Vol 8, Issue 7, 2025 **Impact Factor: 8.535** DOI: https://doi.org/10.31426/ijamsr.2025.8.7.8513

I J A M S R

International Journal of
Advanced Multidisciplinary Scientific Research (IJAMSR) ISSN:2581-4281

AI-Integrated Wireless Sensor Networks: A Review Study toward Autonomous, Energy-Efficient, and Adaptive Intelligent Systems

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ABSTRACT

Integration of WSNs with AI technologies has transformed intelligent and decision-making system paradigm in various domain such as smart city, healthcare, agriculture, and industrial automation. DSNs are formed by tens or hundreds distributed sensor nodes, which gather a huge amount of environmental and physical data, but this alone cannot exploit to the full potential without AI in order to perform smart processing, anomaly detection, predictive analytics, and autonomous control. Such a synergy improves the efficiency of the network by minimizing the use of energy in routing and transmitting data, and extend sensor nodes lifetime. Context-aware sensing and relevant data reporting escape unnecessary data transmissions and allow proactive, localized actions in highly dynamic environments through AI. Applications span from early disaster detection to precision farming all the way to continuous health monitoring and predictive maintenance, showing that AI-enhanced WSNs are versatile and serve multiple purposes. Despite the challenges posed by computational power, privacy issues, and scalability, the benefits of edge computing, low power AI hardware, and 5G connectivity are pushing the development of robust, adaptive, and self-sustaining sensor networks. The fusion of WSNs with AI technology is an intervening progression to the development of autonomous intelligent systems which can sense, learn and adapt in a real-world situation with little help from human.

Keywords: *Wireless Sensor Networks, Artificial Intelligence, Energy Optimization, Predictive Analytics.*

1. Introduction

In recent years, combination of Wireless Sensor Network (WSN) with Artificial Intelligence (AI) emerged as a powerful alliance leading innovation in a broad spectrum of fields such as smart cities, healthcare, agriculture, defense, and environmental monitoring. a Wireless Sensor Network is a geo-distributed embedded system composed of spatially distributed, resource-constrained sensors to monitor physical or environmental conditions, such as temperature, sound, vibration, pressure, motion or pollutants and cooperatively pass their data through the network to a main location. These networks provide for real-time data acquisition and monitoring in locations where conventional hard-wired systems would be difficult or infeasible to deploy. Although WSNs can collect data ok, they are much more powerful when combined with AI [1]. AI is the ability of a digital computer or computer-controlled robot or "smart" machine to perform tasks that we ascribe to human thought processes e.g. the ability to learn and solve problems. The advantage that AI confers on WSN is the capability to process, interpret and take decision from the huge amount of data produced by sensor nodes [2]. This integration results in smart decision making, predictive analytics, anomaly detection, and system optimization without presenting a constant need for hu man intervention. Conservation of energy is one of the major challenging issues in WSNs [3]. AI approaches like machine learning and deep learning could also allow routing protocols to be more efficient, data transmissions to be less duplicated and power management plans to be flexible [4]. This extends network life by a large factor, and increases performance remarkably. AI algorithms can be used to predict sensor node failures, or to identify malicious activity, such that more reliable and secure communication is achieved [5]. Another significant benefit of combin- ing AI and WSN is context-sensitive sensing. Instead of managing all data as it enters the system, AI and machine learning processes can enable the network to decide which data is most important based on the network's environment, thus increasing data collection and analysis accuracy and efficiency [6]. Environmental monitoring In environmental monitoring applications, AI can learn to identify patterns that signal the early stages of natural disasters like floods or forest fires, "to raise timely alerts and prepare for scene intervention". In industrial and medical fields, AI-WSNs help to monitor and make decisions in real time. In smart factories, sensors monitor machines and collect data, while AI analyses this data to identify defects, predict maintenance and increase productivity. Even in healthcare, wearable sensor networks gather patients' vital signs and use AI to make sense of them, warning medical staff of potential health problems before they turn serious [7]. Integration of WSN with AI Considered as a breakthrough in the new era towards intelligent autonomous systems that perceive, learn, and act. However, despite the pros, some challenges are still there in such kind of network such as data privacy, computational capacity of the sensor nodes, and the requirement for scalable AI models [8]. However, with the continuous development of edge computing, low-power hardware, and intelligent distributed AI, more and more robust, adaptive, and intelligent WSN systems can be realized [9].

1.1 Synergistic Integration

The combination of the Frontier technologies as wireless sensor networks and AI described in previous subsections represents a main technological innovation that reshapes the functioning of systems based on data. Typical WSNs include numerous scattered sensor nodes, which are employed to measure various environmental conditions such as temperature, humidity, motion and pollutants. These networks are used in a variety of applications i.e., smart cities, farming and agriculture, healthcare, military surveillance, environmental monitoring etc [10]. However, the enormous amount of data created by such sensors needs to be analysed in an intelligent manner to obtain meaningful insights, and that is where AI makes it a game changer. OMER AI, and specifically machine learning

International Journal of
Advanced Multidisciplinary Scientific Research (IJAMSR) ISSN:2581-4281

and deep learning algorithms, can be combined with WSNs so as to provide an instantaneous interpretation and utilization of the data gathered without the involvement of a human. This synergy allows systems to acquire the capability to accomplish complex tasks like anomaly detection, predictive analysis, and self-autonomous decision. For instance, in smart agriculture artificial intelligence can analyse sensor data to forecast irrigation requirements or identify crop disease, ultimately increasing efficiency and yield [11]. In healthcare, AI-based WSN can monitor the patient bodies vitals continuously and it can also give the alert to medical staff if any health issues have arisen early then it became severe. In addition, for WSNs devices usually offer very limited power budget, AI can greatly improve network efficiencies such as routing protocols evolution, elimination of redundant data transmission, and energy management among nodes for they are able to work within the constrained power for WSN. The joint implementation preserves the context-aware sensing that is AI-based to prioritize sensor information that is relevant to an application for improved decision accuracy. This technology trends toward more adaptable, intelligent, and self-sustaining systems in the growing complexity of the environment. In summary, when WSN meets AI, it is no longer only about technical upgrades, but a paradigm shifts towards smarter, more autonomic and efficient systems that will reshape industries and our daily lives [12].

1.2 Enhanced Efficiency and Optimization

Knowledge Discovery and Decision-Making: AI combined with WSN allows for intelligent processing of data in sensor networks and decisions to be made by converting incoming raw sensor data into useful information. WSNs produce huge amounts of data concerning temperature, humidity, pressure, movement, etc., from a multitude of environments. The data they can gather and interpret on their own is limited. AI, more specifically machine learning and deep learning methodologies, knows how to fill this gap by examining data pattern and detecting anomalies as well as predicting. A smart-agriculture system is providing the sensors that keep an eye on soil moisture and weather, and the AI that processes that data to determine when to irrigate in order to use resources most efficiently to maximize the crop yield [13]. AI in the healthcare sector can always be checking on the vital signs of patients recorded by wearable devices, and sound the alarm at the first sign of any medical condition. This smart processing decreases the amount of human interaction required and allows the systems to function in an autonomous manner in unstable environments [14].

Improved Network Efficiency and Energy Optimization: Integrating AI and WSN also provide the reasonable advantages in effective energy utilization and overall network quality. As sensor nodes usually work on limited power, energy efficient is an essential for long-time network operation. The routing protocol in WSN can be improved by the AI so that unnecessary transmission of data can be avoided and the battery life is also saved as it will not allow congestion in the network. It can further facilitate the adaptive sensing by transmitting only the useful data according to the current environment. In addition, AI has the capability to forewarn node failures or timely catch the security threats in the network, in order to guarantee the reliability and system security. These improvements render the system further robust, scalable, and sustainable, which is important for remote or large deployments such as environmental monitoring or military actions [15].

1.3 Context-Aware and Predictive Capabilities

Context-Aware Sensing and Preference Based Data Prioritization: In a conventional Wireless Sensor Network, data collection is performed uniformly without being sensitive to the relevance or the urgency of the data. However, when we integrate Artificial Intelligence, WSNs are allowed to be context-aware in the sense that they process and react according to the specific requirements of a situation. It allows sensor nodes to take advantage of AI algorithms to recognize which data is the most important depending on environmental COMSOC'10 2010 Applications of AI in Sensor Networks changes or application-oriented requirements. A smart building could use sensors to monitor and measure motion, temperature, and light at different parts of the day. Using these inputs, AI algorithms can make real-time analyses to automatically adjust lighting or HVAC systems, thus advancing energy efficiency and comfort. It achieves effective energy saving and improves the rate and accuracy of decision-making by filtering the network traffic according to the relevance of the context [16].

Predictive Analytics and Proactive Decision-Making: Prediction is one of the most beneficial deliverables by coalescing AI with WSNs. Instead of only responding to a sensor stimulus, AI systems can predict future events and conditions based on previous patterns or real-time examples. This particularly gains importance in the implementation in domains like disaster management, agriculture and healthcare. For example, in environmental monitoring, AI can look at temperature, humidity, and wind trends to forecast the risk of forest fires or flooding, providing the opportunity for early warning and preventative measures. For example, in agriculture, predictions based on soil and weather sensor data through AI can be used to determine the best times for planting and harvesting. In medicine, wearable WSNs and AI can be used to predict possible health problems like heart conditions and breathing difficulties through pattern detection on vitals. These early indications make it possible to intervene early, mitigates risks and deliver better results. In general, AI can transform WSNs from merely a passive observer to systems that are conscious and able to predict and react to problems before they occur [17].

1.4 Smart Applications and Future Potential

Intelligent Applications in Various Domains: WSN and AI integration has resulted in intelligent systems in different domains which lead to smarter and more responsive and adaptive environments. In smart cities, it is very common to use AI-based WSNs for real-time traffic monitoring, street light efficiency for power savings, waste management, and air quality monitoring. These applications assist and support city planners and municipal bodies to utilize resources in an efficient manner and to enhance quality of life. Healthcare monitoring systems In healthcare, wearable sensors networks, monitors user parameters such as heart rate, Oxygen levels and activity and sends data to a gateway. Artificial intelligence software parses this data to spot early signs of medical issues, thus enabling people to intervene, when necessary, consequently reducing hospital trips. In smart agriculture, soil sensors monitor soil moisture, nutrients and temperature while AI models predict ideal timings for irrigation and fertilization. This leads to greater crop yields, less water usage, and environmentally-friendly farming techniques. For factory-automation applications, AI-integrated WSNs are employed to monitor equipment condition (vibration, temperature, performance, etc.), which leads to predictive maintenance, reduced downtime, and safer operation. These use-cases show us the collaboration between AI and WSN for the development of intelligent and autonomous systems that run with little human intervention [18].

Future Potential and Emerging Technologies: There is great potential for AI-combined WSNs in the future particularly with development in edge computing, low-power AI chips, and 5G links. Characterized by local data processing close to sensor nodes, Edge AI minimizes latency and dependence on cloud infrastructure. This makes possible rapid decision making, essential for time-critical applications such as autonomous vehicles, military surveillance or emergency response systems. Moreover, with the emergence of ultra-low-power AI chips, it becomes possible that even energy-limited sensor nodes can carry out a series of complex calculations without significantly draining the batteries. With the wider availability of 5G, this low delay, high speed communication also integraes in AI-based WSNs, resulting in better scalability and responsiveness. In the future, such an integration will help to realize advanced concepts, such as self-healing networks, adaptive learning algorithms or even fully answers over autonomous environments. The ability to build intelligent systems of systems—where devices sense, reason and act in concert with others—represents a transformational shift in how the physical world is to be engaged [19].

2. Related Reviews

Author (Year)	Methodology	Objective	Findings
Priyadarshi et al. (2025)	Modular AI-based routing framework combining reinforcement learning (RL), supervised learning, GA, PSO; MATLAB simulation	To develop a hybrid AI routing framework dynamically adapting to network changes in WSNs	Improved packet delivery ratio, latency, energy efficiency vs. traditional protocols; scalable and secure architecture proposed
SK et al. (2025, March)	Real-time performance comparison of WSNs (20-50 nodes) using AI-enhanced AODV routing protocol	To analyze network size impact on packet delivery, delay, throughput, and energy efficiency	100% packet delivery; delay and throughput degraded with size; energy efficiency reduced in denser networks
Hadi et al. (2025)	Q-learning-based dynamic energy optimization; MATLAB simulations and real-world tests	To enhance energy efficiency and network performance in WSNs	34.92% energy savings; PDR increased from 85% to 96.38%; latency reduced by 24 ms; operational time extended from 7 to 10 hours
Zing and Zhao (2025)	Survey of meta-heuristic AI algorithms (PSO, GA, ACO) combined with deep learning and RL for routing in WSNs	To review optimization of routing via meta-heuristic AI techniques in dynamic WSN environments	Meta-heuristic AI enhances energy efficiency, scalability, adaptability; real-world case studies support improved routing decisions

Takore et al. (2025)	Review of AI techniques for QoS enhancement in WSNs focusing on routing and data aggregation	To explore AI integration for dynamic routing, energy optimization, and security in WSNs	AI-driven routing reduces congestion, conserves energy; data aggregation improves accuracy and resource use; supports IoT deployments
Priyadarshi (2024)	Review of AI integration in WSN routing and clustering with focus on bio-inspired algorithms	To survey AI and optimization methods addressing WSN challenges like energy and scalability	Identified challenges including energy limits, scalability; bio-inspired routing improves network longevity and resource management
Arulmurugan et al. (2024)	Comparative analysis of ML-based, conventional, and AI-driven encryption techniques in WSNs	To evaluate security methods for WSN focusing on overhead, energy, and speed	ML approaches offer enhanced security and flexibility; AI-based encryption architecture reduces overhead and energy consumption
Ahmed (2024)	Survey on integration of WSN, IoT, AI, and DL in smart agriculture	To review technologies enabling real-time data management and predictive analytics in agriculture	WSN+IoT enables real-time monitoring; AI/DL improve disease detection, resource use; challenges include energy, scalability, security
Shrivastav & Battula (2023)	Review of WSN and IoT integration with AI in heterogeneous wireless systems	To highlight advancements enabling real-time intelligent applications in IoT-AI systems	WSNs facilitate data/control transmission; AI integration enhances smart system responsiveness; challenges include scalability, QoS
Aruchamy et al. (2023)	AI-based energy-aware intrusion detection and secure routing model for IoT-enabled WSNs	To improve security and energy efficiency in IoT-WSNs against DoS attacks	Achieved 95% attack detection accuracy; 38% energy consumption reduction; game theory-based protection and energy-aware routing effective
Osamy et al. (2022)	Survey of AI methods addressing coverage, deployment, and localization challenges in WSNs	To provide a comprehensive review of AI techniques enhancing WSN performance	AI methods improve routing, coverage, and localization; identified open research issues and future directions
Agarwal et al. (2021)	Application of AI in routing and message aggregation in WSNs	To optimize energy consumption and routing efficiency in WSNs	AI techniques enhanced message aggregation and routing, conserving energy in large sensor networks
Turchan & Piotrowski (2020)	Framework development for AI application deployment on WSN nodes focusing on energy efficiency	To facilitate AI-based applications directly on sensor nodes to reduce data transmission and energy use	Proposed framework enables local AI processing; reduces network load and electricity consumption

Benzekri et al. (2020)	AI and deep learning-based forest fire detection system using IoT and LPWAN	To improve early detection of forest fires via WSN and AI	Deep learning model enables precise real-time fire prediction; system outperforms traditional surveillance
Doibale & Kurundkar (2019)	AI-based blockage control to mitigate congestion in WSNs	To reduce congestion effects and improve routing via AI	AI enables proactive congestion control and alternative routing; enhances network reliability and speed
Kumar & Singh (2018)	Analysis and development of AI-based data aggregation techniques in WSNs, compared with ACO and PSO	To assess and improve AI data aggregation methods for network lifetime and throughput	Modified AI protocol outperformed existing methods; suggested future research on AI and metaheuristic aggregation techniques
Menaria et al. (2018)	Artificial bee colony and Q-MST based fault-tolerant data aggregation in WSNs	To improve fault tolerance and resource use in WSN data aggregation	Q-MST approach enhanced fault tolerance and reliability; used multiple AI-based algorithms for optimized data paths
Kalnoor & Agarkhed (2017)	AI-based intrusion detection systems (IDS) for securing WSNs	To analyze AI techniques protecting WSNs from intrusions and attacks	AI and IDS critical for detecting/preventing attacks; essential for WSN security especially in critical applications
Purohit & Mathur (2016)	Review of AI systems (expert systems, neural networks) in wireless sensor and actuator networks	To describe sensor types and AI integration in wireless networks	AI systems enhance communication and control in WSNs; enable diverse applications by managing heterogeneous sensor data

3. Findings

Synergy of Integration Improves System Intelligence: WSN and AI are combined to form intelligent complex data-driven systems which have such capabilities as autonomous sensing, learning and decision-making. AI (including machine learning, and deep learning) algorithms can efficiently handle and analyse the high volumes of sensory data produced by the sensor nodes to support real-time anomaly detection, predictive analytics and autonomous responses without human intervention.

Remarkable Enhancements in Energy Efficiency and Network Optimization: The AI-based optimization methods dramatically increase the lifetime of WSNs by decreasing energy consumption. This is done through smart routing, adaptive sensing techniques, and eliminating excessive transmissions. AI that predicts the failure of nodes and identifies security threats also enhances the network reliability and robustness.

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International Journal of Advanced Multidisciplinary Scientific Research (IJAMSR) ISSN:2581-4281

Proactive Operations Using Context-Aware and Predictive Features: The incorporation of AI provides WSNs with the ability to be context-aware, such that the sensor nodes can forward the relevant data based on the context and application requirements. With predictive analytics, various proactive applications (e.g., early disaster warnings, optimized agriculture management, and preventive healthcare alarms) are made available, thus enabling WSNs from passive data collectors to become capable anticipatory systems.

Multi-sector Wide Application of Smart Things: AI-based Wireless Sensor Networks (WSNs) have great advantages in different areas, e.g., smart city (traffic, lighting, air quality), health care (continuous patient monitoring), agriculture (precision irrigation and fertilization) and industrial automation (predictive maintenance). These systems will help to reduce the consumption of resources, increase operational safety, and enhance service quality.

Next-Generation Technology Enables Scalability and Autonomy: Technology breakthroughs in edge computing, ultra-low-power AI hardware, and 5G will meet challenges like latency and compute power. These advances will support scalable, autonomous, and self-powered WSN systems, such as autonomic healing networks and learning-by-example frameworks [20].

4. Conclusion

The integration of the AI and WSNs is a new turing point in the intelligent system theory and technology development. Such hybrid systems, which integrate the real time sensing and actuation with the advanced AI based analytics and decision-making, are unprecedented in their levels of operational autonomy, efficiency and predictive insight. The fusion encounters a number of challenges such as energy limits, avalanche, context ignorance, revjsona sensiti on, which arsona is to be jsona rged in the resides jsona al wound -shifting jsona or for mobile networks. Wide-spread practical applications of the AI-enhanced WSNs, which go from smart urban infrastructure, precision agriculture, healthcare, industrial automation, etc., demonstrate the widespread usefulness to which standard applications can benefit from AI-enhanced WSNs. Although there are still challenges, such as data privacy, limited computation capability, and network expansion, rapid progress in edge AI and communication infrastructures will help reduce these problems. The synergy between WSN and AI is not a technological improvement, but a paradigm changes towards intelligent and autonomic ecosystems that sense, learn and act in the physical world. And this combination will dramatically transform how we sense the environment, control resources and, with dynamic real-time data, act autonomously based on new heterogeneous conditions.

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