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# Integrated Energy Distribution and Management Techniques in Wireless Sensor Networks for Sustainable Operations

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**Abstract:** A WSN refers to networked systems of autonomous sensors (also known as “motes”) that are distributed over a certain region and which collect information about the physical or environmental conditions at different locations. One of the most crucial issues in WSNs is an efficient energy resource management for battery powered nodes to maximize the network liveliness, and assure a reliable operation. The differences in energy consumption particularly between the nodes that are close to base station cause the following problems: a) spy network energy depletion tends to be too early, b) the network becomes fragmented and c) coverage holes are discovered. In this paper, different forms of energy distribution schemes from the source nodes to the destination in order to reduce energy consumption among the sensor nodes are examined. The original methods such as clustering and routing, its energy saving tries (duty cycling, data aggregation), and power saving all follow in the footsteps of balance and minimize of the communication overhead of energy consumption. Emerging techniques such as energy harvesting and wireless power transfer, provide hope to charge the nodes autonomously and to prolong the network lifetime even more. The research suggests there exists a trade-off among behavior of aggressive energy conservation and communication reliability, indicating the importance of adaptive protocol so that these conflicting requirements can be compromised. Ongoing research is motivated mainly by desired new applications for environmental monitoring, healthcare, industrial automation, and military surveillance, that require increasingly efficient and reliable energy management. This survey emphasizes the role of integrated energy distribution approaches to ensure a sustainable, scalable and maintenance-free operation of WSN deployments.

**Keywords:** Wireless Sensor Networks, Energy Distribution, Energy Harvesting, Energy-Efficient Routing

## I. INTRODUCTION

Wireless Sensor Network (WSN) has a large number of spatially distributed sensing devices which work together to monitor and report the natural or physical conditions. These sensor nodes often run on batteries and are deployed in unusable or hostile environment where battery replacement or recharging is too burdensome. Therefore, the energy limitations of each sensor node that directly affect the lifetime and functionality of the network are emphasized. Thus, maintaining long-term and high-quality networks' operations require efficient power management and distribution in time among nodes in WSNs. According to Jha and Maurya (2015), Energy Distribution Network in WSN refers to the policies and techniques adopted to distribute and preserve the limited energy resources amongst sensors. Because sensor nodes near sink or base station have a high communication load caused by data handover, the imbalanced energy consumption easily leads to energy holes and network fragmentation. This imbalance may also cause significant deteriorations in the performance of a network or even earlier network failures.

To contend with these challenges, several energy-efficient protocols and mechanisms have been proposed such as adaptive clustering, energy-aware routing, duty cycling and load balancing. These methods try to balance the energy consumption, reduce the redundant communication overhead, and prolong the lifetime of sensor nodes. Moreover, new technologies like energy harvesting and wireless power transfer provide good alternatives to increase node energy. developing an efficient WSN Energy Distribution Network, which aims to balance energy-saving, reliability for communications and adaptability to network conditions. It is still a very important research and development topic, particularly as WSNs becomes more and more applied to such areas as environmental monitoring, industrial automation, military surveillance, and smart cities. ***(Hajian, et.al. 2025)***

**1.1 Overview of Wireless Sensor Networks (WSNs)**

WSNs comprise numerous spatially distributed autonomous sensor nodes, which work conjointly for monitoring and recording environmental/physical conditions (temperature, humidity, pressure, movement, sound, pollution etc.). These so-called sensor nodes are typically endowed with sensing, processing, and wireless communication components, which make them capable of measuring data and sending over the network 2 to a centralized base station (sink) for processing and analyzing.

A sensor network is an infrastructure comprised of sensing (measuring), computing, and communication elements that gives users the opportunity to observe and react to phenomena in the physical world and the cyber world. The nodes in sensor networks are small, with a low cost, and constrained power supply (e.g., batteries). These nodes are wire-lesses and communicate over radio frequency creating multi-hop network environment where data are transmitted over different hops of forwarding nodes and reach the sink.

WSNs have a broad range of applications in various fields, including environmental monitoring (e.g., forest fire detection, air pollution measurement), industrial automation (e.g., remote machinery condition monitoring), health (patient vital signs monitoring), military (surveillance), smart agriculture, and smart cities infrastructure. Due to its flexibility, ease deployment and scalability, WSNs are particularly suitable for harsh, dangerous or human inaccessible environment.

Although they have their own advantages, WSNs are confronted with a number of problems, such as limited energy of sensor nodes, which directly determine the lifetime and the reliability of a network. Energy-efficient data transmission, energy conservation, and fault tolerance are significant issues while forming a WSN. Further, because nodes may act unsupervised, each of them should be self-organizing, routing dynamically and able to accommodate to environmental and behaviour changes and node failures. ***(Sharma, et.al 2025)***

**1.2 Energy Constraints in Sensor Nodes**

Energy scarcity is one of the most challenging issues in Wireless Sensor Networks (WSNs). Most sensor nodes are battery operated devices with limited energy supply, and in most field, we cannot replace or recharge batteries. This energy constraint has a direct impact on the lifetime, reliability, and throughput in the network. There are several activities in a sensor node which consume most of the energy: sensing, data processing, and wireless communication. Of these, wireless communication including data reception and transmission account for the greatest proportion of energy. Nodes that are close to the base station or sink tend to forward not only their own data but also that of others, resulting in imbalanced energy consumption. Thus, “energy holes” are created regions in the network which nodes run out of energy before their neighbors do and the network conglomerates and the connectivity deteriorates.

In addition to communication, sensor nodes consume energy in sensing the physical phenomenon and processing the sensed data. While this takes less energy than transmission, power-consuming processing and unnecessary sensing may speed up battery exhaustion. In addition to this, the idle listening (idle listening occurs when the nodes keep their radios on to wait for data) also results in a substantial amount of energy waste. Power limitations demand high standards from protocol design in all network layers, from physical to application. Energy can be saved by means of strategies such as duty cycling, i.e., having the nodes sleep periodically and wake up occasionally. In the same line, energy efficient routing protocols aim at spreading the energy consumption of nodes, in order to avoid early draining of a subset of nodes. The limited energy capabilities also affect the scalability and deployment density of WSNs. Higher density of nodes can improve network reliability but also increase energy consumption because of higher communication overhead. Consequently, it is crucial to deal with the energy scarcity in a WSN due to the efficient management and optimization, in order to extend network lifetime and guarantee durable WSN operations. ***(Singh, et.al 2025)***

**1.3 Significance of Energy Distribution**

Energy balancing is a crucial factor for the efficiency and lifetime of WSNs. Considering that sensor nodes are powered by battery supply, efficient energy management is fundamental to prolong the lifetime of the whole network and to maintain long-term sustainability and reliability of monitoring operations. Nonuniform power consumption between nodes may induce early failure of critical parts in the network, leading to data inaccuracy and disruption in communication flow. The importance of energy distribution is mainly equalizing the energy consumption of all sensor nodes. The nodes that are nearer to the base station or sink node have to forward the data of more sensors (load), and their batteries are rapidly drained. The resulting inhomogeneity can lead to “energy holes,” since energy holes partition the network and cause coverage holes that chunk out parts of the sensing field which are no longer accessible. Such devastating network failures are averted by ensuring that the network remains connected, and that energy consumption is balanced.

Node energy is preserved by the energy-efficient distribution approaches, which also decrease the redundant data transmissions and save the communication overhead. A few of which includes protocols that maximize routing based on residual energy, sleeping schedules that alternates between sleep and active node states, and clustering schemes that circulate leadership using the nodes, to mention but a few**.** Efficient network performance is closely associated with the way energy is conserved and distributed. If selected sensor nodes are out of energy, they can neither sense nor forward data, which will reduce the quality of real-time and data fidelity. Thus, the energy distribution procedures ensure the trustworthiness operation of sensed data and the QoS. Also, the use of energy-efficient energy distribution makes WSN scalable to serve extensive areas with high node density, yet without sacrificing lifetime and performance. WSN Applications are becoming more sophisticated and energy distribution is still a core consideration to provide robust, lasting and reliable sensor networks ***(Yilmaz, 2024)***.

### 1.4 Unequal Energy Consumption Issue

One of the main problems on WSNs is the unbalancing of energy among sensor nodes which may compromise the network lifetime and functionality. In communi cation, the nearer the base station/sink the nodes are, the more messages are generated for commu nication, since in addition to their sensed data, they forward data packets from nodes that are far away. This augmented relay load drains out the very constrained battery power of these nodes much faster than those located at the periphery. As a result, these nodes get to consume their energy earlier and then near their death, forming "energy hole" or "coverage hole" in the network ***(Elmonser, et.al. 2024).*** Such energy gaps result in data transmission pathways being constantly broken, which can cause the network division and the loss of connections as well as the decreased overall sensing coverage. Such an energy-football balance process leaves severe trade-offs, particularly for one that aims at running continuously and reliably. Also, uneven energy consumption makes it difficult for network maintenance, because it is not practical to replace or recharge the batteries in those places that are hard to approach or dangerous. To address this problem, energy-aware protocols and load balancing algorithms have been proposed to balance communication load, balance role communication like cluster heads among nodes evenly and route with a consideration of residual energy. Solving the unequal energy consumption is therefore crucial in extending network lifetime and preserving data correctness while also contributing to robust and sustainable WSN operation ***(Han, et.al. 2024).***

### 1.5 Energy-Efficient Strategies

Designing energy efficient Wireless Sensor Networks (WSNs) is a key goal for lifetime elongation as well as to enforce standard performance. Because the energy of sensor nodes is limited and we ca n't put up doing replace battery frequently, a number of approaches have been proposed to reduce energy consumption in WSNs. These methods try to minimize the use of energy in data acquisition and communication. Cluster-based methods One popular way of organizing nodes is clustering, where fusion nodes are in charge of capturing and forwarding data to the fusion centre ***(Sun, et. al 2023).*** Protocols such as LEACH (Low-Energy Adaptive Clustering Hierarchy) rotate the position of cluster head among the nodes, which balances the energy consumption and prevents predilection of certain nodes. Clustering eliminates data redundancy, and reduces communication distance, then leads to save more energy.

**Energy-conscious routing protocols** choose transmitting paths according to the remaining energy and link quality of the nodes to prevent energy drain of low energy nodes. These dynamic protocols adjust according to changing network state and traffic load, thus avoiding early nodes death. Techniques such as duty cycling and sleep scheduling are employed in which the sensor nodes periodically wake up (active state) and go to sleep (low-power mode). Duty cycling conserves energy remarkably well by cutting down on idle listening and useless transmissions. Synchronized sleep schedule-based protocols, such as S-MAC and T-MAC, ensure the network connectivity and reduce the energy wastage.

Other techniques are data compression and aggregation that decrease the amount of data sent by aggregating and processing information from sensors in a close-by way, as communication energy costs are also reduced. New approaches, such as energy harvesting have nodes recharged with renewable energy -solar or vibration- to complement their power. it is the inclusion of such energy-efficient techniques that allows WSNs to be long lived, resource adaptive and capable of robust monitoring in a variety of applications ***(Rodriguez, et.al. 2023).***

### 1.6 Emerging Energy Solutions

The energy-constrained nature of battery-operated sensor nodes has led to the emerging of new energy solutions to improve the sustainability and adaptability of Wireless Sensor Networks (WSNs). Mainly Depending on limited battery energy has prevented networks from good performance and long operational lifetime, specially in remote or difficult conditions. As a response to this, new technologies such as energy harvesting and wireless power transfer are developed to replenish or reinforce node energy independently.

**Energy harvesting** is a way to harness ambient energy from the environment and transform it to electrical power that sensor network nodes may use. Typical sources include, for example, solar irradiation, temperature variation, mechanical vibration, wind, and radio frequency (RF) signals. Among these methods, solar-energy harvesting is one of the most well-established owing to its abundant source and relatively high-power density. When miniaturized energy harvesters, such as those considered in this paper, working with sensor nodes are used, a continuous or regular energy supply can be obtained, so that the network life can be much prolonged without human intervention ***(Misbha, 2023).***

**Wireless Power Transfer (WPT)** techniques offer another promising solution; they can wirelessly deliver power to sensor nodes from power sources. Various techniques (e.g., inductive coupling, magnetic resonance, and RFbased power transfer) allow nodes to reenergize batteries or supercapacitors without physical connections. WPT is especially suitable for applications where energy harvesting conditions are either adverse or variable. Such exciting developments not only alleviate the energy restrictions but also make it possible to deploy the WSNs that are more reliable and can do away with maintenance. The energy harvesting and wireless power transfer integrated with intelligent energy management protocols to optimally consume the harvested energy and maintain the network operations. It is anticipated that they will become an essential bottom layer in sustainable and self-powered WSNs for various purposes as these technologies mature in the near future ***(Zulfiqar, et.al. 2023).***

### 1.7 Balancing Energy and Network Performance

In WSNs, the closely related issues of energy and communication reliability are the core concerns. However, as a principle of restricting both energy resource and bandwidth, conservation of energy should not deteriorate the performance and data fidelity of the network. Hence the need to design protocols and systems that are energy efficient while preserving a reliable means of communication is fundamental to successful WSN operation. Energy saving usually means shortening communication operations because wireless communications consume the most energy in sensor nodes. Methods like duty cycling that make the nodes switch between sleep and active states, mitigate the energy consumption on idle listening ***(Kuthadi, et.al 2022).*** But, excessive duty-cycling can lead to latency and lost packets, which would degrade the real time responsiveness of the network. Likewise, data aggregation and compression allow less data transmissions resulting in less energy consumption but also in information loss if not well-controlled.

Routing protocols should also trade-off between network life and reliability. The energy-aware routing pathway should route traffic through the path where its total energy consumption over the whole network would be as minimal as possible and it would not overburden the nodes with little remaining energy. But these paths can occasionally be further or less stable than desired, which can cause greater transmission errors or delays. The consideration of measurements such as link quality and node stability supports robustness together with the energy saving. Furthermore, the adaptive protocols that can adjust their parameters depending on network conditions are even able to achieve a better compromise between these two antagonistic constraints. For example, boosting transmission power in critical data forwarding, or occasionally reducing sleep interval improves dependability when necessary (but with higher energy consumption) ***(Mishra, et.al. 2020).***

After all optimal trade-offs require a comprehensive solution approach that takes energy efficient hardware design, smart communication protocols, and context aware adaptation into account. By properly balancing this trade-off, WSNs are able to perform realiably over time and maximize their lifetime mission, enabling a wide variety of critical applications (i.e., environmental monitoring, health care, industrial automation, etc.)

### 1.8 Applications Driving Energy Efficiency Research

With its ever-increasing application of WSNs in various domains; energy efficiency is becoming a hot research topic. The network long lifetime, reliable data transmission and the least maintenance are required by many applications, making energy management necessary for practical applications and long-lasted operation. Currently, the most common application for WSNs is environmental monitoring, and data gathered by these WSNs includes information regarding temperature, humidity, pollution, seismic activity. These deployments are often made in inaccessible or hostile environments that make battery changeout difficult, and all but require low-power protocols to be used for months to years ***(Pavithra, 2019).***

In the industrial automation field, WSN are used for monitoring health of machinery, fault detection, and process optimization. Here, reduced downtime and maintenance costs are translating directly to energy efficiency, when nodes are situated in machines or harsh environments, where they need to run autonomously for a long period of time without human interaction. Healthcare services use WSNs to monitor patient, collecting live patient's vital and physiologic data. Wearable or implantable sensors need ultra-low power consumption for maximum patient comfort and longevity of devices, and hence, energy-aware designs and communication schemes have been investigated.

The militaries and security organizations employ WSNs for field monitoring, intrusion detection, and assets tracking. They should also be work reliably and securely under energy limitations and with real-time traffic. Otherwise, making traffic divided by secure and real time, a requirement of energy-saving, robustness protocols would be pushed to be invented. Applications such as smart city and smart agriculture also need energy-efficient WSNs for traffic control, resource management, and precision agriculture. With dense deployment and largescale coverage, the trade-off between the power consumption and the network performance is paramount. Taken together these various application areas underline the need to continuously explore new energy management methods, hardware improvements and adaptive communication protocols that can optimize the overall energy use, yet preserve the reliability of WSNs, thereby allowing them to reach their transformative role in different domains ***(Zhang, et.al. 2022).***

## II. RELATED REVIEWS

**Hajian et al. (2025)** had explored the persistent challenge of consolidating the Internet of Things (IoT) with Software Defined Networks (SDN), recognizing the Wireless Sensor Network (WSN) as a vital communication component within IoT. They also observed that the tremendous amount of data in IoT along with the limitations of WSN have made the load distribution a big issue. It was suggested that Base Stations (BSs) operating in these networks would suffer from substantial delays on account of the computation overhead and that delivering data to users on time would still be crucial in this context. So they'd said that not just load balancing, but response time was the key. How To overcome this problem, we had suggested to distribute loads between several BSs, taking into account that BS relationships with network nodes and to prevent their overload via common nodes between the BSs [1], [2]. They had addressed how to manage a common node in a cluster to balance its load to other BSs using load balancing node-finder algorithm. In addition, they used load transfer through forwarding node which was mentioned in the proposed routing process. Coloured Petri Nets (CPNs) were used to model their approach, evaluating parameters including queue length, residual energy, nodes, BSs, and delay under three scenarios. Their results showed that the designed SDN based algorithm had reduced the residual energy, queue length and delay to 18%, 9.5% and 35%, respectively, showing great performance in load balancing in terms of nodes and BSs.

**Sharma et al. (2025)** had explored the significance of wireless sensor networks (WSNs) in fields like environmental monitoring, healthcare, and smart cities while highlighting the persistent challenge of limited battery life affecting energy efficiency. They proposed a novel method using Spotted Hyena Optimization (SHO) for cluster Head optimization in WSNs to maximize network life time and to minimize energy consumption. It was claimed that the SHO algorithm is dependent on the hunting behavior and social hunting life of the spotted hyena and it integrates the searching and exploitation in the clustering algorithm to select the right cluster heads and this causes lowering the energy consumption and promoting the transmission to the network. Authors have compared performance analysis results of the present clustering technique (MATLAB) with the existing ones such as TEEN, LEACH, LEACH-SF, DEEC, and found that energy distribution among sensor nodes can be even, the network lifetime and deployment cost can be minimized by 2% and 4% respectively, the death rate get minimized by 4%, and the energy efficiency also become 3% and of course better than them. They had, however, pointed out a few limitations of SHO (sensitive to local optima, computational complexity is large for large-scale networks and parameters need fine tuning), which they expected to improve in future work. They deduced that the SHO approach permits to delay the death of nodes, the first node dies after 1300 rounds and half of the nodes dies after 1425 round while other metaheuristics methods did not have the first node to die after more than 1500 rounds. In the same setup, 0.50 J energy was consumed up to 1350 round whereas other algorithms had already done so way earlier also demonstrating the efficiency SHO in energy maximization and obtaining better network lifetime, thus, we can implement the same in near future low energy WSNs and wireless communication.

**Singh et al. (2025)** had examined the challenges posed by high energy consumption in wireless sensor networks (WSNs), where each node contained multiple sensors for environmental data collection. They claimed that the energy-constraint capability of such nodes made the optimization of routing algorithms as being critical for prolonging the network lifetime and improving the network performance. The focus of their work was to develop an Energy-Efficiency Optimization and Trust-Based Secure Routing protocol (EEOTSR), as a solution for energy-efficient routing techniques and trust-based security approach in an ACO environment. This biologically inspired work was also meant to replicate the ants pheromone-based path selection for the dynamic determination of the optimal path routing while checking security. The protocol was based on a distributed trust model for recognition and isolation of compromised or malicious nodes, thereby enhancing the general resilience of the network. The authors reported had done simulation on which EEOTSR increase the network lifetime 23%, increase the packet delivery ratio 17% and decrease the average latency 14 % as compared to those of existing protocol. Furthermore, the protocol has shown the great resistance to the BH (blackhole) attacks, with the packet delivery ratio of over 90% in the BH compromised level of 30%. This combination of features made of EEOTSR a promising and viable framework to enhance the performance and security of WSN in industrial systems.

**Yilmaz and Dener (2024)** had explored Smart Grids as a domain where next-generation technologies, applications, architectures, and approaches had been utilized to equip and manage electrical systems through information and communication technologies. They had emphasized that by developing data-driven methodologies and integrating them with Internet of Things (IoT) applications had now been identified to have become major characteristics of Smart Grids. Cartesian musings had noticed that such a dynamic system was born from symmetrical aspects that tran- scended the advanced technologies of systems. Their survey had stated that symmetrically combining Wireless Sensor Networks (WSNs) with energy harvesting techniques had contributed to improving robustness and reliability and also forming a uniform and coordinated energy management system. It had been pointed out that WSNs have unique advantages in residential applications such as energy saving, economy, and reliability, spanning from power generation, and distribution at one side, monitoring, and control management at the other side covering measurement, demand response, pricing, fault detection, and power automation. The lawmakers had emphasized that Smart Grids were critical infrastructure, and not securing them from a cyberattack could result in national security vulnerability, law and law and order disruption, loss of life, or even significant economic disruptions. They had therefore emphasized the need for a solid cybersecurity to be developed for Smart Grids. Their research had compiled literature on "Cybersecurity with WSN in Smart Grids" by performing a systematic review of literature and provided insights for the applications, challenges & standards and recommendations for further research aligned with symmetrical design principles.

**Elmonser et al. (2024)** had examined the influence of heterogeneous wireless sensor networks (WSNs) on wireless communication systems, particularly within the context of Internet of Things (IoT) enabled smart grids. They had proposed a novel strategy for the equitable scheduling of energy and computational sources to SNs, which was considered as a key to extend network lifetime, improve performance, and enhance smart grid stability. Their work had emphasized the importance of the initial energy and processing capabilities of sensor nodes. Even though hierarchical clustering techniques have been known as a successful solution in WSNs, the authors had also mentioned that it was still a problem to find the optimum routing protocol in WSNs by large scale deployment. For energy efficiency and network lifetime enhancement, they had suggested the incorporation of the HDM technique with the LEACH protocol (IoT Smart City applications). The HDM model was conceived to couple multi-hop communication and dynamic hierarchical clustering, differentiating between regular nodes and high-tier nodes on the basis of their energy status so as to maximize the probabilities for the choice of CH. Their approach was a comparative study between the HDM protocol and LEACH on heterogeneity (H-LEACH) in terms of energy efficiency and network lifetime. The performance had shown that the HDM protocol had consumed less amount of energy by fifty percent over 4600 rounds compared to H-LEACH which did so for 3000 rounds. Impact These results had profound implications for WSN deployment in smart grid use cases, and a more sustainable and robust urban IoT ecosystem.

**Han et al. (2024)** had aimed to address the issue of non-uniform energy consumption in wireless sensor networks by proposing a weighted scale-free topological evolution model incorporating localized energy isomers. The relationship between node energy, load, and energy consumption had been simulated, and then the relationship of node energy, strength, and weight had been modeled. In addition, the work in [26] designers proposed a power law characteristic based wireless sensor network energy balanced topology control algorithm according degree distribution, node weight and edge weight distribution, thus that whole network energy balanced by controlling the energy parameters. According to the intensities and weights of the topology, they had calculated the propagation index of node importance through two levels global and local to avoid the one-sided of one's property. Furthermore, they have proposed a multi-attribute decision function for the influence indicators of neighbouring nodes (Katz), W-MDD and W-PageRank. This multi-attribute decision function was further transformed by the TOPSIS method into a multi-attribute weighted decision matrix, so that the importance index (weight) of network nodes can be determined according to the distance from them to the good-bad solution. Their simulation studies have shown that the proposed model is able to accurately evaluate the load of nodes and edges and plethorically mitigate the problem of power imbalance in scale-free networks. Furthermore, the designed critical node decision algorithm had been proved to be more effectual than the single decision algorithm.

**Sun et al. (2023)** had explored the application of wireless sensor network (WSN) technology within smart distribution grids (SDG), recognizing that SDG environments imposed strict requirements on communication delays. They had observed that dynamic interference factors such as the competition for channel access, variations in transmitting powers and node failures had a strong influence on WSN delay and that the traditional offline optimization approaches were inappropriate. They also noticed that the online optimization methods based on reinforcement learning (RL) would suffer from problems such as dimension explosion and slow convergence. To this end, the authors had previously suggested a dynamic cooperative optimisation model optimising both end-to-end delay and power in WSNs under a group RL model. First, they created an environment model to evaluate an optimization objective value, and then reward of the RL algorithm was calculated using it. They had also proposed a new approach for grouped RL to speed convergence without the loss of effective exploration in the presence of high-dimensional action spaces. They sought to adapt the transmitting power of each node by iterative learning so as to minimize the tradeoff between end-to-end delay and power consumption. Their simulations had shown that this algorithm was able to satisfy the SDG delay constraints and still have low energy consumption, an end-to-end delay reduction of up to 20.3%, as well as a decrease in the computational cost between 6.2 and 52.7% with respect to two other RL algorithms.

**Rodriguez et al. (2023)** had examined the transformation of conventional electric power grids into smart grids, emphasizing the necessity of integrating advanced instrumentation, automation, and communication technologies to enhance their efficiency, safety, and reliability. They had noticed that traditional grids had kept communication and control inside the substation which limited their operations to mostly power plants and other high-voltage structures. As Distributed Generation (DG) resources were increasingly deployed throughout the grid, the creation of a bi-directional power flow had required more advanced monitoring and control functionality at the Transmission and Distribution (T&D) level, which was the largest part of the grid. The authors claimed that it was essential for ICT to be used as a tool to control energy flows efficiently and to enhance consumer participation in demand-side management. They had proposed wireless sensor networks (WSNs) as potential technology to facilitate communications in the distribution network, but observed that how to choose appropriate technologies among the existing ones was still an open issue. In their paper, they had discussed various wireless communication technologies and compared them against their robustness, reliability, speed, scalability and cost-effectiveness for monitoring of distribution lines. They had also proposed a smart grid communication architecture, characterized sensor network requirements under power line conditions, and surveyed previous research that compares technologies. In the end, we had hoped to be able to chart the current technological terrain and signal potential future research avenues in this space.

**Misbha (2023)** had examined the persistent challenges faced by Wireless Sensor Networks (WSNs) due to their open, expansive, and resource-constrained nature, highlighting major concerns regarding energy consumption, efficiency, and security. The survey noted that a variety of lightweight cryptographic algorithms had been developed in an attempt to provide a compromise between security and efficient energy usage and other resource consumption, whereas these proposals remained challenged by issues such as scalability, key management, security gaps as well as power profiling. To overcome these vulnerabilities, the author also suggested a novel low-cost key distribution scheme, to secure communications while avoiding energy consumption. The above framework used optimal Cluster Head Selection (CHS), enhanced the Elliptic Curve Cryptography (ECC) based encryption scheme and developed a lightweight key management mechanism. The work was in its early work and developed a hybrid optimization model called Coot updated Butterfly algorithm with Logistic Solution Space algorithm (CUBA-LSS) for finding the optimal CH by taking into account parameters like RSSI, energy availability, delay, and distance. In the second phase of data transfer, Secure message delivery was implemented using Improved ECC, during the last phase of presentation and to provide security to encryption key a lightweight key management system was presented based on session key generation.

**Zulfiqar et al. (2023)** had investigated the crucial role of sensor node distribution in mobile wireless sensor networks (WSNs) for enhancing their functionality. They had also noted that previous work addressed existing or hybrid algorithms that focused on optimizing either energy or network coverage but not both, while also minimizing equipment costs. Their research had proposed a new bio-inspired ruminant algorithm, which based on the volumetric consumption of crude foods and how that mimics the volumetric consumption of energy sheets in the salient sheet of powders in natural systems. The algorithm had already been tested on few benchmark functions. "Based on the biological inspiration, they claimed that the proposed algorithm could enhance the network coverage and the energy efficiency both at the same time in WSNs resulting in life span elongation of the devices." Furthermore, the results of their study also showed that improved network coverage would result in better energy profile without additional deployed sensors, which in turn confirmed that better coverage and equipments life span could be obtained without higher spend.

**Kuthadi et al. (2022)** had explored the crucial role of data dissemination as a transmission technique within sensor networks for delivering information to end-users across interconnected frameworks. They had noted that Wireless Sensor Networks

(WSN) had long been a key part of the Internet of Things (IoT) and that in a typical setup for such a mesh network that various sensors within the network could all collect information and send it back to the web via a router. The authors had argued that the conventional approaches of WSN data dissemination were not able to meet anymore the new requirements of the IoT systems and applications. They had seen that finding a prosperous transmission link with optimal energy was still a bottleneck in IoT communication systems. Thus, then had been introduced an Optimized Energy Management Model for Data Dissemination (OEM-DD) to optimally enhanced energy optimization across the boards of all sensor nodes within the IoT paradigm. The approach presented in this work provided an efficient data propagation resultation for the single source to multiple destination problem when non-adaptive routing is considered. Furthermore, the static routing took advantage of a distributed cooperation scheme and a priority-based task-scheduling rule embedded with an integer model in order to enhance energy and decoding grouping of datas in the sensor network. Optimization carried out by non-adaptive routing w.r.t its energy conservation had made lower power requirement and least energy consumption per sensor node, which was contributing in better data transfer/pack processing even a fit severe tie up with respect of data packet. Their experimental results showed that the OEM-DD model could boost the data transmission rate up to 96.33%, while at the same time saving up to 20.11% of energy in WSNs, which were crucial part of the IoT landscape.

**Zhang et al. (2022)** had explored the broad development prospects of wireless sensor networks within intelligent distribution networks, acknowledging that numerous types of wireless sensor network topologies and communication protocols existed. They had already pointed out the pressing problem on design of low-power wireless sensor networking scheme for application of the scenarios like distribution station buildings, column transformers and box transformers in intelligent distribution networks. Their research has studied and compared a series of wireless network topologies in order to design wireless intelligent distribution networks as well as analysing the wireless communication protocols. They had already undertaken certain standard solutions by including the actual distribution station building features, column transformer and box transformer, and so had chosen a proper wireless sensor network communication protocol. At last, they provided a network design scheme specifically for such kind of smart distribution network cases. Their work had made contributions to achieving high-quality solutions to facilitate the widespread application of wireless sensor networks in intelligent distribution systems.

**Abbas et al. (2021)** had explored the role of Wireless Sensor Networks (WSNs), which typically comprised numerous wirelessly connected sensors designed to gather data from geographically dispersed fields and transmit it to a centralized database. They intimated that WSNs were a convenient instrument for the monitoring of extensive gas distribution infrastructure such as that of Sui Northern Gas Pipelines Ltd., Pakistan. Their work had analyzed the behavior of several routing protocols in gas pipeline monitoring scenario. A quasi-experiment to evaluate the performance of several routing protocols for WSNs within gas distribution pipeline networks had revealed useful information regarding the functionality, performance, and critical system design parameter. They created a list of topics including the estimated network lifetime, the best deployment of nodes for full coverage, the impact of energy harvesting from the field, and the intelligent placement of the sink node, which they used to support the relevance of WSN design for pipeline monitoring. These aspects had been studied through the simulations that had considered real node geographical distribution, real power levels, and actual power requirement during various WSN activities. The simulation results had shown that a DDEEC driven WSN for a large-scale gas distribution network with several nodes could retain round about 99.9% of nodes as active for a benchmark time of 10 years.

**Mishra et al. (2020)** had investigated the critical challenges faced by wireless sensor networks, particularly highlighting the constraints of sensor nodes powered by limited battery sources. They had stressed that it is important to have reliable network coverage to facilitate periodic data communication to the Base Station, those implying long lifetime of the sensor nodes as well as an energy-efficient coverage to become important issues to address. Their work had presented a corona-shaped energy aware node deployment model for non-uniform sensor nodes with limited sensing, subject to the probability density function (PDF), recently. They determined the optimal number of nodes to be placed in every corona with the help of this PDF. Also, they had tested the performance of the proposed scheme by simulation including network coverage, energy balance and lifetime with respect to different parameters. The authors concluded that the inherent properties of the designed PDF contributed to more uniform distribution of nodes, which led to denser coverage on each corona layer which, in response, could encounter energy hole (coverage dot hole) and hole (coverage hole) issues in the field of sensors. Finally, the work showed that this strategic placement strategy may increase the network lifetime of the WSN.

**Pavithra and Babu (2019)** had examined the role of Wireless Sensor Networks (WSNs) as comprising numerous sensor nodes distributed over a vast area for transmitting data packets efficiently from one point to another. They had indicated that the main methods associated with WSNs consisted of clustering, power management, network life extension and both secure and efficient information passing among the interconnected mobile nodes. They explained in their study that clustering consists in grouping nodes for route of data packets in "clusters" to transmit around the cluster members through cluster heads with the aim to maximize network lifetime. To optimize this, they employed a hybrid technique of K-Means clustering with Hybrid Ant Colony and Particle Swarm Optimization (HACOPSO) that formed a hierarchical structure of cluster heads and achieved better power consumption with the increase in hierarchy levels. It was also explained how Ad hoc On-Demand Distance Vector Routing (AODV) protocol was working using route discovery and route maintenance that they have defined. Finally, it was demonstrated that their proposed "K-Means-HACOPSO" technique could facilitate the accuracy of the data transfer from source to destination and could also achieve enhanced throughput, in terms of PDR, packet loss, end-to-end delay, and energy utilization in a secure network environment.

**Mittal et al. (2018)** had discussed that wireless sensor networks (WSNs) comprised densely distributed nodes intended to observe and respond to events occurring within a sensor field. Moreover, they had shown that there were difficult tasks about the design issues of cluster-based routing protocols: energy control as well as lifetime enhancement network. The authors have stressed in their work that clustering has been found to be very energy efficient way of data gathering and minimizing energy drain down while organizing nodes under certain groups. However, they had pointed out in clustering protocols, cluster heads (CHs) were further weighted in managing many cluster activity functions. As they had witnessed, wrong choice of these CHs, resulted in higher usage of energy and the decrement of WSN performance. So it is argued that the efficient CH selection and load balance distribution was required for the prolonged lifetime of WSNs in the literature. It was also reported there that balanced load clustering is an NP-hard problem, and it should also satisfy the ability to achieve solutions with exploration of the entire solution space. As a potential algorithm, they introduced spider monkey optimization (SMO), a new evolutionary algorithm based on foraging behaviour of spider monkeys has also been successful in optimizing benchmark functions and antenna design. The SMO-based threshold-sensitive energy-efficient clustering protocol was presented by them [ 23] in their research work which was to extend the network lifetime and stability period of the network. They also introduced two-hop communication between CHs and BS to balance the load of far CHs and to save the energy. Their experiments showed that the proposed protocol was superior to the existing solutions in energy consumption, system lifetime, and stability period.

## III. RESEARCH METHODOLOGY

**Research Design:** This study employs a **quantitative research design** focused on modeling and analyzing energy consumption patterns within Wireless Sensor Networks (WSNs). The methodology integrates theoretical modeling, simulation, and performance evaluation to assess energy-efficient strategies and their impact on network lifetime and reliability. ***(Abbas, et.al 2021).***

**Data Collection**

- **Literature Review:** Comprehensive analysis of existing energy-aware protocols (e.g., LEACH, PEGASIS, TEEN) and emerging technologies like energy harvesting and wireless power transfer.
- **Simulation Data:** Data generated through network simulators (such as MATLAB-based custom simulators) to replicate typical WSN deployment scenarios with varying node densities, communication ranges, and traffic patterns.

**Mathematical Modeling**

- Development of analytical energy models incorporating transmission, reception, processing, and idle state energy consumptions.
- Formulation of models for clustering algorithms, duty cycling, and load balancing.
- Modeling of residual energy dynamics and energy hole formation near sink nodes.

**Simulation Setup**

- **Network Topology:** Randomly deployed sensor nodes within a specified area; base station positioned at a fixed location.
- **Parameters:** Number of nodes, initial battery energy, packet size, transmission distance, duty cycle periods.
- **Protocols Tested:** Implementation of energy-efficient protocols such as LEACH and duty cycling mechanisms.

- **Performance Metrics:** Energy consumption, network lifetime (time until first node dies and network partition), data delivery ratio, and coverage.

**Analysis Techniques**

- Statistical analysis of energy consumption patterns across nodes to identify imbalances and critical regions.
- Evaluation of network lifetime improvements by comparing baseline protocols with energy-aware adaptations.
- Trade-off analysis between energy savings and network performance metrics like latency and packet loss.
- Sensitivity analysis on protocol parameters (e.g., cluster head probability, duty cycle ratios).

**Validation**

- Validation of the proposed models and simulation results against benchmarks reported in established literature.
- Cross-verification through multiple simulation runs with varied random seeds to ensure robustness.

**Tools and Software**

- Use of network simulators (e.g., MATLAB) for modeling and simulation.
- Data analysis and visualization with tools such as MATLAB, Python (NumPy, Matplotlib).

## IV. MATHEMATICAL MODEL

**Energy Consumption Model**

The total energy consumed $Etotal$ by a sensor node in WSN over time T can be expressed as:

$$Etotal = Etx + Erx + Eproc + Eidle$$

**Where**

- $Etx$: Energy consumed in transmitting data
- $Erx$: Energy consumed in receiving data
- $Eproc$: Energy for processing and computation
- $Eidle$: Energy consumed in idle state

**Transmission and Reception Energy**

According to the first-order radio model:

$$Etx(k,d) = Eelec \cdot k + \epsilon amp \cdot k \cdot d^n$$

$$Erx(k) = Eelec \cdot k$$

Where:

- $k$: Number of bits
- $d$: Distance between transmitter and receiver
- $n$: Path loss exponent (typically $2 \le n \le 4$)
- $Eelec$: Energy dissipated to run the transmitter/receiver circuitry (J/bit)
- $\epsilon amp$: Energy for amplifier (J/bit/m$^2$ or J/bit/m$^4$)

**Cluster Head Rotation (LEACH Protocol)**

Let:

- N: Total number of nodes
- p: Desired percentage of cluster heads
- r: Current round number

Cluster head probability threshold T(n)is given by:

$$T(n) = \begin{cases} \dfrac{p}{1 - p.(r \quad mod \ \frac{1}{p})}, if\ n \in G \\ 0, \qquad\qquad\qquad otherwise \end{cases}$$

Where G is the set of nodes that have not been cluster heads in the last $\frac{1}{p}$ rounds.

**Energy Hole Formation Near Sink**

For nodes near the sink forwarding data from others, the **load $L_i$** on a node i is:

$$L_i = D_i + \sum_{j \epsilon N_i} f_{ji}$$

Where:

- Di: Local data generation by node i
- fji: Data forwarded from node j to i
- Ni: Set of upstream nodes forwarding data to i

The **residual energy** $Eres(i, t)$ at time t is:

$$E_{res}\ (i,t) = E_{init}(i) - \int_0^t p_i(\tau) d\tau$$

Where:

- $Einit(i)$: Initial energy
- $Pi(t)$: Power consumption at time t

**Duty Cycling Model**

Let Tcycle be the total cycle time, Tsleep and Tactive be sleep and active durations respectively. Then:

$$D = \frac{T_{sleep}}{T_{cycle}}\ (Duty\ cycle)$$

$$E_{dc} = E_{active} \cdot (1 - D) + E_{sleep} \cdot D$$

Where:

- Edc: Average energy consumed per cycle
- Eactive: Energy consumed during active state
- Esleep: Energy consumed during sleep state

**Data Aggregation Energy**

When a cluster head aggregates data:

$$Eagg = Eda \cdot k$$

Where:

- Eda: Energy for data aggregation per bit
- k: Total bits from member nodes

## V. FINDINGS AND CONCLUSIONS

**Findings:** Examining the energy distribution in a WSN demonstrates that energy management is the key for the lifespan and reliability of the network. Sensor nodes, with limited power supply on battery, consume most of their energy in wireless communication, i.e., sending and receiving data. This relatively high energy consumption for communication has emphasized the role of energy-conscious protocol design. One of the great problems discovered is the unequal pattern of energy consumption among sensor nodes. Nodes closer to the base station or sink nodes take extra communication loads, because they also forward data of other nodes, which favours the rapid drain of energy in these important regions. This asymmetric energy will often lead to "energy holes" areas where nodes have all died and where network partitions and coverage holes may appear substantially degrading the network operation and data collection efficiency.

Several efficient techniques such clustering algorithms, adaptive routing protocols, duty cycling and data aggregation algorithms are able to mitigate the adverse effects of energy exhaustion by balancing workloads and reducing excessive and redundant data transmissions. Rotating cluster heads through protocols like LEACH is such an example of how early node failures and energy consumption are balanced. Likewise, duty cycling techniques help to save energy by letting the nodes to sleep during the time slots in which they are idle without degrading connectivity. New approaches, like energy harvesting (e.g., from solar, thermal or vibration sources) and wireless power transfer (WPT), offer promising ways to scavenge energy for sensor nodes self-sustenance. The devices would greatly extend network lifetime and relieve the logistical burden of changing batteries, eliminating the need for repeated and difficult battery replacement in hard-to-reach locations. But there is a trade-off: between aggressive energy savings and preserving the performance of the network. Methods that can significantly diminish the energy consumption may add various forms of delays; causing more packet losses or loss of fidelity in the data – this requires providing protocols adaptive to the degree of re-sources that compromise the energy saving against the quality of communication for given net-work states and application interest. The variety of application domains (e.g., environmental monitoring and industrial automation, healthcare, military surveillance) additionally imposes difference in energy management algorithms taking into account the specific operating context and the service quality requirements.

**Conclusions:** Finally, distribution and management of energy is considered as the heart of WSNs for attaining sustainable operations. Efficient energy saving solutions are able to prolong network lifetime, ensure stable data transmission, and maintain sensing coverage. Energy aware routing, load balancing, duty cycling and data aggregation are the basic for existing energy efficient protocols. Meanwhile the combination of emerging energy harvesting and wireless power transfer technologies presents great opportunities to address the inherent limitations of battery energy. There is thus no silver bullet for sensor networking: With the conflicting design requirement of high energy efficiency simultaneously with network performance, the developed protocols need to adapt and reflect the changing environment and conditions to tune their own operations in a way that meets the desired energy optimality while maintaining reliable communication and application characteristics. The development of such intelligent mechanisms must be a priority for further research together with hardware energy efficiency improvements and autonomy of energy acquisition. Finally, an improved energy-efficient WSN technology will allow for more reliable, wider range and virtually maintenance-free sensor deployments, making their use viable in such applications as environmental monitoring, smart cities, health care systems, and defense. Such advancement will further enable WSNs to serve as a key technology in addressing pervasive sensing and smart automation.

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