



A Review on Battery Life and Energy Management in HWSNs using Adaptive Energy Harvesting Techniques

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ABSTRACT

This review article scrutinizes the limitations and improvements in battery life and energy management models within HWSNs that employ adaptive energy harvesting techniques, enhancing consumption strategies on real-time predictions. The hierarchical wireless sensor networks face several limitations in battery life and energy management, such as limited battery capacities, energy consumption, energy harvesting limitations, communication overheads, network scalability, environmental factors, etc. Effective energy management is vital as Wireless Sensor Networks (WSNs) advance into various implementations, including monitoring ecological parameters and smart cities. This review paper examines the responsibility of communication protocols, precisely routing and Medium Access Control (MAC) protocols, in optimizing energy efficiency. We scrutinize existing energy-efficient schemes and their comparative performance, concentrating on their adaptability to changing energy sources. Examining these protocols, we accentuate the best techniques and potential areas for development. Furthermore, the review highlights the necessity for advanced approaches integrating energy harvesting with resilience communication frameworks to maximize network lifespan. The discoveries are targeted to lead future research and advancement in WSNs, providing more reliable and efficient energy management schemes for WSNs.

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1. INTRODUCTION

Wireless Sensor Networks (WSN) have developed as an essential technological infrastructure for various implementations, comprising environmental examination, smart cities, healthcare services, and automation technology [20][41]-[46]. These wireless sensor networks comprise various sensor nodes that transmit wirelessly to receive and send packets. Energy management is a significant wireless sensor network challenge since most sensor nodes depend on powered batteries with a limited lifetime [21][47]-[50]. Effective energy utilization is crucial, particularly when frequent battery replacements or recharging are unfeasible [19][51]-[56].

Heterogeneous Wireless Sensor Networks (HWSNs) add an extra level of complexity because of the variety of sensor nodes with different abilities, battery energy levels, and energy utilization configurations. Specific sensor nodes may have greater processing capacities or energy levels in these networks. In contrast, others may possess enhanced processing power or energy resources, and others may be inhibited by limited energy availability [22][57]-[62]. This heterogeneity can result in disparities in energy utilization, which could be

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prone to premature node failures and minimize network performance [23][63][66]. The problem of HWSNs in term of battery and energy management is critical due to the reliance on battery-powered sensor nodes, this happen when different types sensors consume varying amount of energy depending on their operational state, such as sensing, transmitting, and receiving, and also, the limited battery life that is due to sensors' limited battery capacity, and frequent recharging or replacement that is often impracticable constitutes its challenges.

Adaptive energy harvesting techniques present a promising approach to improve battery longevity and optimize energy efficiency in Heterogeneous Wireless Sensor Networks. By utilizing ambient energy assets like "solar, wind, and kinetic energy," these approaches permit sensor nodes to complement their battery energy dynamically. Adaptive schemes can regulate their energy harvesting strategies based on real-time eco-friendly conditions and available energy, leading to enhanced energy efficiency and maximized network lifetime [24][66][67].

This review article aims to holistically explore the meeting of battery life, energy efficiency management, and adaptive energy harvesting in HWSNs. We will scrutinize existing research articles on energy consumption configurations, battery systems, and energy harvesting approaches, accenting the significance of incorporating adaptive schemes into energy management strategies. By scrutinizing existing knowledge and detecting gaps in the literature, this review article offers insights into future research directions and practical implementations of adaptive energy harvesting in HWSNs [25][68][70].

The existing schemes repeatedly disregard Adaptive Energy Harvesting Techniques (AEHT), essential for improving energy efficiency by dynamically adjusting collection techniques based on environmental conditions and energy demands, prolonging the network's operational lifespan, and enhancing overall performance. The existing schemes lack the following in their work:

- a) Self-optimization algorithm that enhances nodes' energy harvesting and consumption strategies based on real-time predictions.
- b) A multi-modal energy harvesting combination integrates energy harvesting methods, such as kinetic and solar energy, at the node level.
- c) Predictive energy management employs artificial intelligence to predict energy availability and consumption patterns based on historical data.

The subsequent review article will be structured as follows: Session 2 scrutinizes similar works, Section 3 discusses the energy consumption in WSNs, and Section 4 provides an overview of battery life considerations in heterogeneous environments. Section 5 delves into various adaptive energy harvesting techniques, followed by an analysis of energy management strategies in Section 6. Sections 7 and VII address communication protocols and the challenges associated with energy management, respectively. Finally, Section 8 outlines future directions and concludes the review article.

2. METHOD

2.1. Review Of Similar Works

The work of [1] proposed a scheme called TESEES to optimize energy-efficient protocols in IoT-based HWSNs. This "Threshold Enabled Scalable and Energy Efficient Scheme" TESEES protocol deployed higher levels of heterogeneity that is up to four types of sensor nodes by leveraging on the packets reporting process, eliminating redundant frequent packet transmission, and mitigating the level of energy-wasting from the nodes' sensing module and the network system. In their work, they offered a general method for establishing unique thresholds for network sensor nodes in each formulated zone, which enables each entity to configure the sensor nodes with communication settings to be modified to their respective roles that are independent of the "heterogeneity level and maintains effective data communication control by estimating "current sensor node count." Furthermore, the introduction of an enhanced TMCC algorithm that functions at the sensor node level and maintains effective data communication control by estimating "current sensor value, heterogeneous events thresholds, and previous packets record." The simulation result shows that the improved scheme performs better than the existing scheme in terms of energy conservation, lifetime maximization, and packet communication reduction by 29%, 68%, and 26% respectively.

The researchers in [2] proposed a scheme called the Advanced LEACH (ADV-LEACH2) technique, where cluster formations are carried out with the Modified Fuzzy C-Mean (MFCM) technique. In their work, the clusters are formed using the MFCM technique, and CHs are chosen using ADV-LEACH2. The cluster formations and cluster head selections are chosen at the beginning of each round. Furthermore, the MFCM technique creates a balanced cluster and balances sensor nodes' even load distribution among the cluster heads. The simulation result shows that the existing scheme performs better than the existing scheme by an average of 13%.

The authors in [3] proposed a scheme called EEHCT to minimize energy utilization in cluster formation and distribute even load across the sensor nodes to their heterogeneity level to maximize network lifetime.

Furthermore, they employed both dynamic and static clustering techniques in their network. The simulation result shows that EEHCT achieves a gain of up to 90.27% concerning network lifetime over its peers. The researchers in [4] proposed a scheme, KF-BA, configured to remove noise and data mining and gather in the network. In their work, this technique prolongs network lifetime and increases energy efficiency using the Kalman filter (KF) and the Bat Algorithm (BA). The simulation result shows that the improved algorithm performs better than the existing algorithm by 57% in network longevity.

The work [5] proposed a scheme called AASEEM that considered the network's heterogeneity. In their work, they estimate both network stability and the selection of cluster heads. The energy efficiency was achieved by clustering the network. The simulation results show that the improved scheme performs better than the existing schemes regarding network performance.

In [6] the authors proposed power optimization and hybrid data aggregation (POHDA) to mitigate limitations associated with heterogeneous wireless sensor networks. This scheme concentrated on congestion avoidance and power improvement via efficient cluster head selection by employing hybrid data aggregation due to some predefined parameters like "residual energy, mobility, threshold value of the node, and end-to-end delay." The POHDA technique estimates some parameters by comparing the simulation results with the existing algorithms like HCCS-WSN, FMCA-WSN, and APCC-WSN, which show that the improved algorithm performs better than the existing algorithms regarding energy efficiency and delivery ratio.

The work [7] proposed a scheme called improved LEACH to optimize the operations of the conventional least energy adaptive clustering hierarchy technique. Their article focused on cluster head formation and transmission energy utilization by improving performance, such as throughput and network lifetime. The simulation result shows that the improved algorithm performs better than the existing algorithm by 25% and 30% in terms of throughput and network lifetime, respectively.

In [8] the researchers proposed a scheme called SWARAM in an Internet of Things-based wireless sensor network to select the best cluster head within the cluster. In their articles, the authors approached this technique in two ways: cluster formation and selection of cluster head. These sensor nodes are grouped into clusters by using Euclidean distance before the cluster head node selection by employing the SWARAM technique. The simulation results show that the improved scheme performs better than the existing scheme by 10%, and 10% in terms of packet delivery ratio and network lifetime, respectively.

In [9] the authors proposed a scheme called the "statistical center energy efficient clustering approach" (SEECA), the responsibility of which is to maximize the network lifetime while minimizing its energy utilization. The simulation results show that the improved algorithm performs better than the existing algorithm by 32%, 16%, and 12% in residual energy, network lifetime, and throughput respectively.

In [10] the authors proposed the EE-OLEACH technique for packet transfer by a well-meaning combination of effective optimum clustering and optimal path selection technique, thereby offering energy-efficient routing in the networks. Furthermore, homogeneous Hunter-wolf optimization is employed for clustering, and a CH is selected for each cluster to minimize energy wastages and improve efficiency in using the network's available resources. Also, the PPAO technique was used to mitigate energy utilization throughout the route selection process. The simulation results show that the improved algorithm performs better than the existing algorithm by 30%, 35%, 45%, 56%, 47%, and 38% respectively.

The work [11] proposed a scheme called HarborSync to optimize network stability, energy, durability, efficiency, and congestion control. This technique implements the Optimized Stable Clustering Algorithm (OSCA) and the weighted clustering Algorithm (WCA). HarborSync offers optimized routing, dynamic reconfiguration, effective aggregation methods, and adaptive congestion monitoring. The simulation results show that the improved algorithm performs better than the existing algorithm by 6.17%, 7.811%, 6.89%, and 7.973% in LEACH, LEACH-C, TEEN, and PEGASIS, respectively.

These review articles scrutinize the existing work on Energy management protocols in Heterogeneous Wireless Sensor Networks. Most of the articles focused more on the following areas: energy efficiency, network lifetime, distance, end-to-end delay, packet delivery, and so on, by using their various clustering techniques. However, none of the articles carefully consider Adaptive Energy Harvesting Techniques, which ensure efficient energy consumption and prolong the network lifespan.

2.2. Energy Consumption In Wireless Sensor Networks

Energy consumption in WSNs is a critical key determinant affecting network performance, lifespan, and reliability. An apparent comprehension of the dynamics of energy consumption is vital for creating efficient energy management strategies, particularly in heterogeneous networks where sensor nodes display varying abilities and energy levels [26][27].

2.2.1. Components of Energy Consumption

The energy consumed by a sensor node can be broadly categorized into three primary components, and it will be briefly highlighted [28]:

Sensing:

The energy needed for data securing via sensor nodes. This comprises the power required to initiate the sensing component and process the raw data. Diverse sensor nodes utilize varying amounts of energy depending on their kind such as “temperature, humidity, motion”, sampling rates, and data processing algorithms [29].

Transmission:

One of the major vital energy drains in wireless sensor networks is packet communication, which transmits received packets from the sensor node to a base station (BS) or other sensor nodes. The energy utilization is affected by numerous factors, such as “the distance to the receiver, the data rate, and the communication protocol employed”. For example, radio frequency transmission characteristically utilizes more energy than other forms of communication, such as infrared or acoustic [30].

Reception:

The energy is utilized when a node receives packets from other sensor nodes. Unlike transmission, reception energy utilization varies based on the data rate and protocol. Although it mostly requires less energy than transmission, it still plays a vital part in the sensor nodes’ complete energy expenditure [31].

2.2.2. Factors Influencing Energy Consumption

Numerous factors play some roles in the unevenness of energy consumption in Wireless Sensor Networks, and it will be briefly highlighted [32]:

Node Density and Distribution:

The configuration of sensor nodes affects transmission distances and, consequently, energy utilization. A higher-density node enables shorter transmission paths, thereby minimizing energy utilization. However, it might also result in heightened contention and interference, negatively impacting networks’ energy efficiency [33].

Environmental Conditions:

External influences, like “temperature, humidity, and atmospheric pressure”, can affect sensor functionalities and energy utilization. For example, intense temperatures may influence battery efficiency and sensor accuracy, leading to heightened energy demands [34].

Communication Protocols:

The preference for transmission protocol plays a vital role in energy efficiency. Protocols are designed to reduce energy utilization, such as those using “data aggregation, efficient routing, and sleep modes,” which can meaningfully improve battery life. Heterogeneous networks need adaptive protocols that can dynamically regulate based on the energy levels and abilities of the involved sensor nodes [35].

Data Aggregation Techniques:

Techniques employed for minimizing the number of packets sent by aggregating information at intermediate nodes can lead to substantial energy savings. By reducing redundant transmissions, data aggregation helps save sensor node energy resources [36].

2.2.3. Implications for Energy Management

Considering the intricacy of energy utilization in wireless sensor networks, efficient energy management approaches must consider these different elements and contributing factors. Adaptive energy management schemes that are dynamically regulated to changing conditions can improve energy efficiency, mainly in heterogeneous networks where the energy levels of sensor nodes vary significantly. By applying strategies that optimize sensing, transmission, and reception, as well as harnessing adaptive energy harvesting schemes, the overall energy utilization can be meaningfully mitigated, prolonging the networks’ lifetime [37].

2.3. Adaptive Energy Management Techniques

The application of adaptive techniques will look out for individual nodes’ energy levels to prolong the network’s lifetime. Techniques such as “load balancing, duty cycling, and energy-aware routing” can enhance energy utilization and guarantee the nodes’ operation within their battery limits [38].

2.3.1. Effects for Network Design

To optimize the life of a battery in heterogeneous Wireless Sensor Networks, researchers must look out for the following strategies [38].

2.3.2. Optimized Node Placement

Tactical positioning of sensor nodes according to the energy resources available can reduce energy utilization [38].

2.3.3. Energy-Aware Protocols

Creating transmission protocols prioritizing energy efficiency can greatly enhance battery longevity [38].

2.3.4. Real-time Monitoring

Incorporating energy monitoring systems can offer insights into battery conditions, facilitating proactive energy resource management. In conclusion, the life of a battery in heterogeneous Wireless Sensor Networks is impacted by the preference for battery technology, precise life prediction models, and the inherent limitations posed by node diversity. Addressing these factors via innovative energy management techniques is vital for enhancing the lifetime span of WSNs [38].

2.4. Battery Life In Heterogeneous WSNs

Battery life is exciting in WSNs, particularly in HWSN arrangements where sensor nodes have varying abilities and energy levels. The functional and lifetime maximization of these networks heavily relies on the effectiveness of battery management, as many sensor nodes function in remote or inaccessible geographical locations where replacement of the battery is impractical. This section examines the crucial facets of battery life in heterogeneous WSNs, covering battery technologies, prediction models, and the implications of heterogeneity on battery functionalities [39].

2.3.1. Battery Technologies Used in WSNs

The preference for battery technology predominantly influences the functional lifespan of sensor nodes. Numerous types of batteries are used in Wireless Sensor Networks, each consisting of its advantages and limitations [39].

2.3.2. Lithium-Ion and Lithium-Polymer Batteries

Lithium-ion and Lithium-Polymer Batteries are widely employed because of their high energy density, lightweight nature, and relatively low self-discharge rates. These batteries accommodate significant cycles of charges, yet they are costly and susceptible to temperature fluctuations.

2.3.3. Nickel-Based Batteries

“Nickel Cadmium (NiCd) and Nickel Metal Hydride (NiMH) batteries” are choices, providing evenhanded operation and cost-effectiveness. However, they characteristically have lower energy densities compared to lithium-based batteries and undergo memory effects that can minimize their practical capacity.

2.5. Emerging Energy Storage Technologies

Emerging technologies like “super-capacitors and solid-state batteries” are being examined for WSN uses. Super-capacitors offer swift charge and discharge capabilities, making them appropriate for implementations and necessitating bursts of energy, but they usually have lower energy density. Solid-state batteries potentially improve safety and energy density, but they are still in evolving stages for practical implementation in WSNs.

2.4.1. Battery Life Prediction Models

Given an accurate prediction of battery life is essential for efficient energy management in heterogeneous WSNs, numerous models exist that aim to estimate the remaining battery life based on different parameters:

2.6. Empirical Models

These models depend on historical records and evaluated performance metrics to estimate battery life. They are relatively simple to apply but may not account for all variables influencing battery operation under dynamic conditions.

2.6.1. Mathematical Models

More refined techniques are employed for mathematical equations to designate the discharge features of batteries, incorporating factors such as temperature, current load, and cycle count. These models can provide more precise predictions but may need complex estimations and calibration. Mathematical models play a

fundamental role in estimating battery life by offering a systematic context to comprehend the characteristics of batteries in different circumstances. Here are some key mathematical models that will be used for battery life prediction.

Level of Charge (LoC) Models

A battery's Level of Charge (LoC) estimates the available energy stored in the battery relative to its total capacity. Level of Charge (LoC) is a key factor that specifies the current charge level of a given battery relative to its capacity. The LoC is evaluated mathematically as:

$$\text{LoC} = \frac{q_C}{q_M} \times 100\% \quad (1)$$

The equation (1) defines the charge level of a battery, where q_C defines the current charge in the battery and q_M signifies the battery's maximum capacity.

To comprehend why LoC estimations, employ the use of integrating the current overtime:

$$q_{\text{current}}(t) = q_{\text{max}} - \text{limit } 0 \text{ to } t \quad (2)$$

$I(t)$ is the current drawn from the battery at t .

The relationship that could exist between the Battery's capacity and its rate of discharging is been indicated that the efficient capacity decreases as the discharge current increases. Thus, it can be evaluated as:

$$C = iK \times t \quad (3)$$

Where C is the capacity of the battery in Amper-hour (Ah).

i is the discharge current.

t signifies time in an hour.

K defines the packet exponent, which varies for different batter types.

For battery life's prediction under a specific load, the capacity can be regulated using this:

$$t = \frac{C}{iK} \quad (4)$$

The above model equation will be used to determine the longevity of a battery when in operation under various current loads, accentuating that higher currents result in shorter operational times.

Mathematical models for battery life prediction in HWSNs offer vital comprehension of battery characteristics under different functional scenarios. By implementing models like LoC evaluation, the Relationship that could exist between the Battery's capacity and its rate of discharging has indicated that the efficient capacity decreases as the discharge current increases, and for battery life's prediction under a specific load, the capacity can be regulated, researchers and engineers can improve more efficient energy efficiency techniques. These models enable a better comprehension of the battery's functionalities, thereby allowing for enhanced design and function of WSNs, finally leading to improved longevity and reliability [40].

3. RESULT AND DISCUSSION

3.1. Adaptive Energy Harvesting Techniques (Aeht) In HWSNs

The need for effective and sustainable energy solutions grows as reliance on Wireless Sensor Networks (WSNs) grows, particularly in distant and energy-constrained environments. In heterogeneous WSNs, adaptive energy harvesting techniques present a possible means of improving energy management and extending battery life. By using these methods, sensor nodes can dynamically adjust to changes in energy demand and availability by absorbing ambient energy from their surroundings. The key AEHT relevant to heterogeneous WSNs are examined in this section.

3.2. Energy Harvesting Apparatus

The practice of obtaining and storing energy from natural sources, including thermal, kinetic, wind, and solar energy, is known as energy harvesting. Sensor nodes can augment their battery power through the incorporation of energy harvesting devices, which lessens reliance on conventional battery sources and increases network endurance [5]-[8].

3.3. Materials of Adaptive Energy Harvesting Techniques in HWSNs.

The review utilized various energy harvesting devices, which include the following:

3.3.1. Solar Energy Harvesting

Photovoltaic Cells: The conversion of sunlight into electrical energy is carried out using the instrumentality of photovoltaic cells. Adaptive techniques can improve the angle and orientation of solar panels based on sunlight attainability, enhancing energy capture throughout the day, such that the panels are tilted at an angle that matches the latitude of the installation site for maximum exposure to sunlight throughout the year.

Dynamic Load Matching: By regulating the load in the solar cell, the system can improve energy transformation efficiency, adapting to changing light conditions. That technique adjusts the load on a power system to improve real-time performance and efficiency.

3.3.2. Wind Energy Harvesting

Wind Turbines: Small-scale turbines can generate wind energy. Adaptive control systems can adjust the turbine's orientation and pitch to optimize energy capture based on wind speed and direction. It is a device that converts the wind's kinetic energy into mechanical power, which can then be transformed into electrical energy.

Hybrid Systems: Combining wind energy with other sources like solar and traditional fossil fuels can generate a more stable energy supply, adapting to seasonal variations in energy attainability. It benefits in many areas such as increasing reliability, optimizing resource use, lowering emissions, etc.

3.3.3. Thermal Energy Harvesting

Thermoelectric Generators (TEGs) transform temperature variations into electrical energy. Adaptive systems can improve the location and operation of TEGs based on environmental temperature changes. That device transforms heat energy into electricity using the Seebeck effect.

Heat Recovery Systems: This technology is designed to capture and reuse waste heat generated from industrial processes, buildings, or other sources to enhance energy efficiency. The system reduces energy utilization and lowers operational costs by recovering this heat.

3.3.4. Kinetic Energy Harvesting

Piezoelectric Materials: When subjected to mechanical stress or vibrations, these materials generate electricity. Adaptive techniques can optimize the positioning and loading of piezoelectric devices based on movement patterns.

Electromagnetic Generators: Utilizing the movement of magnets relative to coils to generate electricity can provide supplemental power, especially in mobile or dynamic environments.

Adaptive Control Strategies

Effective adaptive energy harvesting requires robust control strategies that respond to real-time energy availability and demand changes. Key strategies include:

Adaptive energy harvesting techniques embody a momentous progression in the energy management of HWSNs. By effectively utilizing ambient energy from different sources and flexibly adjusting to changing conditions, these schemes improve battery life, maximize reliability, and enhance sustainability. As these technologies continue to emerge, they hold the potential to revolutionize the landscape of energy efficiency in WSNs, tilting the way for more efficient and resilient sensor networks.

3.3.5. Processing

The data collected from various sensor nodes in real-time is processed using embedded algorithms designed to optimize energy usage. Adaptive energy management strategies will evaluate their effectiveness in prolonging battery life.

3.3.6. Variable

The studies considered various variables such as environmental conditions, energy consumption rates, and the efficiency of different adaptive energy harvesting techniques, which provides a comprehensive approach to examining battery life and energy management in hybrid WSNs.

3.4. Energy Management Strategies In HWSNs

Efficient energy management is vital for networks' operation and lifetime, mainly in heterogeneous environments where varying capabilities and energy resources characterize nodes. Practical approaches improve energy utilization and optimize the reliability and operation of the wireless sensor network. This

section deliberates different energy management approaches geared for HWSNs, aiming at “dynamic load balancing, adaptive duty cycling, energy-aware routing, and the integration of energy harvesting systems” [35].

3.4.1. Energy-Efficient Protocols in Heterogeneous WSNs

The concept of dynamic load balancing allocates energy utilization evenly across all sensor nodes in a Wireless Sensor Network, thereby preventing early depletion of individual sensor nodes and prolonging the network lifetime. The following are the key components to achieve the above [37]:

3.4.2. Energy-Aware Node Selection

This technique prioritizes communication via sensor nodes with higher energy reserves, reducing the risk of premature sensor node failure. This technique ensures that higher tasks are assigned to the sensor nodes with higher energy reserves and lower tasks with lower energy reserves [38].

3.4.3. Task Redistribution

This ensures that when specific sensor nodes start to experience depletion due to network activities, tasks can be reallocated to other sensor nodes that carry higher available energy. This network’s adaptability optimizes effective and efficient network operation while preserving battery life [37].

3.4.4. Monitoring and Feedback Systems:

The real-time monitoring of sensor node energy levels enables timely adjustments in load distribution, leading to efficient energy consumption across the network [39].

a. Adaptive Duty Cycling

This creates effective and efficient energy management with a strategic adoption of schemes that manage the functional phases of sensor nodes to manage energy, by activating active nodes, and putting the nodes that are not active into sleep mode, thereby conserving energy [39].

- **Dynamic Sleep Scheduling:** Sensor nodes can go to sleep or active intervals based on network conditions and traffic patterns. For example, when a network observes low data communication, sensor nodes can raise their sleep duration to save energy [35].
- **Event-Driven Activation:** A threshold can be set to activate the continuous activity of the sensor nodes; these sensor nodes can be programmed to wake up only to continue operation with specific events or stimuli by detecting a certain threshold in sensor readings. This approach minimizes unnecessary energy usage [36].

b. Energy-Aware Routing Protocols

Routing protocols play an essential role in energy efficiency by considering how packets are sent across the network. Energy-aware routing protocols consider minimizing energy utilization while maximizing packet delivery efficiency. Important features include:

- **Energy Cost Metrics:** The routing decision can be based on an energy utilization estimate, which considers the finest paths that reduce the energy cost related to data transmission. This may involve selecting sensor nodes with greater energy levels or reducing transmission distances [37].
- **Multi-Path Routing:** Employing multiple paths for packet communication can enable balanced energy utilization among sensor nodes, thereby preventing any single sensor node from early depletion. This approach optimizes reliability and extends network life [37].
- **Adaptive Routing Strategies:** With the help of real-time, Protocols can adjust routing decisions due to the current energy status of sensor nodes and dynamic environmental conditions, ensuring that the most energy-efficient routings are employed for data communication [35].

3.5. Communication Protocols For Energy Efficiency

These protocols are configured to reduce energy consumption while ensuring reliable data transmission.

3.5.1. Routing Protocols Tailored for Energy Efficiency

Energy-efficient routing protocols are vital for maximizing network lifetimes for WSNs, mainly those operating in heterogeneous configurations. These protocols are configured to reduce energy utilization by improving packet transmission routes and minimizing the number of participating sensor nodes during transmission. Key approaches comprise hierarchical routing, configuring sensor nodes into clusters, and allowing localized packet aggregation before transmission to the base station. LEACH and EARP are good

examples of this protocol, which illustrate these strategies' advantages, as they optimize energy minimization while maintaining effective communication [37].

3.5.2. MAC Protocols and Their Role in Energy Management

Medium Access Control (MAC) protocols play an essential role in managing how multiple sensor nodes access the shared communication medium, directly impacting energy efficiency. “These protocols can be grouped into contention-based and contention-free methods”. For example, Contention-based protocols, such as Carrier Sensing Multiple Access with Collision Avoidance (CSMA/CA), help mitigate idle listening and optimize channel utilization. However, contention-free protocols, like Time Division Multiple Access (TDMA), assign specific time slots to each sensor node, thereby minimizing energy wastage. The selection of the MAC protocol significantly impacts the overall energy management approach in heterogeneous Networks. Therefore, it needs careful consideration to align with adaptive energy harvesting techniques [37].

Table 1: Comparison of the existing protocols in Energy-Efficient HWSNs

Ref Pub. Year	Technic Used	Problem Solved	AEHT	Limitations
[12] 2024	SZP-H	<ul style="list-style-type: none"> Stability Life time Throughput 	No	Lack of self-optimization algorithm Lack of multi-modal energy synergy Lack of predictive energy management
[13] 2024	CPHN	<ul style="list-style-type: none"> Life time Throughput Stability 	No	Lack of self-optimization algorithm Lack of multi-modal energy synergy Lack of predictive energy management
[14] 2024	BGS	<ul style="list-style-type: none"> Life time Stability Packet delivery 	No	Lack of self-optimization algorithm Lack of multi-modal energy synergy Lack of predictive energy management
[15] 2024	GA.	<ul style="list-style-type: none"> Life time Number of Alive Nodes 	No	Lack of self-optimization algorithm Lack of multi-modal energy synergy Lack of predictive energy management
[16] 2024	K-LionER.	<ul style="list-style-type: none"> Number of Alive nodes Stability Life time 	No	Lack of self-optimization algorithm Lack of multi-modal energy synergy Lack of predictive energy management
[17] 2024	SCHSM	<ul style="list-style-type: none"> Distance Energy Density and Capacity of nodes 	No	Lack of self-optimization algorithm Lack of multi-modal energy synergy Lack of predictive energy management
[18] 2024	WHO	<ul style="list-style-type: none"> Residual energy Life time Throughput Alive nodes 	No	Lack of self-optimization algorithm Lack of multi-modal energy synergy Lack of predictive energy management

Various energy-efficient protocols have been established for heterogeneous WSNs as depicted by Table 1, each with distinct strengths and weaknesses. Comparative analyses regularly concentrated on metrics such as “energy consumption, network lifetime, distance and data delivery ratio”. For example, protocols such as BGS (network’s lifetime, its stability, and packet delivery for Energy Efficient sensor Network protocol) and K-LionER (alive nodes, stability, and lifetime as parameter metrics for energy efficient sensor network protocol). But none of the existing protocols considered Adaptive Energy Heterogeneous Technology (AEHT) for networks’ self-optimization algorithm which enables the sensor nodes to autonomously enhance their energy harvesting and utilization scheme based on real-time packets and predictions, multi-model energy harvesting combination which leverage a scenario of combining various energy harvesting schemes, like solar and kinetic energy at sensor node level, and predictive energy management using artificial intelligent to predict energy availability and utilization patterns based on historical data.

Adaptive energy harvesting techniques present a dynamic facet to energy management in Wireless Sensor Networks. Performance evaluations of energy-efficient protocols must focus on the changeability of energy sources, such as solar or kinetic energy, which can influence the dependability and efficiency of communication. Research shows that protocols that adjust to dynamic energy availability will optimize overall network performance and prolong operational lifetime when integrating energy harvesting techniques into routing decisions, thus enabling more sustainable energy utilization configurations, effectively balancing load and maximizing the lifespan of an individual sensor node.

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energy sources, such as solar or kinetic energy, which can influence the dependability and efficiency of communication. Research shows that protocols that adjust to dynamic energy availability will optimize overall network performance and prolong operational lifetime when integrating energy harvesting techniques into routing decisions, thus enabling more sustainable energy utilization configurations, effectively balancing load and maximizing the lifespan of an individual sensor node.

4. CONCLUSION

In this review article, we have scrutinized the critical facets of battery life and energy management schemes in HWSNs by leveraging adaptive energy harvesting schemes. Incorporating energy-efficient communication protocols, comprising tailored routing and MAC protocols, plays a vital role in enhancing energy utilization and prolonging network lifetime. We highlighted the significance of choosing the proper protocols to adjust to the adaptive nature of energy sources, thereby ensuring stable performance under different environmental conditions.

In addition, our comparative analysis of existing energy-efficient protocols showed essential variations in their efficiency and reliability for specific implementations. Performance assessments revealed that protocols integrating adaptive energy harvesting optimize energy utilization and improve overall network stability.

The Adaptive Energy Management techniques are the best energy scheme management in HWSNs due to their enhanced balanced energy consumption in the networks.

As WSNs linger to advance, future research should focus on developing more sophisticated algorithms and protocols that optimize adaptability to energy fluctuations while maintaining robust communication abilities. This will be important for evolving the deployment of WSNs in diverse real-world implementations, eventually contributing to more reliable and effective energy management techniques.

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