Educational Administration: Theory and Practice
2024,30(11), 1000-1005
ISSN:2148-2403
https://kuey.net/
Research Article

Review on Optimization Techniques for Prolonging the Lifetime of Wireless Sensor Network

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Citation: Ravi Kant et al. (2024), Review on Optimization Techniques for Prolonging the Lifetime of Wireless Sensor Network, *Educational Administration: Theory and Practice*, *30*(11), 1000-1005
Doi: 10.53555/kuey.v30i11.8950

ARTICLE INFO

ABSTRACT

From industrial automation to environmental monitoring, wireless sensor networks (WSNs) are now rather crucial in many different applications. Nevertheless, the lifetime of these networks is seriously threatened by the finite energy resources of sensor nodes. A thorough overview of optimisation methods meant to extend WSN lifetime is given in this work. We investigate several methods including data aggregation methods, clusterings, duty cycling systems, and energy-efficient routing protocols. Furthermore included in the article are developing trends including energy harvesting techniques and machine learning-based optimisation. By means of a methodical review of current studies, we pinpoint the most interesting approaches and draw attention to areas of future WSN lifespan optimisation research need.

Keywords: Wireless Sensor Networks, Energy Efficiency, Network Lifetime, Optimization Techniques, Routing Protocols, Clustering Algorithms

1. Introduction

Spatially scattered autonomous sensors cooperating in monitoring physical or environmental factors make up wireless sensor networks (WSNs). Environmental monitoring, healthcare, military surveillance, and industrial process control are just a few of the disciplines these networks have found uses for [1]. Nevertheless, the lifetime and efficiency of WSNs [2] are seriously threatened by sensor nodes' low energy resources [2].

Usually, the lifetime of a WSN is defined as the period from the network's deployment until the point when energy depletion or loss of connectivity causes it to be unable of fulfilling its intended use [3]. Ensuring the continuous operation of WSNs depends on maximising this lifetime, particularly in cases when regular battery replacement is either impractical or impossible.

A thorough overview of optimisation methods meant to extend WSN lifetime is given in this work. We investigate several methods including data aggregation methods, clusterings, duty cycling systems, and energy-efficient routing protocols. We also review developing trends including energy harvesting techniques and machine learning-based optimisation.

The rest of the work is set out as follows: Section 2 addresses energy-efficient routing protocols; Section 3 investigates clustering algorithms; Section 4 looks at duty cycling mechanisms; Section 5 concentrates on data aggregation techniques; Section 6 investigates developing trends; Section 7 ends the paper with a summary of results and future study directions.

2. Energy-Efficient Routing Protocols

The energy economy of WSNs depends much on routing techniques. Energy-aware routing systems seek to minimise the total energy use by balancing the energy consumption over the network. Several of the most well-known energy-efficient routing techniques for WSNs are compiled in this part.

2.1 Leach Low Energy Adaptive Clustering Hierarchy

Aiming to equally divide the energy load among sensor nodes, LEACH is a novel clustering-based routing system [4]. It runs in rounds, with a steady-state period sandwiched between a setup phase. Cluster heads are chosen and clusters develop during the setup phase. Data moves from nodes to cluster heads then back to the base station in the steady-state phase.
LEACH guarantees that the energy-intensive role of cluster head is rotated among all nodes by selecting clusters using a probabilistic technique. This rotation serves to balance the energy consumption over the network, therefore extending the total lifetime of the network.
2.2 Power-Effective Acquisition in Sensor Information Systems (PEGASIS)
Eliminating the overhead of dynamic cluster building, PEGASIS is a chain-based technique meant to surpass LEACH [5]. Nodes in PEGASIS create a chain in which each one interacts just with its closest neighbour. Along the chain, data is passed via nodes who alternately send to the base station.
PEGASIS achieves notable energy savings over LEACH by reducing the transmission distance for most nodes and distributing the energy burden equally. On big networks, meanwhile, the process of chain building might cause latency.
2.3 TEEN, Threshold-Sensitive Energy Efficient Sensor Network Protocol
TEEN is a hierarchical protocol meant for time-sensitive uses [6]. It explains the ideas of hard and soft thresholds and applies a two-level clustering method. Only when the sensed attribute crosses the hard threshold and varies by at least the soft threshold will nodes broadcast data.
This method greatly lowers the gearbox count, so conserving energy. For applications needing regular data collecting, however, nodes may not interact at all if criteria are not crossed, hence it is inappropriate.
These routing systems are compared in Table 1 depending on their main features and energy economy.

Table 1: Comparison of Energy-Efficient Routing Protocols

Protocol	**Network Structure**	**Cluster Head Selection**	**Data Aggregation**	**Energy Efficiency**
LEACH	Hierarchical	Probabilistic	Yes	Medium
PEGASIS	Chain-based	Fixed rotation	Yes	High
TEEN	Hierarchical	Based on residual energy	Yes	Very High

3. Clustering Algorithms

A commonly utilised method in WSNs to increase energy economy and extend network lifetime is clustering. Clustering nodes lowers the transmission overhead and lets data aggregation at cluster heads possible. Some advanced clustering techniques meant to maximise energy consumption in WSNs are reviewed in this part.

3.1 Hybrid Energy-Effective Clustering (HEED)

Considered in the cluster head selection process both residual energy and communication cost, HEED is a distributed clustering method [7]. HEED guarantees that cluster heads are evenly distributed across the network and have enough energy to carry out their responsibilities, unlike LEACH, which makes only probabilistic cluster head selection.
The method chooses cluster heads iteratively depending on a mix of residual energy and node degree or density. This method increases the general network lifetime and results in a more equal energy usage all around.

3.2 Energy-efficient Unequal Clustering (EEUC)

In multi-hop WSNs, EEUC tackles the "hot spot" issue whereby greater relay traffic causes nodes nearer the base station to run out of more quickly [8]. It forms unequal-sized clusters with smaller ones close to the base station and bigger ones farther apart.
Although heads of smaller clusters can save some energy for inter-cluster data forwarding, this unequal clustering method balances the energy usage among cluster heads. Particularly in large-scale WSNs, EEUC considerably increases network longevity.

3.3 Distribution Energy-Efficient Clustering (DEEC)

DEEC is a clustering method that evenly distributes the energy usage among all the nodes by use of a fresh methodology [9]. It approximates the optimal percentage of cluster heads and the network lifetime, then applies this knowledge to ascertain the likelihood of a node assuming a cluster head.
Higher residual energy nodes have more chance of developing cluster leaders. This adaptive strategy guarantees that nodes with more energy participate more to the network operation, therefore ensuring a better balanced energy consumption and long lifetime of the network.

Figure 1 shows these clustering algorithms' energy usage trends relative to a non-clustering method.

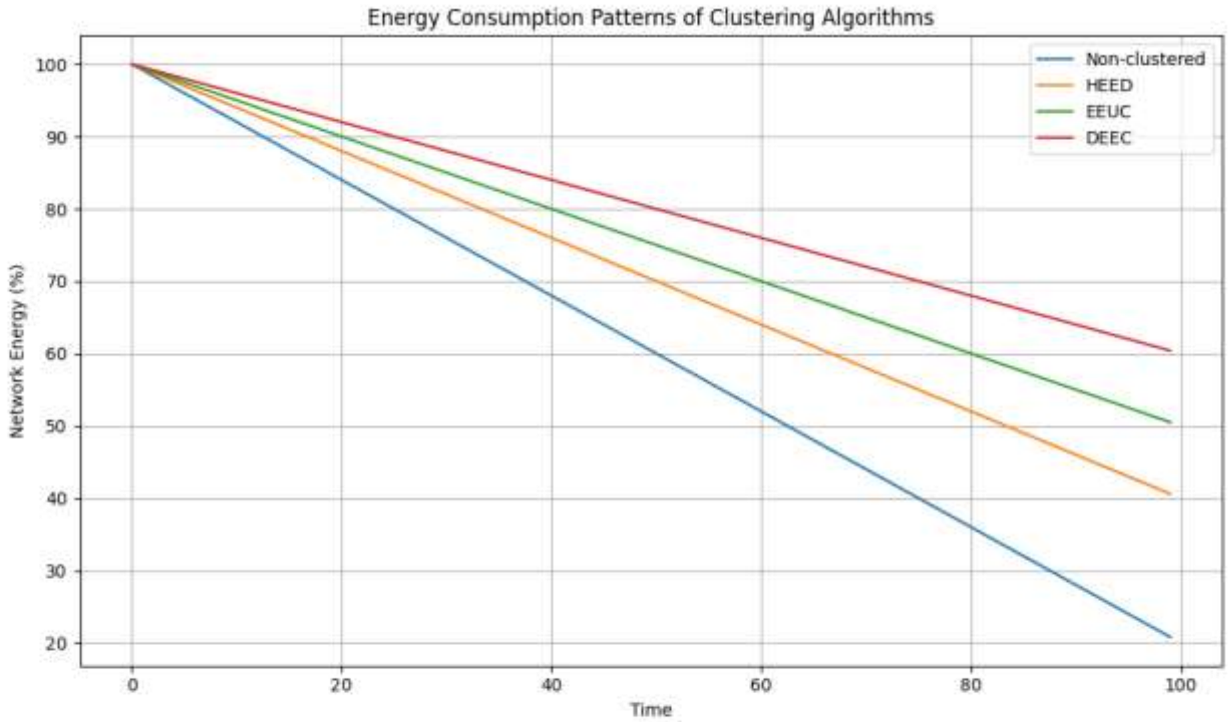

Figure 1: Energy Consumption Patterns of Clustering Algorithms

4. Duty Cycling Mechanisms

By cycling nodes between active and sleep modes, duty cycling helps WSNs save energy. The several duty cycle systems and their effects on network lifetime are investigated in this part.

4.1 Synchronised Wakeup Calendar

Synchronised wake-up scheduling is the coordination of the sleep and wake intervals among nodes spread over the network [10]. Simultaneously waking to communicate, nodes then go back to sleep to save energy. This method minimises idle listening by guaranteeing that nodes are awake as needed for communication.
Maintaining synchronising across the network is a difficulty with this approach, particularly in large-scale installations. Effective implementation of it, however, can greatly lower energy consumption.

4.2 Asynchronous Wake-up Timing

Asynchronous wake-up scheduling lets nodes create independent sleeping schedules [11]. This method is more scalable since it does away with the necessity of network-wide synchronising. Periodically waking to search for overdue messages, nodes then go back to sleep should no communication be needed.
Although this approach is more adaptable than synchronised scheduling, it can cause extra latency since nodes might have to wait for their neighbours to wake up before passing on data.

4.3 Demand Wake-up on Demand

Separate low-power radio in on-demand wakeup systems listens for wakeup signals [12]. A node signals wake-up to activate the intended recipient when it needs to transmit data. This method reduces pointless listening and lets quick reaction to events possible.
The additional hardware needed for the low-power radio presents the major obstacle with this approach. Still, in event-driven applications specifically, the energy savings usually exceed the additional expense.
Table 2 compiled the features of several duty cycling systems.

Table 2: Comparison of Duty Cycling Mechanisms

Mechanism	**Synchronization**	**Latency**	**Energy Efficiency**	**Scalability**
Synchronized	Required	Low	High	Low
Asynchronous	Not required	Medium	Medium	High
On-Demand	Not required	Low	Very High	Medium

5. Data Aggregation Techniques

Reducing the amount of data sent in WSNs by means of data aggregation is essential to save energy. Advanced methods of data aggregation meant to maximise energy use while preserving data integrity are reviewed in this part.

5.1 Aggregation based on Clusters

Cluster-based data aggregation [13] uses the network's clustering structure to do in-network processing. Before forwarding to the base station, cluster chiefs compile data from their individual nodes. This method drastically cuts the data sent, so saving energy.
In this area, advanced methods consist in:
Cluster heads change the degree of data compression depending on the data properties and present energy levels.
Using the temporal correlation in sensor readings will help to lower unnecessary transmissions.

5.2 Tree-Based Data Consolidation

With data flowing from leaf nodes to the root—usually the base station—tree-based aggregation arranges nodes into a tree form [14]. Data aggregates at intermediary nodes as it rises the tree.
Tree-based aggregation has lately advanced with:
Dynamic tree reconstruction: Often balancing energy use by periodically rebuilding the aggregation tree.
Considering elements including energy efficiency, data correctness, and latency in tree construction, multi-objective optimisation

5.3 Sensing Compressionally

An sophisticated technique called compressive sensing lets signals from significantly fewer samples be rebuilt than conventional approaches demand [15]. This translates in WSNs into less transmissions and hence energy savings.

Compressive sensing for WSNs has lately advanced in two directions:

Using spatial correlations among sensor readings, distributed compressive sensing seeks to further lower the necessary measurement count.
Adaptive sampling is dynamically changing the sampling rate depending on the energy restrictions and signal properties.

Figure 2 shows, in comparison to a no-aggregation method, the energy savings attained by many data aggregation methods.

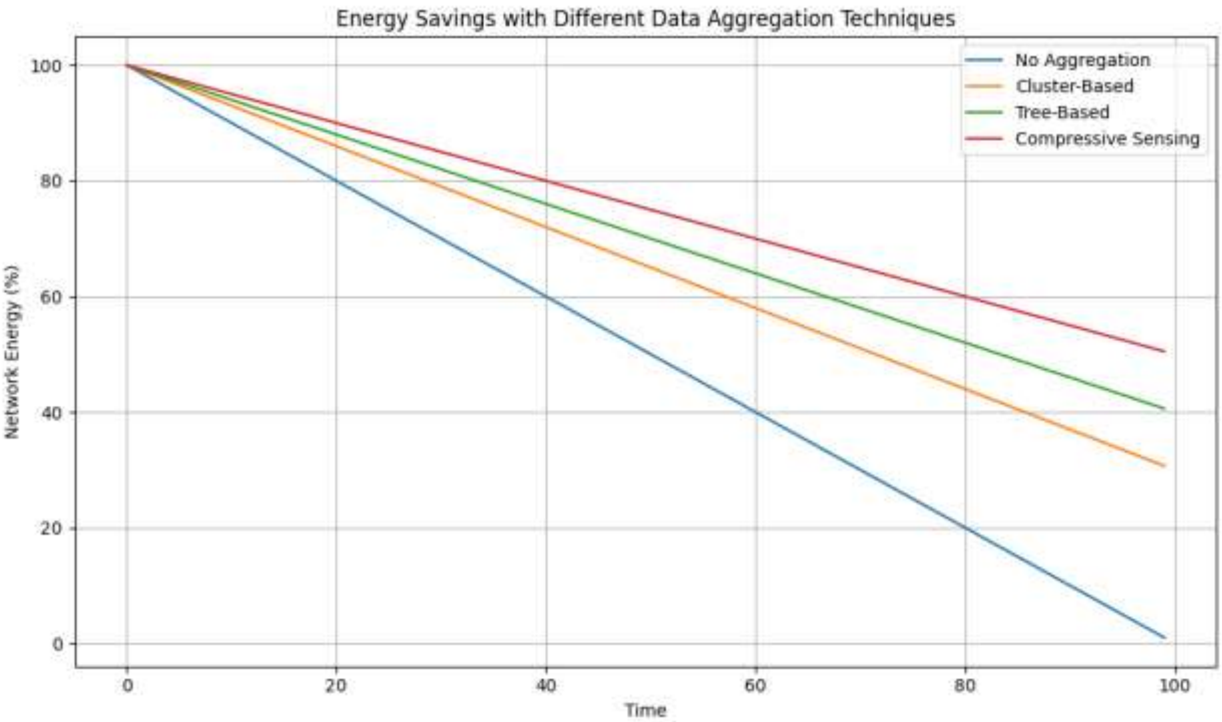

Figure 2: Energy Savings with Different Data Aggregation Techniques

6. Emerging Trends

As WSN technology develops fresh methods for lifetime optimisation are starting to surface. Two intriguing trends—energy harvesting methods and machine learning-based optimization—are investigated in this part.

6.1 Machine Learning-Based Optimisation

Techniques of machine learning (ML) are being used more and more to maximise several facets of WSN running [16]. Among some important uses are:
Predictive maintenance made possible by ML models lets load balancing and proactive repair target node problems.
Reinforcement learning systems provide dynamic adjustment of routing strategies depending on network conditions.
ML methods help to find trends and correlations in sensor data, hence facilitating more effective aggregation.
Although ML-based methods show considerable potential, they also bring difficulties including the computational burden of executing ML algorithms on limited resources.

6.2 Energy Harvesting Methodologies

Energy harvesting solutions seek to extend WSN lifetime by letting nodes recharge their energy from environmental sources [17]. Typical approaches of energy collecting consist in:
Photovoltaic cells turn light into electrical energy in solar energy collecting.
Piezoelectric materials let one capture energy from environmental vibrations.
Using temperature differences to create electricity is known as thermal energy collecting.
Recent developments in this subject concentrate on enhancing the efficiency of energy collecting devices and creating intelligent energy management systems able to maximise the use of acquired energy.
Table 3 lists the possible advantages and difficulties of these newly developing trends.

Table 3: Emerging Trends in WSN Lifetime Optimization

Trend	Potential Impact	Challenges
Machine Learning	High	Computational overhead, Training data requirements
Energy Harvesting	Very High	Environmental dependence, Hardware complexity

7. Conclusion

The several optimisation methods meant to extend the lifetime of Wireless Sensor Networks have been investigated in this research. From duty cycling systems and data aggregation methods to energy-efficient routing protocols and clustering algorithms, every method presents special benefits and drawbacks.
By matching energy consumption across nodes, energy-efficient routing systems as LEACH, PEGASIS, and TEEN have shown notable increases in network longevity. By incorporating residual energy and node dispersion, advanced clustering techniques include HEED, EEUC, and DEEC further maximise energy use.
With synchronised, asynchronous, and on-demand wake-up schedules each fit for various network needs, duty cycling systems provide still another way for energy savings. Particularly compressive sensing, data aggregation methods offer great potential to drastically lower the data transfer energy cost.
Emerging technologies including energy harvesting methods and machine learning-based optimisation offer great chances to improve WSN lifetime. These methods, meantime, also bring fresh difficulties that must be resolved.
Future studies in this subject should concentrate on creating hybrid methods combining several optimisation strategies to get synergistic advantages.
Investigating how clever energy management systems might be combined with energy harvesting.
Looking at using cutting-edge ML methods including federated learning to maximise WSN performance at lowest computational overhead.
Dealing with the scalability issues of several optimisation methods in big-scale WSN systems.
Long-term deployments and new uses for this flexible technology will be made possible by pushing the envelope of WSN lifetime by ongoing innovation in these fields.

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