Wireless Sensor Networks: A Survey of Design Challenges, Routing Protocols, and Emerging Applications

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Abstract. Wireless Sensor Networks (WSNs) are a popular area of study, with applications in recent trends such as environmental monitoring, smart agriculture and military surveillance. The Internet of Things is a type of large-scale system where the sensors use the wireless sensor networks for environmental monitoring and act cooperatively by collecting the data, processing it and forwarding information to the base station. Although WSN has numerous advantages, it also faces some challenges, including energy limitations, scalability, routing efficiency and security. Design challenges in wireless sensor networks: a top-down perspective Routing protocols in wireless sensor networks: a survey, Emerging applications of WSNs. The paper partitions three types of routing protocols according to three mechanisms for partitioning and summarize the performance characteristics for each category. In addition to that, the recent ones include AI-injected clustering and energy-proficient routing mechanisms. It also explores new applications of WSN technology.

Keywords: Wireless Sensor Networks, Routing Protocols, Energy Efficiency, Clustering, IoT Applications.

1 Introduction

Wireless Sensor Networks (WSNs) are made of distributed sensor nodes, which collaboratively observe physical or environmental conditions, including temperature, humidity, pressure and motion [1]. These nodes wirelessly communicate with each other and send the collected data to a base station for processing. The evolution of microelectronics, wireless communication, and embedded systems has resulted in a significant rise of interest for WSNs. Basically, in a WSN node, there are sensing devices, processing units, communication elements and a limited power supply. Energy efficiency becomes a critical design consideration since sensor nodes are often battery-powered and deployed in remote areas. Therefore, the routing protocols are important in maximizing the network lifetime under reliable data delivery. Several routing mechanisms and network topologies have been proposed to tackle these issues. In early foundational studies

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of WSNs, energy-efficient communication, data aggregation, and scalable routing architectures [2] [3] were emphasized. More surveys categorized routing protocols as hierarchical, data-centric and location based [4] [5]. Other types of studies focused on cognitive routing techniques, i.e., exploiting ML and AI to improve network performance (i.e., lifetime) in a few recent studies [6] [7].
This work gives a detailed survey focusing on design challenges in wireless sensor networks and the classification of routing protocols. This also gives a clear picture of existing routing protocols and their comparison with the explanation of wireless sensor network architecture. At the end emerging applications and future research directions will be summarized. Table 1 shows the comparison of related work based on the above-discussed areas.

Table 1: Comparative analysis of related work

Ref. No.	Protocol / Method	Category	Key Idea	Advantages	Limitations
[2]	Survey of Routing Protocols	General Routing Survey	Classification of routing protocols into flat, hierarchical and location-based	Provides complete taxonomy and performance comparison	Does not propose new protocol
[3]	WSN Architecture Survey	General WSN	Defines architecture, design factors, communication models	Fundamental understanding of WSN design	Early generation assumptions lack modern IoT integration.
[4]	Clustering Routing Survey	Hierarchical Routing	Analysis of clustering techniques for energy saving	Improves scalability and network lifetime	Cluster head selection overhead
[5]	Routing Techniques Survey	General Routing	Reviews multipath, query-based and negotiation-based routing.	Covers reliability and QoS issues	Limited experimental validation
[6]	Energy-Efficient Routing Survey	Energy-aware Routing	Focus on minimizing energy consumption in routing decisions.	Extends network lifetime significantly	Trade-off with delay and throughput
[7]	Hybrid Faster Routing Scheme	Hybrid Routing	Combines shortest path and energy awareness	Reduces delay and improves packet delivery	Performance degrades in dynamic networks.
[8]	Design Space Methodology	Network Design Framework	Identifies constraints such as energy, topology and deployment	Helps in protocol design optimization	Conceptual — no implementation

[9]	LEACH	Hierarchical (cluster-based)	Random rotation of cluster heads for load balancing	Reduces energy consumption and prolongs lifetime	Not suitable for large-scale or heterogeneous networks
[10]	Data Aggregation Techniques	Data Aggregation	Eliminates redundant data transmission	Saves bandwidth and energy	May introduce data latency
[11]	Secure Routing Protocol	Security-aware Routing	Uses authentication and encryption in routing	Improves data confidentiality and integrity	Extra computation and energy overhead
[12]	Directed Diffusion	Data-centric Routing	Data dissemination based on interest queries	Reduces unnecessary transmissions	Flooding during interest propagation
[13]	PEGASIS	Chain-based Routing	Forms a chain of nodes for sequential data transmission	Further reduces energy compared to LEACH	Large delay due to long chains
[14]	GEAR	Location-based Routing	Uses geographic information and residual energy	Efficient routing towards target region	Requires GPS / location awareness
[15]	WSN Comprehensive Survey	General WSN	Discusses coverage, connectivity, localization and routing.	Broad system-level perspective	Limited discussion on emerging AI-based routing
[16]	Underwater Routing Survey	Specialized Routing	Routing challenges in underwater acoustic sensor networks	Addresses harsh channel conditions	High propagation delay and packet loss
[17]	Advanced WSN Trends	Emerging Technologies	Integration with IoT, AI and smart environments	Shows future research directions	Mostly conceptual analysis
[18]	Application-based Survey	Application Layer	Reviews healthcare, agriculture, and industrial monitoring uses	Demonstrates real-world feasibility	Does not focus deeply on routing performance
[19]	Future Landscape Survey	Research Trends	Timeline-based evolution of WSN technologies	Identifies open research challenges	Lacks protocol-level performance comparison.
[20]	Delay-Tolerant Low-Duty Cycle Scheme	Energy-Efficient / Duty-Cycle Based Routing	Uses adaptive sleep–wake scheduling to reduce unnecessary transmissions and conserve node energy in	Improves network lifetime, reduces energy consumption, and is suitable	Increased latency in real-time scenarios; performance depends on optimal duty

			IoT-enabled WSNs	for delay-tolerant applications.	cycle configuration.
[21]	Load Balancing Clustering and Routing	Hierarchical / Cluster-Based Routing	Distributes traffic load among cluster heads to balance energy usage and avoid early node failure	Enhances scalability, prolongs stability period, improves throughput	Cluster head selection overhead, possible congestion in dense networks
[22]	DST-WOA Trust-Based Clustering	Trust-Aware / Optimization-Based Routing	Integrates dempster–Shafer theory with Whale Optimization Algorithm for secure and efficient cluster formation.	Improves security, reliability, and packet delivery ratio; better energy utilization	Higher computational complexity, increased control overhead
[23]	Threshold-Sensitive Energy-Efficient Routing	Threshold-Based / Application-Specific Routing	Utilizes sensing thresholds to trigger transmissions only when significant environmental changes occur (precision agriculture)	Reduces redundant data transmission, increases network lifetime, and is suitable for event-driven monitoring.	Limited applicability to general WSN scenarios, threshold tuning required

2 Architecture of Wireless Sensor Networks

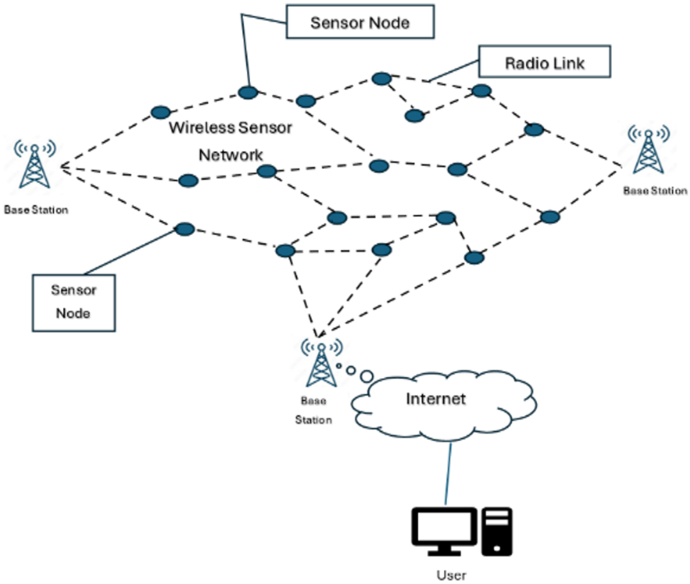

Fig. 1 Architecture of a Wireless Sensor Network

A typical WSN architecture consists of the different components as shown in Fig. 1, which help to transmit data with consideration of QoS parameters. Sensor nodes are devices including sensors, processors, communication components, and power units. They are primarily used to collect environmental data and send it to other nodes or the base station. The sensor nodes deployed in a wireless sensor network may have limited energy, and this may be a challenge in finding a cluster head for better QoS parameters. In a wireless sensor network, the nodes are deployed in the form of clusters, as the deployed nodes may be higher in number, so the whole network is divided into area-based clusters for better communication in terms of delay, jitter and packet loss. Each cluster consists of a cluster head; the cluster head is selected from the participating nodes in the cluster. The cluster head communicates with each cluster head for data transmission. The sink node collects information from all sensor nodes and sends it to outside networks for further processing. In this communication method, nodes communicate using wireless communication protocols like ZigBee, Wi-Fi or Bluetooth. This unit's process sensed data before relaying it to the base station [2][8]. The architecture design should find a trade-off between communication, energy consumption, and scalability.

3 Design Challenges in Wireless Sensor Networks

The inherent limitations of sensor hardware and the dynamic characteristics of a wireless sensor network present a number of technical challenges. The most important issue is energy efficiency since sensor nodes are powered by a limited battery. Energy-efficient routing and data-aggregating mechanisms are very vital to increase the network lifetime [9][10]. WSNs are designed to have hundreds or thousands of nodes. Routing protocols should also efficiently handle large-scale deployments. Kwon's opinion is that whatever node has less data to share will send it out to nearby closely situated nodes in a similar way, sending out previous unchanged data with the combined one, which can help in increased efficiency of different nodes by merging their data [2]. Hardware failure or energy depletion may cause sensor nodes to fail. The remaining operation of the network in the face of node failures. Due to the broadcast nature of wireless channel communication, WSNs are susceptible to various attacks, including node compromising and data sniffing [11].

4 Design Challenges in Wireless Sensor Networks

Fig. 2 shows the routing protocol used in a wireless sensor network based on their design perspective. There are four categories of routing protocol based on how routing decisions are made and how communication happens in a network.

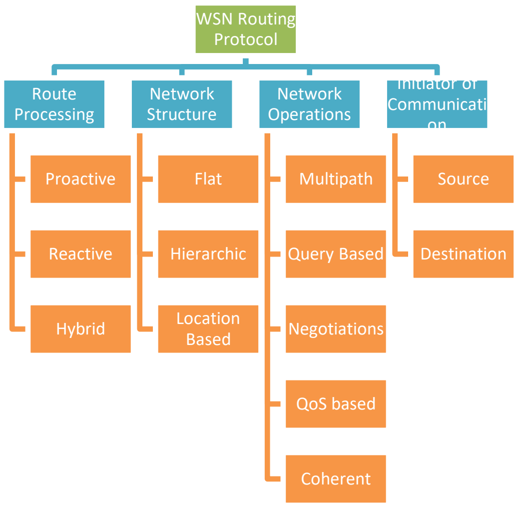

Fig. 2 Routing Protocol Classification

4.1 Data-Centric Routing

These are attribute-based protocols which rely on the properties of data, rather than identities of nodes. Directed Diffusion [12] is an example of data-centric routing. Data aggregation, reduced redundancy transmission and suitability of query-based systems are the main characteristics of this routing technique.

4.2 Data-Centric Routing

LEACH [9] and PEGASIS [13] are hierarchical routing protocols because they cluster the nodes together. This routing technique is energy efficient because they work on clusters by forming clusters and cluster head selection. The process of working with these techniques consists of cluster formation, cluster head selection, data collection, data aggregation and data transmission. The main advantages of these techniques are energy efficiency, scalability, data aggregation and load distribution.

4.3 Data-Centric Routing

To optimize routing in a wireless sensor network, location-based routing is used. In this routing technique the sensor node uses their geographic location or coordinates to transmit data to the base station. The geographic routing protocol [14] is the example of this type of routing. Instead of maintaining a complex routing table, the nodes use the geographic location of the next hop to transmit the data, which helps in reducing routing overhead and energy efficiency.

5 Design Challenges in Wireless Sensor Networks

We follow a systematic review methodology using a directed approach to extract qualitative and quantitative dimensions of the literature on WSN routing protocols and design issues. Fig. 3 shows the methodology which has been followed in this paper.

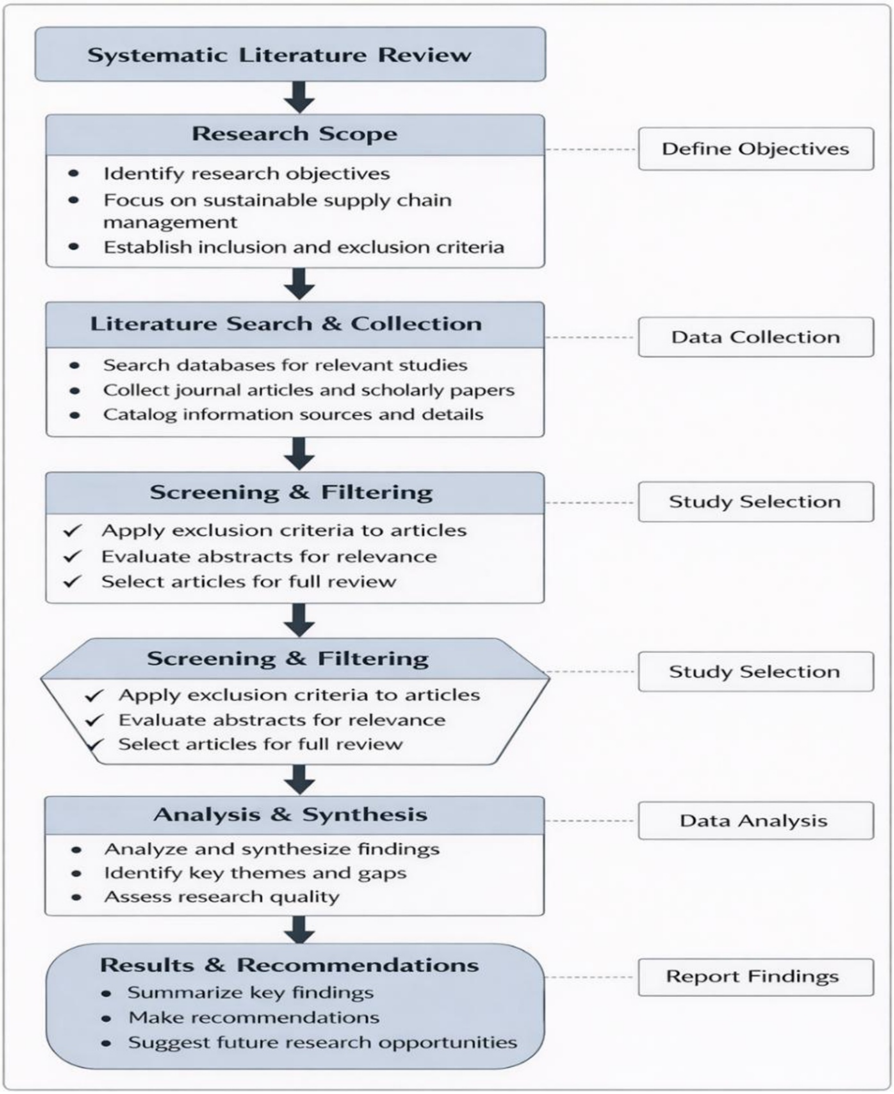

Fig. 3 Methodology

6 Comparison of Major Routing Protocols

There are different routing protocols which are being used in wireless sensor networks based on their performances. In Table 2 some of them are briefly discussed along with their energy efficiency, scalability and key features.

Table 2: Different Routing Protocol Comparison

Protocol	Type	Energy Efficiency	Scalability	Key Feature	Reference
LEACH	Hierarchical	High	Medium	Cluster-based routing	[9]
PEGASIS	Hierarchical	Very High	Medium	Chain-based communication	[13]
Directed Diffusion	Data Centric	Medium	High	Data aggregation	[12]
Geographic Routing	Location-Based	High	High	Uses node location	[14]
Energy-Aware Routing	Hybrid	Very High	High	Adaptive energy management	[6]

7 Performance Comparison Graph

Fig. 4 shows the lifetime of sensor nodes in different routing schemes, and the chart is prepared in comparison of the number of rounds with each routing protocol.

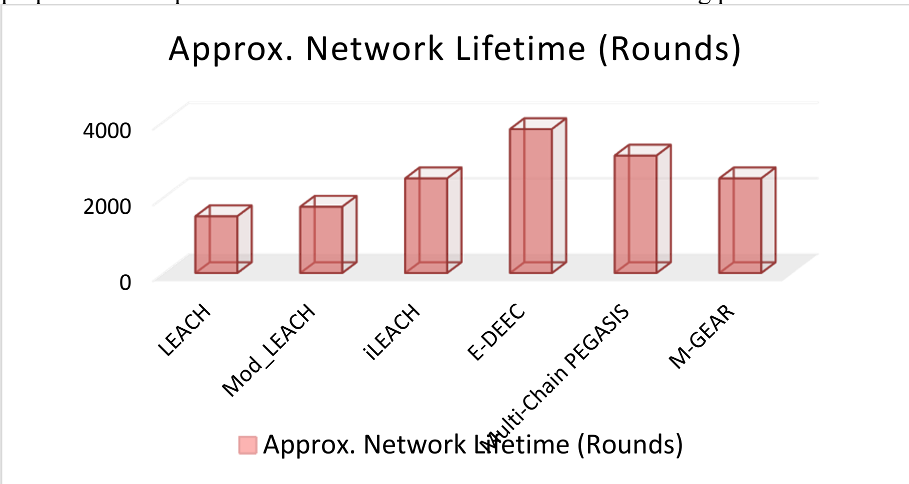

Fig. 4 Network Lifetime Comparison of WSN Routing Protocols

Fig. 5 shows the comparison of the number of rounds and different routing protocols to show the network lifetime after each round. The comparison shows that the extended DEEC shows a significant improvement compared to LEACH.

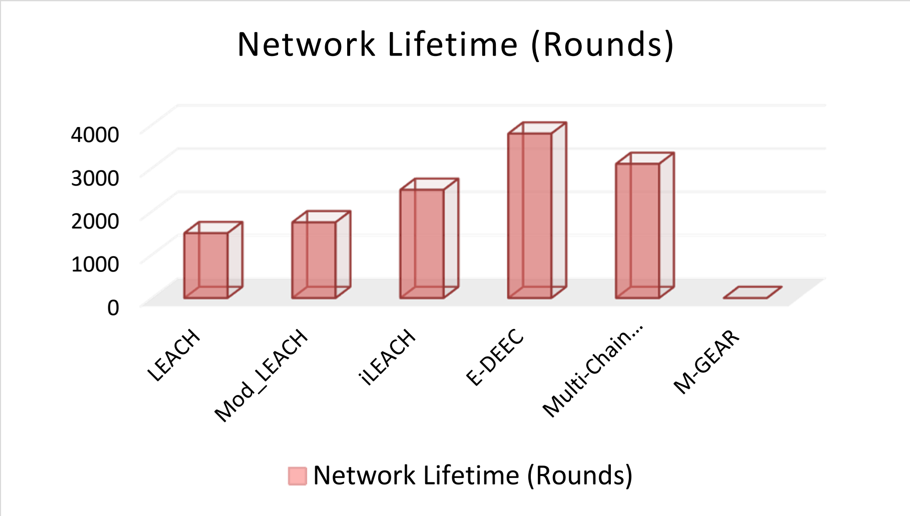

Fig. 5 Network Lifetime Comparison Graph

Fig. 6 shows the comparison of network lifetime percentage and number of nodes deployed in three different strategies in WSNs, like random distribution, grid distribution and circular distribution.

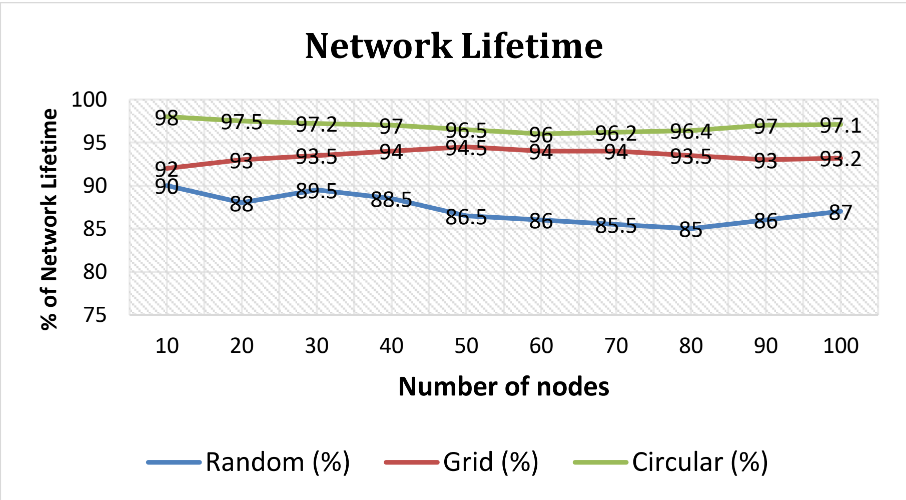

Fig. 6 Network Lifetime vs Number of Nodes Graph

Fig. 7 shows how the number of alive nodes will increase if the initial energy in nodes increases from 0.5 0.5J to 5.0 5.0J in two different routing protocols, like A&F and EERP.

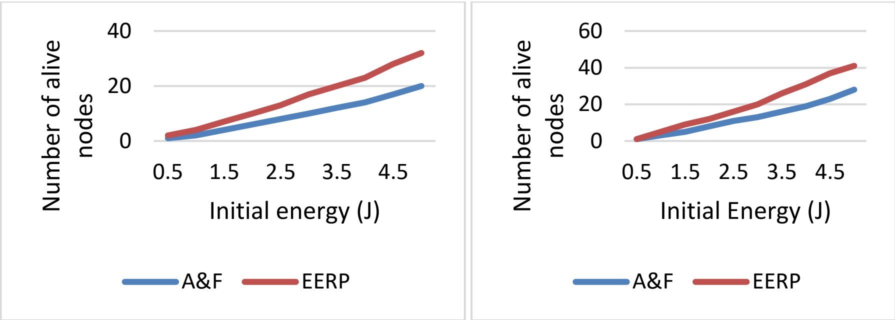

Fig. 7 Energy Efficiency Comparison of Routing Protocols

8 Emerging Applications of WSN

The ability to sense, process and transmit environmental data in real time has positioned Wireless Sensor Networks (WSNs) as a key enabling technology for a multitude of emerging applications, as shown in Fig. 8. One of the most promising new applications for WSNs is smart agriculture based on sensor data to improve precision farming and irrigation management by monitoring key parameters such as temperature, soil moisture and humidity. In the healthcare field, WSN is utilized in wearable devices and remote patient monitoring systems to continuously monitor physiological parameters like heart rate, body temperature, and blood pressure to increase healthcare accessibility and responsiveness. WSNs are also being deployed in the establishment of smart cities; they can be utilized for traffic regulation, smart parking structures, air quality tracking and intelligent refuse management to improve urban lifestyle. Moreover, WSNs have been widely implemented in environmental monitoring, allowing for the early detection of natural catastrophes like forest fires, floods and landslides while also helping with wildlife tracking and climate observation. The tech is then also used for industrial automation and the Industrial Internet of Things (IIoT) powering asset condition monitoring, predictive maintenance, or energy management, which allows industries to cut costs while improving operation reliability. In addition, military and security-related applications of WSNs include battlefield monitoring, target tracking, and infiltration detection in sensitive zones. Because of their scalability, low power consumption, and operation in remote or harsh environments, WSNs keep expanding to new application domains and are regarded as an underlying technology for future intelligent systems and Internet of Things (IoT) infrastructures [17][18][19][15][3].

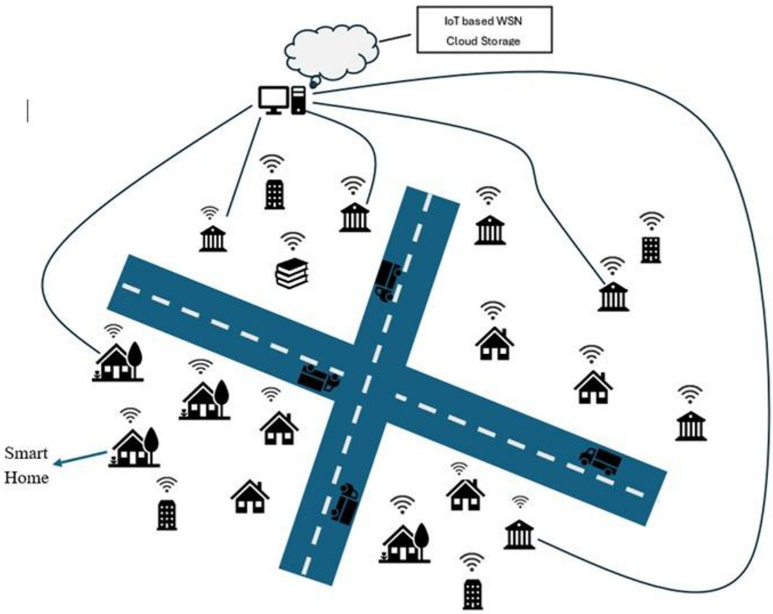

Fig. 8 Emerging Applications of Wireless Sensor Networks

9 Future Research Directions

In the case of Wireless Sensor Networks (WSNs), future works/lines in research will likely follow these modern technological lines. For example, one of the key aspects is targeted decision-making via AI-orientated routing protocols where we can use ML/AI mechanisms to make the correct options concerning routes or forecasts about network situations, a designed artifice to improve energy efficiency. Another important avenue is the design and optimization of IoT system hardware / software platforms that support clicking via sensor nodes, gateways, and cloud services. Another fundamental research challenge is the establishment of secure communication mechanisms; many WSNs are deployed in open and susceptible environments, necessitating that data integrity, confidentiality and authentication be guaranteed. WSNs will also start supporting large-scale smart applications with deep integration of Internet of Things (IoT) platforms, including smart cities, healthcare monitoring, and industrial automation. Moreover, future networks would be anticipated to last without human intervention and configuration of sensor nodes such that nodes can organise themselves and manage and recover from failures autonomously [16]. In addition, AI-enabled WSN paradigms are emerging as a critical enabler for next-generation WSN systems that power applications in the areas of predictive maintenance, intelligent sensing, adaptive resource management and real-time analytics over varying use scenarios. Some research directions listed in this form indicate that WSN, IoT and AI techniques are converging toward designing a range of smart or autonomous sensing systems.

10 Conclusion

Wireless Sensor Networks (WSNs) are a widely used technology for data collection and monitoring. The major design challenges, routing protocols & potential new applications in WSNs are summarised in this survey. A survey of the routing protocols is conducted and categorized as hierarchical, data-centric, and location-based. They have proposed energy-saving algorithms to develop a technique more on efficient clustering protocols and avoid consumption of power to help in increasing network lifetime. Advanced AI and ML algorithms also offer promising opportunities to improve routing performance and increase network abilities. Then, WSN is interested in deploying smart monitoring applications by providing secure and eco-friendly communications with intelligence at all levels for improved protocols such as routing.

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