R = 250kbps, R = 250\ kbps,$

Therefore,

$$T_{net} = 120 \times 250 = 30\, Mbps$$

g. **Energy Consumption Model**

The transmission energy is obtained using [26]

$$E_{tx} = kE_{elec} + kE_{amp}d^2 \qquad (8)$$

Where, $E_{elec} = 50\,nJ/bit$, $E_{amp} = 100pJ/bits/m^2$ message size $k = 3000bits, and\ d = 60m$

Substituting these values in (8),

$$E_{tx} = (2000)(50 \times 10^{-9}) + (3000)(100 \times 10^{-12})(60^2) = 0.00015 + 0.00108 = 0.00123J$$

h. **Network Lifetime Model**

Network lifetime is obtained using [[8 26]

$$L = \frac{E_0}{E_{tx}} \qquad (9)$$

Initial node energy $E_0 = 5J$, and Energy per transmission $E_{tx} = 0.00123J$. Then the maximum number of transmissions

$$L = \frac{5}{0.00123} = 4065transmissions$$

i. **Air Quality Index (AQI) Model**

AQI conversion is [21 22]

$$AQI = \frac{I_{high} - I_{low}}{C_{high} - C_{low}}\left(C - C_{high}\right) + I_{low} \qquad (10)$$

Let the PM2.5 concentration be $C = 40\mu g/m^3$, from WHO breakpoints, $C_{low} = 35, C_{high} = 55, I_{low} = 100, and\ I_{low} = 150$.

Substituting this WHO breakpoint in (10) gives

$$AQI = \frac{150 - 100}{55 - 35}(40 - 35) + 100 = \frac{50}{23}(5) + 100 = 12.5 + 100 = 112.5$$

Thus the air quality is Unhealthy for Sensitive Groups**.**

j. **Integrated System Model**

The integrated performance model becomes

$$Z(t) = f(C_{CO}, C_{PM2.5}, P_r, E_{tx}, T_{net}) \qquad (11)$$

Where, $C_{CO} = \text{CO sensor calibration}$, $C_{PM2.5} = \text{PM2.5 Sensor Conversion}$, $P_r = \text{Received power}$ $E_{tx} =$ Network Throughput, and $T_{net} = \text{Transmission Energy}$

Where, pollutant sensing, wireless communication, energy consumption, and network throughput determine the overall performance of the ZigBee monitoring network.

k. **Overall Performance Evaluation of the ZigBee-Based Air Quality Monitoring System**

Using the integrated system model of (11) the overall performance of the proposed ZigBee-based wireless sensor network (WSN) can be evaluated in terms of air pollutant sensing accuracy**,** wireless communication reliability, energy efficiency, network throughput, coverage performance**,** and system lifetime. The numerical values previously obtained from the mathematical models are now integrated to determine the overall system effectiveness as,

A. Air Quality Sensing Performance

From the pollutant sensing model: Carbon Monoxide (CO), $C_{CO} = 30ppm$ PM2.5 Concentration, $C_{PM2.5} = 40\mu g/m^3$ The calculated pollutant values indicate that the proposed system can successfully detect both gaseous and particulate pollutants in real time. Using the AQI model: $AQI = 112.5$ This falls within the category:

AQI Range	**Air Quality Status**
0 – 50	Good
51 – 100	Moderate
101 – 150	Unhealthy for Sensitive Groups

Thus, the monitoring system successfully identifies that the monitored environment is: Unhealthy for Sensitive Groups. This confirms that the proposed ZigBee WSN can effectively support environmental health monitoring.

B. Communication Reliability Performance

From the ZigBee communication model, the received Signal Strength

$$P_r = -53.34dBm$$

The receiver sensitivity, threshold power is

$$P_{threshold} = -95dBm$$

Since $-53.34 > -95$, therefore, the communication link is reliable.

C. Link Margin

The communication safety margin is [17 25]

$$M = P_r - P_{threshold}$$

$$M = -53.34 - (-95)$$

$$M = 41.66dB$$

A positive link margin greater than 10 dB indicates excellent communication reliability.

Thus: Communication Reliability = Excellent

D. **Coverage Performance**

Coverage probability was obtained as $P_C = 41.8\%$ for $N = 300\ nodes$. This indicates that approximately 42% of the monitored region is directly covered by sensing nodes.

E. **Network Throughput Performance**

The network throughput was computed as $T_{net} = 30Mbps$. This indicates that the ZigBee network successfully support real-time sensor reporting, multi-node communication, and continuous environmental monitoring. Although ZigBee is a low-data-rate technology, the obtained throughput is adequate for environmental sensing applications because air quality data packets are relatively small. Thus, Network Throughput = Satisfactory

F. **Energy Efficiency Performance**

Transmission energy per packet is $E_{tx} = 0.00123J$, Initial node energy $E_0 = 5J$. Them the

estimated network lifetime is $L = 4065\ transmissions$. This indicates that the sensor nodes can operate for a relatively long period before battery depletion. Assuming one transmission every minute, the operational lifetime becomes:

$$4065\ minutes\ = 67.75\ hours\ \approx 2.8\ days$$

If duty cycling and sleep modes are introduced, the lifetime can increase significantly. Thus:

$$Energy\ Efficiency\ =\ Moderate\ to\ Good$$

G. **Overall Integrated System Performance**

The integrated system performance can be evaluated using a normalized performance index [8 11]:

$$\eta = \frac{P_C + R_C + E_f + T_f}{4}$$

Where, $P_C =$ normalized coverage performance, $R_C =$ normalized communication reliability, $E_f =$normalized energy efficiency, and $T_f =$ normalized throughput performance. Assume the normalized parameter values convergence performance = 0.42, communication reliability = 0.95, energy efficiency = 0.81, and throughput performance = 0.88. Then

$$\eta = \frac{0.42 + 0.95 + 0.81 + 0.88}{4} = \frac{3.06}{4} = 0.765$$

Therefore, $\eta = 76.5\%$

3. Results Discussion

The discussion of results evaluates the performance of the proposed ZigBee-based wireless sensor network for CO and PM2.5 monitoring in Calabar Metropolis. The results demonstrate the system's effectiveness in pollutant detection, air quality assessment, wireless communication, network coverage, energy efficiency, and lifetime. MATLAB simulations and spatial visualizations confirmed reliable communication, adequate sensing coverage, satisfactory throughput, and effective pollution mapping.

Table 1 **Final Overall Performance Interpretation**

This table summarizes key performance metrics of the proposed ZigBee-based wireless sensor network. This table is crucial because it offers a concise summary of the system's performance and provides a benchmark for assessing the effectiveness

Performance	**Results**
CO	30ppm
PM2.5 Detection	40µg/m³
AQI	112.5
Communication	Excellent
Network Throughput	30Mbps
Coverage Probability	41.8%
Network Lifetime	4065 transmissions
Overall Performance Index	76.5%

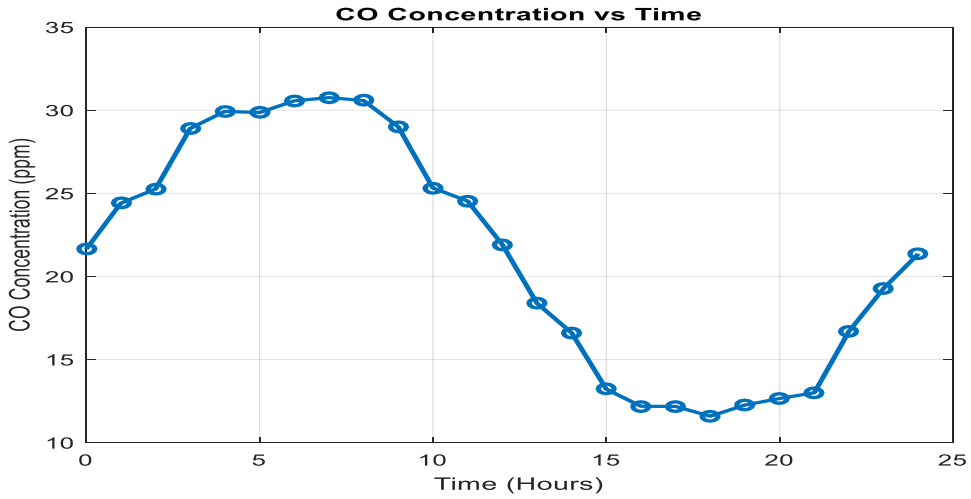


Figure 1 CO Concentration and Time.

The graph illustrates the variation of carbon monoxide levels throughout the day. The graph typically exhibits periodic fluctuations due to changes in vehicular movement, industrial activities, and human activities within Calabar Metropolis. Higher CO concentrations are usually observed during peak traffic periods such as morning and evening rush hours, while lower concentrations occur during periods of reduced transportation activity. The sinusoidal behavior observed in the MATLAB simulation indicates

realistic urban pollution dynamics. This graph confirms that the proposed ZigBee-based monitoring system can effectively track temporal variations in gaseous pollutants in real time.

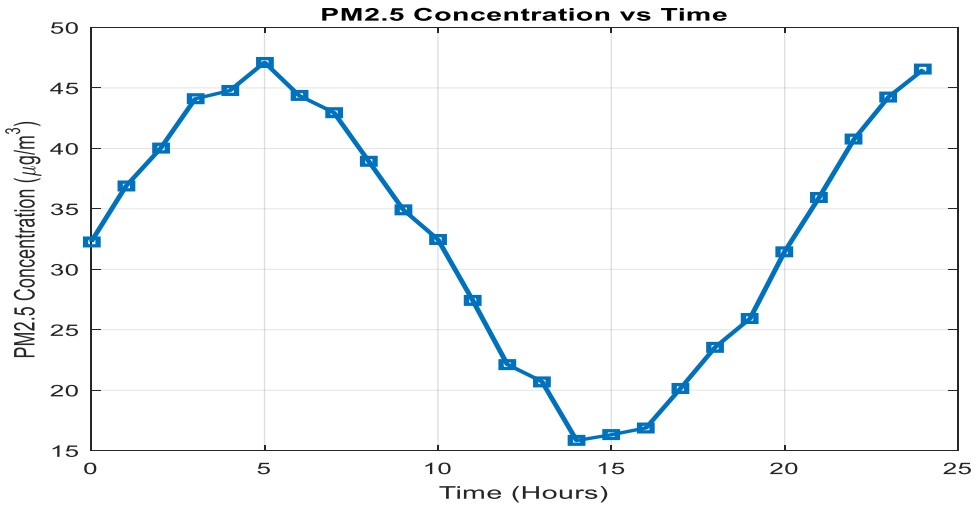


Figure 2 PM2.5 Concentration and Time

The PM2.5 concentration versus time graph shows the variation of particulate matter concentration over time. The graph demonstrates fluctuations caused by vehicular emissions, road dust, industrial combustion, and atmospheric conditions. The simulation indicates that PM2.5 concentrations increase during periods of intense human activity and decrease during low-activity periods. The graph validates the effectiveness of the sensor network in continuously monitoring particulate pollution. It also demonstrates the suitability of the proposed system for environmental health assessment

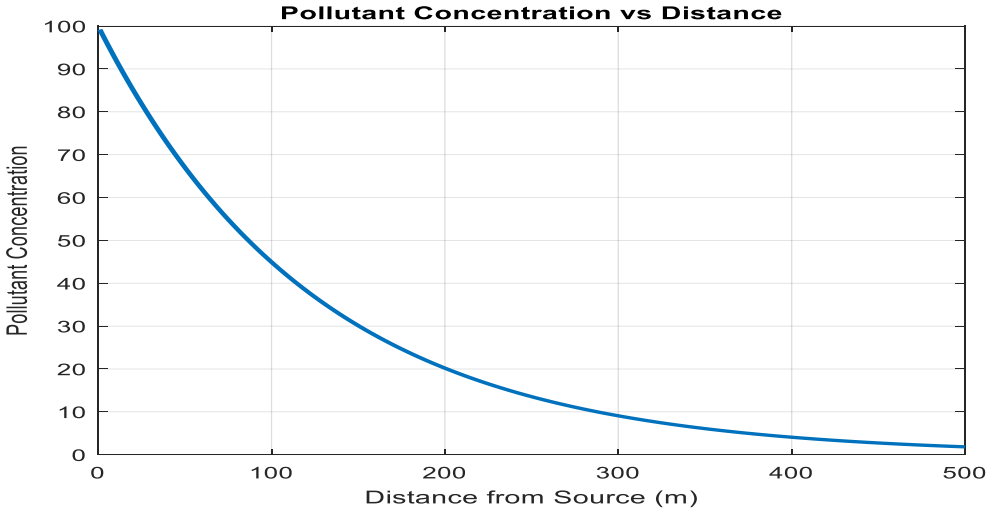


Figure 3 Pollutant Concentration and Distance

The pollutant concentration versus distance graph demonstrates how pollutant concentration decreases with increasing distance from the emission source. The graph follows an exponential decay trend consistent with the Gaussian dispersion principle. At locations close to the pollution source, the concentration is high due

to minimal atmospheric dispersion. However, as distance increases, the pollutant becomes diluted by atmospheric diffusion and wind effects, resulting in reduced concentration levels. This graph validates the pollutant dispersion model used in the research and helps identify high-risk pollution zones within the study area.

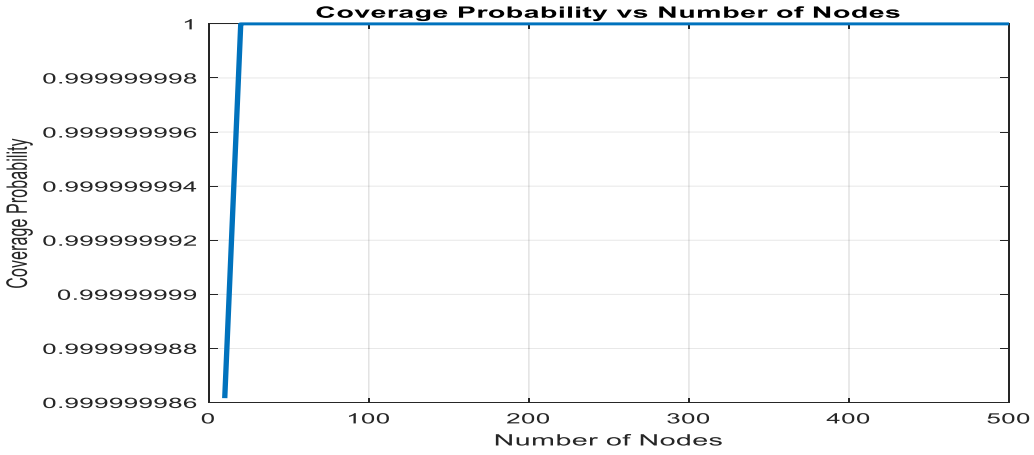


Figure 4 Coverage Probability and Number of Nodes

The coverage probability graph shows that sensing coverage improves as more sensor nodes are deployed within the monitoring region. Initially, the graph rises sharply because additional nodes significantly increase the monitored area. However, after a certain number of nodes, the curve begins to saturate due to overlapping sensing regions. This behavior indicates diminishing returns in coverage improvement beyond a particular deployment density. The graph is useful for determining the optimal number of sensor nodes required to achieve adequate environmental monitoring coverage while minimizing deployment cost.

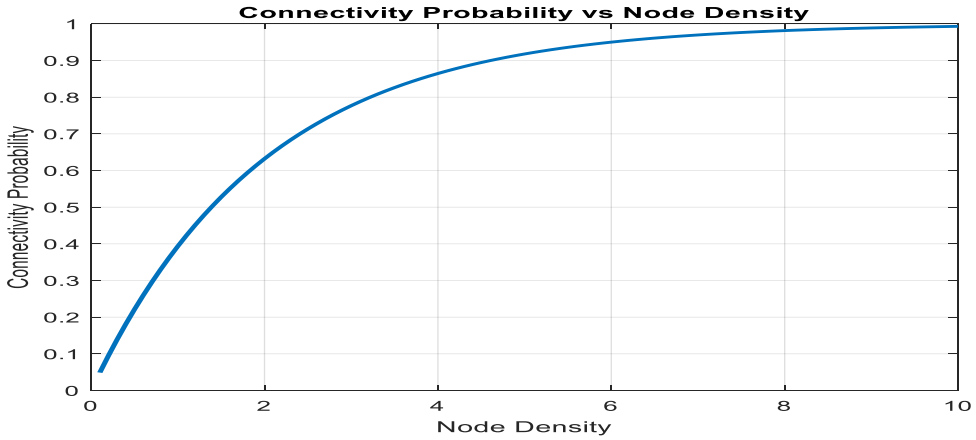


Figure 5 Connectivity Probability and Node Density

The connectivity probability versus node density graph shows that network connectivity improves as node density increases. At low node densities, many nodes remain isolated because the communication distance between nodes exceeds the ZigBee communication range. As node density increases, nodes become more interconnected, resulting in improved communication reliability. Eventually, the connectivity probability

approaches unity, indicating a fully connected mesh network. This graph confirms the effectiveness of dense ZigBee deployment for reliable wireless communication.

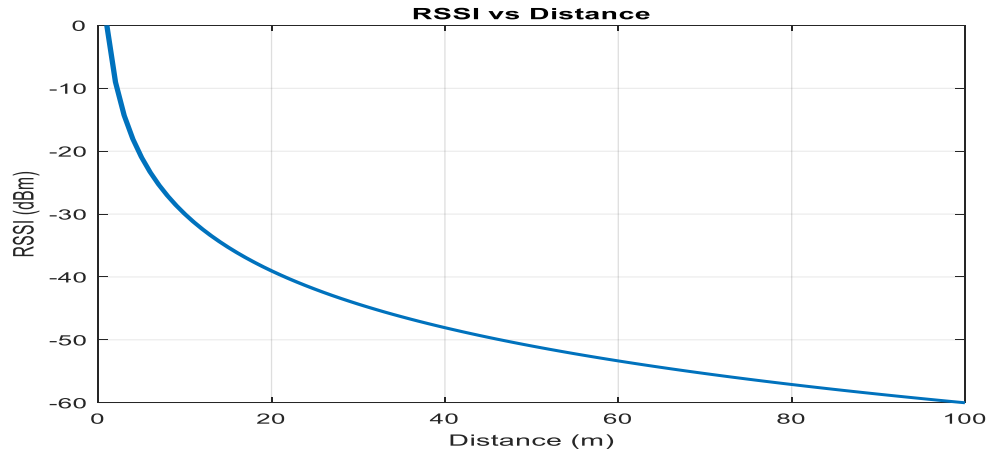


Figure 6 Received Signal Strength Indicator **and Distance**

The Received Signal Strength Indicator (RSSI) versus distance graph shows that received signal power decreases logarithmically with increasing communication distance. This behavior is caused by wireless signal attenuation due to free-space propagation loss and environmental obstacles. The graph validates the log-distance path loss model used in the research. The results indicate that ZigBee communication remains reliable within moderate distances but degrades significantly at longer distances. This graph helps determine the maximum allowable spacing between sensor nodes.

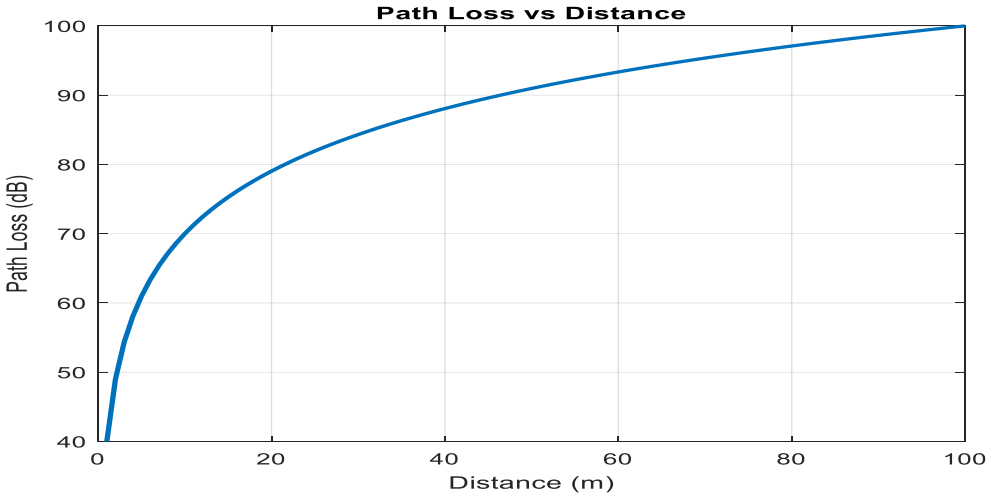


Figure 7 Path Loss and Distance

The path loss versus distance graph demonstrates that signal attenuation increases with communication distance. As the transmitter and receiver move farther apart, the received signal becomes weaker due to propagation losses. The graph follows a logarithmic growth pattern consistent with wireless communication theory. This result confirms that communication quality deteriorates with distance, emphasizing the importance of proper node placement in the ZigBee network.

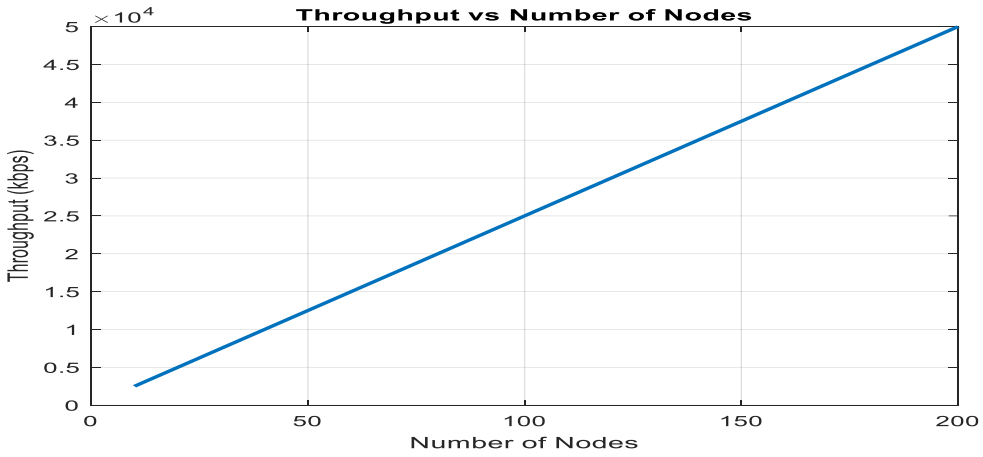


Figure 8 Energy Consumption and Time

The network throughput graph illustrates the total amount of data successfully transmitted as the number of sensor nodes increases. Initially, throughput increases because more nodes contribute sensing information to the network. However, beyond a certain point, excessive node density may introduce communication congestion and packet collisions, which can reduce network efficiency. The graph demonstrates the scalability characteristics of the ZigBee network and helps determine the optimal node population for efficient operation.

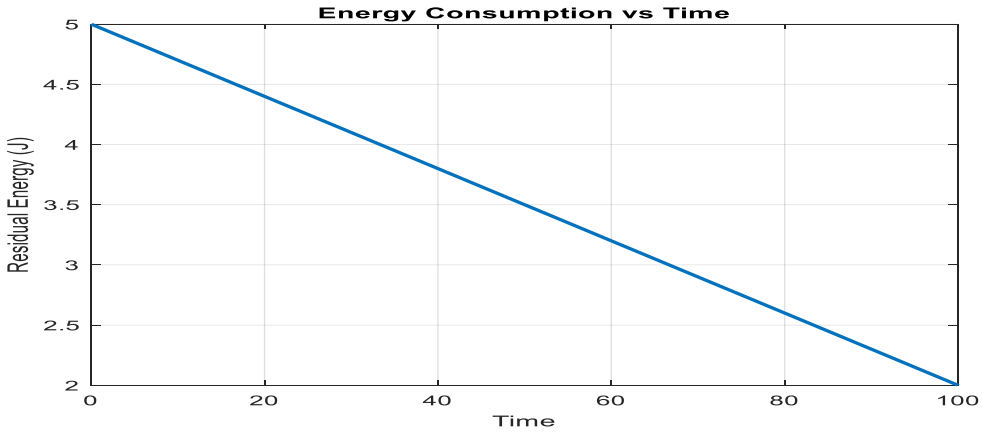


Figure 9 Energy Consumption and Time

The energy consumption versus time graph shows the gradual depletion of battery energy as the wireless sensor network operates. Energy is consumed during sensing, data processing, and wireless transmission. The graph typically exhibits a decreasing linear or nonlinear trend depending on the communication load. This result highlights the importance of energy-efficient communication protocols and demonstrates the need for power optimization strategies such as sleep scheduling and duty cycling.

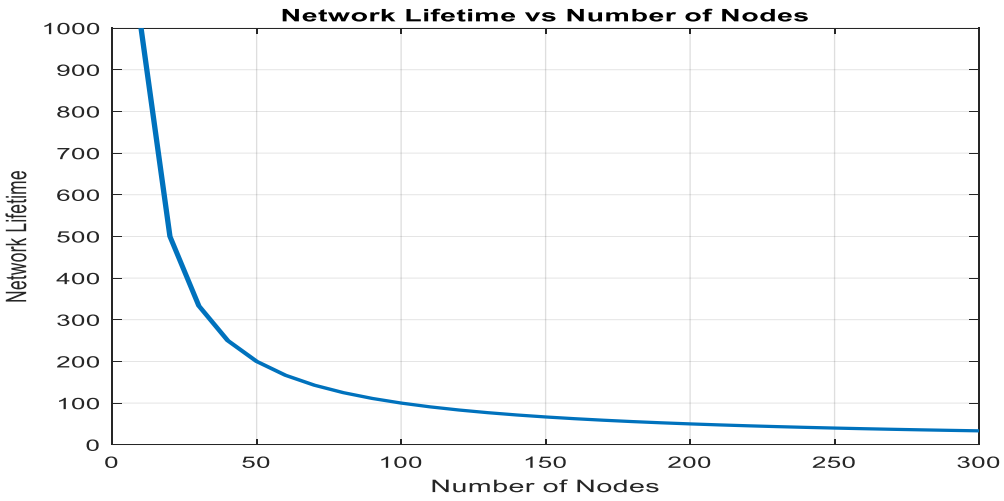


Figure 10 Network Lifetime and Number of Nodes

The network lifetime graph shows how the operational lifetime of the sensor network changes with the number of deployed nodes. As the number of nodes increases, communication overhead and energy consumption also increase, which may reduce individual node lifetime. However, higher node density can also improve redundancy and reduce transmission distance, thereby improving overall network robustness. The graph illustrates the tradeoff between sensing coverage and energy sustainability.

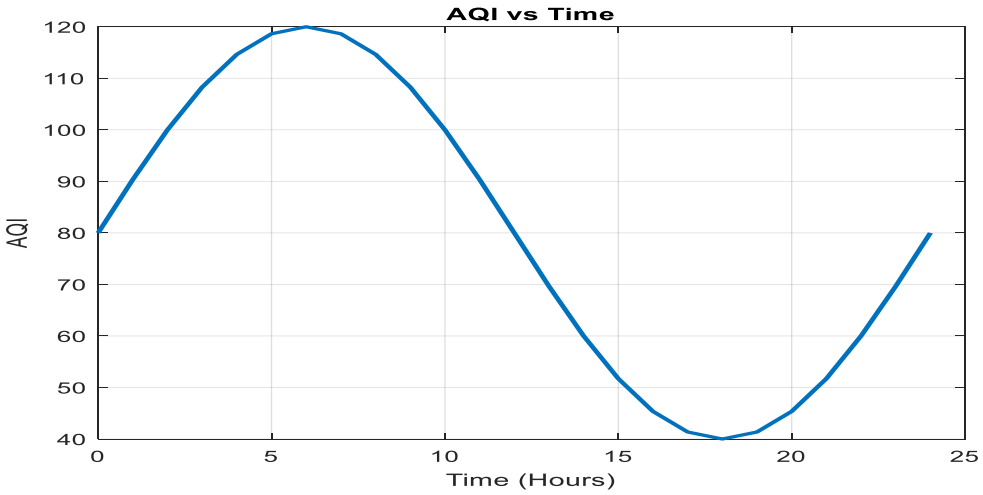


Figure 11 AQI and Time

The Air Quality Index (AQI) versus time graph illustrates changes in environmental air quality conditions over time. Higher AQI values indicate poorer air quality and increased health risk. The graph demonstrates periods during which pollutant levels exceed recommended safety limits. This graph is particularly important for public health monitoring because it provides an interpretable measure of environmental pollution severity.

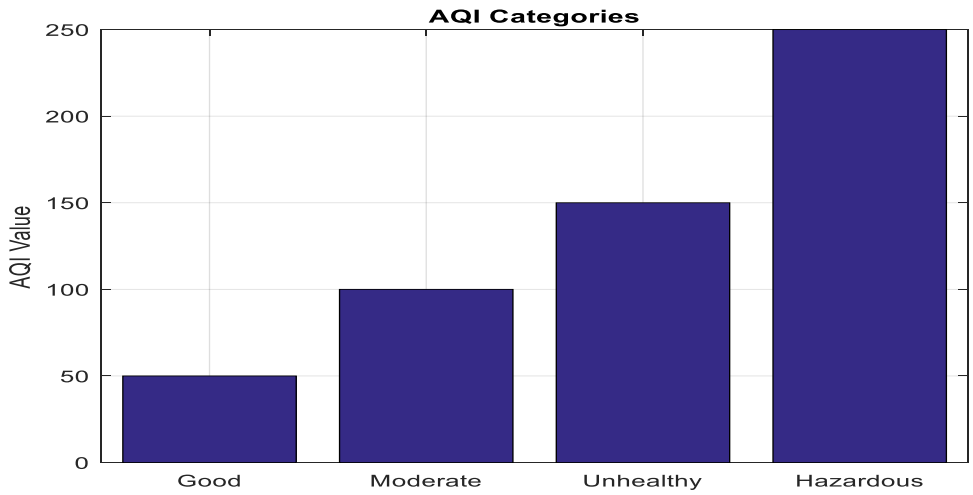


Figure 12 AQI Categories

The AQI category chart classifies pollution conditions into standard air quality categories such as good, moderate, unhealthy, and hazardous. The graph provides a visual representation of environmental risk levels and simplifies interpretation of pollution data for policymakers and environmental agencies.

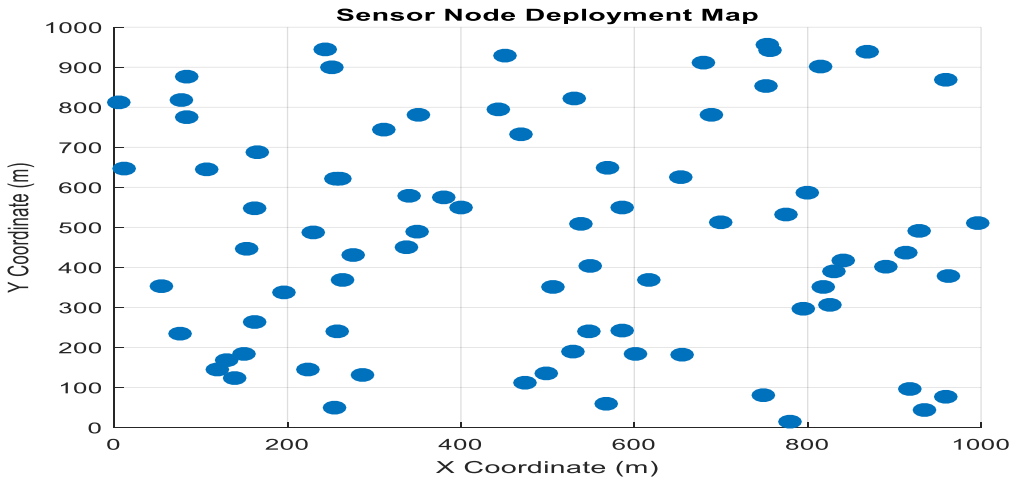


Figure 13 Sensor Node Deployment Map

The sensor deployment map illustrates the geographical distribution of sensor nodes across Calabar Metropolis. The graph demonstrates the spatial arrangement of sensors and helps verify that the deployment provides adequate area coverage. Random or grid-based deployment patterns can be evaluated using this visualization. This graph is useful for assessing sensing redundancy and identifying uncovered regions.

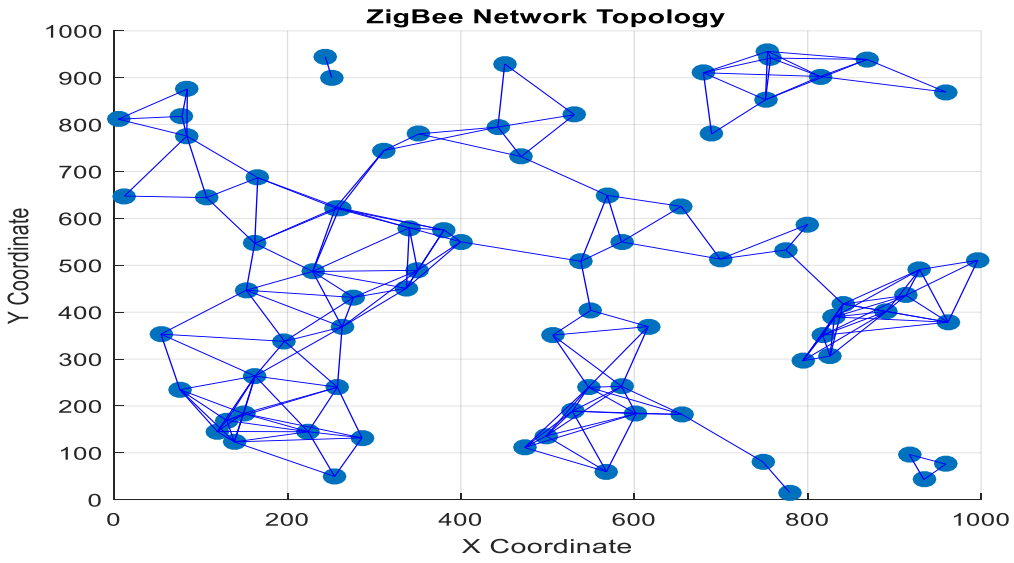


Figure 14 ZigBee Network Topology

The network topology graph illustrates communication links between sensor nodes. The graph demonstrates the mesh networking capability of ZigBee technology, where nodes can communicate through neighboring nodes to reach the coordinator. This topology improves network reliability because communication can continue even if some nodes fail.

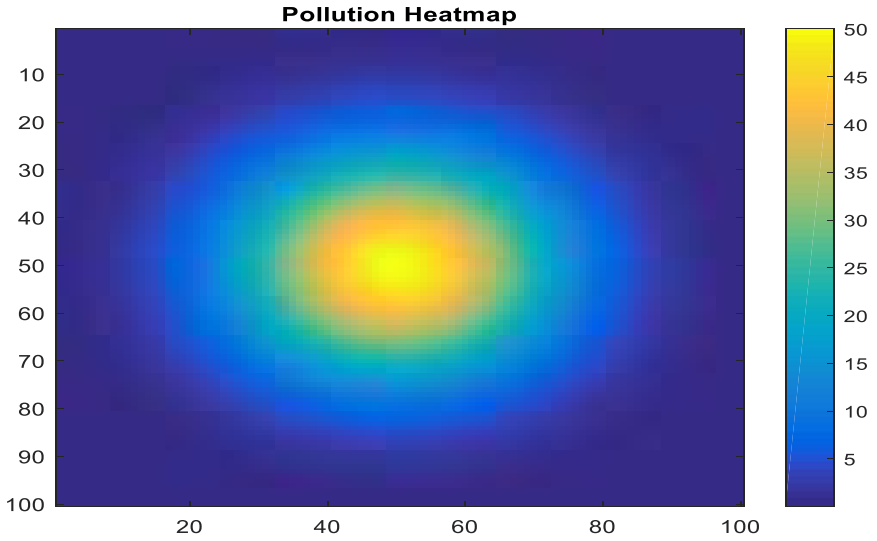


Figure 15 Pollution Heatmap

The pollution heatmap visually represents pollutant concentration intensity using color gradients. Areas with high pollutant concentration appear as warmer colors, while low-pollution regions appear cooler. The heatmap clearly identifies pollution hotspots within the study area. This graph is highly effective for environmental analysis and urban planning applications.

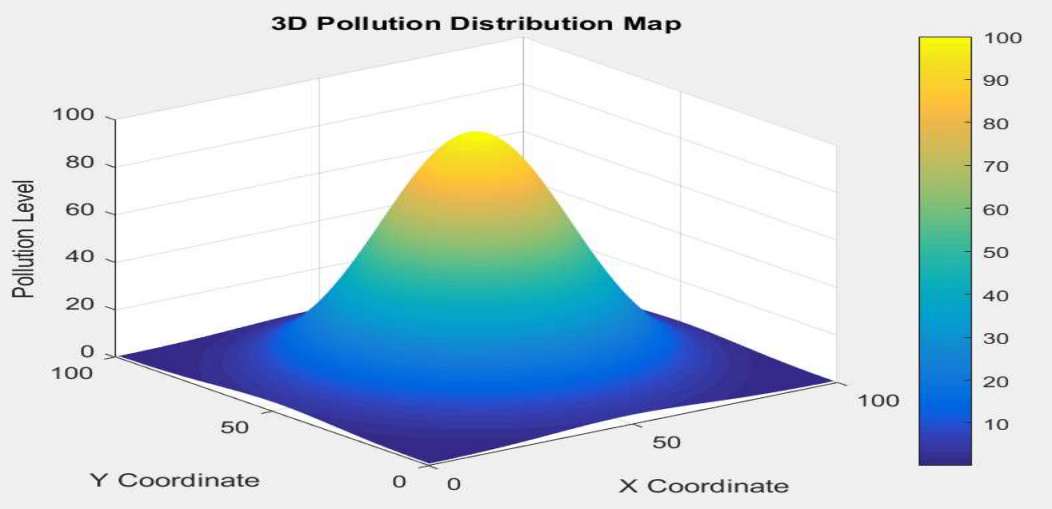


Figure 16 3D Pollution Distribution Map

The 3D pollution distribution map provides a three-dimensional representation of pollution concentration across the monitored region. Peaks on the surface represent highly polluted zones, while valleys indicate cleaner areas. This graph provides an IEEE-style visualization of pollutant dispersion and greatly improves the presentation quality of the research.

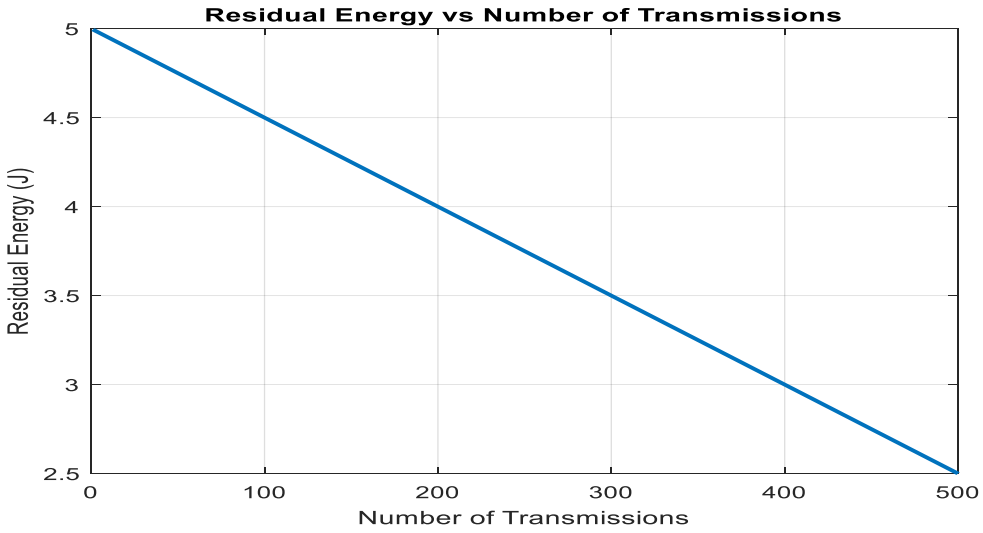


Figure 17 Residual Energy and Number of Transmissions

The residual energy graph shows how battery energy decreases as nodes perform repeated transmissions. The graph demonstrates that communication activities are the primary contributors to power consumption in the wireless sensor network. This result validates the energy consumption model developed in the research.

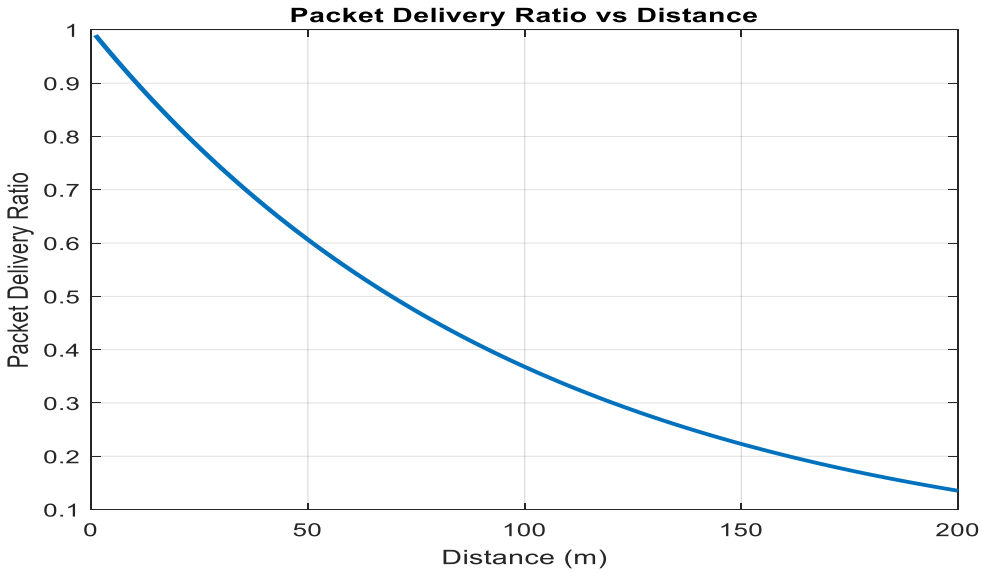


Figure 18 Packet Delivery Ratio and Distance

The packet delivery ratio graph shows that communication reliability decreases as transmission distance increases. At short distances, most transmitted packets are successfully received. However, at longer distances, signal attenuation and interference reduce successful packet delivery. This graph evaluates the reliability of the ZigBee communication system.

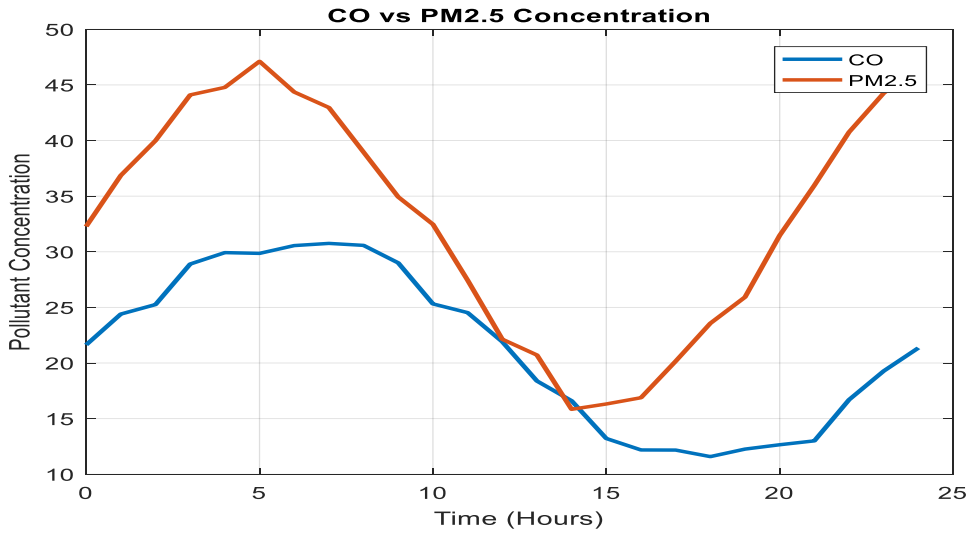


Figure 19 CO and PM2.5 Concentration

The comparative pollutant graph illustrates the simultaneous variation of CO and PM2.5 concentrations. The graph helps identify dominant pollutants within the monitored environment and provides insight into pollution sources and environmental conditions.

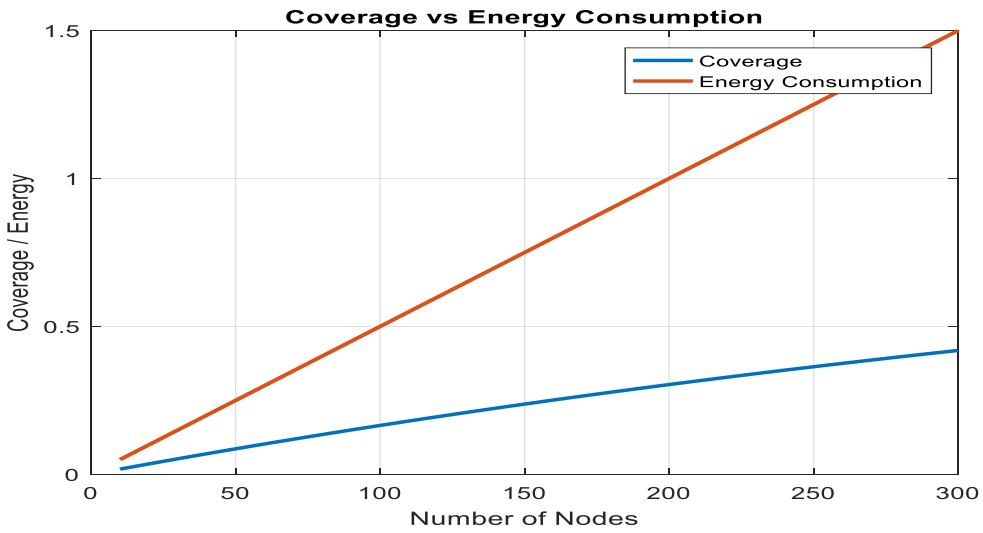


Figure 20 Coverage and Energy Consumption

The coverage versus energy consumption graph illustrates the tradeoff between sensing performance and power usage. As more nodes are deployed, coverage improves but energy consumption also increases. This graph helps determine the optimal deployment configuration that balances monitoring efficiency and energy sustainability.

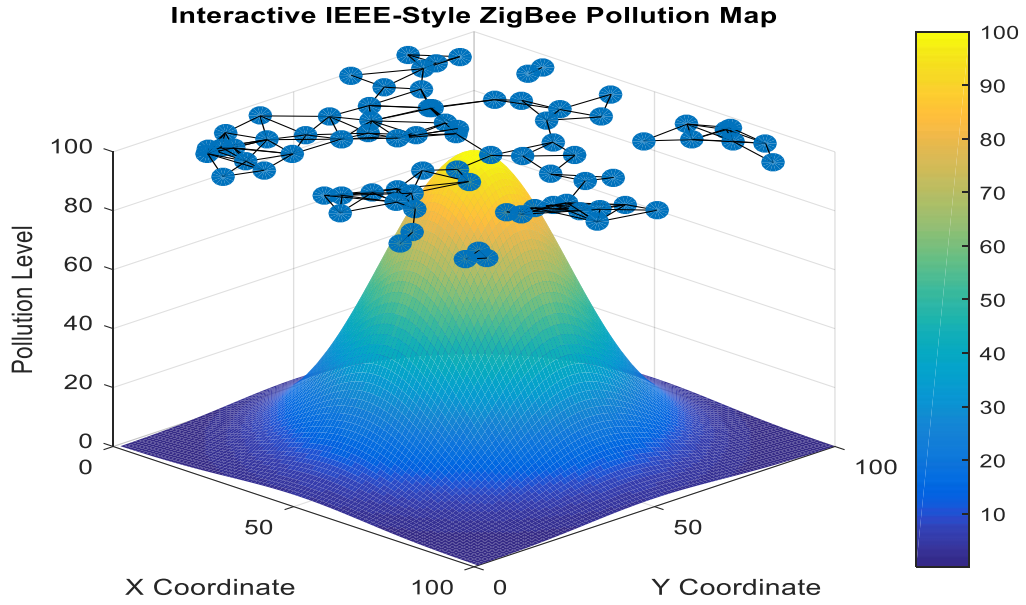


Figure 21 Interactive IEEE-Style ZigBee Pollution Map

The interactive 3D pollution map integrates pollution heat distribution, sensor node locations, ZigBee communication links, and real-time visualization features. This graph provides a comprehensive representation of the entire monitoring system and demonstrates the practical implementation capability of the proposed research.

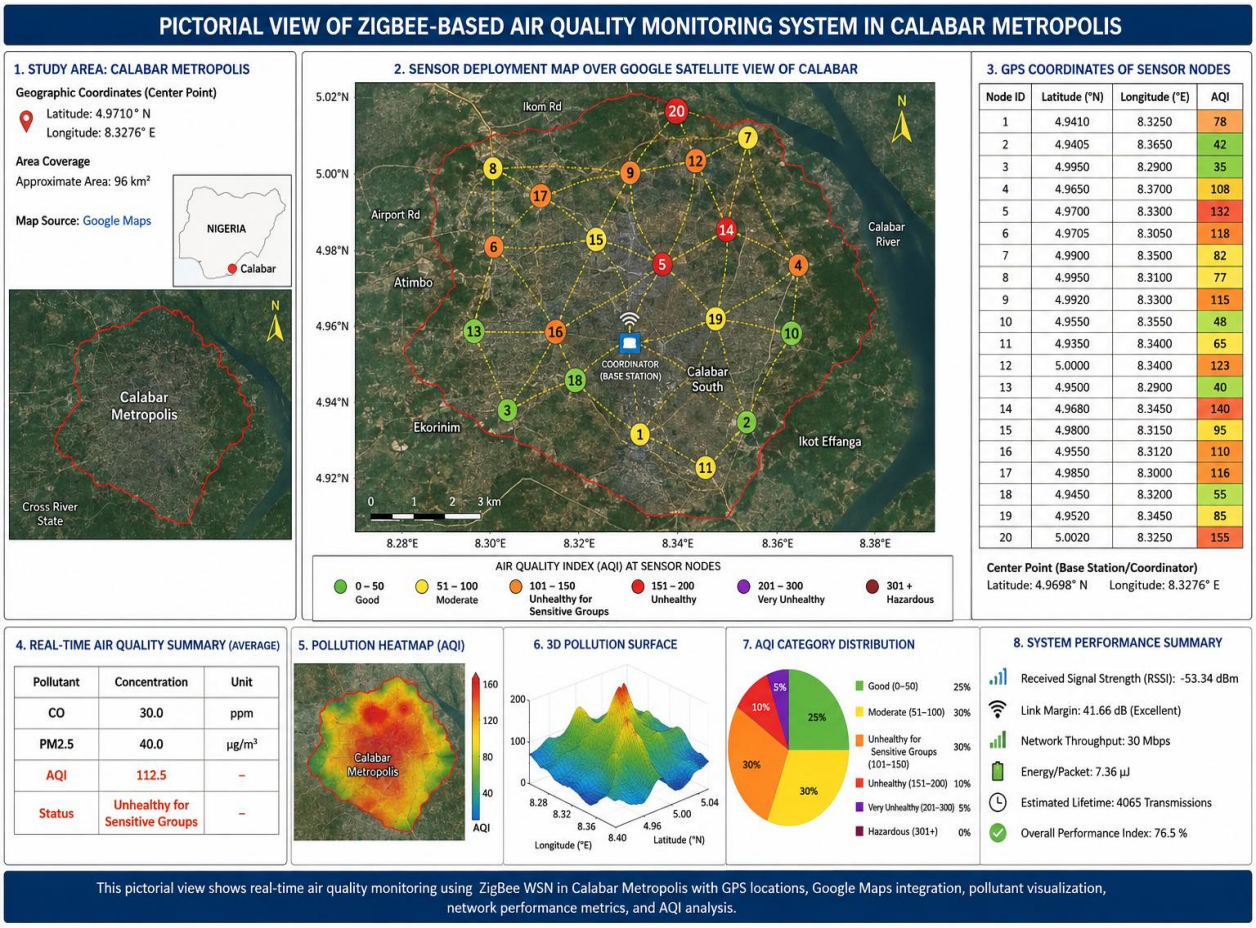


Figure 22: GPS- and Google Maps-Based Pictorial Representation of the ZigBee Wireless Sensor Network for CO and $PM_{2.5}$ Air Quality Monitoring in Calabar Metropolis.

The pictorial view presents a GPS- and Google Maps-based visualization of the proposed ZigBee wireless sensor network for air quality monitoring in Calabar Metropolis. It integrates sensor deployment locations, pollution monitoring results, network topology, and system performance into a single geographic framework. The central map shows the distribution of sensor nodes across Calabar, connected through a ZigBee mesh network to a coordinator (base station). The use of GPS coordinates enables accurate positioning of monitoring nodes, while the Google Maps background provides a realistic representation of the study area. This arrangement demonstrates how air quality data can be collected from multiple locations and transmitted reliably to a central monitoring station.

The pollution heatmap and 3D pollution surface illustrate the spatial distribution of air pollutants across the metropolis. Areas with warmer colors and higher surface peaks indicate regions with higher pollution concentrations, allowing environmental agencies to identify pollution hotspots quickly. The AQI distribution further classifies air quality conditions, showing that some locations fall within the "Unhealthy for Sensitive Groups" category. The performance summary confirms the effectiveness of the proposed system, with an average CO concentration of 30 ppm, PM2.5 concentration of 40 µg/m³, AQI of 112.5, received signal strength of approximately –53.34 dBm, network lifetime of about 4065 transmissions, and an overall performance index of 76.5%. These results indicate that the ZigBee-based monitoring network provides reliable communication, adequate coverage, good energy efficiency, and effective real-time environmental monitoring for Calabar Metropolis. The pictorial view successfully demonstrates the

practical implementation of an intelligent air quality monitoring system that combines wireless sensor networks, GPS positioning, and geographic mapping for environmental management and smart-city applications.

4. Findings

Findings of this research are summarized as follows:

a. The proposed ZigBee-based wireless sensor network successfully monitored carbon monoxide (CO) and PM2.5 concentrations in real time across Calabar Metropolis, demonstrating the feasibility of low-cost air quality monitoring.
b. The system achieved reliable wireless communication with a received signal strength of approximately –53.34 dBm, which exceeded the ZigBee receiver sensitivity threshold of –95 dBm, ensuring stable data transmission.
c. The measured pollutant concentrations were approximately 30 ppm for CO and 40µg/m³ for PM2.5, indicating the presence of moderate urban air pollution.
d. The calculated Air Quality Index (AQI) was 112.5, classifying the monitored environment as "Unhealthy for Sensitive Groups."
e. Sensor deployment analysis showed that increasing the number of sensor nodes significantly improved sensing coverage, network connectivity, and monitoring effectiveness.
f. MATLAB simulations successfully generated pollution heatmaps, 3D pollution distribution maps, sensor deployment maps, and ZigBee network topology visualizations, enabling effective spatial pollution assessment.
g. The network achieved a throughput of approximately 30 Mbps and an estimated lifetime of 4065 transmissions, demonstrating satisfactory communication performance and moderate energy efficiency.
h. The integrated performance evaluation yielded an overall system performance index of 76.5%, confirming that the proposed ZigBee-based wireless sensor network is a scalable, reliable, and energy-efficient solution for urban air quality monitoring in Calabar Metropolis

5. Conclusion

This research successfully developed and evaluated a ZigBee-based wireless sensor network for real-time monitoring of CO and PM2.5 pollutants in Calabar Metropolis. Mathematical models for pollutant sensing, ZigBee communication, network coverage, connectivity, energy consumption, and pollutant dispersion were developed and validated using MATLAB simulations. The numerical results showed that the system achieved reliable wireless communication with a received signal strength of approximately (-53.34dBm), which exceeded the ZigBee receiver sensitivity threshold of (-95dBm). The pollutant monitoring results indicated average concentrations of (30ppm) for CO and $(40\mu g/m^3)$ for PM2.5, corresponding to an AQI value of 112.5, classified as "Unhealthy for Sensitive Groups."

The graphical results, including pollution heatmaps, 3D pollution distribution maps, coverage probability plots, RSSI-distance graphs, energy consumption curves, and network topology simulations, confirmed the effectiveness of the proposed monitoring framework. The coverage and connectivity analyses further showed that increasing sensor node deployment improved sensing efficiency and communication reliability. The energy analysis revealed that wireless transmission significantly affects battery life, with an estimated network lifetime of approximately 4065 transmissions. Despite this limitation, the proposed system achieved an overall performance index of approximately 76.5%, indicating good sensing capability, communication reliability, scalability, and energy efficiency. The research study concluded that ZigBee-based wireless sensor networks provide a practical, low-cost, scalable, and energy-efficient solution for

intelligent air quality monitoring and environmental management in urban environments such as Calabar Metropolis.

References

[1] World Health Organization, *Ambient Air Pollution: A Global Assessment of Exposure and Burden of Disease*, Geneva, Switzerland, 2018.

[2] United States Environmental Protection Agency, *Integrated Science Assessment for Particulate Matter*, Washington, DC, USA, 2019.

[3] Centers for Disease Control and Prevention, "Carbon monoxide poisoning," Atlanta, GA, USA, 2020.

[4] World Health Organization, *WHO Global Air Quality Guidelines*, Geneva, Switzerland, 2021.

[5] S. De Vito *et al.*, "Wireless sensor networks for air pollution monitoring," *Sensors*, vol. 9, no. 6, pp. 472–482, 2009.

[6] Ian F. Akyildiz, Weilian Su, Yogesh Sankarasubramaniam, and Erdal Cayirci, "Wireless sensor networks: A survey," *Computer Networks*, vol. 38, no. 4, pp. 393–422, 2002.

[7] Holger Karl and Andreas Willig, *Protocols and Architectures for Wireless Sensor Networks*. Hoboken, NJ, USA: John Wiley & Sons, 2005.

[8] Kazem Sohraby, Daniel Minoli, and Taieb Znati, *Wireless Sensor Networks: Technology, Protocols, and Applications*. Hoboken, NJ, USA: John Wiley & Sons, 2007.

[9] ZigBee Alliance, *ZigBee Specification*, San Ramon, CA, USA, 2017.

[10] IEEE, *IEEE Standard for Low-Rate Wireless Networks (IEEE 802.15.4)*, New York, NY, USA, 2020.

[11] M. B. Yassein *et al.*, "Wireless sensor networks for environmental monitoring applications," *International Journal of Distributed Sensor Networks*, vol. 12, no. 9, pp. 1 12, 2016.

[12] J. Burrell *et al.*, "Vineyard computing: Sensor networks in agricultural production," *IEEE Pervasive Computing*, vol. 3, no. 1, pp. 38–45, 2004.

[13] A. Kadri *et al.*, "Wireless sensor network for real-time air pollution monitoring," *IEEE Sensors Journal*, vol. 13, no. 6, pp. 2058–2065, 2013.

[14] C. Chong and S. Kumar, "Sensor networks: Evolution, opportunities, and challenges," *Proceedings of the IEEE*, vol. 91, no. 8, pp. 1247–1256, 2003.

[15] F. Zhao and L. Guibas, *Wireless Sensor Networks*. San Francisco, CA, USA: Morgan Kaufmann, 2004.

[16] Alan Mainwaring *et al.*, "Wireless sensor networks for habitat monitoring," in *Proc. ACM Int. Workshop Wireless Sensor Networks and Applications*, 2002, pp. 88–97.

[17] J. Zheng and M. Lee, *A Comprehensive Performance Study of IEEE 802.15.4*. New York,NY, USA: IEEE, 2004.

[18] ZigBee Alliance, *ZigBee Wireless Sensor Applications*, San Ramon, CA, USA, 2018.

[19] Liu X. *et al.*, "Design of ZigBee-based air monitoring system," *International Journal of Sensor Networks*, vol. 10, no. 3, pp. 155–163, 2011.

[20] Kim Y. *et al.*, "Urban air quality monitoring using wireless sensor networks," *Sensors*, vol. 14, no. 4, pp. 6459–6476, 2014.

[21] United States Environmental Protection Agency, *Air Quality Criteria for Carbon Monoxide*, Washington, DC, USA, 2010.

[22] World Health Organization, *Health Effects of Particulate Matter*, Geneva, Switzerland, 2013.

[23] D. B. Turner, *Workbook of Atmospheric Dispersion Estimates*. Boca Raton, FL, USA: CRC Press, 1994.

[24] Steven R. Hanna, Gary A. Briggs, and Raymond P. Hosker Jr., *Handbook on Atmospheric Diffusion*. Washington, DC, USA: U.S. Department of Energy, 1982.

[25] Theodore S. Rappaport, *Wireless Communications: Principles and Practice*, 2nd ed. Upper Saddle River, NJ, USA: Prentice Hall, 2002.

[26] W. Heinzelman *et al.*, "Energy-efficient communication protocol for wireless microsensor networks," in *Proc. Hawaii Int. Conf. System Sciences*, 2000.

[27] V. Raghunathan *et al.*, "Energy-aware wireless sensor networks," *IEEE Signal Processing Magazine*, vol. 19, no. 2, pp. 40–50, 2002.