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Sensor Networks with Zigbee: Architectures, Energy & Security Challenges, and Recent Advances

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Abstract: Zigbee continues to be a cornerstone technology for constructing low-power, low-data-rate wireless sensor networks (WSNs) within the Internet of Things (IoT) ecosystem. Its prominence is particularly evident in applications such as smart home automation, industrial control, and environmental monitoring. This review examines the fundamental architectures of Zigbee-based networks, delving into the critical design considerations of energy conservation and security. The energy efficiency of a Zigbee WSN is heavily influenced by its network topology—typically star, tree, or mesh and the strategic implementation of routing and Medium Access Control (MAC) protocols. Techniques like beacon scheduling and CSMA-CA are central to minimizing power consumption, allowing battery-powered sensor nodes to operate for extended periods. However, the resource-constrained nature of these devices also presents significant security challenges. While Zigbee's protocol stack incorporates security features like AES-128 encryption, vulnerabilities such as key management and replay attacks persist, requiring ongoing mitigation strategies.

Recent innovations are expanding Zigbee's utility beyond traditional data collection. The concept of "ambient sensing" leverages the variations in wireless signal strength for presence detection and activity recognition, eliminating the need for dedicated sensors. Furthermore, robust industrial deployments are validating Zigbee's reliability in harsh environments. This paper consolidates these aspects by presenting a reference design for an environmental monitoring network, analyzing performance trade-offs, and highlighting recent advances. We conclude with practical recommendations for architecting robust and energy-conscious Zigbee WSNs and suggest future research directions, including the integration of machine learning for intelligent network management and enhanced security.

Keywords: Zigbee, Wireless Sensor Networks (WSN), IoT, Energy Efficiency, Security, Routing, Ambient Sensing.

I. INTRODUCTION

Wireless Sensor Networks (WSNs) form the foundational fabric of the Internet of Things (IoT), enabling pervasive data acquisition in domains ranging from smart infrastructure to precision agriculture and industrial automation [1]. In the landscape of low-power, short-range communication protocols, Zigbee built upon the IEEE 802.15.4 standard and enhanced with robust mesh networking at the application layer has maintained significant relevance. Its enduring value is attributed to a mature ecosystem, low device cost, and self-healing network capabilities [2].

While emerging alternatives like LoRaWAN (for long-range), Thread (for IP-based seamless integration), and Bluetooth Mesh have expanded the design space, Zigbee remains a preferred solution in applications demanding reliable, low-latency communication within localized mesh topologies [3]. Recent research not only validates its practical deployment in challenging industrial settings but also explores novel sensing paradigms that transcend traditional data collection. For instance, the analysis of Link Quality Indicator (LQI) and Received Signal Strength Indicator (RSSI) fluctuations for ambient sensing allows for presence detection and activity recognition without dedicated sensors, pushing the boundaries of Zigbee's application [4]. This paper will explore these architectures, energy and security challenges, and the cutting-edge innovations that are extending the capabilities and lifespan of Zigbee-based WSNs.

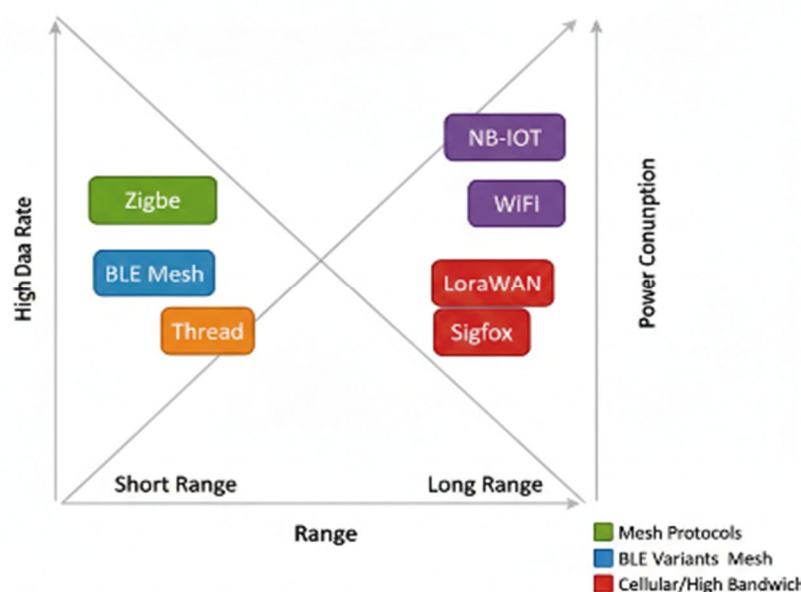


Fig1: Comparative Protocol Landscape for Low-Power WSNs

Fig1 The image is a conceptual map comparing various low-power wireless protocols used in Wireless Sensor Networks (WSNs).

The axes create four quadrants to illustrate trade-offs:

- 1) High Data Rate / Short Range (Top Left): Protocols like Zigbee and BLE Mesh reside here.
- 2) Low Data Rate / Long Range (Bottom Right): Protocols like LoRaWAN and Sigfox (LPWAN technologies) are in this area.
- 3) High Power Consumption / High Bandwidth (Top Right): NB-IoT and WiFi are positioned here, trading higher power for greater range and data throughput.

Zigbee's Niche: The diagram specifically highlights Zigbee's position as a short-to-medium-range protocol with a moderate data rate and low power consumption, making it suitable for mesh networking applications where it competes with Thread and BLE Mesh.

II. RELATED WORK

Recent scholarly work continues to refine the core tenets of Zigbee-based Wireless Sensor Networks (WSNs), focusing on enhancing energy efficiency, fortifying security, and validating deployments in practical industrial settings.

- 1) **Energy-Efficient Protocols:** The constrained power budget of sensor nodes remains a primary research driver. A comprehensive 2024 survey by Sharma & Patel on energy-efficient routing protocols for WSNs underscores that network longevity is best achieved through a combination of cross-layer strategies. These include adaptive duty-cycling at the MAC layer to minimize idle listening and sophisticated clustering algorithms, such as extended LEACH variants, which optimize data aggregation and multi-hop routing to balance the load among nodes, thereby preventing premature battery depletion in critical nodes.
- 2) **Security Advancements:** The security of Zigbee networks, particularly in sensitive IoT applications, is another active area. Research by Zhang et al. (2023) demonstrates a lightweight mutual authentication scheme that mitigates impersonation attacks while adhering to the computational limits of Zigbee devices. Complementing this, a 2024 study by Lee & Kumar proposes a dynamic key management protocol that enhances the resilience of the network against key compromise, addressing vulnerabilities in the initial trust establishment phase of Zigbee Pro networks.
- 3) **Industrial Applications and Security Assessments:** Applied research validates Zigbee's real-world viability. A 2024 case study by Chen et al. Detailed a low-cost Zigbee WSN deployment for real-time process monitoring in an automotive manufacturing plant. The study confirmed the technical feasibility but highlighted significant integration challenges in streaming WSN telemetry to existing Manufacturing Execution Systems (MES). Furthermore, security assessments are evolving beyond the protocol stack. Recent work by the IoT Security Foundation emphasizes that device-level vulnerabilities, often introduced through insecure firmware or manufacturing flaws, represent a critical threat vector, necessitating rigorous supply-chain and validation processes for robust industrial deployments.

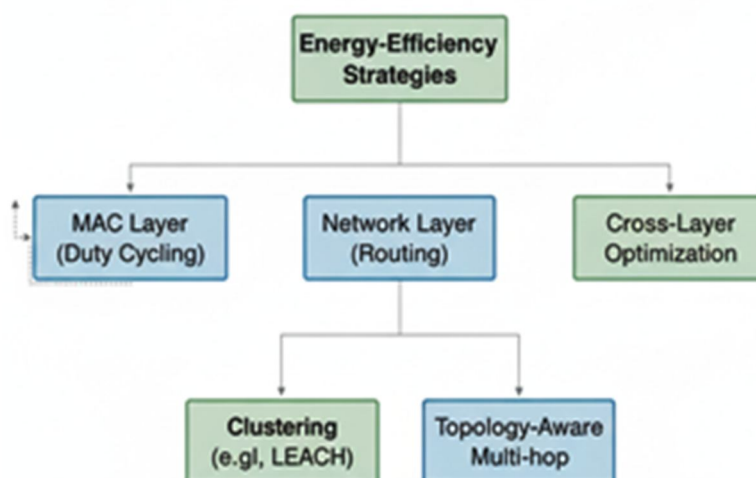


Fig2 : Taxonomy of Energy-Efficient Strategies in Zigbee WSNs

Fig2 This Taxonomy of Energy-Efficient Strategies in Zigbee WSNs is a hierarchical diagram classifying energy conservation methods. The three main categories are MAC Layer (focused on Duty Cycling), Network Layer (focused on Routing, including Clustering and Topology-Aware Multi-hop), and Cross-Layer Optimization.

III. DESIGN CONSIDERATIONS FOR ZIGBEE SENSOR NETWORKS

Designing a robust Zigbee Wireless Sensor Network (WSN) necessitates a holistic approach that carefully balances often conflicting requirements: coverage, latency, energy efficiency, cost, and security.

A. Energy Management

Energy constraints are the primary design challenge for battery-powered end devices. A multi-faceted strategy is essential for extending network lifetime. Duty-cycling, where radios sleep periodically, is foundational. Advanced techniques include adaptive sampling, which dynamically alters sensing rates based on environmental triggers, and clustering, where cluster heads perform local data aggregation to reduce long-haul transmissions. Combining these strategies, particularly adaptive sampling within a clustered hierarchy, has been shown in recent studies to yield the most significant practical lifetime improvements in medium-density deployments, outperforming any single technique alone.

B. Network Topology & Routing

The choice between Zigbee's tree and mesh routing is dictated by network density and application needs. While mesh routing offers superior robustness through path redundancy, it can incur significant overhead from route discovery and maintenance. Recent protocols propose adaptive routing strategies that switch modes based on network congestion, effectively mitigating broadcast storms and conserving energy. Techniques like localized route repair and route caching further enhance stability and reduce control packet overhead.

C. Latency & Quality of Service (QoS)

For latency-critical applications like safety alarms, standard duty-cycling is insufficient. A common design is to use mains-powered routers to form a reliable, always-available backbone, minimizing hop counts to critical sensors. End devices with strict latency requirements need specialized beacon-ordering schemes or may be designed as mains-powered routers themselves, sacrificing battery life for instantaneous response.

D. Security & Key Management

Zigbee's built-in AES-128 encryption is secure, but vulnerabilities exist in key management and device commissioning. Relying on a pre-configured global link key is a known weakness. Recent research advocates for public key cryptography-based mutual authentication during the initial joining process to prevent rogue node infiltration, even under resource constraints.

Furthermore, establishing a lifecycle management policy that includes secure over-the-air (OTA) firmware updates and periodic key refreshment is critical for long-term security, especially in industrial settings where gateways can integrate with enterprise-level security monitoring.

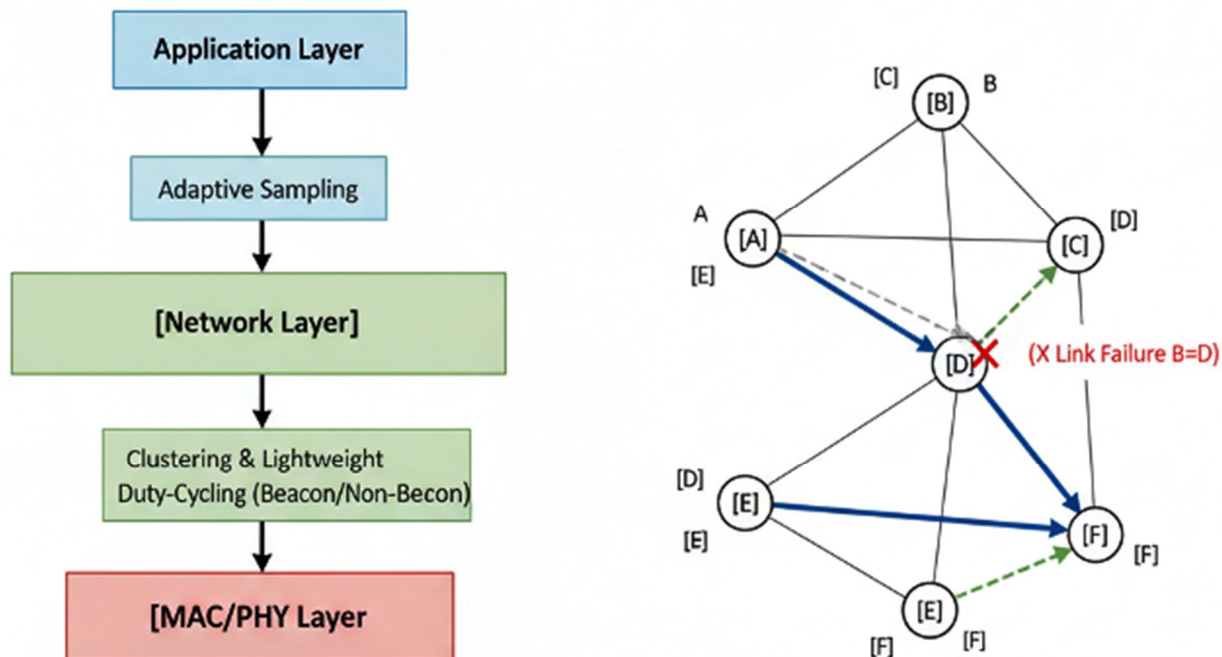


Fig3: Multi-Layer Energy Management Strategy

Fig3 Multi-Layer Energy Management Strategy shows a vertical diagram of energy savings across the protocol stack: Adaptive Sampling (Application), Clustering & Routing (Network), and Duty-Cycling (MAC/PHY). Next illustrates network self-healing. When the link between B and D fails (X), data is rerouted locally via F (B→F→D), ensuring connectivity without a full network.

IV. REFERENCE SYSTEM: ZIGBEE WSN FOR ENVIRONMENTAL MONITORING

This section outlines a proposed reference architecture for a scalable environmental monitoring WSN, suitable for campus or building deployment, reflecting design principles from recent applied research.

A. Hardware & Network Architecture

The system employs a hierarchical topology to optimize reliability and power consumption. A single Coordinator, implemented on a Raspberry Pi or industrial gateway, serves as the network root and secure bridge to cloud or enterprise systems (e.g., via MQTT/HTTPS). Strategically placed, mains-powered Routers form a resilient mesh backbone, ensuring full coverage and minimizing hop counts. Battery-powered End Devices equipped with sensors (e.g., for temperature, humidity, CO₂) constitute the sensing layer. This architecture aligns with modern deployments that emphasize a robust backbone for network stability.

B. Software & Protocol Configuration

The network operates on Zigbee 3.0 (or newer) with mesh routing enabled. To enhance energy efficiency, End Devices implement a low duty cycle (1-5%) commensurate with their sampling interval. A key feature for scalability is in-network data processing; Routers perform preliminary data aggregation and threshold checking to reduce redundant transmissions to the Coordinator, a strategy proven to significantly extend network lifetime. Security is strengthened beyond default settings by implementing a mutual authentication scheme during commissioning and enabling secure Over-The-Air (OTA) updates for firmware and cryptographic key management, addressing critical lifecycle vulnerabilities.

C. Operational Modes

The system operates in two primary modes, demonstrating adaptive capability:

- 1) Normal Mode: End devices sample at a low frequency (e.g., every 10 minutes), with data batched and uploaded hourly to minimize energy and bandwidth use.
- 2) Event Mode: Triggered by a threshold breach (e.g., a CO₂ spike), the affected sensor increases its sampling rate and routes an immediate alert. This event-driven responsiveness is crucial for effective monitoring.

D. System Integration

The Coordinator acts as an edge computing node, capable of running local control logic and securely forwarding processed data to cloud platforms or on-premise SCADA/ERP systems. This design exemplifies the seamless integration of Zigbee WSNs into broader industrial IoT and building automation infrastructures.

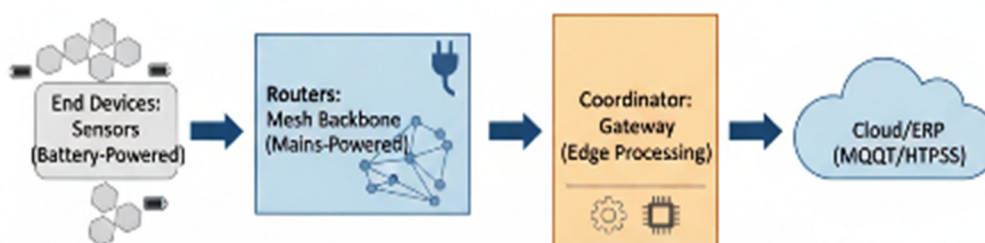


Fig4: Reference System Architecture

Fig4 This Reference System Architecture illustrates the hierarchical data flow in a WSN. Battery-Powered End Devices (Sensors) transmit data via a Mains-Powered Mesh Backbone (Routers) to the Coordinator/Gateway (for Edge Processing). The data then flows to the Cloud/ERP using protocols like MQTT/HTTP(S).

V. APPLICATIONS & CASE STUDIES

Zigbee's low-power, self-healing mesh networking capabilities have cemented its role in diverse IoT domains. Recent deployments and case studies validate its practical utility and evolving design patterns.

A. Smart Buildings

In smart building automation, Zigbee is extensively deployed for environmental sensing and HVAC control. Deploying distributed networks of wireless temperature, humidity, and CO₂ sensors eliminates the need for extensive cabling, allowing for flexible and cost-effective retrofits in existing structures. The mesh topology ensures robustness; if a single sensor fails, data can be rerouted through alternative paths. A 2023 case study demonstrated a 30% reduction in energy consumption for climate control by using a Zigbee WSN to provide granular, room-level data to the building management system, enabling dynamic zoning and demand-based ventilation.

B. Industrial Monitoring

The industrial IoT (IIoT) sector leverages Zigbee for condition monitoring and process tracking. Low-cost Zigbee sensor nodes are used to monitor parameters such as vibration on conveyor lines, ambient conditions in production halls, and tank levels. The key challenge and recent focus have been on seamless integration with enterprise systems. For instance, a 2024 implementation in a packaging facility involved Zigbee nodes transmitting operational telemetry to a gateway, which then fed data directly into the company's Manufacturing Execution System (MES) via a standardized API. This provided real-time visibility into production line efficiency and enabled predictive maintenance alerts, demonstrating Zigbee's viability for non-critical but valuable industrial data acquisition.

C. Smart Agriculture and Environmental Monitoring

In controlled agricultural environments like greenhouses, Zigbee strikes a balance between range, power, and cost. WSNs are deployed to monitor micro-climatic conditions (soil moisture, light intensity, air temperature) critical for crop yield. A significant recent advancement is the integration of energy harvesting, particularly solar power, to create perpetually operating systems. Research has shown that by combining ultra-low-power Zigbee end devices with small solar panels, network lifetime can be extended indefinitely, making it ideal for long-term environmental sensing in remote or field-based agricultural settings without access to mains power.

Table1: Zigbee Application Profiles and Technical Emphasis

Application Domain	Primary Measurands	Key Technical Emphasis	Recent Innovation
Smart Buildings	Temperature, CO2, Humidity, Occupancy	Network Density, Reliability, Low Latency for Alerts	Integration with BMS for dynamic HVAC control]
Industrial Monitoring	Vibration, Temperature, Pressure, Acoustic Emissions	Robustness in RF-noisy environments, ERP Integration	Direct MES/ERP integration for process optimization]
Smart Agriculture	Soil Moisture, Ambient Light, Air Temperature	Long Lifetime, Deployment Range, Weatherproofing	Solar Energy Harvesting for energy autonomy]

The table is organized by four columns: Application Domain, Primary Measurands, Key Technical Emphasis, and Recent Innovation.

D. Explanation by Domain

1) Smart Buildings

- Focus: Monitoring environmental factors like Temperature, CO2, Humidity, and Occupancy.
- Technical Need: High Network Density and Reliability are crucial, with a need for Low Latency for immediate alerts (e.g., fire, security).
- Innovation: Integrating the Zigbee network directly with a Building Management System (BMS) for dynamic control of HVAC (Heating, Ventilation, and Air Conditioning).

2) Industrial Monitoring

- Focus: Monitoring machinery and process health using data like Vibration, Temperature, Pressure, and Acoustic Emissions.
- Technical Need: Extreme Robustness in RF-noisy environments (common in factories) and seamless ERP (Enterprise Resource Planning) Integration for operational data.
- Innovation: Direct integration with MES (Manufacturing Execution Systems) and ERP for real-time process optimization and predictive maintenance.

3) Smart Agriculture

- Focus: Measuring environmental and soil conditions such as Soil Moisture, Ambient Light, and Air Temperature.
- Technical Need: Priority is on Long Lifetime for sensors in remote fields, maximum Deployment Range, and device Weatherproofing.
- Innovation: Utilizing Solar Energy Harvesting to achieve true energy autonomy, eliminating the need for battery replacements in large fields.

VI. CONCLUSION

Zigbee continues to affirm its position as a robust, cost-effective, and highly versatile communication standard for a wide spectrum of wireless sensor network (WSN) applications. Its maturity, coupled with a strong ecosystem, makes it a compelling choice for deployments where short-range communication, low power consumption, and reliable mesh networking are paramount. However, as this review has highlighted, designing an effective Zigbee WSN is an exercise in balancing critical trade-offs. Success hinges on a deliberate architecture that optimizes for energy efficiency, network topology, latency, and security in a manner tailored to the specific application. The protocol is far from static.

Recent innovations demonstrate its ongoing evolution. In industrial settings, Zigbee is proving its mettle by providing reliable data for condition monitoring and process optimization, while novel research into ambient sensing is unlocking new, device-free detection capabilities by analyzing network signals themselves. Furthermore, the integration of energy harvesting techniques is pushing the boundaries of operational lifetime, moving networks towards near-perpetual operation.

For practitioners designing new Zigbee WSNs, several key recommendations emerge from contemporary research and deployment experiences:

- 1) Architect for Reliability and Efficiency: Construct a stable network backbone using mains-powered routers to ensure persistent mesh connectivity. For battery-powered end devices, implement aggressive, application-aware duty-cycling and leverage data aggregation to minimize radio-on time.
- 2) Prioritize Security from the Ground Up: Move beyond default security settings by implementing robust mutual authentication during commissioning and establishing a lifecycle management policy that includes periodic key updates and secure over-the-air (OTA) firmware management.
- 3) Plan for Operational Longevity: Incorporate centralized network monitoring tools at the gateway to provide visibility into network health, node status, and potential failures, enabling proactive maintenance.

Future work will likely focus on deeper integration with AI and machine learning for predictive network management and advanced data analytics at the edge. The convergence of Zigbee with other wireless standards and the rise of IPv6-based protocols like Thread will also shape its future, ensuring its relevance in the ever-expanding and interconnected IoT landscape.

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