A Modified Energy Enhancement in WSN Using the Shortest Path Transmission Technique

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***Abstract*—This study introduced a novel energy enhancement approach for Wireless Sensor Networks (WSNs) by leveraging the shortest path transmission technique to minimize energy consumption and extend the network's lifetime. Unlike traditional methods that heavily relied on cluster heads (CHs) for data transmission, our model proposed a non-cluster-based routing algorithm, utilizing Dijkstra's algorithm to identify the most energy-efficient paths for data transmission. Simulation results, based on varying node densities (100, 200, and 300 nodes) within a 200x200 network area, demonstrated the effectiveness of our approach. Our findings indicated a significant reduction in energy consumption, with the network lifetime extending to approximately 100,000 rounds, surpassing traditional LEACH-based and other related protocols. This enhancement not only promised a sustainable WSN deployment but also offered a scalable solution adaptable to different network sizes and configurations.**

Keywords-Wireless Sensor Network; Network Lifetime; and Cluster Head; Shortest

I. INTRODUCTION

In the realm of modern electronics, sensors emerge as pivotal elements, endowed with the dual capabilities of monitoring environmental variables—such as temperature, pressure, and humidity—and communicating this data to base stations or peer devices. This dual functionality has propelled sensor technology to the forefront of advancements in fields ranging from surveillance and monitoring to the Internet of Things (IoT) and telecommunications. The intrinsic small size of sensors mandates an optimization of energy consumption to maximize their utility, a challenge that becomes even more pronounced in the configuration of Wireless Sensor Networks (WSNs).

WSNs, characterized by the interconnectivity of sensor nodes over wireless mediums, have become integral to the infrastructure of telecommunications, notably in cellular network technology. Despite the apparent simplicity of mobile devices to the end-user, these devices are complex assemblies of multiple sensors, the collective functionality of which defines the device's capabilities. This complexity underscores the importance of efficient sensor operation, particularly in terms of energy consumption, for the sustainability of WSNs.

Historical and ongoing research underscores the persistent challenges in deploying WSNs, notably the issue of energy efficiency. Traditional energy-efficient strategies, such as the Low Energy Adaptive Clustering Hierarchy (LEACH) protocol, have laid the groundwork for optimizing energy use in WSNs. LEACH and its derivatives, including concepts like MOD-LEACH and PEGASIS, have significantly advanced the field. However, these models often result in uneven energy consumption among nodes, with nodes serving as cluster heads (CHs) or relay points depleting their energy reserves at a faster rate than their counterparts. This imbalance presents a critical limitation to the operational longevity and reliability of WSNs.

In response to these challenges, our study introduces a novel approach that diverges from the cluster-based paradigms by employing a shortest path transmission technique aimed at equalizing

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energy load across the network. Inspired by the energy model of [1], which sought the minimum energy route for data transmission but was limited by its cluster-based operation layout, our methodology explores the synergy between shortest path determination and energy efficiency. Unlike the traditional cluster-based approaches, our model utilizes Dijkstra's algorithm to dynamically identify the most energy-efficient transmission paths, thereby minimizing overall energy consumption and extending the network's operational lifetime.

By examining the correlation between minimum energy routes and shortest paths, this study not only addresses the pressing issue of energy efficiency in WSNs but also proposes a scalable, robust framework for future network deployments. Our approach marks a significant departure from conventional methodologies, offering a pathway to more sustainable, efficient WSN operations.

II. REVIEW OF RELATED WORKS

The quest for energy efficiency in Wireless Sensor Networks (WSNs) has catalyzed a plethora of research, focusing on innovative routing protocols that promise to extend the operational lifespan of these networks. [2] delved into existing energy-efficient routing mechanisms, offering a comparative analysis between the Modified LEACH protocol and a Mobile sink-oriented improvement over the PEGASIS-based routing protocol. Their study, utilizing MATLAB simulations, demonstrated superior performance of the Mobile sink-enhanced PEGASIS protocol (MIEEPB) over Modified LEACH, signifying the potential of dynamic sink mobility in enhancing energy efficiency.

The paper [3] introduced the "Position Responsive Routing Protocol" for WSNs, which was benchmarked against the established LEACH and CELRP protocols. Their findings underscored significant advancements in energy efficiency and overall network performance, suggesting that positional awareness within routing decisions could substantially benefit WSN sustainability. In a novel approach to routing, [4] explored the deployment of multiple mobile sinks within clustered networks, investigating how the number of mobile sinks influences network lifetime. Their methodology, which involved segmenting the network into clusters, provided insightful data on optimizing mobile sink deployment for extended network durability. Researchers in [5], also explored the use of mobile sinks technique to improve network efficiency in WSN through the Stable Election Protocol. Their simulations outcome showed a significant improvement in network performance and energy consumption of WSN through the SEP based algorithm. In contrast to the conventional MGEAR, [6] proposed LEAG, a hybrid protocol that uses Zigbee techniques for optimized routing and energy reduction. Gateway nodes enable effective data aggregation and transmission to base stations, and their findings showed improvement in network performance and energy efficiency. Also, in [7], authors proposed an enhanced version of the MGEAR protocol intended for homogenous wireless sensor networks. The methodology optimized cluster-head selection based on energy considerations in heterogeneous wireless sensor networks (HWSNs) which increased the throughput as well as network longevity. When compared to different existing protocols, simulation results show significant gains in network lifetime and performance. Researchers in [8], explored MW-LEACH protocol presented a novel clustering hierarchy that chooses cluster leaders according to residual energy, inter-cluster distances, and the ideal member node count. Compared to existing protocols, MW-LEACH exhibited reduced complexity, faster operation, longer network lifetime, and improved fault tolerance by giving priority to nodes with high residual energy and closeness to the network center. The results of experimental evaluations show that MW-LEACH performs better than previous protocols in throughput, energy consumption, packet delivery, network longevity, and latency. In comparison to non-clustering techniques [9] emphasized the significance of clustering algorithms for improving energy efficiency in Wireless Sensor Networks (WSNs). Current approaches suffered from overhead during cluster formation and usually use periodic clustering and cluster head rotation. A unique routing protocol was suggested to mitigate this challenge. The simulation results showed that this protocol is more energy-efficient than existing ones like LEECH and HEED, as it chooses cluster heads based on residual energy, density, and base station distance. [10] proposed a unique cluster head selection protocol that utilizes the existing cluster head to determine the subsequent leader based on a combination of residual energy and proximity metrics. This method aimed to minimize energy dissipation and enhance the network's longevity by ensuring that the most energetically viable node assumes the cluster head role. [11] study suggested the Optimal Multi-hop Path Finding Method (OMPFM), which finds effective multi-hop paths between cluster heads (CHs) and base stations (BS) to maximize power consumption and network lifetime. Through the use of pre-processing techniques and a genetic algorithm with a novel fitness function, OMPFM outperformed LEACH, GCA, EAERP, GAECH, and HiTSeC by significant margins in terms of first and last node die metrics.

Echoing the sentiment for minimum energy consumption, [1] developed a routing protocol that seeks the least energy-intensive path for data transmission from nodes to the base station. Employing the Hausdorff distance for calculating inter-cluster distances, their protocol optimized energy use across transmissions, offering a fresh perspective on energy-efficient data routing in WSNs. [12] contributed to the dialogue with an energy-balanced routing protocol that leverages the K-means++ algorithm for cluster formation and the Fuzzy Logical System (FLS) for cluster head selection. This approach not only facilitated balanced energy consumption across the network but also introduced a systematic method for cluster formation and leadership assignment, reflecting a growing trend towards algorithmic sophistication in WSN management. Previous study in [13] presented the EE_AC_DR protocol, which uses a Dijkstra Front-Back algorithm for effective data routing and scheduling, to reduce energy consumption in WSNs Large-scale simulations showed that the protocol enhanced network performance and cost-effectiveness by carefully choosing cluster heads and optimizing communication pathways, highlighting its potential to maximize WSN efficiency while consuming less energy. In order to improve security and efficiency in WSNs [14] presented the TBC-DBR method, which uses Dijkstra-based routing and trust-based clustering to provide safe data aggregation. Through simulations, it performed better than the LEACH algorithm, with reduced energy consumption and higher packet delivery rates. In [15], presented a novel method for minimizing latency and increasing network lifetime using Dijkstra's shortest path routing in conjunction with sleep-wake scheduling (DSRSS). Simulation analysis demonstrated this method's superior performance in energy reduction, making it a viable option for optimizing network longevity.

While these studies have collectively advanced our understanding and capabilities in energy-efficient WSN routing, the persistent challenge of equitable energy distribution among nodes remains a critical concern. The reviewed works primarily focus on optimizing routing protocols through cluster head selection, mobile sink deployment, and algorithmic pathfinding. However, most strategies inadvertently impose disproportionate energy burdens on certain nodes, hastening their depletion and, by extension, reducing the network's overall lifespan.

Our current investigation seeks to address this gap by proposing a modified energy enhancement model that diverges from the traditional reliance on cluster heads or fixed routing paths. Instead, it employs a shortest path transmission technique, predicated on the hypothesis that minimizing transmission distance and thereby energy expenditure can achieve a more balanced energy consumption across all nodes. This approach not only promises to extend the operational lifetime of WSNs but also introduces a scalable and flexible framework capable of adapting to varied network topologies and sizes, thus offering a significant contribution to the ongoing efforts in WSN optimization.

III. METHODOLOGY

We structured our methodological stages as follows:

IV. DEPLOYMENT STRATEGY

The deployment of sensor nodes in our study is conceptualized on a geometrically structured, rectangular grid, mirroring the strategic layout akin to a football pitch. This structured approach facilitates a uniform distribution of nodes across the designated area, with the central base station positioned at the midpoint of the rectangle to ensure optimal accessibility. Such a layout is pivotal for minimizing transmission distances and ensuring uniform energy consumption across the network. Key features of our deployment strategy include:

A. Uniform Distribution

Sensor nodes are evenly spaced within a rectangular grid, ensuring each node is equidistant from its neighbors, akin to the positions of players on a football pitch. This uniformity is crucial for maintaining consistent communication paths.

B. Central Base Station

The base station's central location is strategic, minimizing the maximum distance any node must transmit data, thereby optimizing energy usage.

C. Transmission Methodology

Contrary to traditional cluster-based approaches, our methodology does not rely on the election of cluster heads. Instead, data transmission follows a dynamic leader selection based on proximity and the shortest transmission path, significantly reducing the system's overall energy consumption. The core aspects of our transmission methodology include:

D. Dynamic Leader Selection

Each node, upon its turn to transmit, calculates the shortest path to the base station. The node along this path that receives the data acts as a temporary leader, a role that dynamically shifts as the data hops towards the base station.

E. Dijkstra’s Algorithm for Pathfinding

The shortest path for data transmission from any given node to the base station is determined using Dijkstra’s algorithm. This algorithm optimizes the route for energy efficiency, dynamically adjusting to the network's current state.

F. Operational Premises

The operational framework of our study is built on several foundational premises that ensure the integrity and efficiency of data transmission within the WSN:

G. Fixed and Centralized Base Station

The base station's position remains unchanged and centrally located to minimize transmission distances across the network.

H. Equal Energy Consumption

A fundamental goal is ensuring that energy consumption for data transmission and reception is equitable across nodes, achievable through adherence to the shortest path strategy.

I. Non-Hierarchical Node Status

All nodes operate on an equal footing, with no distinctions made for cluster heads, ensuring a democratic and energy-efficient data transmission process.

J. Timed Transmissions

Data transmissions are scheduled based on time slots, allowing for organized and predictable network behavior.

K. Single and Multiple Hops

Depending on a node's proximity to the base station, data can be transmitted directly (single hop) or through multiple hops, with the path determined by the shortest route algorithm.

L. Static Node Positioning

Nodes are stationary, simplifying the network topology and making the shortest path calculations more predictable.

M. Base Station-Initiated Communication

All communications are initiated by the base station, centralizing control and simplifying network management.

From our methodology, figure 1 illustrates the flow of data in a wireless sensor network, capturing the essential components and interactions among them. This diagram visually represents how sensor nodes collect and transmit data to the central base station, either directly or through relay nodes along the shortest energy path, based on energy-efficient routing without predetermined cluster heads.

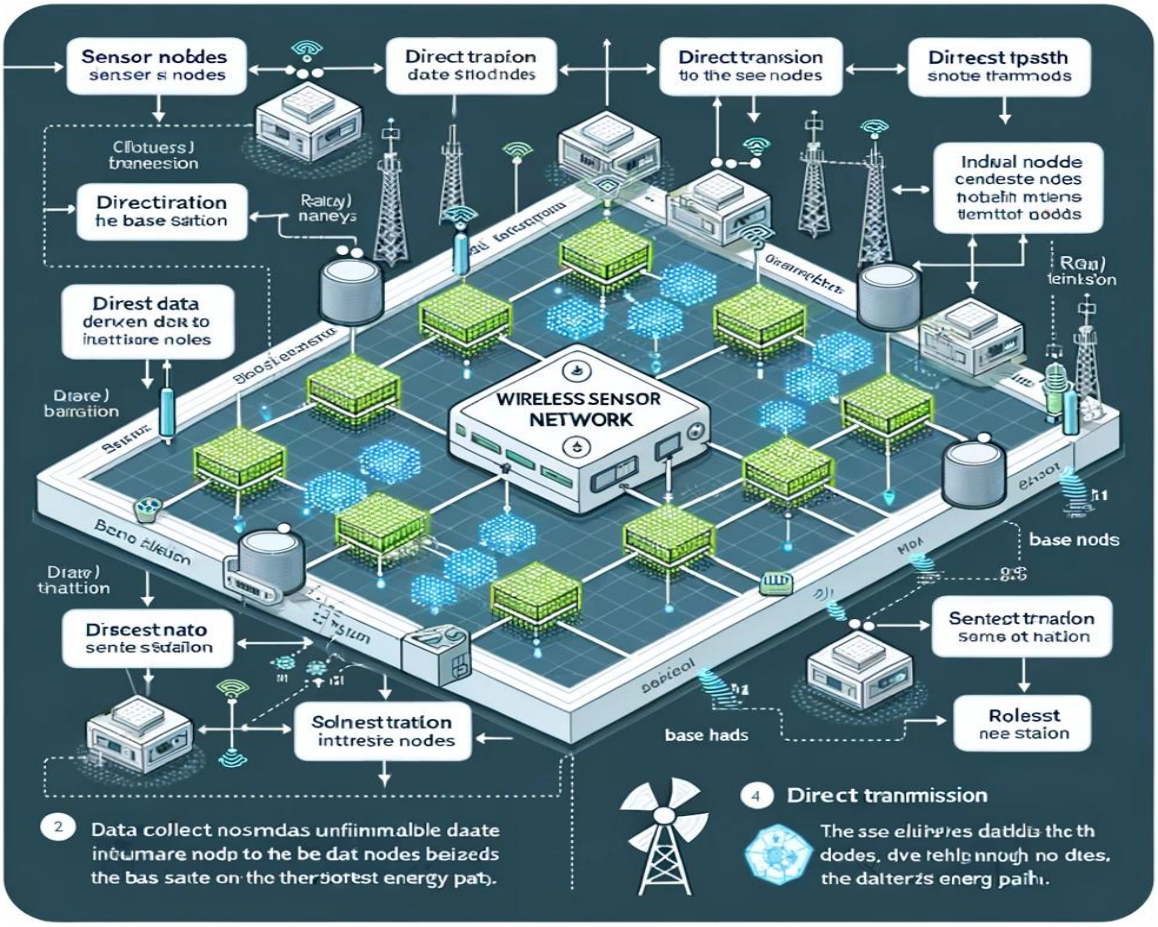

Figure 1. Model of researcher's methodological layout

V. ENERGY MODEL

Our study advances the energy model by innovating beyond the traditional Low Energy Adaptive Clustering Hierarchy (LEACH) protocol, as outlined by Paul and Dey (2015). The cornerstone of our model is the dynamic selection of transmission paths based on the shortest distance criteria, significantly diverging from LEACH's reliance on static cluster head elections. This approach inherently democratizes the role of cluster heads, distributing energy consumption more evenly across the network and thereby enhancing network longevity.

A. *Transmission Energy Model*

The transmission energy model is pivotal for calculating the energy expended during data transmission from a node to the base station. Unlike LEACH, where energy expenditure is concentrated around elected cluster heads, our model ensures that any node can assume the role of a temporary relay based on proximity and optimal path selection. The model is encapsulated by the equation:

$$E_{TX} = E_{elec} + E_{PL} \tag{1}$$

where:

- E_{TX} represents the total energy expended in transmission.

- E_{elec} is the energy dissipated per bit to run the transmitter or receiver circuit.

- E_{PL} denotes the power loss during transmission, calculated as $e_{fs} * (d_1 * d_2)$, e_{fs} representing the energy dissipated in the free-space model.

B. Receiver Energy Model

The receiver energy model calculates the energy consumed during data reception, essential for understanding the total energy dynamics of the network. It is expressed as:

$$E_{RX} = E_{elec} + E_{MP} \tag{2}$$

where, E_{RX} is the total energy consumption for receiving data, E_{elec} signifies the multipath fading channel's energy consumption, calculated as $e_{mp} * d_2^2$, with e_{mp} indicating the energy dissipated in the multipath model.

Our methodology introduces a pivotal shift by eliminating the need for cluster head elections, thereby reducing the redundancy and inefficiency associated with re-election processes. Every node, positioned within the shortest path to the base station, dynamically becomes a relay, optimizing the energy expenditure across the network. This model not only simplifies the operational mechanics but also ensures a more equitable distribution of energy consumption.

Furthermore, by integrating Dijkstra's algorithm for real-time calculation of the shortest transmission path, our energy model aligns with the operational realities of sensor networks, where maintaining energy efficiency is paramount. This alignment allows for adaptive path selection, ensuring that data transmission always follows the least energy-intensive route.

The proposed energy model underscores the importance of adaptive, path-optimized WSN operation. By systematically calculating energy consumption for potential routes and prioritizing the least costly paths, our model significantly extends the operational lifespan of WSNs. This approach not only demonstrates a considerable improvement over traditional methods but also provides a scalable framework adaptable to diverse network topologies and varying node densities.

In essence, our energy model provides a robust framework for enhancing WSN energy efficiency, highlighting the shift from clustered dependencies to a more fluid, path-optimized network operation. This advancement promises significant implications for the design and deployment of future wireless sensor networks, prioritizing sustainability and operational efficiency.

Assumptions:

- A fixed number of N sensor nodes are uniformly distributed in a rectangular area.
- All nodes have an initial energy E_{init} .
- The base station is centrally located.
- Nodes use a free space or multipath model for energy dissipation during transmission and reception, depending on the distance to the next hop.
- There are no cluster heads; instead, nodes relay data based on the shortest energy path.

C. Modified Energy Model

The energy dissipated for a node to transmit a k-bit message over a distance d is given by:

$$\begin{cases} E_{elec} \cdot k + e_{fs} \cdot k \cdot d^2 & if \quad d < d_0 \\ E_{elec} \cdot k + e_{mp} \cdot k \cdot d^4 & otherwise \end{cases} \tag{3}$$

Hence the energy dissipated to receive this message is:

$$E_{RX}(k) = E_{elec} \cdot k \tag{4}$$

Also the Network Lifetime Model is given as N is the total number of sensor nodes in the network, E_{init} is the initial energy of each sensor node, and $E_{consumed}(i)$ is the energy consumed by node i in one round of communication which includes both transmitting and receiving energy.

Thus the network lifetime T can be modelled as the minimum number of communication rounds that any node can participate in before depleting its energy:

$$T = \min_{i \in \{1,\dots,N\}} \left(\frac{E_{init}}{E_{consumed(i)}} \right) \tag{5}$$

$$E_{consumed}(i) = E_{TX}(i) + \sum_{J \in P_{i \to BS}} E_{RX}(j) \tag{6}$$

Where, $E_{TX}(i)$ is the energy consumed by node i to transmit data, $E_{RX}(j)$ is the energy consumed by node j to receive data, and $P_{i \to BS}$ is the set of nodes along the shortest path from node i to the base station (BS), excluding the transmitting node i.

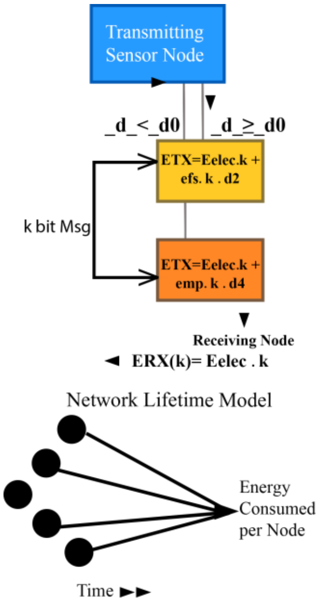

Figure 2. Energy Dissipation Model

VI. ALGORITHM: ENERGY-EFFICIENT DIJKSTRA'S ALGORITHM

Input: A graph G(V, E) represented by an adjacency matrix where each edge weight E_ij is the energy cost of transmission from node i to node j, and a source node s.

Output: The shortest paths and their energy costs from the source node s to all other nodes in V.

```
Procedure DijkstraEnergyBased(G, s)
    Initialize energyCosts[] := {∞, ..., ∞} with size |V|
    Initialize prevNode[] := {null, ..., null} with size |V|
    Initialize visited[] := {false, ..., false} with size |V|
    Set energyCosts[s] := 0

    While there exists a node u in V that is not visited
        Select u such that energyCosts[u] is minimum and visited[u] is false
        Set visited[u] := true

        For each neighbor v of u in V
            If visited[v] is false and E_uv > 0
                Set tempCost := energyCosts[u] + E_uv
                If tempCost < energyCosts[v]
                    Set energyCosts[v] := tempCost
                    Set prevNode[v] := u
                EndIf
            EndIf
        EndFor
    EndWhile

    For each node v in V
        Initialize path[] := empty list
        Set current := v

        While prevNode[current] is not null
            Insert current at the beginning of path[]
            Set current := prevNode[current]
        EndWhile

        If path is not empty
            Insert s at the beginning of path[]
        EndIf

        Output the path from s to v and its total energy cost energyCosts[v]
    EndFor
EndProcedure
```

VII. ALGORITHM EXPLANATION

A. *Initialization*

`energyCosts[]`: An array holding the cumulative energy cost from the source node `s` to every other node. It is initialized with infinity (∞) to represent that at the start, the cost to reach any node is unknown and assumed to be very high.

`prevNode[]`: An array that tracks the immediate predecessor of each node on the path from the source. It is used to reconstruct the shortest path once the algorithm completes. Initialized with `null` to indicate no predecessors have been determined yet.

`visited[]`: A boolean array indicating whether a node has been visited and its minimum energy cost has been determined. Initially, all nodes are unvisited.

B. *Algorithm Process*

1) Selecting the Node with Minimum Energy Cost: At each iteration, the algorithm selects the unvisited node `u` with the smallest known energy cost from the source. Initially, this will be the source node itself, as its energy cost is zero.

2) Updating Neighbor Costs: For each neighbor `v` of the selected node `u`, if `v` is unvisited and the edge `E_uv` (representing the energy cost from `u` to `v`) is greater than zero, the algorithm calculates a temporary cumulative energy cost (`tempCost`) from the source to `v` via `u`.

- If `tempCost` is less than the current known cost to reach `v`, the algorithm updates `energyCosts[v]` with `tempCost` and records `u` as `v`'s predecessor in `prevNode[v]`.

3) Path Reconstruction: Once all nodes have been visited, the algorithm reconstructs the shortest path for each node by tracing back through the `prevNode[]` array. Starting from each node `v` and moving through its recorded predecessors, the path is built in reverse until the source node is reached.

- The path for each node, along with its total energy cost (`energyCosts[v]`), is output by the algorithm.

C. *Relation to Energy Cost Considerations*

The edge weights `E_uv` in your network graph represent the energy costs associated with transmitting data from one node to another. In the context of your study, these costs are calculated based on the distance between nodes and the energy dissipation model (free space or multipath depending on the distance).

By selecting paths that minimize these energy costs, the algorithm aligns with the goal of your study to ensure energy-efficient routing in the WSN. It ensures that data is transmitted along the routes that will conserve the most energy, extending the operational lifetime of the network.

Since the algorithm finds the path with the minimum energy cost to each node, the first node to deplete its energy will define the network lifetime `T`, as per the study's scope. This node's energy expenditure rate, dictated by the paths chosen by the algorithm, will directly impact the overall network lifetime.

The pseudocode for the Energy-Efficient Dijkstra's Algorithm is designed to find the most energy-efficient paths in a WSN. This is crucial for your study's objective to maximize the network's operational lifetime while ensuring that data is relayed to the central base station in the most energy-conserving manner possible.

The detailed explanation of the algorithm's steps, with emphasis on energy cost considerations, demonstrates the algorithm's appropriateness for your study and its potential for extending the network's lifetime, which is a key metric for the performance and sustainability of WSNs.

VIII. SIMULATION PARAMETER

The simulation framework is designed to systematically evaluate the performance of the proposed energy model under varying conditions. Key parameters are defined as follows:

Number of Nodes: Simulations were conducted with node sets of 100, 200, and 300 to assess scalability and performance under different network densities. This variation allows us to explore the model's adaptability to networks of varying sizes.

Network Area: The network is modeled within a 200m x 200m square area. This dimension provides a balanced field for assessing the effectiveness of the shortest path algorithm across different distances and densities.

Channel Type: A wireless channel is utilized, reflecting the operational environment of real-world Wireless Sensor Networks (WSNs). This choice ensures the simulation reflects practical constraints, such as signal attenuation and interference.

Source Node Configuration: Among the nodes, 99 are designated as sensor nodes equipped with a UDP agent, simulating a typical WSN scenario where multiple nodes collect and transmit data to a central node or sink.

Number of Cluster Heads: Although our model moves away from traditional cluster head elections, for comparative analysis, a baseline of 4 cluster heads was established. This parameter is crucial for benchmarking against LEACH-based models.

Antenna Model: An Omni Antenna model is adopted for all nodes, facilitating uniform signal propagation in all directions. This choice simplifies the simulation and aligns with common WSN deployments.

Interface Queue Type: The Queue/Drop Tail/PriQueue mechanism is employed to manage data packets at the node level. This queuing model allows for realistic simulation of packet handling, prioritization, and potential congestion scenarios.

Initial Energy of Sensor Nodes: Each node is initialized with an energy reserve of 5 Joules, setting a uniform starting point for energy depletion studies. This parameter is pivotal for analyzing the network's operational longevity.

Time for Each Round: The simulation progresses in rounds, each lasting 5 seconds. This temporal framing facilitates the observation of energy consumption patterns and network behavior over time.

Transmission Power: Set at 50 picojoules (pj), this parameter dictates the energy cost of data transmission, a critical factor in evaluating the energy efficiency of the proposed model.

Receiving Power: The energy cost for receiving data is set at 10 picojoules (pj), allowing the differentiation between transmission and reception energy expenditures.

Transmission Range: A maximum range of 40 meters for data transmission is established, determining the reach of each node's signal. This range affects the calculation of the shortest path and the selection of relay nodes.

IX. ANALYSIS AND RESULT

Our simulations of the Wireless Sensor Network (WSN), employing the shortest path technique and Dijkstra’s algorithm with a load-balancing strategy, have provided significant insights into the distribution of energy consumption and workload across the network. The results, illustrated in Figures 1, 2, and 3, underline the efficacy of our proposed model in enhancing network performance and energy efficiency.

Figure 4 showcased a uniform grid layout simulating the strategic distribution of cellular towers or small cell base stations within an urban setup. This configuration optimized coverage with minimal overlap and coverage gaps, ensuring that each node had the opportunity to transmit directly to the centrally located base station or relay through adjacent nodes efficiently. This model demonstrated that optimal placement and routing, based on the shortest path principles, could significantly reduce operational costs and improve sustainability by minimizing transmission power. The findings suggest that such a grid layout, by facilitating strategic infrastructure planning, allows for enhanced coverage and service quality, making it an essential blueprint for the deployment of cellular networks in urban environments.

The simulation graph in Figure 5 depicted a Wireless Sensor Network with a minimum energy path for data transmission from sensor nodes to the central base station. The visualization of the most energy-efficient route, indicated by the green line, highlighted how distance and energy cost minimization are critical for preserving sensor nodes' limited energy resources. This dynamic routing capability is vital for prolonging the operational life of each sensor node and, consequently, the entire network. The simulation emphasized the importance of a deliberate planning strategy to ensure uniform node distribution, thereby guaranteeing coverage, connectivity, and multiple potential routing paths. This insight is invaluable for real-world WSN deployment, suggesting that a uniform grid layout significantly contributes to consistent connectivity and efficient routing protocol implementation.

Figure 6 presented a plot of the minimum energy level of nodes over time, measured in simulation rounds. The graph illustrated a steady, linear decline in energy levels, culminating in the depletion of energy reserves after approximately 100,000 rounds. This decline indicated a consistent energy consumption rate among the network's most demanding nodes and defined the network's lifetime by the point at which the first node's energy was exhausted. The initial setting of 2 joules for node energy levels and the observed network lifetime underscored the critical nature of managing energy consumption within cellular networks to ensure sustainability and cost-effectiveness. Moreover, the graph advocated for the necessity of load balancing across the network to extend the operational lifetime, suggesting strategic traffic routing through less congested cells as a viable energy conservation strategy.

The simulation results have provided profound insights into the energy dynamics and operational efficiencies achievable within a WSN through the implementation of shortest path routing and load-balancing strategies. These findings not only demonstrate the potential for substantial improvements in network longevity and reliability but also offer a predictive model for energy management and sustainability within cellular network deployments. For cellular operators, these insights are instrumental in ensuring network reliability and optimizing energy usage, contributing significantly to the ongoing efforts in the development and optimization of energy-efficient WSNs for various applications.

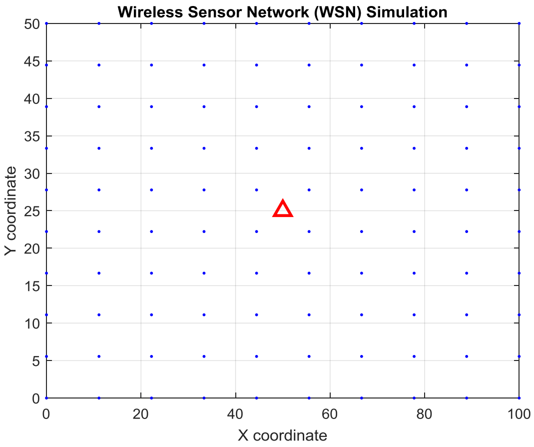

Figure 3. Wireless Sensor Network (WSN) Simulation

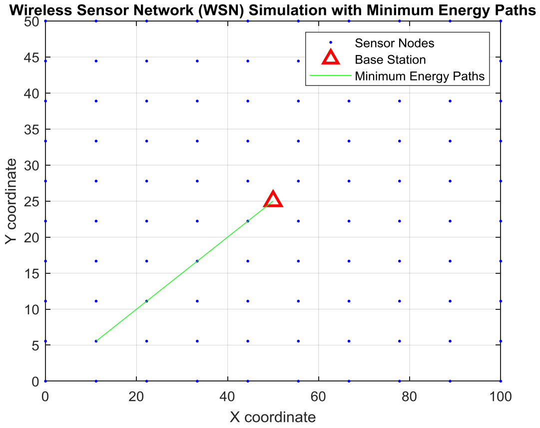

Figure 4. Wireless Sensor Network Simulation with Energy Paths

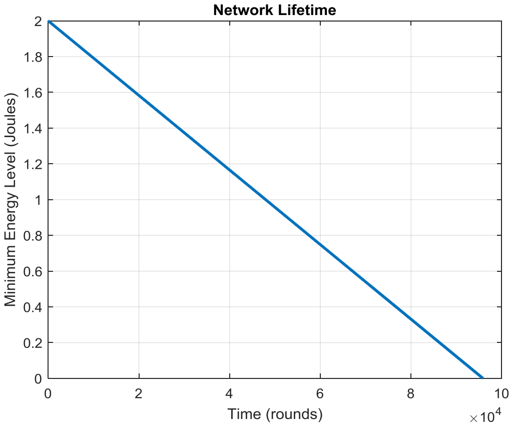

Figure 5. Network Lifetime

X. COMPARATIVE EVALUATION OF MINIMUM ROUTING ENERGY PATH

Network Topology and Energy Consumption: Our study introduces a paradigm shift in the design of Wireless Sensor Networks (WSNs), transitioning from the conventional ad-hoc network topology, wherein nodes serve both as data collectors and routers, to a more streamlined model. This novel approach simplifies the network structure, allowing nodes to communicate directly with the base station or via a singular relay. Such a configuration markedly reduces the incidence of node failure, diminishes the potential for signal obstruction, and curtails the overall energy expenditure inherent in multi-hop transmissions.

Advancements over Previous Models: Contrary to the ad-hoc WSN models, where energy consumption patterns were erratic and unpredictable due to the variable number of hops and the dynamic nature of cluster head elections, our model demonstrates a systematic reduction in energy usage. By leveraging a direct or single-relay communication protocol, the network achieves a significant decrease in operational energy demand. This is evidenced by a more gradual decline in energy levels across the network, as depicted in our simulation results.

Sustainability and Network Longevity: The efficiency of our proposed model is further exemplified by the extended network lifetime. Traditional models often reported a steep increase in the number of non-functional (dead) nodes over time, directly impacting network reliability and data integrity. In contrast, our simulations exhibit a controlled, linear reduction in energy levels (Figure 3), indicating a sustainable usage pattern and prolonged network operability.

Predictability and Uniformity in Energy Consumption: A notable advantage of our approach is the predictability and uniformity in energy consumption among the nodes. Previous studies highlighted a rapid depletion of energy reserves in nodes serving as cluster heads, leading to uneven energy distribution and shorter network lifetimes. Our methodology circumvents this issue by distributing the energy load evenly across the network, ensuring that no single node bears a disproportionate burden of the energy expenditure. This not only enhances the network's overall energy efficiency but also contributes to a more balanced and equitable operational framework.

XI. IMPLICATIONS FOR WSN DEPLOYMENT

The implications of our findings are multifaceted, extending beyond theoretical advancements to practical applications in WSN deployment and management. By demonstrating a viable alternative to ad-hoc and cluster-based topologies, our study paves the way for the development of more energy-efficient, reliable, and sustainable WSNs. Such networks are crucial for a wide array of applications, including environmental monitoring, smart cities, healthcare, and industrial automation.

In summary, our comparative evaluation underscores the superiority of our proposed model in terms of energy efficiency, network longevity, and operational reliability. By adopting a simplified communication structure and optimizing the routing mechanism, we present a compelling solution to the perennial challenges of WSN design and implementation. This study not only contributes to the existing body of knowledge but also sets a new benchmark for future research in the domain of wireless sensor networks.

XII. CONCLUSIONS

The study successfully demonstrated the potential of a modified energy enhancement model in WSNs through the implementation of the shortest path transmission technique. By moving away from the conventional cluster-based routing protocols and employing an energy-efficient Dijkstra's algorithm, we observed a substantial improvement in the network's energy conservation and operational longevity. The simulation results clearly indicated a more gradual and uniform energy depletion across the network, thereby ensuring a predictable and extended network lifetime. This approach not only addressed the inherent challenges of energy consumption in WSNs but also provided a scalable and efficient framework for future deployments in various applications. Our study contributed to the ongoing efforts in optimizing WSNs, offering a viable solution that could significantly impact the design and implementation of energy-conscious wireless sensor networks in real-world scenarios.

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