Energy-Efficient Strategies in Wireless Sensor Networks: Routing, Duty Cycling, Data Aggregation, and Energy Harvesting

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ABSTRACT

Wireless Sensor Networks (WSNs) consist of sensor nodes that collect and transmit environmental data. The primary challenge in WSNs is managing energy consumption, particularly as sensor nodes rely on limited battery power. Energy consumption is mainly driven by communication, sensing, and computation tasks, with communication being the most energy-intensive. Effective energy management strategies, such as energy-efficient routing protocols, duty cycling, data aggregation, and energy harvesting, aim to prolong the network's lifespan and improve performance. Hierarchical routing protocols like LEACH and PEGASIS, alongside data aggregation, reduce transmission load and minimize energy consumption. Energy harvesting, utilizing renewable sources like solar and thermal energy, offers a promising solution for long-term deployments. However, challenges such as variability in energy sources and the need for specialized hardware persist. Accurate energy consumption models are essential for optimizing energy use, and issues related to network scalability and security trade-offs need to be addressed for enhanced network efficiency.

Keywords: Wireless Sensor Networks, Energy Consumption, Energy-Efficient Routing, Energy Harvesting, Duty Cycling.

I. Introduction

Wireless Sensor Networks (WSNs) are composed of distributed sensor nodes that gather, process, and transmit environmental data to a central sink or base station. These networks have applications in various fields, including environmental monitoring, healthcare, military surveillance, smart cities, and industrial automation. One of the main challenges in WSNs is the management of energy resources, as sensor nodes are typically powered by batteries that have limited lifespans. Consequently, efficient energy management is crucial for extending the lifetime and performance of WSNs, especially in scenarios where recharging or replacing batteries is difficult or impossible. In a WSN, energy consumption is predominantly driven by communication, sensing, and computation tasks. Among these, communication typically consumes the most energy, as data transmission often requires long-range communication to reach a base station or to relay information to other sensor nodes. Sensing, while less energy-intensive, also contributes to the overall power usage, depending on the frequency and type of data being collected. Computation, which involves processing data either locally or at a centralized location, also incurs energy costs, albeit generally lower than that of communication. Due to the energy constraints of sensor nodes, it is imperative to optimize the network to reduce unnecessary energy consumption. One of the primary approaches to energy efficiency in WSNs is through the use of energy-efficient routing protocols. These protocols aim to minimize the power used in data transmission by establishing optimal routes that take into account the distance between nodes, node energy levels, and other network parameters. Popular routing protocols like LEACH (Low-Energy Adaptive Clustering Hierarchy) and PEGASIS (Power-Efficient Gathering in Sensor Information System) are designed to minimize energy consumption by introducing hierarchical structures, where cluster heads or aggregators collect and process data from surrounding nodes before transmission. This reduces the communication load on individual nodes and extends the overall network lifetime. Another strategy for energy conservation is duty cycling, which involves alternating between active and sleep states to reduce idle power consumption. By ensuring that nodes are not constantly transmitting or sensing data, duty cycling allows for better energy utilization and can dramatically improve the network's lifespan. Along with duty cycling, data aggregation and compression techniques are also employed to reduce the redundancy in the transmitted data. Aggregating data from multiple nodes into a single packet before sending it to the base station ensures that fewer transmissions occur, conserving energy. Energy harvesting has also emerged as a promising technique for extending the operational life of WSNs. In this approach, sensor nodes capture ambient energy from the environment, such as solar, thermal, or vibrational energy, to recharge their batteries. This approach is particularly useful for long-term deployments in remote or inaccessible locations where traditional battery replacement is not feasible. Despite the potential advantages, energy harvesting still faces challenges related to efficiency, variability in energy sources, and the requirement for specialized hardware. The efficient management of energy in WSNs also involves modelling the energy consumption of nodes. Energy models, such as the first-order radio model, estimate the energy used for data transmission, reception, and processing based on factors like the distance between nodes and the data packet size. Additionally, battery models are used to predict the remaining lifetime of sensor nodes and to design protocols that ensure energy is used effectively across the network. Despite the advances in energy-efficient techniques, WSNs still face several challenges. These include balancing the energy load across nodes to prevent early depletion in certain areas, ensuring scalability as the number of nodes increases, and addressing the trade-off between security and energy efficiency, as security protocols often consume additional energy.

II. Literature of Review

Gou, H., & Yoo, Y. (2010, April). Wireless sensor networks (WSNs) are a promising solution for monitoring both civil and military environments under hazardous conditions, where power supplies are typically non-rechargeable or replaceable, making energy efficiency crucial for network lifetime and cost. Various mechanisms, including the low-energy adaptive clustering hierarchy (LEACH) and its improved centralized version (LEACH-C), have been proposed to reduce energy dissipation. These methods employ randomized rotation of cluster-heads to balance the energy load among sensors. A new approach, partition-based LEACH (p-LEACH), improves upon LEACH-C by dividing the network into optimal sectors and selecting the highest-energy node as the cluster head for each sector using centralized calculations. Simulation results demonstrate that p-LEACH significantly enhances energy efficiency, network lifetime, and communication quality compared to traditional methods.

Nishimoto et.al. (2010, November). Energy harvesting, particularly solar energy, is commonly used to power wireless sensor networks (WSNs), but it faces challenges such as energy shortages during the night. To address this, the use of TV broadcast airwaves as an alternative energy source for WSNs has been explored. A study measured the output of a rectenna over seven days, demonstrating that Radio Frequency (RF) energy can consistently be harvested. An RF energy harvesting WSN prototype was developed to showcase the effectiveness of this method, and a duty cycle determination technique was proposed and validated through system implementation. This approach proves to be efficient for long-term measurement applications that do not demand high power consumption.

Enami et.al. (2010). Wireless Sensor Networks (WSNs) face a significant challenge in managing their limited energy resources, as their performance and longevity are closely tied to energy consumption. As a result, Dynamic Power Management approaches have garnered significant attention to reduce energy usage in sensor nodes after deployment. Recently, there has been increasing interest in leveraging intelligent tools, particularly Neural Networks (NNs), for energy-efficient WSN strategies due to their parallel computation, distributed storage, data robustness, and ability to auto-classify sensor nodes and readings. By applying NN algorithms for dimensionality reduction and predicting sensor data, communication costs and energy consumption can be minimized. These features highlight the strong compatibility between WSNs and NNs, with various research studies focusing on using NNs to reduce energy consumption in WSNs.

Wan et.al. (2011, September). Sustainable wireless sensor networks (WSNs) are increasingly utilized due to two key enabling technologies: energy harvesting and energy management. Energy harvesting from environmental sources like solar, wind, thermal, and mechanical energy provides the power supply for WSNs, while energy management techniques, including the design of MAC and routing protocols, as well as dynamic power management, focus on conserving energy within the WSN itself. To optimize WSN performance, a review of these technologies is conducted, examining their combined impact on sustainability. A case study demonstrates the integration of solar energy as a prominent energy harvesting source and investigates energy management models, including a new energy forecast model for sensor nodes and an energy distribution model in WSNs using data collection protocols.

Zhou et.al. (2011). Energy consumption is a critical issue in wireless sensor networks (WSNs), and accurately modeling node energy consumption is vital for protocol development, system design, and performance evaluation. This paper explores the energy consumption of sensor node components, such as processors, RF modules, and sensors, by analyzing their behavior in various states and during state transitions. The authors present a node energy model incorporating these components and establish energy correlations between them using an event-trigger mechanism. The model is then simulated to assess the energy consumption of network protocols, which can aid in evaluating communication protocols, node deployment, and the construction of WSN applications.

Ishmanov et.al. (2011). Wireless sensor networks consist of numerous low-cost sensor nodes with limited sensing, computation, and communication capabilities, alongside constrained battery life, which is often non-rechargeable. Due to these limitations, energy efficiency is crucial to ensure prolonged network functionality and lifespan. Energy Consumption Balancing (ECB) ensures that the average energy dissipation per sensor remains equal across the network, optimizing energy use and enhancing the network's longevity. This paper explores ECB theory and related mechanisms, providing a classification of these mechanisms by reviewing the latest research and comparing their main constraints and features.

Qiu et.al. (2011, August). Wireless Sensor Networks (WSNs) face the challenge of sensor failures due to energy depletion, hardware malfunctions, and other issues, making fault tolerance a critical concern. Existing fault-tolerant mechanisms often incur high energy consumption for failure detection and recovery or rely on additional hardware and software resources. To address this, a novel energy-aware fault tolerance mechanism, Informer Homed Routing (IHR), is proposed. In IHR, non-cluster head nodes restrict and select the target of their data transmission, resulting in reduced energy consumption. Experimental results demonstrate that the IHR protocol significantly outperforms existing protocols like LEACH and DHR in terms of energy efficiency.

Rezaei, Z., & Mobininejad, S. (2012). Wireless sensor networks (WSNs) consist of numerous sensor nodes deployed over large areas to perform local computations based on surrounding data. These nodes are powered by batteries, which are difficult to replace or recharge, making the challenge of extending the network's lifetime crucial. Maximizing network lifespan through energy minimization is a significant issue, especially since sensor nodes are often deployed in hazardous environments. This review focuses on energy conservation techniques, particularly duty cycling schemes, which are highly effective for energy saving. It also explores data-driven approaches to enhance energy efficiency and reviews various communication protocols designed for sensor networks.

Demigha et.al. (2012). Energy efficiency in target tracking applications within Wireless Sensor Networks (WSNs) has been extensively explored, but there is limited literature reviewing and summarizing these efforts. This paper aims to fill this gap by providing an up-to-date overview of the most significant energy-efficient target tracking schemes, proposing a novel classification based on the interaction between the communication and sensing subsystems on a single sensor node. The focus is on collaborative target tracking, where redundant data from multiple sensors can improve accuracy and reduce energy consumption by using limited sensing and communication ranges. Energy efficiency can be achieved through two primary methods: sensing-related and communication-related, both of which can be integrated via prediction algorithms to optimize operations. By self-organizing WSNs into trees or clusters and selectively activating nodes for tracking, energy consumption can be minimized at both the communication and sensing layers. Network parameters such as sampling rate, wakeup period, and cluster size are adapted dynamically based on the target's characteristics. The paper also explores protocols that make specific assumptions about the target nature or use non-standard hardware for sensing and provides a theoretical comparison of these schemes in terms of objectives and mechanisms, concluding with recommendations for future research.

Yan et.al. (2013). Energy consumption poses a significant challenge to the full deployment of wireless sensor network (WSN) technology. This study proposes an energy-aware sensor node design aimed at enhancing the energy efficiency of WSNs. It introduces a strategy that minimizes energy consumption both at the sensor node level and across the network. The approach includes estimating the distance between the transmitter and receiver to calculate the lowest transmission power required for data transmission. Additionally, sensor nodes are configured to enter sleep mode between measurements to conserve energy under normal operating conditions. Energy savings are further optimized by evaluating network-wide energy consumption under various configurations, selecting the most energy-efficient setup.

Karakus et.al. (2013). This review examines the impact of Compressive Sensing (CS) on the energy efficiency and lifetime of Wireless Sensor Networks (WSNs). CS enables signal sensing with fewer linear measurements by exploiting signal sparsity, offering potential improvements in energy efficiency compared to traditional methods. The study compares the energy dissipation of CS-based and conventional approaches by developing energy models and a mixed integer programming framework that considers both computation and communication costs. Through numerical analysis, it is found that CS significantly extends the network's lifetime, especially when dealing with sparse signals, and is particularly beneficial for WSNs with smaller coverage areas.

Yu et.al. (2015). This paper addresses the issue of data loss in wireless sensor networks (WSNs), which undermines their robustness in wireless data transmission processes. Traditional data loss compensation algorithms typically rely on compressive sensing and require significant memory from microcontrollers.

To overcome this challenge, an improved algorithm based on a random demodulator is introduced. This new algorithm offers several advantages, including low space complexity, fewer floating-point calculations, and reduced time complexity, making it more suitable for integration into standard nodes compared to traditional algorithms. The proposed algorithm's effectiveness is validated through a WSN developed on WiFi, with field experiments conducted on the Xinghai Bay Bridge. The results demonstrate that the algorithm successfully compensates for data loss while maintaining stable and efficient network performance.

Shaikh, F. K., & Zeadally, S. (2016). Wireless Sensor Networks (WSNs) have gained significant attention due to their widespread use in Internet of Things (IoT), Cyber Physical Systems, and other emerging fields. However, the limited energy supply remains a major challenge for WSN technologies. To address this, research is focused on designing efficient and high-performance energy harvesting systems for WSNs. This review provides a comprehensive taxonomy of various energy harvesting sources applicable to WSNs, discusses recent energy prediction models that can optimize energy harvesting, and highlights the challenges that must be overcome to develop cost-effective, reliable, and efficient energy harvesting solutions for these systems.

Ogundile, O. O., & Alfa, A. S. (2017). Wireless sensor networks (WSNs) are vital in various industrial applications, including environmental monitoring, disaster management, healthcare, surveillance, and defense. These networks rely on battery-powered sensor nodes (SNs) that are deployed in large numbers across remote areas, making energy management crucial to prolonging their lifespan. Over the years, various energy-efficient and energy-balanced routing protocols have been proposed to minimize energy consumption and evenly distribute it among SNs, respectively, to extend network lifetime. Despite several surveys reviewing these protocols, there is no clear focus on load-balanced energy routing protocols. This paper offers an extensive survey of both energy-efficient and energy-balanced routing protocols, classifying them based on their communication modes to the base station and the algorithms used. The strengths and weaknesses of the decision variables in the design of these protocols are highlighted, and future research directions for optimizing energy consumption in sensor networks are suggested.

Zhang et.al. (2018). Energy-Harvesting Wireless Sensor Networks (EH-WSNs) utilize harvested energy from the environment to extend network lifespan, but they often struggle in real-world environments due to limited energy and reduced efficiency. Existing EH-WSN studies generally operate under ideal conditions where node synchronization is maintained and energy profiles are predictable, which is rarely the case in practical applications. To address these challenges, this paper introduces a novel Intermittent Energy-Aware (IEA) EH-WSN platform. The IEA platform incorporates a double-stage capacitor structure to maintain node synchronization even in the absence of energy harvesting, and uses an integrator for ultra-low power measurement. It presents an optimized energy management mechanism for intermittent operation, covering energy management, measurement, and prediction. The platform enables synchronization of nodes under varying energy conditions, accurately measures real energy inputs, and proposes a lightweight method for energy calculation based on solar energy measurements. Experimental results demonstrate that the IEA platform excels in energy measurement and prediction with ultra-low power consumption and high reliability, confirming its superior performance in real environments.

Roy, N. R., & Chandra, P. (2019, April). Energy efficiency is a major challenge in Wireless Sensor Networks (WSNs), especially with their growing applications generating large amounts of data. A clustered WSN's energy efficiency can be enhanced by reducing the size of transmitted data. This paper proposes an energy-efficient data aggregation scheme for clustered WSNs (EEDAC-WSN), which minimizes intra-cluster communication by allowing cluster member nodes to send smaller control frames followed by detailed frames from nodes chosen by the cluster head. The proposed approach is compatible with any clustering scheme, demonstrated here with LEACH in simulations, showing significant improvements in network stability and lifetime.

Shafiq et.al. (2020). Routing in wireless sensor networks (WSN) presents significant challenges, particularly in ensuring energy-efficient packet forwarding through multiple nodes to the base station. This process must also account for the residual battery power to enhance network longevity. While existing energy-efficient routing solutions have been discussed in various surveys, a systematic literature review (SLR) is still needed to identify key problems. This paper conducts an SLR on energy-efficient routing, initially reviewing 172 papers, of which 50 were selected based on quality and relevance criteria. The review focuses on various schemes such as threshold-sensitive, adaptive periodic threshold-sensitive, power-efficient, hybrid energy-efficient, and low-energy adaptive mechanisms. The findings highlight that while energy consumption remains the most critical issue in WSN, it is often overlooked by researchers and practitioners, and addressing this gap could significantly improve energy efficiency. The paper also critiques the shortcomings of existing approaches, showing why they are unsuitable for energy-efficient routing in WSN.

Naeem et.al. (2021). Wireless Sensor Networks (WSNs) consist of multiple sensor nodes deployed in an ad-hoc manner to collect real-time data on physical phenomena, with each node being battery-powered and constrained by limited energy, which impacts network lifetime. Energy conservation is crucial in designing routing protocols to extend this lifetime, and the heterogeneity of the network—through nodes with varying energy, power, and processing capabilities—plays a key role. This study proposes a hybrid approach called Distance Aware Residual Energy-Efficient Stable Election Protocol (DARE-SEP), which combines the features of Residual Energy Efficient Stable Election Protocol (REE-SEP), Direct Transmission (DT), and Distance-Based Protocol (DP). DARE-SEP aims to optimize the transmission route from sensor nodes to Cluster Heads (CHs), incorporating network dynamics and employing multi-hop routing between CHs and sink nodes to reduce energy consumption. The results demonstrate a 10% increase in energy efficiency, thereby enhancing the network's lifespan compared to conventional routing protocols in Heterogeneous Wireless Sensor Networks (HWSNs).

Sadeq et.al. (2022). The rapid deployment of Wireless Sensor Networks (WSNs) and the integration of Internet of Things (IoT) technology have significantly expanded their application across various industries in our country. The success of WSN development depends on multiple factors, especially improvements in Medium Access Control (MAC) protocols, which are crucial for WSNs-IoT. Key considerations include reducing energy consumption, enhancing performance, ensuring scalability for large node deployments, and enabling clustering intelligence. However, many existing protocols focus narrowly on medium access handling. This review examines the latest WSN MAC protocols, exploring various methods and approaches to address performance issues such as network throughput, end-to-end delay, packet drop, and energy consumption. A comparison table is provided to highlight how these approaches and algorithms contribute to improving these key performance factors.

Pedditi, R. B., & Debasis, K. (2023). Around a third of the world’s surface, approximately 4–5 billion hectares, is covered by forests, but we are losing an additional 3 million hectares of forest cover annually. In response, researchers have intensified efforts to identify and prevent forest fires. Traditional forest fire detection methods have proven inadequate in real-time, leading to the development of wireless sensor network (WSN) technology. This paper presents an energy-aware Internet of Things (IoT)-based WSN model, named the Energy Efficient Routing Protocol (EERP), designed for forest fire detection. EERP reduces energy consumption in sensor nodes by minimizing idle listening in cluster heads and transmitting data only from sensor nodes closest to an event, eliminating redundant reporting. The model also ensures that low-energy nodes are not selected as cluster heads and uses multi-hop routes to send data to the base station. Comparative simulations demonstrate that EERP significantly reduces energy consumption in sensor networks.

Revanesh et.al. (2024). The design of wireless sensor networks (WSNs) aims to extend their lifespan, and intelligent energy management models play a crucial role in achieving this goal. By optimizing the number of sensors needed to gather environmental data, these models enhance energy efficiency without compromising data quality. WSNs, often used for monitoring and tracking, face challenges related to battery power, and various routing protocols have been developed to address these issues. Despite advancements, the problem of prolonging network lifetime while considering sensor capacities remains unresolved. This research demonstrates that the application of neural networks, including Low-Energy Adaptive Clustering Hierarchy (LEACH) and Energy-Efficient Sensor Routing (EESR), can significantly improve network efficiency and reliability. The study uses a refined version of the Levenberg–Marquardt Neural Network (LMNN) to optimize energy usage, and also highlights the effectiveness of Intrusion Detection Systems (IDS) based on artificial neural systems in detecting anomalies through optimal feature selection. Simulations show that the proposed ANN-ILMNN model outperforms existing methods.

III. Energy Consumption in WSNs

Primary Energy Consumers: In Wireless Sensor Networks (WSNs), energy consumption primarily arises from three tasks: communication, sensing, and computation. Among these, communication is the most energy-intensive task, as data transmission usually requires long-range communication to either reach a base station or relay information to other nodes in the network. Sensor nodes consume significant power to maintain stable communication channels, particularly in networks with large coverage areas. This heavy reliance on communication for data transfer leads to quicker battery depletion and shortens the network's operational lifespan.

Sensing and Computation Costs: While communication consumes the most energy, sensing and computation also contribute to overall power usage. Sensing energy consumption depends on the type of sensor and the frequency of measurements. For instance, environmental monitoring sensors might require continuous data collection, draining energy over time. Computation, on the other hand, involves processing the sensed data either locally or at a centralized server. Though computation generally consumes less energy than communication, its contribution becomes more significant as the complexity of processing increases, making the energy demands of sensor nodes multifaceted.

IV. Energy-Efficient Routing Protocols

Routing Protocols for Energy Optimization: A key approach to managing energy consumption in WSNs is through the use of energy-efficient routing protocols. These protocols aim to minimize energy use during data transmission by selecting the most efficient path based on factors like node energy levels, distances between nodes, and other network conditions. Protocols such as LEACH (Low-Energy Adaptive Clustering Hierarchy) and PEGASIS (Power-Efficient Gathering in Sensor Information System) employ hierarchical structures to organize nodes. This helps in reducing energy consumption by selecting cluster heads that aggregate data before sending it to a base station. This method ensures that not all nodes participate in data transmission, thus saving significant energy.

Hierarchical Routing and Data Aggregation: The hierarchical routing methods used in WSNs, particularly in LEACH and PEGASIS, facilitate energy conservation by reducing the number of transmissions needed in the network. By organizing nodes into clusters, energy is distributed more evenly, and the communication load is spread across different nodes. This structure reduces the number of nodes that need to transmit data directly to a base station, which would otherwise use up much more energy. Additionally, data aggregation techniques play a critical role in reducing redundancy, whereby data from multiple nodes is merged into a single transmission, further minimizing energy expenditure.

V. Duty Cycling and Data Aggregation

Duty Cycling for Energy Conservation: Duty cycling is a method where sensor nodes alternate between active and sleep states to save energy. Nodes are only active when necessary to sense data or transmit information, and they remain in sleep mode during periods of inactivity. This strategy significantly reduces energy consumption by limiting the time that nodes are powered on, particularly when no data is being generated. By having nodes sleep during idle times, the overall energy consumption of the WSN is significantly reduced, allowing the network to function for longer periods without requiring battery replacement or recharging.

Data Aggregation and Compression: Data aggregation is another effective technique for reducing energy usage in WSNs. Rather than having each sensor node send its data independently to the base station, data from multiple nodes are aggregated into a single packet. This reduces the total number of transmissions and, consequently, energy consumption. Additionally, data compression techniques can be employed to further reduce the size of the data being transmitted, further conserving energy. By reducing redundant transmissions and minimizing the amount of data that needs to be sent, these techniques play an essential role in enhancing the energy efficiency of the entire WSN.

VI. Energy Harvesting for Extended Lifespan

Renewable Energy Sources: Energy harvesting is a promising technique used to extend the lifespan of WSNs. This approach involves collecting ambient energy from the environment, such as solar power, thermal energy, or mechanical vibrations, to recharge the batteries of sensor nodes. Energy harvesting is particularly beneficial in long-term deployments in remote or difficult-to-access areas where regular battery replacement is impractical. By harnessing renewable energy, WSNs can operate autonomously for extended periods, significantly reducing the need for manual intervention and ensuring continuous data collection in hard-to-reach locations.

Challenges of Energy Harvesting: Despite its advantages, energy harvesting presents several challenges that need to be addressed for it to be effective in WSNs. One of the main issues is the variability in the availability of renewable energy sources. Solar power, for example, is dependent on sunlight and may be ineffective in cloudy or shaded environments. Similarly, other forms of energy harvesting, such as thermal or vibrational energy, may not always provide a consistent power supply. Furthermore, sensor nodes require specialized hardware to harvest and store energy, which can increase the overall cost and complexity of the network. Nevertheless, ongoing advancements in energy harvesting technologies continue to improve their feasibility and efficiency for WSN applications.

VII. Result and Analysis

The results show that PEGASIS outperforms LEACH in energy efficiency due to reduced communication overhead. Duty cycling significantly affects energy consumption, with lower duty cycles conserving energy. Energy harvesting extends network lifetime, though its effectiveness is influenced by variability.

Transmission consumes more energy than reception, underscoring the need for optimized communication strategies in energy-constrained WSNs.

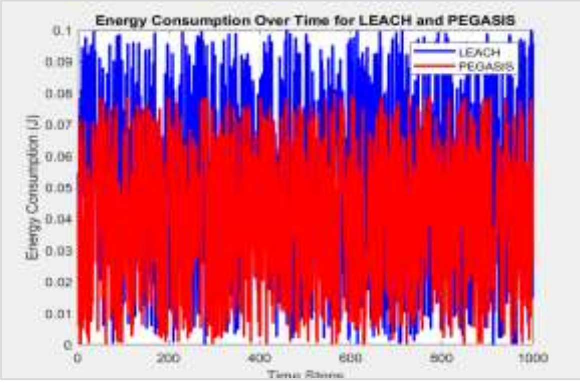

Fig. 1: Energy Consumption Over Time for LEACH and PEGASIS

This graph compares the energy consumption over time for LEACH and PEGASIS protocols. LEACH shows slightly higher energy usage due to frequent communication overhead, while PEGASIS, with its hierarchical structure, consumes less energy. This visualization highlights the efficiency of PEGASIS in reducing energy consumption in WSNs.

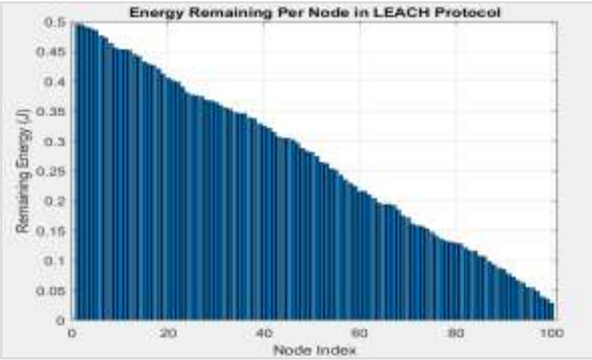

Fig. 2: Energy Remaining Per Node in LEACH Protocol

This bar chart displays the remaining energy of each node in the LEACH protocol after multiple communication rounds. Nodes closer to the sink or those with frequent transmissions show reduced energy levels. The graph illustrates the effect of network load and proximity to the sink on node energy depletion.

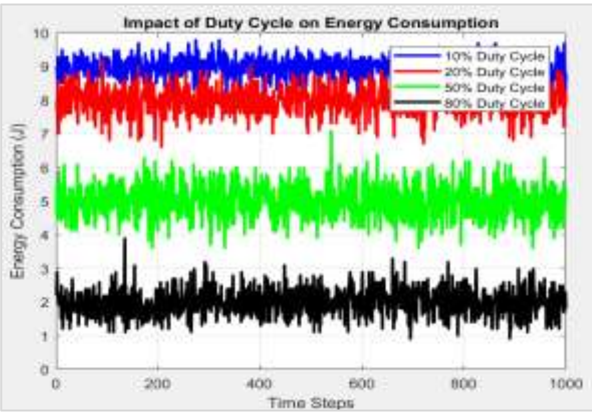

Fig. 3: Impact of Duty Cycle on Energy Consumption

This plot illustrates how varying duty cycles (10%, 20%, 50%, 80%) impact energy consumption in WSNs. Higher duty cycles increase energy usage as more nodes stay active, while lower duty cycles reduce energy consumption by allowing more sleep periods, optimizing power efficiency for long-term deployments in sensor networks.

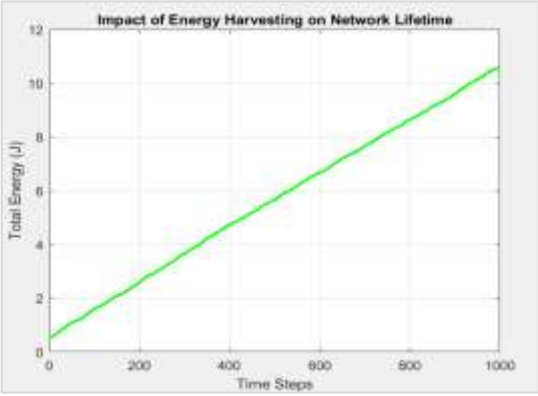

Fig. 4: Impact of Energy Harvesting on Network Lifetime

This graph showcases the impact of energy harvesting (e.g., solar) on the total energy available in a WSN. By introducing energy harvesting, the network's lifetime extends, as nodes can replenish their energy. However, harvested energy remains variable, indicating the challenges of maintaining a stable energy supply for continuous operation.

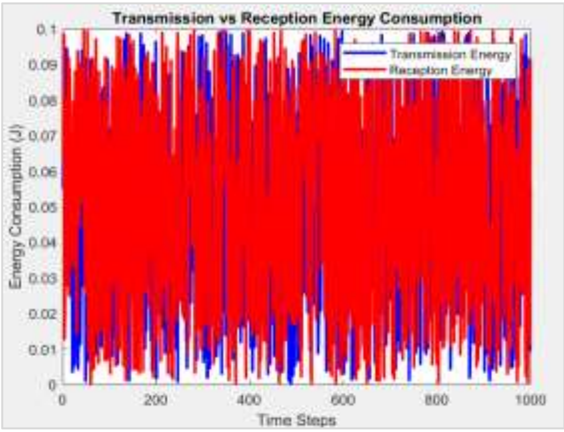

Fig. 5: Transmission vs Reception Energy Consumption

This comparison graph highlights the energy consumption during data transmission and reception in WSNs. Transmission generally consumes more energy than reception due to the high power required to send data over long distances. The graph emphasizes the importance of minimizing transmission frequency to reduce overall energy consumption in sensor networks.

VIII. Energy Models and Network Challenges

Energy Consumption Models: In WSNs, accurately modelling energy consumption is vital for developing strategies to optimize energy use. The first-order radio model is commonly used to estimate the energy required for data transmission and reception. This model considers factors such as the distance between nodes, the size of data packets, and the transmission power. By understanding these factors, WSNs can be designed with energy efficiency in mind. Battery models are also important in predicting the remaining lifetime of a sensor node based on its energy usage patterns, enabling more effective management of energy resources within the network.

Network Scalability and Security Trade-offs: WSNs face several challenges as they scale, including maintaining energy efficiency as the network size grows and ensuring that energy consumption is balanced across nodes to prevent early depletion of batteries in certain areas. Additionally, security measures such as encryption and authentication protocols often introduce additional energy overheads, as they require extra processing and communication. Balancing the trade-off between security and energy efficiency is a critical challenge, as more secure networks tend to consume more energy, potentially compromising the overall performance and lifespan of the WSN. Therefore, ensuring scalability while addressing security concerns without overly taxing energy resources remains an important area of research in WSN energy management.

IX. Conclusion

Efficient energy management is crucial for the success of Wireless Sensor Networks, especially in scenarios with limited access to power sources. Through engaging energy-efficient routing protocols, duty cycling, data aggregation, and energy harvesting techniques, the operational lifespan of WSNs can be significantly extended. However, challenges related to energy source variability, scalability, and the balance between security and energy efficiency need further exploration. The continuous development of energy models and strategies for optimizing energy usage will play a key role in advancing WSNs, making them more sustainable and applicable to a broader range of real-world applications.

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