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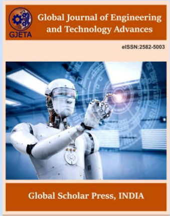

(Review Article)

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Efficient algorithms and protocols for energy conservation of wireless sensor networks: A survey and future directions

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Abstract

Wireless sensor networks (WSNs) play an increasing role in very large-scale Health applications, environmental monitoring, industrial automation, science and military and agricultural industries, as well as smart and large cities. and large-scale applications. These nodes have limited resources such as limited memory and power. These nodes are responsible for transmitting data in real-time and must be secure and reliable. An important consideration is how to keep the energy of these nodes running efficiently for as long as possible. These requirements pose a major challenge in selecting appropriate protocols for routing and data transmission in a secure and continuous manner without interruption. Previous studies have focused on innovating and developing energy-saving algorithms and ensuring network scalability using machine learning methods to predict energy consumption behavior. This paper focuses on reviewing energy-optimizing algorithms and their types, energy-minimizing protocols and their working mechanisms, strengths, and weaknesses, as well as the relationship between energy and energy-optimizing encryption algorithms.

Keywords: WSN; PEGASIS; TEEN; EADAT; LEACH; Gathering; Grain; Trivium

1. Introduction

Wireless sensor networks have become the cornerstone of modern technological systems [1, 2]. WANs are used in healthcare applications, smart cities, military science, industrial automation, and environmental monitoring such as ecological pollution, different climatic conditions, desertification, and weather conditions such as temperature, humidity, earthquakes, and volcanoes [3,4]. Sensor networks consist of wireless sensors interconnected together that operate in different environmental conditions (hot and cold), remote areas, and for long periods. Therefore, the main task that must be studied is how to conserve battery power so that the network operates efficiently and extends its life [5,6]. Naturally, the wireless sensor unit consists of four components, which are the sensor unit, the processor unit, and the communication unit, in addition to the battery. The most energy-consuming unit is the communication unit that sends and receives data [7]. The battery power of sensor nodes has limited energy and it is essential how to maintain this energy for the longest period to increase the life of the network. This energy depends on communication and transport protocols, routing protocols, data collection methods, and network distribution and management methods [8,9]. The need for energy-efficient algorithms for wireless sensor networks has become a major concern for developers because it is difficult to replace the batteries of thousands of nodes spread across multiple locations. Another important reason is that the failure of one battery to work leads to the neutralization of the rest of the nodes and their failure to send and receive data and perhaps the failure of the system to continue. [10]. In recent years, researchers have been directed to develop advanced protocols and algorithms in the field of network energy by balancing energy consumption and reducing duplicate data operations and unjustified energy consumption to some extent so that these algorithms do not affect the efficiency of the network and the energy of idle nodes can be utilized by scheduling nodes according to certain criteria without compromising the optimal performance of the network [11,12]. The interplay between

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hardware and software components in wireless sensor networks significantly determines energy efficiency. Devices with limited power and processing capabilities often face challenges when executing complex algorithms or processing extensive data streams. Consequently, this scarcity compels developers to innovate energy-efficient solutions in both software design and hardware architecture. For instance, software optimization strategies, such as compression algorithms and energy-aware scheduling, can dramatically reduce the processing load on constrained devices. In parallel, advancements in hardware, including low-power circuits and application-specific integrated circuits (ASICs), directly contribute to reduced energy consumption during data transmission and processing tasks. The adoption of a cloud/edge communication architecture has gained attention in this context, as it can offload computation-heavy tasks away from the device, which can extend battery life while maintaining operational efficiency [13]. Therefore, understanding and addressing the synergy between hardware and software is essential for advancing energy efficiency in these networks [14].

Moving forward, researcher must focus on developing hybrid methodologies that fuse existing protocols with innovative energy-efficient strategies, ensuring seamless scalability. Additionally, exploring the potential of machine learning algorithms to predict energy consumption patterns could provide valuable insights into optimizing network performance. Ultimately, addressing these future trends is vital to promoting the design and implementation of sustainable wireless sensor networks.

2. Related Works

Rajiv Yadav et. al., in 2022 they presented research in which they used hybrid algorithms (DE-GA, GA-PSO, PSO-ACO, PSO-ABC, PSO-GWO, etc.) to produce advanced biologically inspired techniques to provide a solution to improve the efficiency of energy-efficient networks based on node location, sensor coverage area, and data collection. Variables such as power, energy loss, data transmission delay, and overhead were used. They were also studied to improve QoS, wireless network stability, and secure transmission lines [15].

Qianao Ding et al. in 2021 developed a virtual machine learning model to produce an energy-efficient green routing model in wireless sensor networks to improve the efficiency of wireless sensor networks and address the barriers to green routing strategies. Energy-efficient routing algorithms are classified into a set of categories such as data flow optimization according to single- or multi-path routing paths, hierarchical node selection, and energy-efficient node scheduling [16].

The researchers Lucia K. Ketshabetswe et. al. In 2024, he presented a study to improve the energy consumption of wireless sensor networks for lossless data compression using (ALDC) and (FELACS) to reduce the number of bits required for encoding. This new technique improved the energy from 73% to 77% and is effective in identifying and replacing outliers, which improved the performance of compression results [17].

Neda Nilsaz Dezfuli, et.al., in 2024 presented a method based on dividing the WSN network area into square areas then, searching for the nodes with the highest energy, identifying them and keeping them using the Firefly algorithm and using Omnet++ to study the simulation and compare the results with the TCO, ACO-Greedy models and deactivating other nodes, which resulted in a 30% reduction in energy demand [18].In 2021, researchers Zahid Yousuf et al. proposed an improved version of the LEACH protocol. They called it LEACH-PRO, with the aim of extending the network lifetime by calculating the distance between CH and BS, in addition to the remaining energy. This method has proven superior to previous methods in extending the network lifetime and is more flexible in smart city applications, as the network can be expanded [19].

Behzad Saemi, et.al., they proposed a hybrid metaheuristic algorithm called the global search algorithm (GSA) which combines the local search algorithm (LSA) and GSA. This hybrid algorithm aims to search for the best optimal path to the transmission area and reduce the time during the GSLS operation, which leads to reduced energy consumption and increased efficiency [20].

Adumbabu et.al. 2022 in their paper relied on a dynamic variable cluster head and relied on an algorithm consisting of three stages: preparation, transfer, and measurement, which they called the improved Coyote Optimization Algorithm (ICOA) to determine the best ideal path between the BS and the communication channel in light of the node rank and the remaining energy in addition to the distance between them. The case was studied on 100 and 200 and the results were very good in extending the network lifetime compared to previous methods based on TEEN and PEGASIS [21].

3. Motivation

Energy-saving algorithms are essential in building WSNs to extend the network life for a longer period of time because it mainly depends on the power source, and replacing batteries in a wide area is difficult and expensive, so energy-saving algorithms are most important in WSNs. Below is a set of algorithms as shown in Table 1

Table 1 Algorithm and key technique in WSN

RE. No.	Algorithm	key technique
[22]	Duty Cycling Algorithms	Sensor Medium Access Control (S-MAC). Timeout MAC (T-MAC) Berkeley MAC (B-MAC)
[23]	Energy-Efficient Routing Algorithms	Low-Energy Adaptive Clustering Hierarchy (LEACH) Power-Efficient GAthering in Sensor Information Systems (PEGASIS) Threshold-sensitive Energy Efficient Network (TEEN)
[24]	Data Aggregation Algorithms	Tiny Aggregation (TAG) Synopsis Diffusion. Energy-Aware Data Aggregation Tree (EADAT)
[25]	Clustering Algorithms	LEACH. Hybrid Energy-Efficient Distributed Clustering (HEED) Distributed Energy-Efficient Clustering (DEEC)
[26]	Power Control and Topology Management Algorithms	Geographical Adaptive Fidelity (GAF) SPAN Connected Coverage Set (CCS)
[27]	Machine Learning and AI-Based Algorithms	Reinforcement Learning-Based Routing Deep Learning for Energy Prediction

4. Energy Efficiency in WSNs

The energy efficiency in WSNs can be studied in terms of routing protocol algorithms and encryption algorithms:

4.1. Energy-Efficient Algorithms for WSNs

Since energy is important to the lifetime of a wireless sensor network, we review some of the most energy-efficient algorithmic protocols that ultimately aim to improve energy consumption and latency speed for sending or receiving data. Table2 illustrate the types of protocols of energy efficiency in WSN.

Table 2 Protocols of energy efficiency

Protocol	Description	Mechanism	Energy Efficiency	Weaknesses
Low-Energy Adaptive Clustering Hierarchy (LEACH) [28].	It is a hierarchical clustering protocol and each cluster of network has a random node CH that transmits data to the BS.	1. Cluster head randomly selected based on the power intensity 2. Data receiving and sending to BS	Changing communication channels between nodes to reduce energy drain in long-distance transmissions.	1.Not suitable for large networks 2. A CH may be an inefficient node
Power-Efficient	Nodes form a chain, pass data to	The nodes are organized in a chain,	In this type, multi-hop communication	Organizing nodes in a chain poses a

GAthering in Sensor Information Systems (PEGASIS) [29].	their nearest neighbors, aggregate data at an intermediate node CH and send data to the BS	and each node transmits data to its neighbor, each CH node is periodically assigned.	is adopted to save energy. The intermediate nodes reduce the amount of data sent each time, and it is better than LEACH in saving energy.	barrier to sending data to multiple nodes in addition to increasing the delay
Geographical Adaptive Fidelity (GAF) [30]	The WSNs are divided into several levels such that one level remains active and the rest of the nodes are in a sleep state	A single node is active and changes periodically to ensure even power consumption	This type is effective and contributes to reducing energy and is used in large networks and contributes to communication efficiency	Inefficient for mobile networks
Threshold Sensitive Energy Efficient Sensor Network Protocol (TEEN) [31]	This hierarchical protocol is designed to handle time-sensitive, event-driven data transmission	Follows a hierarchy where communication channels are two-level and transmit data when they reach a threshold to continuously reduce data transmission at the lowest event	Suitable when data is frequent and constant. Energy-efficient because data is transmitted in critical situations.	Not suitable for variable data applications.
Distributed Energy-Efficient Clustering (DEEC) [32]	This type is energy efficient and suitable for disparate and heterogeneous WSNs.	Based on the average available energy in the total network and the remaining energy of the nodes, the CH will be selected.	The main function of the channel is to collect data from sub-node and send data to BS, to reduce power consumption.	Not suitable for wide area networks, ignores the distance between the communication channel and the base station, and high power consumption.
Stable Election Protocol (SEP) [33]	It is suitable for heterogeneous networks and aims to reduce power consumption, extend the lifetime of the network, and address nodes with varying power levels	Cluster heads are elected based on the remaining energy levels of other nodes. This technique is energy saving.	It is energy efficient for heterogeneous networks and ensures that node do not die quickly because the network is trained to balance the nodes' energy and select the cluster head based on the available energy.	Increased energy consumption for homogeneous networks with constantly changing data

4.2. Energy Efficiency in terms of Encryption Algorithm

All encryption and decryption operations require computational and processing operations. Since wireless sensor networks are resource-constrained, they can consume more overhead, which means power consumption, thus reducing the network lifetime. Below are the most important and least energy consuming encryption algorithms.

4.3. Advanced Network Encryption Standard

It is one of the symmetric encryption algorithms, considered one of the least energy-consuming algorithms, and includes a key for encryption and another for decryption. It is regarded as one of the most secure and fastest algorithms and deals with large data, so it is suitable for various types of applications, especially in wireless applications, as it can deal with 128, 192, and 256-bit keys at a time. This algorithm is considered one of the lightweight algorithms as it can reduce mathematical computational complexity because it deals with small keys, which require a small number of encryption rounds, reduces energy consumption in wireless sensor networks, speeds up network operation, and detects and removes fake nodes [34,35.36].

4.4. Lightweight Encryption

This algorithm is considered one of the symmetric encryption algorithms and a widely important solution in WSN networks to secure data reduce energy consumption to a minimum and ensure extending the network life because these networks often deal with batteries and have the advantage of limited computational power with fewer rounds than other encryption algorithms such as AES, RSA and SHA because they have a limited memory size to deal with large encryption keys and therefore they are lightweight algorithms because they do not deal with the encryption of relatively small block packets and therefore these algorithms suffer from security vulnerabilities and this algorithm includes a group of encryption methods such as Grain, Trivium, Present, Speck, Simon and Hight [37,38,39].

5. Conclusion

In conclusion, WSNs are considered an important means suitable for various vital applications in healthcare, industrial automation, military industries, environmental monitoring, and smart cities. These networks still face several challenges such as limited node memory and energy. This paper focused on reviewing hybrid algorithms for energy reduction, their working mechanisms, and the strengths and weaknesses of each, in addition to the best encryption algorithms with operations that do not increase energy consumption. We hope that in the future, research will expand to find the best hybrid algorithms that are suitable for energy reduction, which ensures optimal network performance.

Compliance with ethical standards

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Disclosure of conflict of interest

No conflict of interest to be disclosed.

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