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A Comprehensive Analsysis on Importance of Energy Efficiency in Wireless Sensor Networks

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Wireless Sensor Networks (WSNs) are increasingly important for environmental monitoring, innovative city development, healthcare, and industrial automation. Given the short battery life of sensor nodes, managing energy consumption becomes a critical issue in WSNs. Longevity, reduced energy waste, and continuous communication are all benefits of energy-efficient algorithms and protocols. This survey research analyzes a variety of energy-aware routing algorithms, clustering procedures, and data aggregation techniques aimed at improving energy efficiency in WSNs. Techniques discussed include efficient data fusion, hierarchical clustering, and energy-adaptive routing. Current innovations are also reviewed, including adaptive strategies for energy consumption balancing, machine learning, and optimization algorithms.
Keywords: Wireless Sensor Networks (WSNs), Energy efficiency, Data aggregation, Energy Harvesting.

1. Introduction

Wireless Sensor Networks (WSNs) have changed the game in terms of tracking and interacting with our environment. These networks consist of autonomous sensor nodes spread out over the network. That has completely changed the way technology is used today. Internet connectivity allows for the communication and data exchange of various electronic devices, such as cameras, medical equipment, and home appliances [1-4]. This means these devices have restrictions on processing speed, storage capacity, power, and bandwidth. Network heterogeneity is the consequence of having different kinds of sensor nodes spread out throughout the target regions. Heterogeneous sensor networks comprise hardware specifications and sensor components of varying capabilities [5-8].

Wireless Sensor Networks (WSNs) have altered how we monitor and interact with our environment by using a network of geographically scattered, independent sensor nodes. These nodes may sense, analyze, and send several physical or environmental characteristics, including motion, humidity, vibration, and temperature. Wide Area Networks (WANs) have widespread use in many domains where real-time data exchange and continuous monitoring are vital, including smart cities, healthcare, agriculture, industrial automation, and disaster management.

The limited energy supply of sensor nodes, often supplied by batteries, is a significant issue with WSNs. These nodes are sometimes situated in inconvenient or far-flung places, making it difficult, if not impossible, to recharge or replace their batteries, making energy efficiency an extremely pressing issue. Energy depletion may result in network partitioning, reduced communication reliability, and decreased data collection accuracy, deleting the network's overall performance [9-12]. Dealing with WSN energy restrictions has prompted many studies into energy-efficient algorithms, system architecture, and protocols. These include data aggregation systems that reduce redundant data transmission, clustering techniques that optimize communication within node groups, and energy-aware routing algorithms that utilize as little energy as possible while transmitting data. Furthermore, advances in machine learning and optimization methods have opened up new avenues for dynamic energy management in WSNs, resulting in more balanced energy utilization and longer network lifetime [13-15].

Hydraulic power plants, the automobile sector, thermal energy in greenhouses, forest monitoring, and many other current applications of WSNs are all part of today's civilization. The ability for WSNs to send raw data to the cloud for processing and storage has recently been enabled by developments in IoT technology [16–19]. This method drains the sensor nodes' power reserves and strains the network's capacity. This method will allow WSNs to have low latency, location awareness, and high bandwidth by minimizing power consumption by sensor nodes during transmission [20-25].

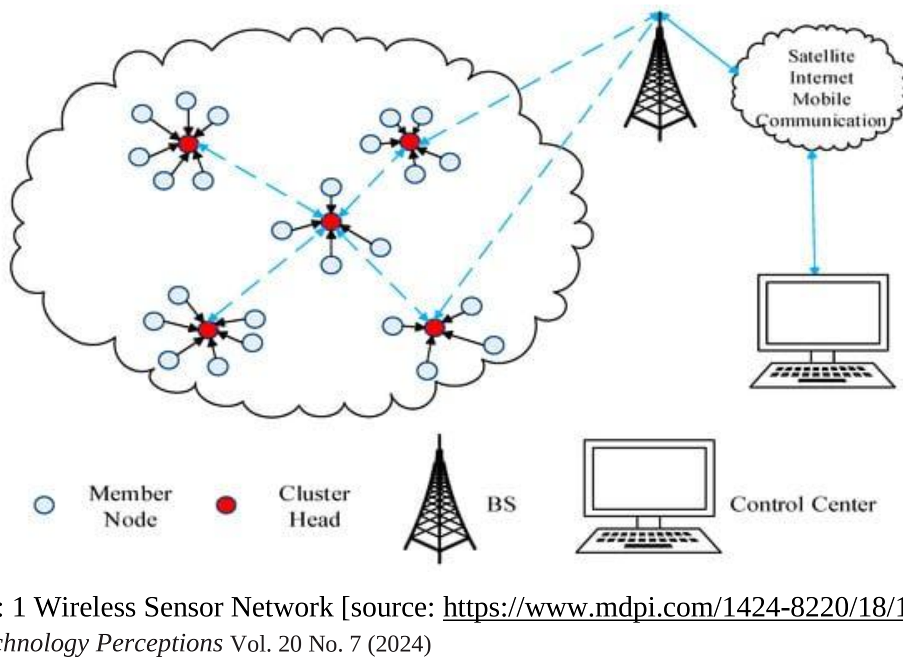


Figure: 1 Wireless Sensor Network [source: https://www.mdpi.com/1424-8220/18/11/3938]

This article comprehensively examines energy-efficient strategies in WSNs, focusing on routing protocols, clustering procedures, and data aggregation approaches.

Also covered are potential energy-collecting devices and future advancements in energy management that might keep WSNs running for a long time. By tackling the energy issues that come with WSNs, the program hopes to help build autonomous sensor networks that can last for a long time and handle current applications.

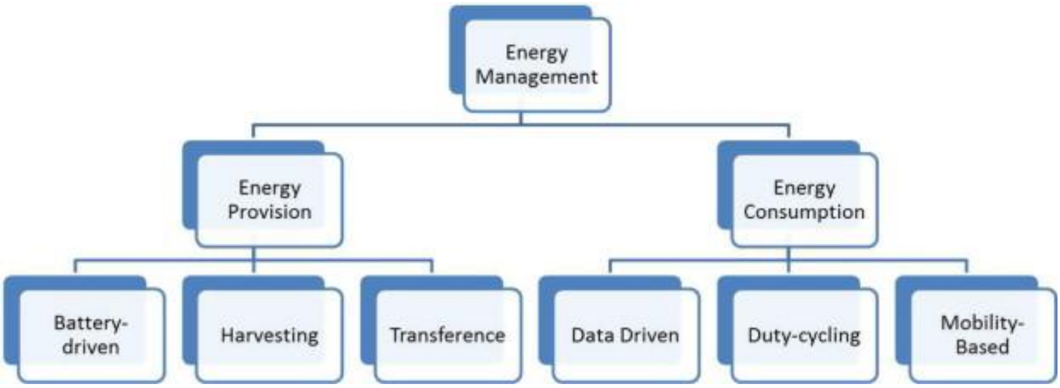


Figure: 2 WSN Energy Management

WSN's limited battery resources create an extra difficulty regarding energy efficiency. The typical definition of network lifespan is the time data goes from the sensing function to the network's sink. A single strategy for reducing energy use is to shorten the sensor range. Additionally, scheduling techniques are used to decrease network energy use. The various modulation approaches assist in shortening the distances between nodes. Cooperative communication approaches assist in increasing the signal quality in the radio module. This technique integrates a large number of single-antenna receivers into a multi-antenna transmitter to circumvent channel broadcasting, which causes given information to be overheard by neighbouring or closest nodes [26-29].

The transfer power control strategy makes radio power transfer more efficient. Relays, interference, connection quality, and connectivity can all be found using this approach.

Wireless charging technology challenges energy cooperation since it requires energy sharing between neighbouring nodes. In the future, nodes in WSNs can anticipate energy harvesting from their surroundings and transmit that energy to other nodes, making the networks self-sustaining [30-32].

2. Background Study

Abidoye, A. P., & Kabaso, B. (2021) Because WSNs are so popular and have such unique characteristics, experts have devised many ways to make sensor nodes operate better in them. One node must be designated as the Cluster Head (CH) in every network, regardless of protocol or size. It was up to the nodes to collect sensed data from all around, compile it, and then send it via multi-hop communication to a base station. Based on a complete graph, this method gives heuristics for route planning. The performance research of this technology demonstrates that it can increase the lifespan of WSNs and effectively distribute MDC. A technique known as Energy-dependent Cluster Formation in heterogeneous WSNs (EDCF) was proposed to improve the efficiency of CH selection and thereby lengthen the network lifetime.

Amutha, J. et al. (2020) WSN's limited battery resources create an extra difficulty in energy efficiency. The typical definition of a network's lifetime were the time it takes from the sensing function to data transmission to the sink. "Wireless Sensor Networks" (WSNs) describe interconnected sensor systems that can gather and analyze data. Wireless Sensor Networks (WSNs) have several potential applications, including healthcare, environmental, meteorological, and military surveillance. The demands of each application must be met. These components cause the sensor nodes' batteries to run out of power. Modulation optimization parameters are used to lower the energy consumption of radio modules.

Azarhava, H., & Musevi Niya, J. (2020) This paper has provided a unique system paradigm in which wireless sensors gather energy for data transmission using the harvest-then-transmit protocol. The sensors maintain TDMA communication with a hybrid access point during the remaining period. The numerical results show that, although throughput was lower than in other approaches, energy consumption will be substantially lower, resulting in improved energy efficiency as the network's performance reflects. For Data-To-Device (D2D) communications that harness energy, this system employs a Non-Orthogonal Multiple Access (NOMA) approach over a cellular network, all while keeping the signal-to-interference-and-noise ratio within the limits set by the cell users.

Bagwari, A. et al. (2023) have been through the process of reviewing the state-of-the-art energy optimization models created for industrial WSNs, such as EEO. More precise energy consumption was possible with the EEO model, which relies on machine learning techniques to predict node energy levels. Using predictive optimization techniques and dynamically changing resource allocation algorithms, the EEO may improve energy optimization in industrial WSNs. The experiments were conducted inside, making use of an actual IWSN deployment. It seems from the simulations that the suggested approach has a good chance of lowering the energy consumption of IWSNs.

Chenthil, R., & Jayarin, P. J. (2022) employed a different clustering algorithm for multi-hop routing in Underwater Wireless Sensor Networks (UWSNs). Nodes may adjust their energy usage with this technology and have excellent network performance. An EOCA node must interact with other nodes within its effective communication range for the clustering method to optimize energy consumption. The authors developed an optimization-based adaptive node clustering routing technique for smart UWSNs in the ocean—increased packet reception at the sink, better residual energy, and a longer lifespan for the network. The suggested protocol for an Energy-Balanced Unequal Layered Clustering (EULC) algorithm was developed with UWSNs in mind to reduce energy consumption in inter-cluster communications.

Debasis, K. et al. (2023) Wireless sensor networks can reduce their power consumption using the ILEACH protocol, which enhances clustering efficiency. The two algorithms were combined to improve the HPSO-ILEACH method of network clustering, reducing energy consumption and increasing network stability during data collection in WSNs. It was a well-known clustering method for WSNs that allows nodes to create clusters and select cluster heads, lowering energy consumption. This endeavour focuses on improving WSN energy efficiency and network endurance.

Dhillon, H. S. et al. (2023) are typically provided by an integrated kind of energy harvesting, a battery, and another source type. Energy harvesting converts ambient energy (that which exists in the surroundings) into electrical energy. This technique was carried out using batteries. I demonstrated a novel intelligent solar energy collection technique for powering IoT WSN sensor nodes. Among the sensor nodes are ARM-cortex-MO, Zig-Bee modules, and sensors. They have proposed extending the lifetime of WSN networks by intelligent agriculture monitoring that uses solar energy collection. This form were labour-intensive since its writers assemble and detail several energy-harvesting resources for use in agricultural wireless sensor networks.

Kalra, H. (2023), essentially, management and control in wireless communication are mutually independent, resulting in insufficient resource utilization, performance, and service guarantees. To increase data transmission efficiency while minimizing energy consumption, the system considers the remaining energy and the state of nearby sensors before sending the packet to the most suitable neighbour. The EERH were a novel approach to dynamic routing for heterogeneous WSNs, and it was introduced in this work. Furthermore, it can alter the EERH parameters to match the demands of the monitoring environment, such as the event occurrence ratio and event latency limitations.

Kocherla R. et al. (2023) noted that many authors aim to achieve low energy consumption in WSN by altering some aspects to increase node energy efficiency. More research was conducted on clustering head selection techniques and energy usage to achieve this purpose. The following clustering algorithms are tested in a wireless sensor network: Genetic Algorithm (GA), Aquila Optimizer (AO), COY, GA, COYA, HHO, and a traditional protocol called Low-Energy Adaptive Clustering Hierarchy (LEACH). The WSN was made up of sensor nodes that are connected wirelessly.

Needham, W. B., et al. (2023) Because of their versatility, WSNs have been the subject of much academic writing. Various network surveillance applications may benefit from the WSN, including animal identification and monitoring, environmental and health monitoring, military tracking, and more. There are a variety of approaches to transmitting sensed data to the base station; they include single-hop, multi-hop, tree-based, cluster-based, and chain-based transmission. Energy management was crucial for WSNs since the energy source cannot be refilled or replaced. While increasing the number of nodes increases energy consumption, the proposed system uses the optimal number of sensor nodes to decrease network energy consumption.

Table 2.1 Comparison of Wireless Network based on energy

Author(s)	Year	Methodology	Advantage	Limitation
Abidoye, A. P., & Kabaso, B.	2021	Heuristic tour-planning algorithm with Energy-Dependent Cluster Formation (EDCF)	Successfully dispatches MDC and extends WSN lifetime through efficient CH selection.	It may not scale well in extensive networks assuming static network topology.
Amutha, J., et al.	2020	Modulation optimization parameter for energy efficiency in WSN	Reduces energy consumption in radio modules and extends	Limited to specific application scenarios, it requires fine-tuning for

			network lifetime.	different environments.
Azarhava, H., & Musevi Niya, J.	2020	Harvest-then-transmit protocol with TDMA for energy harvesting WSNs	Significant reduction in energy consumption and better energy efficiency for network nodes.	There was a slight decrease in throughput, which requires compatible hardware for energy harvesting.
Bagwari, A., et al.	2023	Energy Efficient Optimization (EEO) using machine learning for industrial WSNs	It improved energy optimization through predictive and dynamic resource-allocation strategies.	Requires computational resources and advanced machine learning algorithms.
Chenthil, R., & Jayarin, P. J.	2022	Energy optimization clustering algorithm (EOCA) for UWSNs	A longer lifespan for the network, better packet delivery at the sink, and higher residual energy.	Complex optimization may increase the computational burden and overhead in the network.
Debasis, K., et al.	2023	Enhanced HPSO-ILEACH for clustering in WSN	Reduces energy consumption and boosts network stability during data collection.	It can require significant processing power for real-time clustering adjustments.
Dhillon, H. S., et al.	2023	Intelligent solar energy harvesting system for WSN in IoT	Extends network lifetime through sustainable energy harvesting from solar power.	Depending on environmental factors like sunlight availability, it was not universally applicable.
Kalra, H.	2023	Dynamic routing scheme (EERH) for heterogeneous WSNs	Improves energy efficiency for data transmission by adjusting routing parameters.	It can not handle high-frequency event occurrences effectively; delay constraints may not be met.
Kocherla, R., et al.	2023	Evaluation of clustering head selection algorithms (LEACH, GA, COY, AO, HHO)	Expands energy-saving of nodes through optimization algorithms for CH selection.	Some algorithms may have higher computational complexity or lower convergence rates.
Needham, W. B., et al.	2023	Finding the sweet spot for sensor node density in terms of power savings	Reduces total energy consumption in the network by optimizing node deployment.	Limited to networks with optimal node placement, it may not perform well in highly dynamic setups.

Prasad, V. K., & Periyasamy, S. (2023). Wireless sensor networks are essential for many scientific disciplines that study the physical or environmental processes taking place in the natural world. Due to the prevalence of non-rechargeable batteries used to power the nodes, energy was the greatest challenge. Incorporating WSN energy optimization tactics into the survey's clustering helps with overall network life extension, necessitating innovative energy optimization approaches.

Priyadarshi, R. (2024) wants the sensor network to function for as long as possible. In energy-constrained networks, optimum routing was not feasible. Inspired by this concept, it also gives a collection of helpful algorithms. Unlike the authors' spreading approaches, the DCE combining system decreases total energy, which aims to disperse traffic more equally.

S. S., & Nalband, A. H. (2023) To improve the energy efficiency of wireless sensor networks, a well-placed group of nodes was algorithmically assembled to form a cluster. The primary choice factors are service quality, load balance, and energy efficiency. Because of its unique characteristics, research on WSNs were rapidly growing among academics. WSN consists of numerous fully linked sensor nodes that are wirelessly coupled. Data were sent between Sensor Nodes (SNs) and Base Stations (BS) via a Cluster Head (CH) known as indirect access. Typically, a CH was chosen to ensure total connectivity and reliability of the given WSN via a minimum energy criterion specified using energy thresholds. The proposed strategy improves packet delivery rate by significantly increasing node energy efficiency compared to generic LEACH and other previous approaches.

Sah, D. K., et al. (2023). Minimalist and power-constrained sensor nodes characterize a wireless sensor network. Based on a solar energy collection system, this study focuses on various environmental monitoring applications. In this work, linear programming was first proposed. Regarding EH-ESNs, reaching Maximum Lifetime Coverage with an Energy Harvesting Node (MLCEH) was one of the most prominent challenges. To adaptively fix coverage gaps, the authors created a Two-Phase Lifetime-Enhancing Approach (TLM) using Multi-Objective Particle Swarm Optimization (MOPSO).

Shah, S. M. et al. (2023), among the several WSN strategies covered was energy-aware routing and the factors that impact. This information helps students improve their knowledge, evaluate the usefulness of existing algorithms, and construct algorithms more effectively. It also demonstrates algebraic and graphical modelling of these variables. More efficient packet routing to other NHNs may be possible with an NHN architecture that considers connection burstiness and distance between neighbouring NHNs.

Shaker Reddy, P. C., & Sucharitha, Y. (2023) Cross-Layer Collaborative Communication (CL-CC) was recommended to increase network efficiency. Constant monitoring allows each sensor node to conserve energy by producing states such as active and sleep. The algorithm enhances network longevity, conserves energy, and calculates the next forwarding time and sleep duration. They have introduced an Integer Linear Program (ILP) paradigm for extending network longevity. Several numerical examples support this concept; these discoveries have been combined with EEDS to give the best technique for concurrently developing routing and scheduling for WSN.

Shurman, M. et al. (2019) As a result, several studies have focused on Wireless Sensor Networks (WSNs). In a WSN system, data was efficiently collected and analyzed by a dispersed network of sensor nodes. Instead of introducing the idea of energy categorization, they offered an alternative. During setup, each node makes a timer that corresponds to its energy. The energy clustering approach was used to establish an additional process for identifying the number of cluster heads, building upon the grid-based clustering strategy that was previously mentioned. Based on an effective energy model, this research suggests a new way to extend the lifespan of the LEACH technique.

Tiwari, A. et al. (2019) Designing an efficient WSN design requires understanding the criteria applicable to sensor applications. An Heating, Ventilation, and Air Conditioning (HVAC) plant's wireless CBM sensor network implementation was detailed in this case study. With centralized data-gathering technologies, sensing has progressed from hand-read meters to dispersed Wireless Sensor Networks (WSN). A wireless sensor network may be established for machine Condition-Based Maintenance (CBM) in minor equipment conditions using sensors that are commercially accessible.

Vimalarani, C. et al. (2020), deploying sensor nodes to monitor the physical environment raises several research problems and network challenges, which WSNs aim to solve. To make WSNs more scalable, hierarchical routing methods are used for node organization. To further increase the longevity of sensor networks, they presented Energy Efficient Hierarchical Clustering (EEHC). To maximize energy use by minimizing routing overhead, the research suggests a paper adaptive multipath routing method.

Wu, W. et al. (2020). A WSN was a self-organizing network system that uses wireless communication between several inexpensive microsensor nodes to construct a multi-hop network. To increase the lifespan of WSNs, it was necessary to create energy-balanced and energy-efficient routing algorithms. By optimizing energy efficiency and achieving a balance in node energy consumption throughout the clustering and stabilization phase, the lifespan of the network were greatly extended. By rotating the cluster heads at regular intervals, LEACH may distribute the network's power consumption evenly across all nodes, extending the network's lifespan.

Table 2.2 Other Approaches for Wireless Sensor Networks based on energy.

Author(s)	Year	Methodology	Advantages	Limitations
Prasad & Periyasamy	2023	Survey on energy optimization protocols in WSNs through clustering techniques.	Clustering improves the network lifetime by optimizing energy consumption.	Focus on general protocols, lacking implementation details.
Priyadarshi	2024	DCE combining scheme for optimal routing in energy-constrained networks.	Reduces overall energy consumption and distributes traffic evenly for better efficiency.	Knowledge for routing, which may not be feasible in practical applications.
S. S. & Nalband	2023	Clustering head selection based on energy thresholds for WSNs.	Increases energy efficiency and packet delivery rate significantly compared to LEACH.	Performance depends on accurate energy threshold settings, which may vary by environment.
Sah et al.	2023	Two-phase lifetime-enhancing method (TLM) with solar energy harvesting.	Adaptive coverage and energy-efficient node recovery techniques extend the lifetime of energy-harvesting WSNs.	High reliance on environmental conditions for solar energy harvesting.
Shah et al.	2023	Energy-aware routing techniques in WSNs with NHN scheme.	Improves packet forwarding efficiency and energy consumption through optimized routing.	Complexity in implementing and balancing the burstiness of links with energy efficiency.
Shaker Reddy & Sucharitha	2023	Cross-layer collaborative communication (CL-CC) with ILP model.	Conserves Energy by scheduling sleep/active states and efficiently builds routing tables for a more extended network lifetime.	Implementation complexity in adjusting sleep/active states dynamically.
Shurman et al.	2019	LEACH-based protocol with energy classification and grid-based clustering.	Efficiently enhances network lifetime by adjusting the number of cluster heads and energy	Limited scalability in more extensive networks with dynamic traffic and node distribution.

			consumption classification.	
Tiwari et al.	2019	Wireless sensor network for Condition-Based Maintenance (CBM).	Improves monitoring efficiency in machinery with distributed wireless sensors.	Energy management strategies are not extensively discussed for longer operational periods.
Vimalarani et al.	2020	Energy Efficient Hierarchical Clustering (EEHC) with adaptive multipath routing.	Reduces routing overhead and improves energy utilization in large-scale deployments.	It increased computational complexity due to multipath routing and adaptive clustering decisions.
Wu et al.	2020	LEACH protocol with energy-balanced routing.	Changes cluster heads sometimes to balance network longevity with energy usage.	Potentially higher energy usage due to frequent cluster head re-selection in dynamic environments

3. Existing Methodology

3.1 LEACH (Low-Energy Adaptive Clustering Hierarchy)

Reduced power consumption in medical settings is now a reality thanks to LEACH, which stands for Low Energy Adaptive Clustering Hierarchy. Mo LEACH uses the leftover energy of each node individually instead of the network-wide residual energy used by the original LEACH to determine the next round's threshold. Many believe the LEACH protocol is a forerunner because of its reduced size and more durable network [9]. LEACH reduces overall energy consumption by randomly allocating the same amount of work to each network node. Clustering and assigning sensor nodes to one another is typical practice. As CH, the node collects data reports from her peers and relays them to the sink node. Using a random number between 0 and 1, the LEACH algorithm selects a CH as a node when its probability falls below a predetermined point but increases over a certain threshold. The remaining nodes choose the CH with the lowest power consumption to form a cluster. They are then able to become a part of the cluster. CH's task is to rotate all sensors so that no one sensor runs out of power.

All nodes in the network begin with the value zero and choose an integer between zero and one at random. The setup step of LEACH starts with node clustering. The remainder of the procedure is cycle-based. Data transmission to the sink node occurs in the subsequent steady-state phase. To cut down on needless overhead, the steady-state phase has to be much longer than the setup phase. When a node chooses to be a CH, it starts broadcasting an advertisement message during setup. With this notification, every node that isn't already part of a cluster can join. Every member node is responsible for transmitting data during the steady-state period. The CH gathers data from several cluster nodes and sends it to the selected sink. Due to LEACH's decentralized design, understanding the global network is unnecessary for the sink or the nodes to function [10].

- LEACH has both disadvantages and advantages, which are listed below.
- Since LEACH cluster heads are chosen randomly, there is no assurance that the right amount and distribution will be used.

- It is possible to find cluster leaders among nodes with low amounts of leftover energy and among those with high levels.

- Specific low-level nodes may die sooner. In light of the issues with conventional methods, this study suggests a new, enhanced.

LEACH for use in CH selection that is energy efficient. The standard LEACH can now generate random numbers with an additional Node Rank (NR) parameter. It can be calculated using base station distance, energy consumption rate, and node coverage. CHs with higher overall energy consumption and wider neighbour coverage circles are selected by combining the energy consumption rate with the node coverage parameter.

The LEACH protocol's sensor nodes form a local cluster at random, with one serving as a cluster leader. Both the stable and setup phases make up the LEACH. During setup, sensors may be randomly assigned a specified chance to serve as the leader of a local cluster. This might aid the network in achieving a more uniform distribution of energy dissipation. Cluster heads should make up no more than 5% of the total. When a cluster is selected, its leaders will begin advertising to the network's sensor nodes. Nodes choose their respective heads after getting the ads. Data is sent to the sink by steady-phase sensors via their cluster heads as soon as they detect something. There is just one tier of hierarchy in WSNs since all clustered routing techniques send data to the sink. Once the network reaches a specific steady-state duration, it starts a new cycle of choosing cluster heads by returning to the setup step.

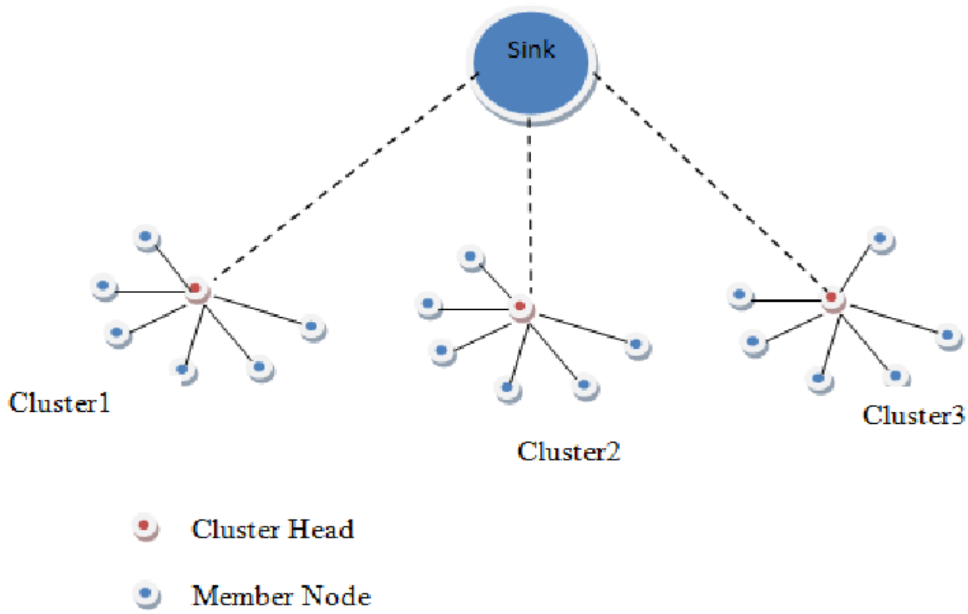


Figure: 3 The LEACH protocol for Wireless Sensor Network

To prevent wasteful energy use, the LEACH method has cluster members vote for a cluster leader [10]. Distributing the energy burden across network sensors is made easy using LEACH, an adaptive clustering method that leverages randomness. A single node known as the local BS or cluster head guides the LEACH nodes as they form themselves into regional clusters. The unfortunate sensors chosen to be cluster heads would perish quickly, reducing the usable lifespan of all nodes in such clusters if the cluster heads were fixed at the outset and maintained constant throughout the system's lifetime, as traditional clustering systems do.

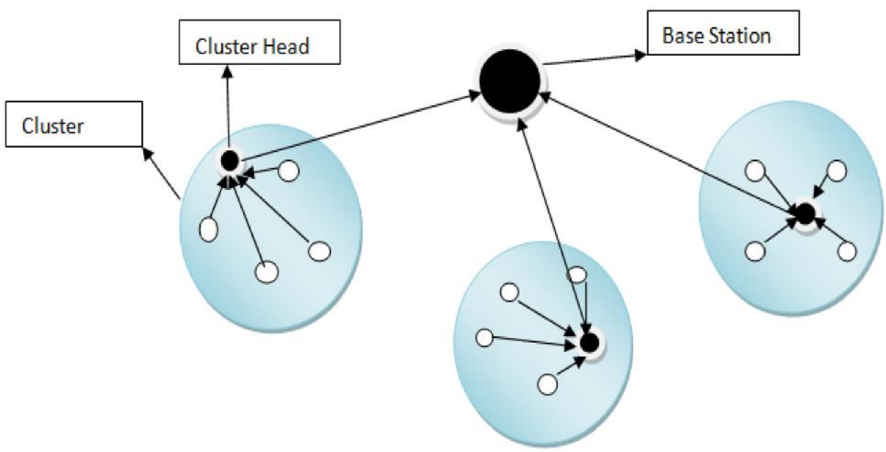
3.2 EEHC (Energy Efficient Hierarchical Clustering)

Energy Efficient Hierarchical Clustering (EEHC) is a popular technique used by Wireless Sensor Networks (WSNs) to reduce energy consumption and prolong the life of networks. Sensors in WSNs are often battery-powered and rely on energy conservation to keep the network operational for extended periods. EEHC achieves this by deploying a hierarchical clustering system that groups sensor nodes into clusters and assigns responsibilities for communication and coordination to each cluster head.

Extra inter-cluster traffic causes CHs closest to the base station to run out faster than those further away. Several methods are proposed in the literature for fixing energy imbalances and gaps in clustering in WSNs. These strategies include equal clustering, data aggregation and compression, and node and base station mobility. Building homogenous clusters is their top priority since it will reduce the distance between sensor nodes and CH, leading to energy savings.

An increasing number of cluster-based routing algorithm suggestions in the literature target WSNs, particularly to extend the overall lifetime of sensor networks. LEACH is the most popular hierarchical routing method for creating decentralized clusters, an acronym for low energy adaptive clustering hierarchy.

In the probabilistic clustering approach, each node is assigned a priori probability for selecting initial cluster heads, which also serves as a primary criterion for picking individual nodes as CHs. After meeting the essentials, any excess power might enhance the network's energy efficiency or extend its lifespan.



Features of EEHC:

- Cluster Heads (CHs) oversee communication within their cluster and provide aggregated data to the base station (sink) in hierarchical clustering.

- Since standard sensor nodes exchange data with their CH, they consume less power. This is because they refrain from having direct conversations with the sink.

- Rotating cluster heads regularly helps to prevent individual nodes from being depleted too quickly. CHs are chosen based on energy levels or other parameters, ensuring that nodes with greater energy are selected and balancing the energy load throughout the network.

- In large networks, CHs may communicate with the base station via multi-hop routing, in which intermediate CHs transfer data to the sink, lowering the energy required for long-distance transmissions.

- In-cluster aggregation, in which the CH combines data from member nodes before sending it to the sink, is one-way EEHC reduces data transfers. The hierarchical structure also helps to decrease energy consumption at the node level and distributes the load more evenly throughout the network.

Advantages:

- Energy Conservation: By limiting the number of transmissions that nodes must perform, a hierarchical clustering strategy allows them to save energy.

- Rotating CHs ensures that no one node is overburdened with communication tasks, which increases the overall network lifetime.

- Scalability: The approach is appropriate for many WSN applications because it can adapt to changing network sizes and is scalable.

3.3 CBM (Condition Based Maintenance)

Equipment Condition-Based Maintenance (CBM) has been considered a reasonably cost-effective strategy compared to preventative and corrective maintenance. Equipment operating conditions in CBM are regularly monitored to detect growing defects before they become severe sources of worry. Preventive maintenance, one of the most costly, can used instead of corrective maintenance since it provides an early warning of potential issues.

CBM may be facilitated via health monitoring systems that include a variety of hardware and software components. Some parts include activity and maintenance planning, data collecting and analysis, condition monitoring and fault detection, diagnostics of faults, prognostics, and activities.

Using preexisting gear, an existing networking architecture, and a medium access communication protocol, a wireless sensor network is constructed for equipment CBM. We can keep tabs on equipment in real-time and process vast volumes of data for control with a single-hop sensor network. An interface for LabVIEW is used to describe signal processing methods, such as kurtosis, multiple moments, and Fast Fourier Transform (FFT). A study of a heating and cooling facility's wireless CBM sensor network installation

Many sectors, including the media, transportation, commerce, healthcare, and emergency services, have begun adopting wireless sensors and WSNs due to their computational and financial feasibility.

This is due to the lack of other necessary components to recognize fault types and project the system RUL. Therefore, the software part, which contains the fundamental algorithms for diagnostic and prognostic duties, is essential for a complete CBM system.

Industrial systems need a comprehensive and applicable CBM system, in addition to the advancement of sensor technologies and stand-alone solutions. As a result, this paper provides a wireless CBM system for rotating machinery based on the mentioned components.

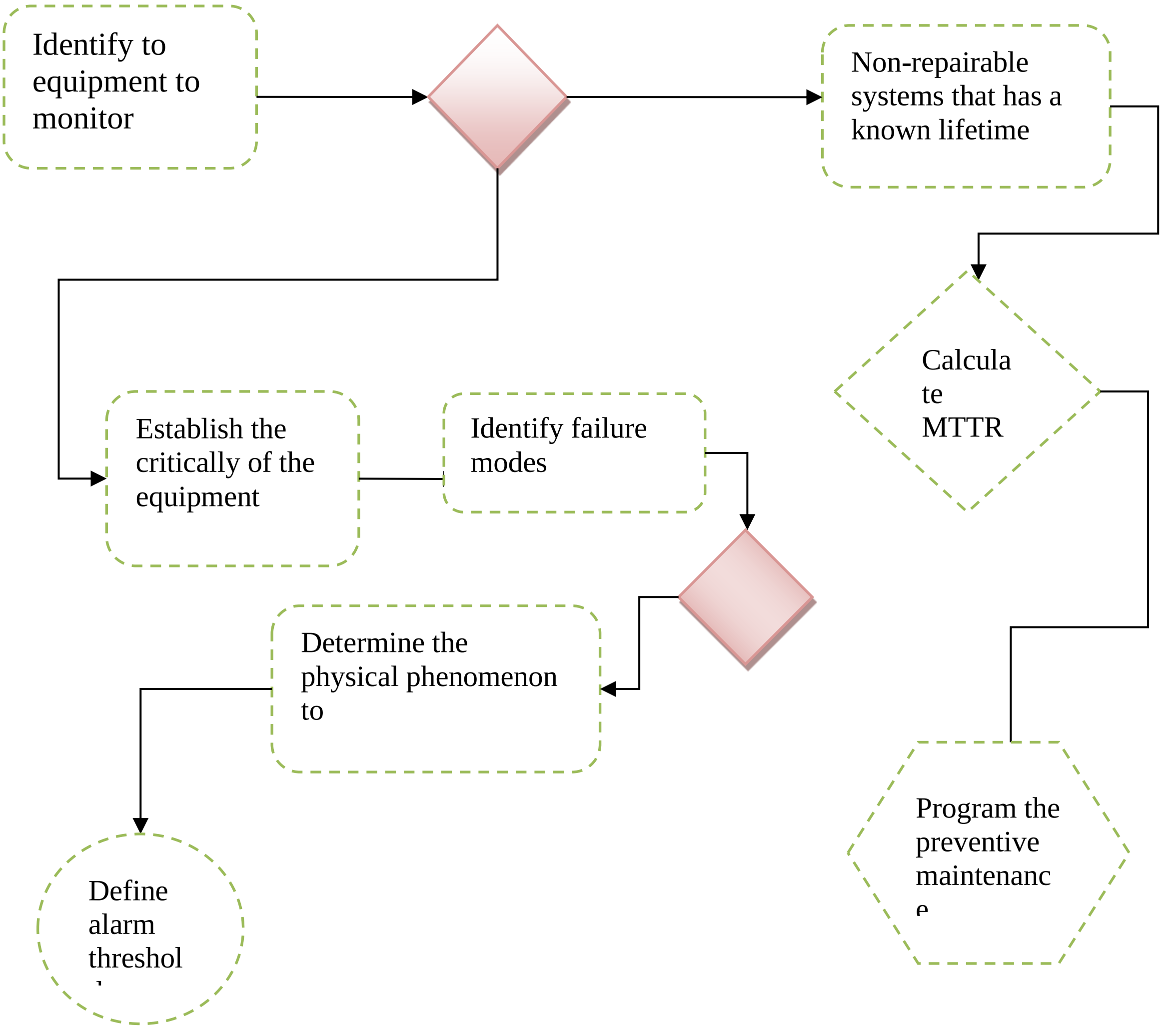


Figure: 5 CBM (Condition-Based Maintenance)

Its many parts gather condition signals and convert them into information that maintainers may use. With this information, administrators can fix the problem before it causes a catastrophic failure, monitor it, and take corrective action as needed. The condition signals show that a Wireless Sensor Unit (WSU) is linked to the machine's sensor nodes.

IMPLEMENTATION OF CBM

Continuous Sensing

Monitoring critical industrial methods and equipment is essential for detecting changes or malfunctions. The general state of the manufacturing equipment or the quality of the product might be put at risk by a bit of change in performance.

Periodic Data Transmission

CBM systems can foresee and avoid problems by analyzing past data. Whenever these adaptive systems are put into action, they acquire new knowledge. Therefore, updating the historical data via periodic data transfer increases the system's effectiveness for defect detection and prognosis, equipment usable lifespan estimation, and overall system performance.

User-Prompted Data Querying

As a network of sensors continuously logs information from various industrial processes and machinery, there may be times when an engineer needs to access data from individual nodes to have a better idea of how things are running. Therefore, a provision that allows one to stop the cycle of periodic contact is necessary to deal with user-initiated queries.

Emergency Addressing and Alarms

Unexpected breakdowns or departures from the prescribed tolerance levels may occur. Each sensor module needs its technique to configure its tolerance bands. The periodic cycle must be interrupted at every given node to signal an emergency if readings exceed the tolerance.

Adaptability

CBM systems, which are adaptive learning systems, show evolutionary behaviour over time. People must be adaptable and receptive to new ideas to expand their existing knowledge. The inherent flexibility requires a WSN design of the same quality as CBM systems.

Network Setup & Reconfigurability

The maintenance engineer can modify the operation of specific nodes throughout the CBM system setup or reconfiguration process. Among these possible adjustments are the sampling rate, data points supplied per transmission, broadcast sequence, channel numbers, tolerance bands, and sensor nodes individually. It is recommended that the WSN be built to switch tasks.

Scalability

During their lifetimes, some sensor nodes may malfunction or even perish due to insufficient battery power. Adding extra sensor nodes to monitor machinery and operations closely might also be necessary. Adapting to changes in the number of nodes without affecting overall performance is essential for a WSN, and scalability plays a key role.

Energy Efficiency

Each sensor node is a self-contained gadget that often runs on its battery. Every part of the WSN system must include an energy-saving concept to make each node last longer. Power awareness must be embedded into every level of the architecture.

Feedback control

If the network has an abnormality, the nodes might get control signals thanks to certain additional characteristics, enabling real-time control of specific dynamic processes. It may be possible to decrease personnel needs by doing away with small manual control or machine resetting activities.

3.4 TDMA (Time Division Multiple Access)

Regarding power consumption, wireless sensor networks are probably best served by the Time Division Multiple-Access (TDMA) protocol. Because of this, more advanced methods employ a variety of algorithms and combine data from several sources. Researchers have looked at the protocols and their pros and cons. Still, they haven't painted a whole picture of TDMA techniques—information that would be helpful for anybody developing a new MAC protocol or deciding which one to employ for a network rollout. We look at the different approaches TDMA systems use and provide a set of characteristics that an effective TDMA protocol should have. In addition, quickly assess a number of procedures.

Only network activity will be planned using TDMA methods, and all nodes will be active during that period. When nodes are idle between data collection sessions, they may go to sleep and turn off their radio interfaces.

Considering topology, mobility, and anticipated data rate should precede the selection of a MAC protocol when TDMA is inadequate for WSN applications. The frequent changes that occur in sensor networks are not well-suited to TDMA due to the possibility of node failure. Furthermore, the clock drift between the nodes should be minimized in terms of slot width.

In Part 3, we covered the conventional approaches to TDMA scheduling, and now we'll look at some of the newer developments. Section 5 offers several suggestions for the optimal operation of a TDMA protocol, whereas Section 4 examines the impact of network design on algorithm selection.

This study has covered the pros and cons of conventional TDMA methods in the previous section. We cover more complex approaches in this part, which are necessary for designing the TDMA protocol that is most suited for sensor networks.

DMA has a low tolerance to topological changes, which makes it less appropriate for MAC protocols in sensor networks. To improve the performance of the conventional CSMA/CA protocols, they may notice that an increasing number of MAC systems are using some of the TDMA techniques outlined below.

protocol.

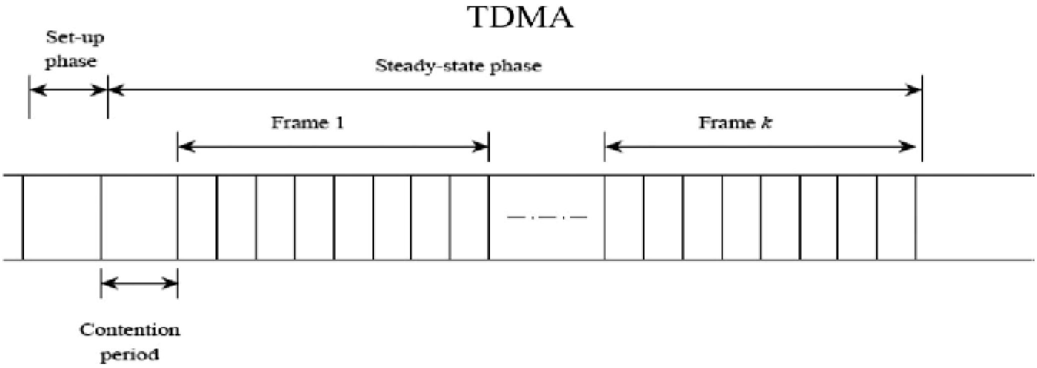


Figure: 6 TDMA protocol

3.5 TDMA IN WSN

WSN articles abound with excellent examinations of MAC procedures. So, we all need to provide a synopsis to back up our statements. The optimal TDMA protocol requirements are satisfied.

Finding the lowest schedule while limiting latency is the goal of PEDAMACS, which stands for Power Efficient and Delay Aware MAC for Sensors. To do this, it mixes distributed and centralized graph node colouring. To show problems, the protocol uses the original network to create a conflict graph. The authors provide formal evidence of the technique's accuracy in addition to test data. One way to colour the edges of a graph is by using distributed edge colouring, which is based on the Grids and Misra methods. Using an updated graph, the authors show the protocol's soundness and solve the previously discussed edge activation problem. It is not suitable for topological changes and is quite a complex procedure.

As a hybrid CSMA/CA and TDMA system that utilizes Explicit Contention Notification (ECN), Z-MAC, also known as Zebra-MAC, adapts behaviour to two-hop neighbourhood traffic levels. Without packet loss or interference, nodes will vie for available slots. A local synchronization mechanism is also a part of the protocol. Slots remain flexible even in the middle of a furious argument; the protocol is more CSMA than TDMA due to its low-power listening. To understand data direction awareness, Z-MAC uses pre-scheduling. Joint TDMA and routings make advantage of TDMA's routing data. The protocol's centralised mechanisms for visiting nodes distribute breadth and depth throughout the routing tree. Our research and testing confirm that energy performance is adequate and that traffic overhead is low. On the other hand, spatial reuse and secondary conflicts are not handled by the protocol. The protocol will cause significant delays on extensive networks.

One protocol that was created specifically for use in sensor networks is DMAC, which stands for Time Division Multiple Access (TDMA). The fact that it deviates from the standard regarding TDMA frame and slot allocations is what sets it apart from the others. The volume of data upstream and the number of children determine the nodes' scheduling activity. More data signals or data predictions may assist in settling disagreements. By using routing information, DMAC operates as a distributed hybrid protocol.

Requirements of TDMA protocol

- Various scheduling techniques and TDMA systems have been investigated. While employing a TDMA approach, it is advised to have in mind the following:
- Dealing with secondary conflicts instead of fundamental ones is more complex to avoid. Turn on spatial reuse if the topology has more than one hop.
- Lessen scheduling delays due to incorrect node order using route data.
- Decrease communication overhead by using a distributed method.
- Keep nodes synchronized to avoid accidental collisions.
- Consider pragmatic difficulties like long, asymmetrical links that might cause crashes and are challenging to follow.

4. Discussion

Energy-efficient designs increase the operating lifespan of sensor networks, which is critical for applications in remote or inaccessible areas. Reducing energy consumption may assist in minimizing operating costs and battery replacement frequency. Using energy efficiently helps to maintain network performance and connectivity. Data transmission requires a lot of energy. Power-aware routing and energy-efficient communication protocols are critical tools for reducing transmission power. Data processing and calculations use energy as well. Reducing computational complexity using optimization approaches helps to save energy. Sleep modes, which turn nodes off or into low-power states during idle periods, help to conserve energy. Data packet compression helps reduce their size, cutting transmission energy requirements. Data aggregation and fusion are in-network processing methods that might reduce data transmissions and allow for energy savings, rather than sending all data to a base station.

5. Conclusion

Wireless Sensor Networks (WSNs) energy efficiency remains crucial in the networks' overall running costs, longevity, and performance. Our findings underline the critical importance of innovative ideas and technologies in maximizing energy utilization, hence boosting network longevity and efficiency. Energy-aware routing protocols, adaptive clustering systems, and optimization algorithms were examined, among other approaches and strategies to handle energy constraints. These methods aim to maintain a steady flow of data, extend the network's lifetime, and balance the energy consumption of nodes. Advanced clustering methods like PSA-LEACH and techniques like the Bacterial Foraging Algorithm (BFA) integrated with RPL have proven to be very efficient with energy by using resources and minimizing energy expenditure while communicating.

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