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Analysing Clustering process and Cluster Head Selection Criteria in Wireless Sensor Networks

S. Syed Noor [1*], Prof. Geethanjali Nellore [2],

[1] Research Scholar, [2] Professor,

[1,2]Dept. of Computer Science & Technology, Sri Krishnadevaraya University, Anantapur, India

Abstract:

Wireless Sensor Networks (WSNs) serve as intricate systems that integrate hardware, networking, and application domains, revolutionizing various fields with their pervasive nature. Within this context, this review aims to delve into the multifaceted components and challenges within the realm of WSNs, providing a comprehensive exploration. The focal points include examining the intricate communication protocols that form the backbone of WSNs and elucidating the myriad applications across domains such as healthcare, environmental monitoring, and industrial IoT. This exploration also encompasses a critical analysis of the challenges faced in WSNs, touching upon energy efficiency, security concerns, scalability issues, and data processing intricacies. Furthermore, this review navigates through the factors that significantly influence the design of sensor networks, internal system considerations crucial for WSN operation, and indispensable network services. A clustering technique is one of the most effective methods for saving energy and extending the lifespan of a network. The nodes of homogeneous WSNs typically possess similar resources, while nodes of heterogeneous WSNs tend to have varying energy levels, making clustering effective as a method to extend the lifetime of the network by selecting the cluster head node based on the energy level of each node. It emphasizes the pivotal role WSNs play across various applications and domains, highlighting their potential in shaping future technological advancements. In essence, this review seeks to offer a comprehensive overview of the complexities and opportunities inherent in WSNs, providing a solid foundation for understanding their significance and the evolving landscape of this dynamic field.

Keywords: Wireless Sensor Networks, Communication Protocols, Network Layers, Energy Efficiency, Security, Scalability, clustering, and cluster head selection.

1. Introduction

Wireless Sensor Networks (WSNs) represent a revolutionary paradigm in the domain of interconnected devices, fostering a pervasive and interconnected world. These networks, comprising spatially distributed autonomous sensors, facilitate data collection, processing, and transmission across various applications and industries. The convergence of miniaturization, wireless communication, and sensor technology has propelled the evolution of WSNs, reshaping how we perceive and interact with our surroundings [1].

WSNs serve as a cornerstone in enabling the realization of the Internet of Things (IoT) ecosystem, transcending traditional boundaries, and empowering seamless connectivity among diverse entities. Their deployment spans across a myriad of domains, from environmental monitoring and healthcare to industrial automation and smart infrastructure. This breadth of applications underscores the versatility and transformative potential of WSNs in redefining operational paradigms.

The genesis of WSNs can be traced back to seminal research endeavours aimed at creating self-organizing, adaptable, and resource-efficient networks. From the inception of early sensor nodes to the contemporary sophisticated architectures, the trajectory of WSNs has witnessed exponential growth, driven by technological advancements and interdisciplinary collaborations.

This comprehensive survey endeavours to encapsulate the multifaceted landscape of WSNs, delving into their architecture, communication protocols, applications, challenges, and future trajectories. By synthesizing existing knowledge and contemporary advancements, this review aims to provide a holistic perspective, guiding researchers, practitioners, and enthusiasts in understanding the intricacies and potentials of WSNs.[2]

The subsequent sections of this review will navigate through the foundational aspects of WSNs, elucidating their architectural frameworks, communication protocols, clustering, cluster head selection criteria, diverse applications across industries, the challenges impeding their widespread adoption, and envisaged future trends design issues, and Network services**.** Each section will delve into specific facets, shedding light on the nuances and complexities inherent in the realm of Wireless Sensor Networks.

2. Architecture of WSNs

Wireless Sensor Networks comprise a sophisticated architecture that integrates sensor nodes, network topologies, and energy management mechanisms, orchestrating a cohesive framework for data acquisition and transmission [3,4,5]

2.1 Sensor Nodes

Wireless Sensor Networks (WSNs) are intricately composed of sensor nodes, the fundamental building blocks responsible for sensing, processing, and communicating data within the network.

Components and Functionalities

2.1.1 Sensing Capabilities: Sensor nodes integrate various types of sensors tailored to specific applications, encompassing a wide spectrum of functionalities:

- **Environmental Sensors**: Measure parameters like temperature, humidity, light intensity, and pollution levels.
- **Biomedical Sensors**: Monitor vital signs, glucose levels, and other health-related metrics in healthcare applications.

2.1.2 Motion and Position Sensors: Detect movement, orientation, and location changes for tracking or surveillance purposes

- **Chemical and Gas Sensors**: Identify gas concentrations, aiding in environmental monitoring or industrial safety.

2.1.3 Processing and Computation: Microcontrollers embedded within sensor nodes facilitate local data processing, aggregation, and decision-making. Despite computational constraints, these nodes execute algorithms for data fusion, noise reduction, and event detection, optimizing data before transmission to conserve energy.

2.1.4 Communication Modules: Transceivers enable wireless communication among sensor nodes and with the base station or other nodes in the network. These modules adhere to various communication protocols, facilitating data exchange and collaboration within the network.

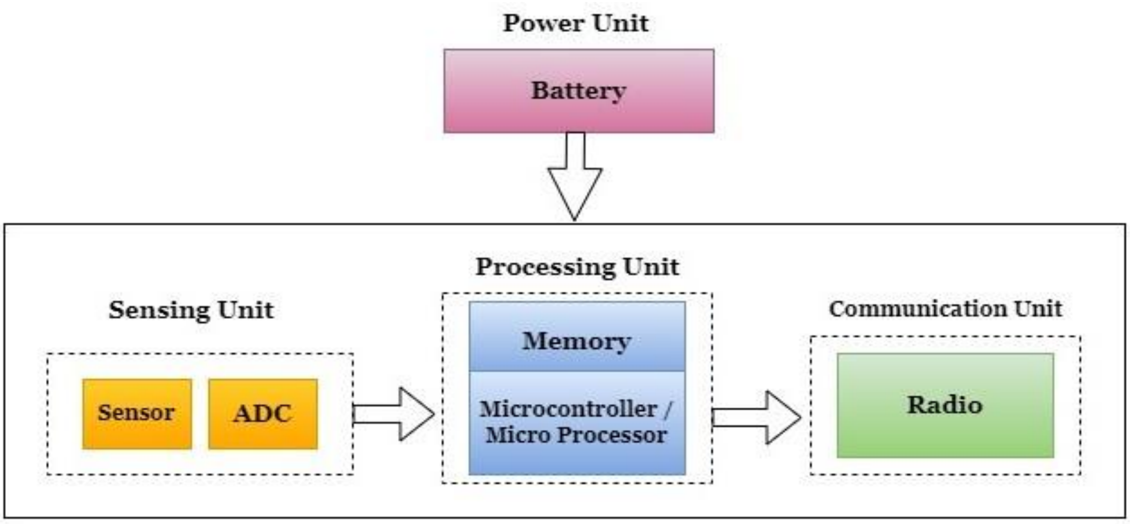

Figure 1. Architecture of a sensor node

2.2Types of Sensor Nodes

2.2.1 Sensing Nodes: Primarily dedicated to data acquisition, sensing nodes specialize in interfacing with specific sensors to collect environmental or contextual information. They form the backbone of WSNs by gathering raw data from the environment.

2.2.2 Processing Nodes: Equipped with enhanced computational capabilities, processing nodes analyze and pre-process data received from sensing nodes. They execute algorithms to filter redundant information, perform data fusion, and extract meaningful insights before dissemination.

2.2.3 Communication Nodes: Tasked with managing communication within the network, these nodes ensure the seamless exchange of data. They relay information between sensor nodes and the central base station or other nodes, optimizing routing and ensuring reliable transmission.

2.2.4 Challenges and Innovations in Sensor Nodes

2.2.4.1 Resource Constraints: Sensor nodes grapple with limited resources, including energy, memory, and processing capacity. Innovations in ultra-low-power design, efficient algorithms, and hardware miniaturization strive to mitigate these constraints.

2.2.4.2 Self-Configuration and Adaptability: Enhancing sensor nodes' autonomy to self-configure, adapt to dynamic environments, and collaborate intelligently remains a focal area of research, aiming for robustness and resilience. Sensor nodes serve as the bedrock of Wireless Sensor Networks, embodying diverse functionalities that harmonize sensing, processing, and communication. Their evolution and innovations drive the efficacy and applicability of WSNs across an extensive array of domains.

2.2.4.3 Sensor Network Communication Architecture: The communication architecture and layers within Wireless Sensor Networks (WSNs) are quite comprehensive. It covers the various layers and their functionalities, providing a thorough understanding of how these components collaborate to enable efficient communication and data transfer within the network.

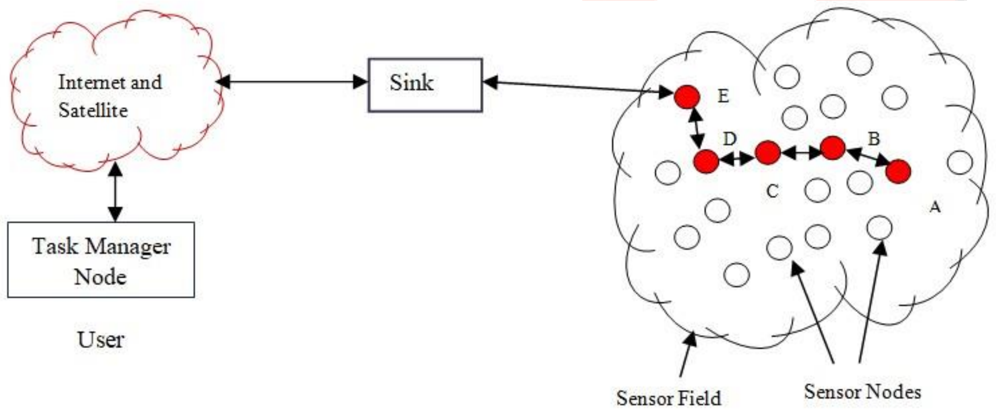

Figure 2: The Schematic Representation of the Communication Architecture of WSNs

2.3 Types of Wireless Sensor Networks (WSNs)

Here are different types of wireless sensor networks

2.3.1Terrestrial WSNs – Terrestrial WSNs can communicate with the base station directly. There are thousands of wireless sensor nodes in this network placed either in an unstructured or structured manner.
2.3.2 Underground WSNs – These WSNs monitor underground physical conditions and are deployed on the ground. When compared with terrestrial WSNs, these are more expensive.

2.3.3 Underwater WSNs – These WSNs are deployed under the water having several sensor nodes to collect underwater data.

2.3.4 Multimedia WSNs – Multimedia WSNs are designed to track and monitor multimedia events like images, audio, and video.

2.3.5Mobile WSNs – Mobile WSNs can move on their own and provide better coverage, energy efficiency, and channel capacity

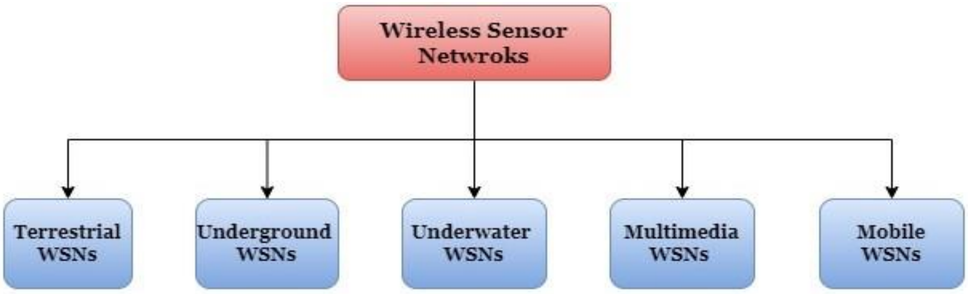

Figure .3 Types of wireless sensor networks

2.4 Communication Protocols in WSNs

Wireless Sensor Networks (WSNs) utilize various communication protocols to enable efficient data exchange among sensor nodes. Several protocols serve different purposes, catering to diverse applications and environmental conditions [26].

2.4.1 Zigbee:

- Designed for low-power, short-range communication.
- Operates on the IEEE 802.15.4 standard.
- Suitable for home automation, industrial control, and healthcare applications.

2.4.2 Bluetooth:

- Enables short-range wireless communication between devices.
- Utilized personal area networks (PANs) for connecting devices like smartphones, wearables, and IoT devices.

2.4.3 LoRa (Long Range):

- Focuses on long-range communication with low power consumption.
- Enables wide-area IoT applications, especially in remote or rural settings.

2.4.4 LoWPAN (IPv6 over Low-Power Wireless Personal Area Networks):

- Optimizes IPv6 for low-power, low-bandwidth wireless networks.
- Allows seamless integration of WSNs with the internet, enabling IoT applications.

2.5 Routing Protocols and Characteristics

2.5.1 LEACH (Low Energy Adaptive Clustering Hierarchy):

- Hierarchical routing protocol that forms clusters to minimize energy consumption.
- Rotates cluster heads to distribute energy usage evenly.
- Suited for prolonging network lifetime in WSNs.

2.5.2 AODV (Ad-hoc On-demand Distance Vector):

- Reactive protocol that establishes routes only when needed.
- Utilizes route discovery and maintenance as nodes communicate.
- Suitable for dynamic networks with frequent topological changes.

2.5.3 DSR (Dynamic Source Routing):

- On-demand, source-initiated routing protocol.
- Maintains a route cache at nodes, reducing the need for route discovery.
- Ideal for networks with high mobility or changing topologies.

2.6 MAC Protocols and Energy Efficiency Impact

2.6.1 TDMA (Time Division Multiple Access):

- Divides time into slots, allowing nodes to transmit during specific time intervals.
- Ensures interference-free transmission but may lead to synchronization overhead.

2.6.2 CSMA/CA (Carrier Sense Multiple Access with Collision Avoidance):

- Listens to the medium and transmits when clear to avoid collisions.
- Reduces collisions but introduces overhead due to contention and backoff mechanisms.

2.6.3 ContikiMAC:

- Designed for low-power operation in WSNs.
- Utilizes duty cycling to switch between active and sleep states, conserving energy.

2.7 Clustering and Cluster Head Selection

Resource-constrained sensor networks, consisting of numerous low-cost nodes, work collaboratively to monitor a specific environment. To ensure network longevity, stability, and dependability, efficient resource management is crucial due to the limited processing power, battery life, and sensing capabilities of these nodes. Extensive research has been dedicated to developing strategies that extend the operational life of such networks.[6].

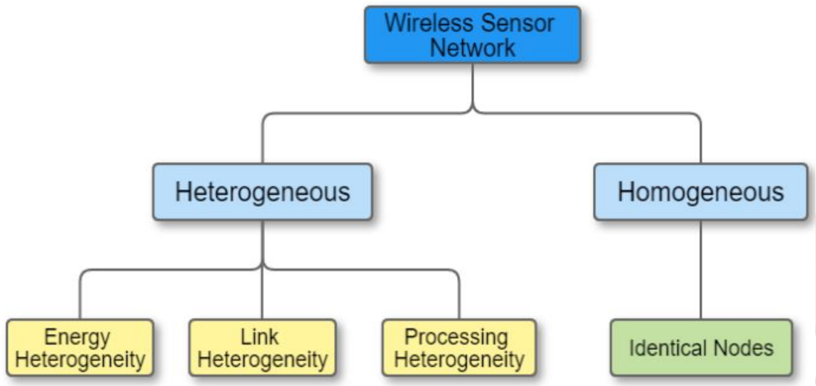

Figure .4 Types of Clustering in WSN

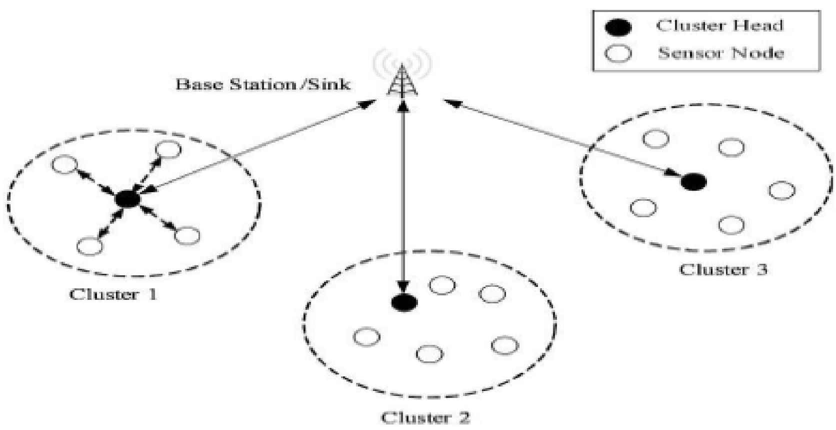

Figure 5. architecture of dividing clusters

Clustering, a cornerstone technique for extending network lifespan, involves grouping nodes into clusters led by designated "cluster heads." These leaders efficiently relay vital information to the central hub, minimizing the need for individual node transmissions, which significantly conserves energy. However, wireless sensor networks are inherently diverse (heterogeneous) compared to uniform (homogeneous) networks. Therefore, energy-efficient clustering methods specifically tailored for heterogeneous networks are crucial, as generic approaches designed for uniform networks are ineffective.

2.7.1 Clustering phases

Clustering in sensor networks involves two primary stages: node grouping and responsibility assignment. Common grouping methods include Voronoi diagrams, where the network space is divided into unequal-sized clusters, each with its own cluster head (CH) for communication with other clusters. Alternatively, non-Voronoi structures like chains and spectrums can be used. Chain structures involve nodes forming a linear sequence to reach the CH, while spectrum structures consider both distance and angle from the base station (BS) when grouping.

Different strategies and criteria are used to determine cluster formation. The figure illustrates various clustering architectures and their comparisons. Both spectrum and chain structures can benefit from layering, employing multi-hop data transmission within the cluster to improve resource efficiency. This approach, known as intra-cluster routing, breaks down long transmissions into shorter hops, reducing energy consumption. However, it can introduce trade-offs like increased delays due to the indirect connections. Similar to CH-to-BS communication, nodes within a cluster can connect directly or indirectly to their CH.

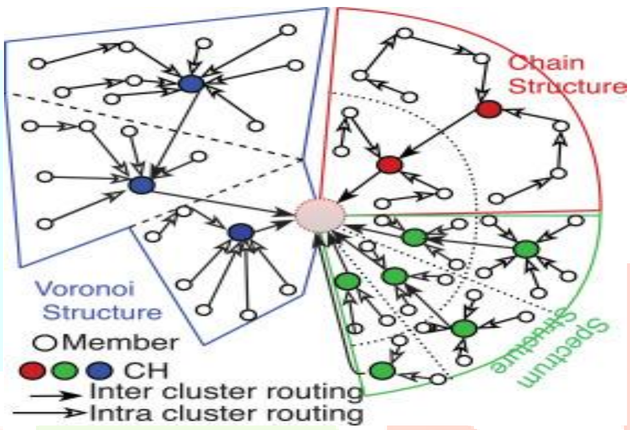

Figure 6. Architecture of Voronoi structure and non-voronoi (chain,spectrum)

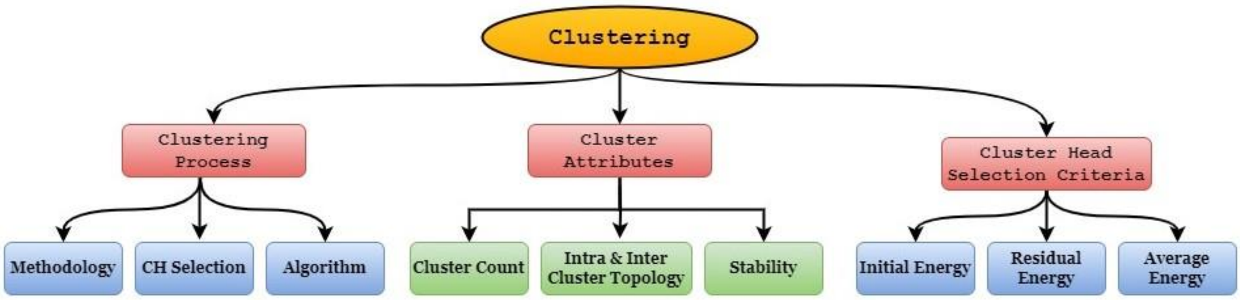

Figure 7. schematic representation of clustering process, clustering attributes, Cluster head selection criteria.

Initial energy :- It refers to the amount of energy while initializing a Sensor Node.
Residual energy:-It refers to the amount of energy left in a sensor node after it has completed its task. It is an important factor in maximizing the network lifetime and reducing energy consumption.

One of the other parameters used for the selection of CH(Cluster Head) is total residual/current energy of the sensor node. The total residual energy is the sum of harvested energy (generated from the external environment by Sensor Node) and residual/remaining energy of the Sensor Node.

$$E_{\text{Total-curr}(i)} = E_{res(i)} + E_{Harvest(i)} \quad (1)$$

where $E_{\text{Total-curr}(i)}$ is the total current energy of the node
$E_{res(i)}$ is the residual/remaining energy.

$E_{Harvest(i)}$ is the total harvested energy from the energy.

Average energy: -Average energy refers, the Total energy of the network divided by total number of nodes.

$E_{avg} = [(E_{total(i)}) / E_{(tot\_nodes)}]$ (2)

2.7.2 Performance measurement

Performance measurement for heterogeneity can be divided into four main categories:

- **Network lifetime:** It is the time when an operation starts until the time when the first node expires in the network.
- **No. of cluster heads in one round:** All the nodes that will send data directly to BS.
- **No. of alive nodes in one round:** All the nodes that still have some energy remaining and are not dead.
- **Throughput:** This is the rate of data transmitted over the network.

3.Applications of Wireless Sensor Networks (WSNs)

Wireless Sensor Networks find diverse applications across various domains due to their ability to collect, process, and transmit data wirelessly. Here are some prominent applications:

3.1 Environmental Monitoring

3.1.1 Agriculture:

- **Crop Monitoring:** Utilizes WSNs to monitor soil moisture, temperature, and humidity for optimized irrigation and crop health management.
- **Livestock Monitoring:** Tracks animal behaviour, health, and grazing patterns using sensor nodes for improved farming practices.

3.1.2 Pollution Detection: Monitors air and water quality using sensor networks to detect pollutants and mitigate environmental hazards.

3.2 Healthcare

3.2.1 Remote Patient Monitoring: Enables continuous monitoring of patients' vital signs, facilitating remote healthcare services and early detection of health issues.

3.2.2 Smart Health Systems: Implements WSNs in hospitals for inventory management, patient tracking, and real-time asset monitoring for efficient healthcare delivery.

3.3 Industrial IoT

3.3.1 Asset Tracking: Tracks and monitors assets, equipment, and inventory in industries using WSNs, optimizing logistics and supply chain management.

3.3.2 Predictive Maintenance: Utilizes sensor networks to monitor machinery health, predict failures, and schedule maintenance, reducing downtime and optimizing operations.

3.4 Smart Cities and Infrastructure Management

3.4.1 Traffic Management: Monitors traffic flow, parking, and congestion using sensor networks, optimizing traffic signal controls and enhancing commuter experiences.

3.4.2 Environmental Monitoring in Cities: Manages waste, noise levels, and energy consumption, contributing to sustainable urban development.

3.5 Military and Surveillance Applications

3.5.1 Border Surveillance: Utilizes WSNs for border security, detecting unauthorized intrusions and monitoring sensitive areas.

3.5.2 Battlefield Monitoring: Implements sensor networks for battlefield situational awareness, tracking troop movements, and monitoring equipment status.

4.Challenges in Wireless Sensor Networks (WSNs)

Wireless Sensor Networks face several challenges that impact their efficiency, reliability, and security, hindering their widespread adoption in various applications.

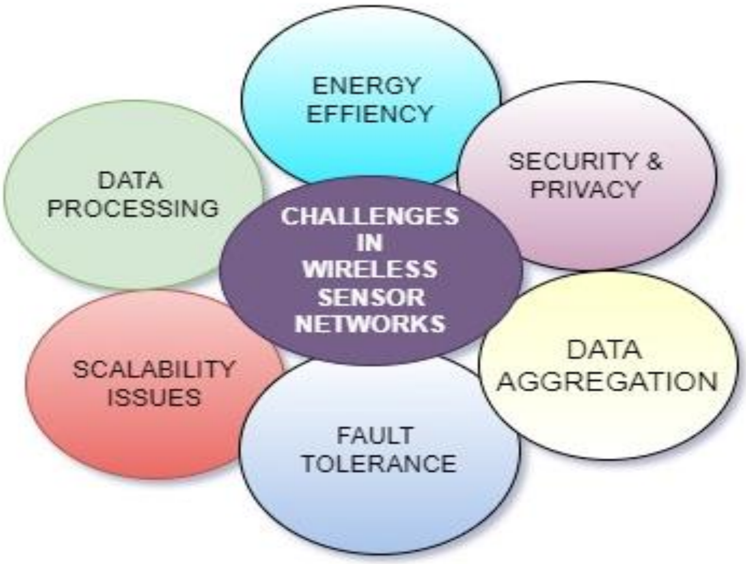

Figure 8. Challenges in WSN

4.1. Energy Efficiency and Battery Life Extension

- **Limited Energy Resources:** Sensor nodes often operate on limited battery power, requiring energy-efficient protocols and algorithms to prolong their lifespan.
- **Duty Cycling Optimization:** Balancing between active and sleep modes to conserve energy without compromising real-time data collection is challenging.
- **Harvesting Energy:** Exploring alternative energy sources (solar, kinetic, etc.) to replenish node energy and extend their operational lifespan.

4.2. Security and Privacy Concerns

- **Vulnerabilities:** Sensor nodes are susceptible to attacks due to their deployment in open and vulnerable environments.
- **Data Integrity:** Ensuring secure communication, authentication, and encryption to protect sensitive data from unauthorized access or tampering.
- **Privacy Preservation:** Managing the privacy of collected data while ensuring its usefulness in various applications.

4.3. Scalability Issues

- **Network Size and Density:** Scaling WSNs to accommodate a large number of nodes while maintaining efficient communication and data transmission.
- **Topology Management:** Handling network growth and changes while ensuring efficient routing and resource management.
- **Interoperability:** Ensuring compatibility and seamless integration of heterogeneous devices and protocols in large-scale deployments.

4.4. Fault Tolerance and Reliability

- **Node Failure Handling:** Developing robust mechanisms to handle node failures or malfunctions without disrupting overall network functionality.
- **Resilience to Environmental Factors:** Adapting to environmental changes or node mobility without compromising data accuracy or transmission.

4.5. Data Aggregation

- **Data Fusion and Aggregation:** Efficiently aggregating and processing vast amounts of sensor data to reduce redundancy and minimize communication overhead.

4.6 Data Processing

- **Real-Time Processing:** Processing data at the edge or within the network to extract meaningful insights while minimizing latency.

5. Future Trends and Research Directions:

The future of Wireless Sensor Networks (WSNs) is poised for exciting developments and advancements. Here are some anticipated trends and potential research directions:

5.1 Energy Harvesting and Efficiency

- **Energy Harvesting Techniques:** Further exploration and implementation of innovative energy-harvesting methods (solar, kinetic, RF, etc.) to supplement node power.
- **Ultra-low-power design:** Advancements in hardware and software technologies for ultra-low-power sensor nodes to extend operational lifespans.

5.2 AI and Machine Learning Integration

- **Data Analytics and Predictive Modelling:** Integration of AI and machine learning algorithms for real-time data analysis, predictive maintenance, and anomaly detection.
- **Edge Computing:** Leveraging edge computing capabilities to process data closer to the source, reducing latency and bandwidth requirements.

5.3 Security and Privacy Enhancements

- **Blockchain in WSNs:** Exploring blockchain technology for secure and immutable data storage, authentication, and decentralized security mechanisms.
- **Privacy-Preserving Protocols:** Designing protocols that ensure data privacy while maintaining usability and integrity.

5.4 IoT Integration and Interoperability

- **Integration with IoT Ecosystems:** Collaborating with broader IoT ecosystems, ensuring seamless integration and interoperability with diverse devices and platforms.
- **Standardization Efforts:** Advancements in standardization to promote compatibility and ease of integration among heterogeneous devices and protocols.

5.5 Cognitive WSNs and Self-Organization

- **Cognitive WSNs:** Development of self-learning, adaptive sensor networks capable of self-configuration, self-healing, and self-optimization.
- **Autonomous Deployment and Management:** Automation of deployment processes and network management to reduce human intervention.

5.6 Bio-inspired and Swarm Intelligence

- **Bio-inspired Algorithms:** Drawing inspiration from nature to design efficient algorithms, such as swarm intelligence for robust and self-organizing networks.
- **Nature-Inspired Topologies:** Exploring hierarchical and dynamic network topologies inspired by biological systems for improved scalability and fault tolerance.

5.7 Sustainable and Green WSNs

- **Environmental Sustainability:** Focus on eco-friendly designs and practices to reduce the environmental footprint of sensor nodes and networks.
- **Energy-Aware Protocols:** Continued research on energy-efficient protocols and resource management strategies for sustainable WSN operations.

The future of WSNs holds promise for revolutionary advancements, including enhanced energy efficiency, integration with AI and IoT, heightened security measures, and the evolution of self-adaptive networks. Research efforts will likely converge on addressing energy constraints, enhancing intelligence and security, fostering interoperability, and creating sustainable and resilient Wireless Sensor Networks for diverse applications [11,12].

Communication protocols, routing schemes, and MAC protocols underscore the importance of efficient data transmission, routing, and energy conservation in these networks. The applications across diverse sectors—environmental monitoring, healthcare, industry, smart cities, and defence—demonstrate the extensive real-world utility of WSNs.[13,14]

However, challenges like energy efficiency, security, scalability, and data processing intricacies pose hurdles. Yet, the ongoing research into future trends—integrating AI, machine learning, and edge computing—offers promising solutions and enhances the capabilities of WSNs.

Conclusion:

In conclusion, Wireless sensor networks are realistically more heterogeneous in nature than homogeneous. Heterogeneity in the network can improve its lifetime and reliability. Clustering is considered a useful method to enhance a network's efficiency in terms of stability and lifetime. This review presents a survey on energy-efficient clustering in heterogeneous wireless sensor networks and makes a tabulated comparison between them. WSNs represent a technological frontier that holds immense potential, albeit with significant challenges. Addressing these challenges while leveraging advancements in technology will unlock unprecedented opportunities, making WSNs pivotal in shaping the future of connectivity, data gathering, and decision-making in various domains.

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