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A Comprehensive Analysis of the Protocols of Wireless Sensor Network (WSN)

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ABSTRACT

The Wireless Sensor Network (WSN) has been widely used in other technologies like the Internet of Things, artificial intelligence, etc. since it is dependable. There have been several uses that are related. The WSN is becoming more dependable and well-liked as one of the apps on the network. WSN is regarded as the most important technology of the twenty-first century and is essential to connecting the rational information world with the existing physical world. Numerous sensor nodes in a Wireless Sensor Network (WSN) have limited power, storage, and processing ability. The performance of these systems can be enhanced by employing clustering. In Wireless Sensor Networks (WSN), the clustering methods concentrated mainly on power consumption, which may cause increased overhead. More energy is consumed when the cluster head periodically sends the data, leading to cluster head re-election. Due to the nonuniform node distribution, the energy consumption among nodes is more imbalanced in cluster-based WSNs. The key challenge in WSN is to schedule the node activities for data transmission by maintaining energy consumption. This article explains the context of WSN and its recent research work, where the recent issue is identified and discussed.

Introduction

WSNs are wireless networks as they consist of many tiny, power-restricted, cheap and independent nodes dispersed over a region for the applications like examining environmental issues such as temperature and humidity. Because of the fast development of wireless technologies, WSNs have become the ideal option for transferring data within several dissimilar domains. WSNs examine physical or environmental conditions at dissimilar places. WSNs have engrossed scientists due to their diverse functions and exceptional confrontations [1].

A WSN is a network formed by numerous nodes interconnected with one another. Initially, these nodes are deployed within a network range and utilized for monitoring or tracking events or targets. These sensor nodes are very effectively used in the environmental domain to sense the data by performing simple computations [2]. Those collected data are transmitted to the sink node known as Base Station (BS). The internet connects the other nodes with sink nodes through the gateway nodes.

WSN applications are divided into two groups such as monitoring applications and tracking applications. In monitoring applications, the sensor nodes continuously watch the environment and regularly provide information about it to the sink or when a specified event occurs. When a sensor node's measurement exceeds a predetermined threshold value, the event is generated either as a response to the user's query or by the sensor node itself. The information regarding the measurements is updated in real-time tracking programs. WSN is widely used in health monitoring, environmental monitoring, military surveillance, habitat monitoring, and structural monitoring. The popular tracking applications are vehicle tracking, human tracking, enemy tracking in the military, and animal tracking.

One of the imperative tasks of WSNs consists of gathering and transmitting the required information by the dissimilar applications having uneven needs on the consistency and data deliverance at the sink node. These tasks are operated on several different platforms. Many routing protocols exist, but MSEEC protocol, which is called Multi – level Stable and Energy Efficient Clustering protocol having the most commanding super nodes, is allocated to cover the reserved sensing areas. Every node acts differently in sensing, aggregation or transmission to the sink.

The location of nodes is static in the field with a different group of energy values. The System is separated into clusters; every cluster has powerful super nodes, advanced nodes and normal nodes. The positioning of a BS is fixed. In M-SEEC, MAN is the proportion of the entire number of nodes prepared with α times extra energy than that of normal nodes (NN), called an advance node(AN). MSN is the portion of the entire number of nodes equipped with β times extra energy than the normal nodes (NN), termed super nodes(SN). An effectual technology that considerably improves the data transmission rate over the wireless network has become a research focus. The clustering is made proficient by choosing the Cluster Head (CH) encircled by a more prominent number of nodes alongside the energy. It decreases the energy utilization of nodes and adds scalability to the System [3].

WSNs are made up of cheap, densely-deployed multifunctional sensors with low energy consumption and communicate with each other to gather information for taking spatial and temporal measurements of parameters such as temperature, sound, and many others. WSN used many applications with environment and surroundings surveillance, manufacturing process control, congestion control, machine health monitoring, health checking applications, and home automation. In a sensor system, sensors are arbitrarily set up over an area without a pre-installed infrastructure. All sensors can examine the surroundings, gathering and routing data back to the sink. As sensors in a WSN are mostly battery-operated and have inadequate ability, energy utilization turns out to be a main concern because the network needs to work for a projected period functionally.

Naturally, most of the energy consumption of sensors is on two main tasks: recognizing and assembling data in the area and uploading information to the base station. Energy utilization on gathering is moderately constant since it only depends on the sampling speed. Nevertheless, the state of power use on information uploading is quite more complex than that of sensing. Information uploading consumes a major quantity of power in sensors for wireless communications, and energy usage is generally non-homogeneous between sensors.

Moreover, energy utilization is also dependent on the type of network topology, the position of the data sink, and the swarm intelligence technique used. Consequently, the sensors' battery near sink nodes depletes faster than others, as these sensors need to transmit a greater number of data packets [4]. Thus, energy consumption during data gathering is a significant and difficult issue in WSNs as it mainly finds out the network life span. Owing to remarkable practical significance, in previous centuries, much research has been dedicated to proficient data collection in WSNs along with ample innovative schemes.

This research aims to minimize power utilization and enhance the network life span via routing and energy consumption to implement an effective and scalable network. The main target is to make the best cluster formation and data transmission to solve the optimization dilemma. Finally, this research aims to look for a hybrid routing technique to help make a better and more proficient network for WSNs [5].

Clustering in WSN for Energy Consumption

Energy conservation is one of the most critical design challenges in Wireless Sensor Networks (WSNs), as sensor nodes are typically powered by non-rechargeable, limited-capacity batteries. Due to the high energy cost of wireless communication, it is imperative to reduce the frequency and distance of data transmissions to maximize the network's operational lifetime. Clustering has emerged as a predominant technique to achieve energy efficiency by organizing sensor nodes into manageable groups, thereby minimizing redundant communication and distributing the energy load among nodes.

In a clustered architecture, the network is divided into several clusters, each managed by a Cluster Head (CH). The CH performs energy-intensive tasks such as data aggregation, compression, and communication with the base station or sink. By aggregating data from member nodes and transmitting only the processed information, CHs reduce the volume of communication significantly, thereby saving energy across the network. This model shifts the high energy burden to a smaller subset of nodes (CHs), which can be managed through periodic CH rotation or energy-aware CH selection to avoid premature node depletion.

Clustering significantly impacts three major components of WSN energy consumption: intra-cluster communication, inter-cluster communication, and data aggregation overhead. Intra-cluster communication refers to the short-range data transmission from sensor nodes to their respective CHs, while inter-cluster communication involves long-range communication from CHs to the sink. By optimizing both, clustering enhances energy efficiency. Additionally, clustering allows the application of localized protocols within clusters, leading to reduced contention and improved spatial reuse of bandwidth.

Various clustering algorithms have been proposed with the objective of minimizing energy consumption. LEACH (Low-Energy Adaptive Clustering Hierarchy) is one of the earliest and most well-known protocols that uses randomized rotation of CHs to balance energy usage. HEED (Hybrid Energy-Efficient Distributed clustering) incorporates residual energy and communication cost into the CH selection metric. TEEN (Threshold-sensitive Energy Efficient sensor Network) introduces reactive communication, allowing nodes to transmit data only when thresholds are crossed, thereby conserving energy during periods of low activity.

Recent advancements leverage bio-inspired metaheuristics such as Particle Swarm Optimization (PSO), Genetic Algorithms (GA), and Ant Colony Optimization (ACO) to dynamically form optimal clusters and select CHs based on multi-objective criteria such as energy, load balancing, coverage, and distance to sink. These approaches offer superior energy efficiency over static clustering schemes, especially in large-scale or heterogeneous environments. However, they may introduce additional computational complexity and require synchronization.

Furthermore, mobile sink-based clustering and multi-hop clustering architectures have been introduced to reduce the energy burden on distant CHs. In such models, mobile sinks periodically visit CHs, minimizing the need for long-range transmissions. Similarly, multi-hop communication between CHs reduces direct sink communication cost, especially in sparse or large-scale networks.

The clustering remains an essential energy-saving mechanism in WSNs, enabling scalable, fault-tolerant, and energy-aware network operation. Future developments are expected to focus on adaptive clustering protocols that integrate energy harvesting capabilities, cross-layer optimization, and real-time QoS-aware clustering to meet the demands of next-generation IoT-enabled WSNs [6-8].

Table 1. Clustering Techniques in WSNs for Energy Consumption

Protocol / Method	Clustering Type	CH Selection Criteria	Energy Efficiency Mechanism	Key Advantages
LEACH	Probabilistic, Distributed	Randomized rotation of CHs	Reduces long-range transmissions, CHs rotated periodically	Simple, low overhead
HEED	Hybrid, Distributed	Residual energy, communication cost	Balanced energy distribution, localized cluster formation	Prolonged network lifetime
TEEN	Hierarchical, Reactive	Hard and soft thresholds	Event-triggered communication, avoids frequent transmissions	Energy-efficient in reactive scenarios
SEP	Heterogeneous, Probabilistic	Energy heterogeneity awareness	Assigns weighted probabilities for CH selection in 2-level heterogeneity	Adapted for heterogeneous environments
PSO-based Clustering	Metaheuristic	Multi-objective: energy, distance, coverage	Global optimization for CH selection and cluster formation	High energy efficiency, adaptability
ACO-based Clustering	Metaheuristic	Pheromone trail and heuristic desirability	Optimal routing paths and cluster formation via ant-based optimization	Scalable, robust to dynamic topology
GA-based Clustering	Metaheuristic	Fitness function: energy, load, proximity	Evolutionary optimization of cluster structure	Improved energy balance

Mobile Sink Clustering	Mobility-assisted	Dynamic CH coordination with mobile sinks	Reduces energy for distant CHs, avoids hotspot problem	Suitable for sparse/dynamic networks
PEGASIS	Chain-based	Greedy chain formation	Nodes form chains and only one node transmits to sink	Minimal transmissions per round

Literature Review

Sanjeevi, P. et al. (2020)[9] Agriculture and farming are now part of a precision sensor network thanks to recent advancements in the Internet of Things (IoT). The Internet of Things (IoT) wide-area network, built on wireless sensor networks (WSNs) and cloud computing, can be useful for the agriculture and farming industry in a remote place. The authors of this research described a scalable wireless sensor network architecture for internet-of-things-based remote farming and agriculture monitoring and control. In precision agriculture and farming, managing water resources and using water efficiently (PAF) is crucial. Resources. Achieving proper water irrigation control can be done by combining WSN technology with IoT. IoT is utilized in agriculture to facilitate the productive communication of numerous wireless sensors and boost farmer output. Writers have looked at the WSN topology regarding throughput maximization, delay reduction, high signal-to-noise ratio (SNR), minimal mean square error, and expanded coverage area. The results of the studies have shown that the suggested methodology performs better than more conventional IoT-based farming and agriculture. The farming system and IoT-based precision agriculture can both attest to their great value. For farmers because both much and insufficient irrigation is beneficial to agriculture. Based on the state of the agricultural field, the parameter values of sensor conditions such as temperature, humidity, and wetness might be fixed. The solution under discussion will create an efficient use of resources and address the issue of inadequate irrigation. The significance performance of WSN is better represented graphically than by prior technologies that could retrieve and display graphics.

Bhasin, Vandana et al. (2020)[10] An effective combination of sensing, processing, and communication are sensor networks. Small, affordable sensor nodes with limited processing power and radio ranges are used to build these networks. They direct themselves toward variousapplications while simultaneously running into severe energy limitations and a lack of memory resources. The hardware design of these nodes is also directly impacted by the sophisticated personalities of sensor networks. Numerous hardware platforms, including Crossbow, Intel, and Inmate, have been developed to investigate research-community theories and to put applications into practice across all branches of science and technology. Due to the sheer number of applications created in this field, security issues are of the utmost significance. This article surveys security architectures at the link layer and network layer, the two layers of the network stack.

Balaji, Subramanian et al., (2019)[11] A wide-area monitoring tool known as a wireless sensor network supports low-power tiny sensors used in scientific research. Memory, compute power, bandwidth, and energy are finite resources used by WSNs. The wireless sensor network's Cluster Routing protocol offers the highest levels of energy economy. Cluster Routing Protocols are employed to create the cluster (CH) when choosing a cluster head. Data packets are finally being sent from one CH to another and then forwarded, reaching the base station. During the setup stage, Chs is chosen. This System looked into a multichip transmission in which data packets are delivered between each hop. After then, the completed data packets are sent to the base station; transmitted. The cluster head moves the packets from the source sensor to the wireless sensor network base station. For fuzzy logic type 1, three factors are used, including the trust and distance factors. Fuzzy logic predicts the nodes that are close to the base station and have high trust. Type 1 fuzzy logic will select CH as the best forwarder. It will decrease network overhead while directly increasing the network lifetime.

Goyal, Nitin et al. (2019) [12] Although the oceans and rivers are still uncharted territories, experts have taken a particular interest in underwater surveillance because disasters and calamities frequently occur there. Underwater Wireless Sensor Networks (UWSN) are designed as an aquatic medium for various uses, including collecting oceanographic data, managing or preventing disasters, assisting with navigation, defending against attacks, and monitoring pollution. Like terrestrial Wireless Sensor Networks (WSN), Unmanned Wireless Sensor Networks (UWSN) comprise sensor nodes that gather data and transmit it to sinks. Water-based medium Mobile sensor nodes, lengthy propagation delays, constrained network capacity, and numerous message receptions are a few of these difficulties. This book presents a thorough overview of challenges relating to underwater sensor networks. The accessible test beds, routing protocols, experimental projects, simulation platforms, tools, and analyses are described by the authors. Oceans, seas, and other water bodies comprise around 96% of the world's water.

The development of networks or procedures to interpret data from a broad undersea environment has always been difficult for researchers. However, UWSN has been built with unique features to gather, transform, and store the massive amounts of data found underwater. UWSN has been a fascinating area of study in the struggle to perform like terrestrials in the challenging environment of aquatic medium. The UWSN functions differently from electromagnetic or radio waves utilized in land-based WSNs—acoustic waves, which have their restrictions. Several unresolved issues in UWSN need to be investigated, including creating energy-efficient routing methods, constrained battery depletion, and accessible bandwidth. These difficulties must be overcome for effective and dependable data conveyance in various applications, such as aided navigation, pollution monitoring, mine detection, offshore exploration, disaster management, and tactical surveillance. The authors in this work have provided the communication architecture of the UWSN to illustrate how the network functions. There is also a discussion of the current quality of service, energy efficiency, and fault tolerance challenges.

Table 2. Comprehensive Analysis

Ref. No.	Authors (Year)	Focus Area	Key Contributions	Inference	Drawbacks

[13]	Henriques et al. (2024)	ML in Residential Energy	Modeled Brazilian household energy consumption patterns using ML algorithms.	Demonstrates potential of supervised ML in forecasting consumption trends.	Not applicable to constrained WSN scenarios; lacks spatial/temporal node constraints.
[14]	Lehtonen et al. (2024)	Spatial Clustering of Energy Poverty	Mapped energy poverty clusters in rural Finland using geospatial analysis.	Highlights spatial clustering as a powerful tool for vulnerability detection.	Contextual focus on socio-economics; lacks technical algorithmic depth for WSNs.
[15]	Yadawad& Joshi (2024)	Fault-Tolerant Clustering in WSN	Developed energy-efficient clustering with fault-resilient routing protocol.	Provides a reliable and scalable WSN routing solution with energy awareness.	Algorithm complexity increases in high-mobility or high-density scenarios.
[16]	Ullah et al. (2024)	Hybrid Clustering in WSNs	Proposed hybrid strategy combining static clustering and dynamic routing.	Achieves a balance between energy saving and extended network lifetime.	Performance degrades in high data-rate conditions; lacks adaptive sink mechanisms.
[17]	Tao et al. (2024)	Macro-level Energy Clustering	Studied labor-capital clustering effects on energy intensity and carbon output.	Offers insight into macroeconomic clustering models applicable to smart grid systems.	Does not address micro-level constraints or node-level energy metrics.
[18]	Wilkins et al. (2024)	LLM Inference Optimization	Introduced hybrid heterogeneous cluster model for LLM inference energy reduction.	Demonstrates clustering benefits in cloud/AI energy optimization contexts.	High-resource setup; limited applicability in low-power sensor deployments.
[19]	Hisaharo et al. (2024)	Energy-Aware LLM Clustering	Optimized LLM inference clustering to reduce latency and power usage.	Shows relevance of clustering at inference level for computational energy efficiency.	Not tested under low-bandwidth or mobile ad hoc conditions common in WSNs.

[20]	Saadati et al. (2024)	GNN-based Clustering for WSNs	Applied Graph Neural Networks for energy-efficient clustering using coverage metrics.	Advances intelligent clustering with spatial awareness and performance gains.	GNN models require significant training data and computing overhead.
[21]	Meenakshi et al. (2024)	LEACH Variant for WSNs	Proposed Engroove-LEACH for enhanced energy-efficient communication.	Enhances classic LEACH with optimized routing, yielding better energy utilization.	Fixed threshold logic may not adapt well in highly dynamic topologies.

Energy Conservation as a Critical Issue

Energy is regarded as one of the most important challenges in WSN since sensor nodes' battery lives are constrained. Earlier approaches to this problem have been developed but have not proven effective. Clustering may be the most effective way to deal with this problem. Clusters have been formed from the network. Each cluster's leader is called the Cluster Head (CH). The CH is responsible for collecting data from nodes, combining it, and then sending it to the BS. Clustering significantly lowers the amount of energy used.

In the WSN, a sensor consumes more energy during the detection, processing, transmission or reception of data to fulfil the objective demanded by the application. The detection subsystem is dedicated to data acquisition. Reducing the data generated will save power from very limited sensors. The redundancy intrinsic to WSNs shall generate identical reports that the network is responsible for routing to the sink. Experimental outcomes validate that the communication subsystem is an avid cause of power dissipation [30]. As for the transmission, a large amount of power is also wasted in useless states from the application viewpoint, such as:

- Collision: when a node gets more packets at once, a collision occurs between the packets. Every packet leading to collision must be retransmitted and rejected.
- Overhearing: As soon as a source sends out a packet, every node within its communication range receives this packet even though they are not the desired destination. Therefore, energy is squandered when a node accepts the packets intended for other nodes.
- Control packet overhead: A minimum number of control packets must be utilized to activate the data communication.
- Interference: Each node positioned among the interference and communication interval receives a packet that cannot be decoded.

Since network lifespan has turned out to be the key feature to evaluate WSNs, ample methods focused on reducing power consumption and ameliorating network lifespan, energy efficiency techniques can be portioned into the following types, namely, topology control, efficient energy path.

- Topology control: Topology control minimizes power utilization by balancing the transmitting energy while maintaining a network connection. A novel reduced topology is formed based on local information.

- Energy efficient routing: Designing routing protocols must maximize the System's period by reducing the power used by avoiding nodes having low remaining energy and end-to-end transmission. Several protocols take advantage of node mobility or the nature of wireless communication transmission to diminish the power utilization at the sink node. However, some, on the other hand, use the nodes' geographical coordinates to make a path to the destination. At the same time,some other protocols create a hierarchy of nodes to minimize their overhead and simplify routing.

Conclusion

Examining the energy-efficient Wireless Sensor Networks (WSNs) protocols has brought to light the vital contribution these protocols make to the network's sustainability, node longevity, and resource efficiency. The study shed light on the possible contributions of various energy-efficient protocols to the area of WSNs by examining their processes, benefits, and drawbacks. The study revealed various strategies used by energy-efficient protocols, such as sleep scheduling, data aggregation, low-power listening, and optimized routing algorithms. The combined goal of these strategies is to reduce energy use during idle and talking times. Numerous adaptable and scalable energy-efficient protocols may suit changing application needs and dynamic network conditions.This versatility makes that WSNs can work well in a variety of situations without sacrificing energy economy. The study uncovered several issues and unexplored areas for WSN protocol development in energy efficiency. These include resolving security issues, reducing control message overhead, and looking for synergies between energy efficiency and data quality. They also involve protocol optimization for heterogeneous networks. The thorough research highlights the crucial role that energy-efficient protocols will play in determining the future direction of Wireless Sensor Networks. The results highlight how creative methodologies and energy-efficient design concepts work together to create WSN installations that are durable and sustainable.

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