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Optimization of Wireless Sensor Networks by the Use of Machine Learning-Based Energy-Efficient Cluster Head Selection Algorithms

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Abstract: Modern, state-of-the-art developments in communications infrastructure often lead to load optimization and energy savings when paired with the architectural resources of WSNs and multi-objective optimization. Separating issues with WSN design, routing, an energy-efficient deployment strategy, and multi-objective optimization is essential. By looking at the building method and cluster gateways with different goals in mind, we can demonstrate the load calculation procedure. Our clustering, Gateway discovery management, load calculation, and load relocation design technique is based on the input variables, anticipated output, objectives, and limitations of wireless sensor networks. Next, we'll put the cluster gateway into action and examine the choices made for traffic optimization and distribution that followed. Optimal load management in wireless sensor networks is problematic due to several constraints. Wireless sensor network multi-objective optimization might use a cluster-based load distribution approach to accommodate for heterogeneous networks, for example, by spreading an ongoing gateways transmission throughout cluster nodes, Collaborative wireless sensor network protocol built on the LEACH architecture

Keywords: wireless sensor networks, Load optimization,clustered wireless sensor networks (CBWSN), LEACH

INTRODUCTION

Some of the technologies used in routing include inter-clustering routing, multi-path selection, probabilistic algorithms, and single-hop and multi-hop network transmission. Technologies such as DSP (Dynamics source Routing) and Low-energy Adaptive Clustering Hierarchy (LEACH) are often used to mimic short-distance communication. The use of a better association approach is the best of bunching's benefits; it boosts the organization's activity life, prolongs the lifespan of the sensor batteries, and has a few other advantages as well. Small, inexpensive wireless sensor nodes with short-range communication capabilities have recently become possible because to innovations in microprocessors, networking, electronics, and wireless communications [1][2]. Powering, transmitting, and receiving data are the three main functions of each sensor in the WSN. Energy consumption may be reduced by the use of appropriate cluster-management algorithms and routing protocols. Some methods for clustering include removing hotspots, maintaining cluster sizes, and hierarchical clustering for nodes with different types of data [3].

Data that has been identified is sent to other nodes in the network once it has been processed. Environmental monitoring, environmental and military applications, and many more uses are found in wireless sensor networks. Routing is a very challenging operation in WSN due to its inherent features. Because of the difficulty in managing unique identifiers and the large number of sensor nodes needed for WSN, a global addressing system is not an option. The energy consumption of WSN communication nodes is higher than that of sensing and processing nodes. To make the network last longer, it is essential. This node gathers data from other sensor nodes and sends it to the base station when the whole network of wireless sensors communicates directly with each other [3]. Seven tiers make up the WSN protocol stack. Layers use energy in accordance with their own requirements. However, routing procedures at the network layer require the vast majority of energy [3][4]. Efficiently maintaining and extending the life of the network requires careful use of the resources at hand [4]. One way to make WSNs last longer and consume less energy is to implement an energy-efficient routing algorithm [3]. Several protocols were created with the goal of reducing power consumption and extending the lifespan of networks. There are three different kinds of routing protocols used in WSN: flat, hierarchical, and location-based. With a hierarchical routing method, however, energy consumption might be drastically cut [5][6]. It is a routing system for layering-hierarchy that is built on clusters. Clustering is a commonly used routing approach that is energy efficient. An algorithm is used to arrange nodes in order to do particular jobs more rapidly and appropriately. Each cluster is assigned a data-responsible cluster head [7].

Transmission of data is accomplished using intra-cluster and inter-cluster routing. Clustering energy efficiency is the primary goal of hierarchical routing methods. Numerous benefits are offered by this route design. It is possible to cluster on several tiers, depending on needs. Simplifying routing tables may guarantee stability [8]. The development of tiny wireless sensors capable of performing a broad variety of digital signal processing (DSP) tasks has been made possible by advancements in hardware design and systems on chip technology. All across the specified region, these sensors undergo random changes; they are independent components. The circumstance might determine its number. These sensors are individual units that undergo haphazard changes in the appropriate region. They might be in the hundreds or thousands, it depends on the circumstances [9][10]. Although their battery life is limited, they are capable of delivering a fault-tolerant network of excellent quality. So, WSNs, or wireless sensor networks, are finding more and more uses in many fields. From surveillance on the battlefield to vital medical applications, WNSs are very demanding [11].

In order to keep tabs on certain areas, gather data, and send it to the base station, a network of tiny sensor nodes is used. Military applications, object tracking, and habitat monitoring have dominated the development and use of WSN applications due to advancements in low power, digital circuitry, and wireless transmission [11]. A large variety of sensor nodes are dispersed across a typical WSN. A sink node is a node that all sensors and data-collecting devices use to gather signals and processes. By use of a network query, the download node seeks for sensor data. The download node initiates a network query to get sensor data. The reply message is sent to the sink node if the node discovers data that matches the query. The Network is able to lower its power usage by enabling clusters, which are referred to as cluster heads. Data from the nodes is combined and compressed by the cluster heads. Data gathering techniques are efficient ways to save energy on sensor systems. Data collecting primarily aims to decrease energy transfer and remove duplicate data. In order to decrease data traffic, a data collecting technique incorporates many aggregation methods. Less communication is required between nodes. Fewer communications are sent and received between nodes and the BS. One way to gauge a WSN's (or a sink node's) data collection capability is to look at how quickly sensing data is collected and sent to the SB. One potential metric for WSN data collecting shortcomings is the capability for multiple data collections. The sink's data gathering capabilities demonstrates the efficacy of sensing data collection from all sensors in the presence of interference [7][8].

The military, smart cities, healthcare, environmental monitoring, and industrial automation are just a few of the many fields that have found use for the recently developed technology known as wireless sensor networks (WSNs). Distributed sensor nodes in these networks gather and relay information about their physical surroundings. Problems with data administration, communication range limitations, and restricted power resources are only a few of the major obstacles that WSNs confront, despite their extensive usefulness [9][10]. Since sensor nodes usually run on limited battery power, energy efficiency is a major challenge. When the battery dies, the network's performance, lifespan, and dependability are all negatively impacted. Research in this area primarily aims at optimizing energy usage in WSNs [11].

Sensor nodes collect information and send it on to a central station, or "sink," in a typical WSN. Most of a sensor node's power goes toward sending and receiving data with the base station. A hierarchical structure is often used in WSNs to decrease energy usage. In this structure, sensor nodes are organized into clusters, and one node within each cluster, called the cluster head (CH), is in charge of collecting data and sending it to the base station [3]. Energy consumption and overall network performance are heavily influenced by the choice of cluster head.

The three primary functions of WSNs that are responsible for the energy consumption are sensing, data processing, and wireless transmission. Data transmission between nodes and the base station uses a lot of power, making communication the most energy-intensive component. Recharging or changing batteries is sometimes not feasible or perhaps impossible due to the distant or harsh conditions in which many WSN systems are placed. Because of this restriction, methods must be developed to reduce energy consumption without compromising network performance. Problems with data loss, network segmentation, and subpar system performance may arise when nodes run out of juice too soon due to poor energy management [4][5].

Efforts to reduce energy use have prompted new developments in both architecture and algorithms. The clustering-based network design, in which nodes are divided into clusters and assigned a Cluster Head (CH), is one of the most efficient ways to reduce energy consumption in WSNs. Instead of each node communicating directly with the base station, the CHs act as go-betweens between their cluster members and the station [6]. The network may cut down on transmission costs, lessen data redundancy, and increase the sensor nodes' operational lifespan by grouping them together. Since CHs take on a disproportionately large share of the communication load, their selection is crucial to the success of clustering in terms of energy efficiency [7].

Machine Learning Approaches for CH Selection

Machine learning offers a promising path for optimizing CH selection by analyzing patterns in network data and dynamically selecting CHs based on various factors such as energy levels, distance to the base station, and node density. Through data-driven decision-making, ML models can address the limitations of static algorithms by adapting to the real-time conditions of the network. Several ML techniques have shown potential in this context:

1. **Supervised Learning**: Algorithms such as decision trees and support vector machines (SVMs) can be trained on labeled data to classify nodes based on their suitability for the CH role. Using features like residual energy, proximity to other nodes, and communication history, these models can identify the nodes most likely to maintain cluster stability and efficiency.
2. **Unsupervised Learning**: Clustering algorithms like K-means and hierarchical clustering can dynamically group nodes based on characteristics such as energy capacity and spatial distribution. These methods allow the network to adaptively form clusters that balance the energy load, particularly in heterogeneous networks where nodes have varying energy reserves.
3. **Reinforcement Learning**: Reinforcement learning (RL) techniques, including Q-learning and deep Q-networks (DQN), can enable WSNs to learn optimal CH selection strategies over time by interacting with the environment. In RL-based approaches, nodes are rewarded for energy-efficient behavior, leading the network to develop adaptive policies that maximize longevity and performance.
4. **Federated Learning and Edge Computing**: As WSN nodes often have limited processing power and memory, lightweight ML models are essential. Federated learning and edge computing frameworks allow WSN nodes to collaboratively train models without transferring raw data to a central location, reducing communication costs and preserving energy.

By incorporating these machine learning techniques, WSNs can shift from static, rule-based clustering approaches to dynamic, context-aware CH selection strategies that optimize energy usage, load distribution, and data reliability.

Energy-Efficient Algorithms for Cluster Head Selection

Distributing tasks evenly across sensor nodes and reducing power consumption during communication are the goals of energy-efficient cluster head selection algorithms. These techniques can be much more effective with the use of machine learning, which gives a smarter, data-driven way to control nodes. For example, by combining clustering techniques with reinforcement learning, the responsibilities of cluster heads may be dynamically adjusted in response to changes in the topology of the network and energy levels in real-time [8][9]. In addition, machine learning models can foresee patterns of energy consumption, which enables the network to anticipate node failure and proactively replace cluster leaders to avoid data loss and keep the network stable.

There is more than simply cluster head selection that machine learning could do to improve WSNs. Additionally, it has the potential to enhance network self-healing capabilities, problem detection, and traffic routing. Longer network lifespans and more reliable data transmission may be achieved by making WSNs more flexible, autonomous, and robust to energy restrictions via the use of real-time analytics and predictive modeling [10][11].

The promise of wireless sensor networks (WSN) to automate, monitor, and administer vital services more efficiently has led to their meteoric rise in popularity in recent years. The core of a WSN consists of small computers. This group of tiny processors is called a sensor node. A WSN's principal role is to monitor sensing activities for the purpose of keeping an eye on things like the field area, equipment, and the environment. All aspects of a sensor network—from design to construction to maintenance—need careful consideration, including signal processing, routing, protocols, data management, and many more. A communication system that detects, collects, and sends data from a localized zone to the main area is the Wireless Sensor Network (WSN). Experts in this field must be able to consistently provide a safe, user-friendly, and informative network [12]. The wireless sensor network may be useful in many fields, including agriculture, forest monitoring, and the military. There are huge benefits to the environment by using wireless sensor networks. At its most fundamental level, the wireless sensor network is shown in Figure 1.

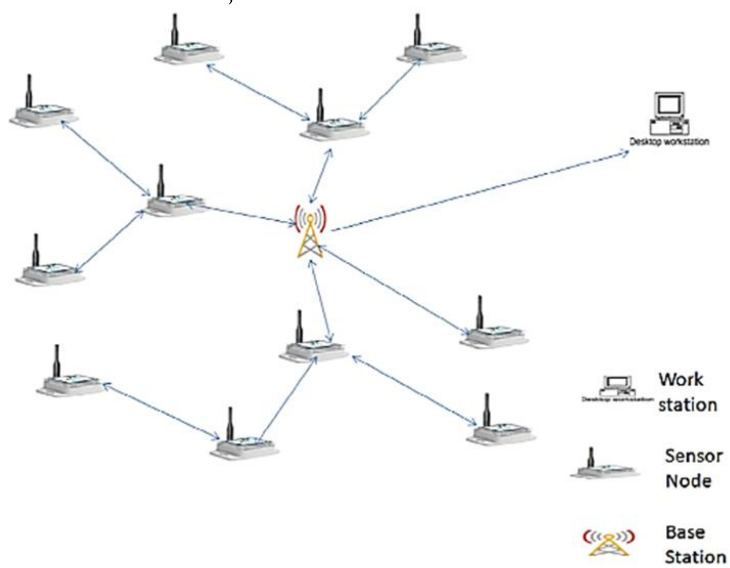

Figure 1: Arrangement of Wireless Sensor Network

Short packet size, low energy consumption, self-organization, automatic node connection, minimal computational memory needs, and cheap network expenses are the main features of a WSN. The wireless sensor network can survive the loss of a single node with ease. Nodes in a WSN are free to roam anywhere they choose. It is possible for a wireless network to have both homogeneous and heterogeneous nodes. Even in harsh environments, the wireless sensor network will continue to function.

The application's specifics will dictate the best approach to sensor positioning. Once installed, the sensor nodes need no more maintenance. A system of wireless sensors has evolved amongst them on its own. Sensor nodes collect data and transmit it to the hub of the cluster. Routing protocols are used to achieve this. What makes a network successful is, therefore, a set of principles called energy-efficient routing protocols. A data transmission path, a cluster leader, and inter-node communication may all be set up using these protocols. The main challenge of creating an energy-efficient routing protocol is controlling environmental effects on applications while minimizing energy consumption.

There are numerous shared characteristics across wireless, wired, and ad hoc networks, despite their distinctions. The modern routing algorithms' reliance on unique, identifying characteristics and layouts is directly responsible for their intricate design. It includes elements like external factors and limited resources (like electricity and bandwidth). Discussed below are issues with the architecture of the routing protocol as it pertains to WSNs.

It is now critical to improve the intelligence and capabilities of sensor nodes because of the extensive usage of WSN applications. There has to be a stronger wireless sensor network since environmental factors like noise and frequency interference might reduce application performance. Customization of the data model is essential for any given application. Using pre-existing data models, data is transmitted from the sensor node to the BS. Among the three types of data models discussed, the first is application-specific. In these setups, the sensor node is the only node that transmits data to the central station. A data collector that captures samples at regular intervals is the second one. Thirdly, communication need to be reciprocal. Thus, our routing algorithm has to be capable of bolstering the data models and enhancing the network's durability, steadiness, reliability, and energy management under certain circumstances. It is ideal to build sensor nodes with less complexity and expense in order to decrease the total cost of the wireless network and increase its lifespan. When it comes to keeping networks running for a long time, energy is key. Less energy will be required to operate the network during its entire lifetime. Efficiently managing energy consumption is the biggest challenge with WSN. Data from communications and sensors, which are sources of energy usage, must be checked for energy management purposes. Consequently, we want to develop a routing algorithm that considers energy sources.

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It is now critical to improve the intelligence and capabilities of sensor nodes because of the extensive usage of WSN applications. There has to be a stronger wireless sensor network since environmental factors like noise and frequency interference might reduce application performance. Every application requires a data model that is uniquely crafted for it. Using pre-existing data models, data is transmitted from the sensor node to the BS. Among the three types of data models discussed, the first is application-specific. In these setups, the sensor node is the only node that transmits data to the central station [13]. A data collector that captures samples at regular intervals is the second one. Thirdly, communication need to be of the talking kind. Accordingly, our routing algorithm has to be capable of bolstering the data models and enhancing the network's durability, steadiness, reliability, and energy management under certain circumstances. Very few Ideally, sensor nodes would be built with less complexity and expense to decrease the total cost of the wireless network and increase its lifespan. When it comes to keeping networks running for a long time, energy is key. Less energy will be required to operate the network during its entire lifetime [14]. Efficiently managing energy consumption is the biggest challenge with WSN. Data from communications and sensors, which are sources of energy usage, must be checked for energy management purposes. Consequently, we want to develop a routing algorithm that considers energy sources [15].

LITERATURE REVIEW

Jiaming Zhang et.al., (2021) The LEACH protocol uses a random method to choose cluster leaders during the wireless sensor network clustering phase. The network's lifetime during data transmission could be reduced if the cluster head nodes burn out early because of variables like their remaining energy or the distance between them. A multi-hop energy-efficient routing system (LEACH-ICM) inspired by LEACH is proposed in this paper to tackle this problem. During the clustering phase, the node's energy and distance from the base station should be considered before picking a cluster head. Afterwards, the optimal path for data transmission within the cluster is determined using the Intra-cluster transmission path planning algorithm. Nodes having a transmission distance greater than the threshold will use the multi-hop approach to transmit data inside the cluster. By extending the lifetime of the network and preventing nodes from dying too soon, the strategy utilized in this study outperforms the leach procedure in a simulated experiment.

Rahma Gantassi et.al.,(2021) The importance of studies aimed at making Wireless Sensor Networks (WSNs) more energy efficient has grown in recent years. The subject of reducing WSN's energy use has been the subject of several study. Quality of service measures, such as latency and throughput, have been examined by only few of them. This study proposes a new hybrid protocol, MDC-LEACH-K, that combines MDC with the Low Energy Adaptive Clustering Hierarchy-K-Means LEACH-K (technique) to improve the LEACH protocol. The proposed protocol is primarily designed to extend the life of the network and improve its quality of service. This technique utilizes the K-Means clustering algorithm to improve Cluster Head (CH) election while decreasing energy use. A mobile data collector (MDC) acts as a go-between for the cluster head and the base station (BS), which further increases the WSN's QoS requirements, decreases data collection delays, and shortens the LEACH protocol's transmission phase. The findings of the simulation show that MDC-LEACH-K significantly affects markers of service quality and energy consumption. To be more specific, this protocol surpasses the aforementioned protocols in terms of latency time and energy efficiency by more than 100%, with gains of 296% in residual energy, 237% in Threshold Sensitive Energy Efficient Sensor Network protocol, and 257% in Low Energy Adaptive Clustering Hierarchy-KMeans protocol.

Shilpi Jain et.al(2020) Everyday devices may now be part of a network called the Internet of Things (IoT) and exchange data with each other thanks to their unique identities. Wireless sensor networks (WSNs) have proven useful in the IoT for gathering data, analyzing it, and then sending it on to the end user or sink node. The limited lifetime of the network and sensors' batteries is a big concern. To solve this issue, an upgraded version of LEACH is used. Information is sent from the sensor node to the sink node using this hierarchical protocol's cluster head selection technique and cache node selection. To identify which nodes will serve as cluster leaders, we compare their energy levels to an established cutoff. In order to transfer data from the cluster master to the cache node, the shortest route is used. When to swap out cache node memory is dependent on priorities. Putting the right algorithm into the network may make it last longer and use less energy. To determine how well the proposed method works, standard parameters have been used. Typical remaining energy, throughput, and the proportion of a network's nodes that are never online.

Seham Nasr et .al (2020) From healthcare and fire detection to agriculture and industrial monitoring, wireless sensor networks (WSN) have become more popular. WSN has several advantages, such as being inexpensive, small, multipurpose, autonomous, and routable using WSN protocols. The limited data storage capacity, short battery life, vast deployment footprints, and high energy costs per sensor are some of the limitations of WSN that restrict its applicability for many applications. In this study, we propose a new approach to optimizing packet delivery timings as a means to enhance the dependability and lifespan of WSNs. Next, we compare the proposed technique's simulated performance to the conventional, fixed-parameter LEACH method in order to assess its efficacy. Network longevity is increased by 128.80% as compared to the usual LEACH approach using the proposed strategy.

Meta-heuristic Techniques

To solve optimization problems, meta heuristic algorithms first produce random responses, which they then use to optimize depending on their operators and by changing the generated random replies. All meta heuristic algorithms, for the most part, use the same strategy to find the best solution. Typically, these algorithms start the search process by generating a sufficient range of random variables and one or more solutions from that range. A population, colony, or group is the main unit of solution generation in algorithms that rely on population dynamics. The solutions are categorized into chromosome, particle, ant, and so on. The next step is to combine the main solutions using operators and other approaches to build new solutions. Once the stop criterion is met, the process will continue by selecting the new solution from the pool of previous ones.

Challenges in Implementing ML-Based CH Selection

Deploying ML algorithms in WSNs presents significant hurdles owing to resource limits and the decentralized structure of WSNs, even though ML-based techniques provide major advantages. Computationally demanding algorithms are often not runnable on sensor nodes because to their low processing power, memory, and energy. Because nodes in WSNs are constantly joining and leaving the network as a result of energy drain or physical obstacles, data collecting and model training are further complicated by this dynamic and dispersed topology.

Lightweight and energy-efficient ML models employed in WSNs are essential for tackling these difficulties. To reduce computing needs, one might use strategies like model reduction, quantization, and simpler algorithms. Further, real-time CH selection choices may be made without causing the system's resources to be overwhelmed by putting ML models at the network's edge. To overcome the shortcomings of WSN hardware while still taking use of ML-driven optimization, one must use decentralized or federated learning architectures and choose ML algorithms with caution.

CONCLUSION

Creating and testing methods for energy-efficient CH selection in WSNs using machine learning is the main emphasis of this study. The goal of this research is to improve the energy efficiency and operational lifetime of WSNs by using ML approaches to optimize cluster head selection according to network circumstances and node characteristics. To prove its efficacy in lowering power usage and distributing loads evenly, the suggested approach will be compared to conventional algorithms. The study's overarching goal is to facilitate the use of next-generation WSNs in energy-sensitive settings where a long network lifespan is paramount by offering a scalable and flexible solution in this way.

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